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Life-Cycle Assessment of Concrete: Decision-Support Tool and Case Study Application

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by

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Abstract

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Professor Arpad Horvath, Chair

Globally, construction and operation of the built environment is recognized as a significant source of greenhouse gas emissions (GHG). About 40% of anthropogenic GHG and 40% of raw materials use are assigned to buildings. Concrete, the most widely used man-made material, is used in buildings because of its flexibility and adaptability, its low maintenance requirements during the service life of the structures, and the economic and widespread accessibility of its constituents. The substantial production and consumption of global concrete manufacturing accounts for more than five percent of the human-related carbon dioxide emissions annually, mostly attributable to the production of cement clinker. However, environmental impacts are not limited to only GHG emissions. The analysis and quantification of the overall environmental impacts of concrete manufacturing and its application in building projects requires a holistic approach that is known as life-cycle assessment (LCA).

In this dissertation, a new process-based LCA tool (GreenConcrete LCA) was developed for the purpose of evaluating the environmental impacts of concrete from extraction of its raw materials to the end-of-life stage. The GreenConcrete LCA has MS Excel and web versions, both of which have the capability of calculating and comparing the LCA of different concrete mixtures designed for specific project purposes. In the tool, not only the direct but also the supply-chain impacts of manufacturing processes of concrete and its materials are evaluated. The integration of regional variations and technological alternatives within the tool offers a wide range of applicability and flexibility for users in the U.S. and worldwide. The new tool will ultimately allow policy makers, researchers, architects, civil engineers, and government agencies to assess the environmental sustainability of concrete in various building construction projects.

With the help of the tool, sensitivity analysis was conducted. GWP reduced significantly with the replacement of ordinary portland cement with supplementary cementitious materials (SCMs) such as fly ash and slag in concrete. Additionally, it was shown that environmentally and structurally advantageous concrete mixtures could be made with high-volumes of fly ash and limestone. A wide range of early and long term strengths were attainable depending on the selected mixture proportion. GHG emissions and criteria air pollutants were also successfully reduced and were in all cases similar to or lower than for ordinary portland cement concrete.

The concrete and steel frame versions of a dormitory building in Istanbul were also analyzed. Results from the case study showed that the operation phase dominated in GWP and energy consumption, which is consistent with literature results.

Finally, Turkish cement and concrete sector case study scenario analysis show that reductions in $CO_{2\text{-eq}}$ emissions can be achieved through, strategic choice of locations for cement and concrete plants for local and international distribution of products by less carbon-intensive modes of transportation, i.e., rail and water; switching to lower-carbon fuels in cement kilns, and expanding the use of biofuels and electric vehicles in delivery of cement and concrete products; Improvements in energy efficiency by installation of existing best available technologies for new plants and replacing older technologies for existing plants, switching to less carbon-intensive energy sources for electricity generation, integration of waste heat recovery systems in cement plants for off-grid electricity generation and using more energy efficient equipment in cement and concrete plants, use of alternative raw materials as sustainable waste management and GHG emission reduction options. Although these strategies can have great potential to abate $CO_{2\text{-eq}}$ emissions in cement and concrete industry both in Turkey and globally, technical, regulatory, and economic challenges are still considered obstacles against implementation of new approaches.

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To my sons,
Bora and Sarp,
who provided endless love, joy, strength, and
encouragement throughout the process.

Acknowledgements

After working for many years in the industry and raising my two sons, returning to a graduate school in a foreign country was an adventure into the unknown. PhD was a long process which required dedication, courage, and endurance. Without the encouragement and support of my family, friends, and many other people, this achievement would not have been possible.

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> "I'm a success today because I had a friend who believed in me and I didn't have the heart to let him down." - Abraham Lincoln

1 Introduction

1.1 Motivation

Construction and operation of the built environment is recognized as a significant source of greenhouse gas emissions [1-4]. In the U.S., residential and commercial buildings are responsible for about 74% of annual electricity use and 39% of annual primary energy use as of 2006 and this rate is expected to grow [5]. Globally, 40% of anthropogenic greenhouse gas emissions and 40% of raw materials use are attributed to buildings [4, 6]. With an estimated global production of 25 billion metric tons (mt) annually [7], which corresponds to over 3.8 mt use per person each year, concrete is the most widely used man-made material. In 2011, about 3 billion mt of portland cement were produced [8], almost all being used in construction projects. The reasons for concrete's domination are diverse. Among the most critical are its flexibility and adaptability as proven by various types of constructions it is used, its low maintenance requirements during the service life of the structures, and the economic and widespread accessibility of its constituents [9].

Being able to meet the high volumes of future concrete demand without placing too much burden on the environment is a major challenge. The massive manufacturing and consumption cycle of concrete has significant environmental impacts making the current concrete industry unsustainable. Currently, global concrete manufacturing accounts for more than five percent, about 2.1 billion mt of the human-related carbon dioxide emissions annually, mostly attributable to the production of cement clinker [7]. Approximately half of these emissions are attributed to the combustion of fossil fuels; as portland cement is one of the most energy-intensive materials, requiring 4-5 GJ per mt [9]. Remaining portion is due to calcination of the limestone. Overall, for one mt of portland cement clinker 0.87 mt of CO_2 is released into the atmosphere [10]. This value can vary depending on the location, technology, production efficiency, electricity grid mix, and selection of fuels. The threat of climate change presents one of the major environmental challenges for today's society, and the rising atmospheric CO_2 concentration is alarming. Thus, the cement industry plays a key role in CO_2-emission mitigation strategies [11]. However, the environmental burden of concrete and buildings is not limited to only CO_2 emissions occurring at one specific life-cycle stage, from one particular raw material (e.g., portland cement) production. The analysis and quantification of the overall environmental impacts of concrete manufacturing and its application in building projects requires a holistic analytical approach that is known as life-cycle assessment (LCA).

The LCA approach is particularly important given the high volume of concrete use and the growing importance of environmentally sustainable infrastructure decisions. As a consequence, there is a diverse audience of decision makers and manufacturers who are interested in understanding and lowering the environmental impact of concrete and other buildings materials. These decision makers include policy makers and urban planners, developers of green building standards (e.g., LEED rating system), and construction/engineering companies. Another audience is manufacturers who are interested in lowering their concrete production footprint and also the footprints of the materials they procure. These manufacturers want to stay competitive in marketplace as demand for "greener" concrete products continues to increase. An LCA approach is particularly important for this audience in understanding the full range of impacts of concrete and its ingredients in a cradle-to-gate life-cycle setting. However, the utility of an LCA is highly dependent upon the accuracy and comprehensiveness of its life-cycle inventory (LCI), in which data on inputs and outputs of mass and energy across the various life-cycle processes are compiled. Without a credible and broad LCI, the utility of an LCA can suffer due to uncertainties introduced into subsequent life-cycle impact analyses (LCIAs) and/or incompleteness in the range of environmental impact categories that can be considered. In other words, credible LCAs of concrete production rely heavily on credible and comprehensive LCIs.

This dissertation presents a comprehensive roadmap for improving the utility of concrete production LCIs for decision makers, manufacturers, researchers, and other interested parties as they seek to lower the environmental burdens associated with concrete.

1.2 Problem Statement

The comprehensive literature review shows that concrete and building LCAs tend to focus on certain life-cycle stages (construction of buildings, etc.), environmental aspects (energy use and CO_2 emissions) or specific constituents (portland cement) of concrete. Nonetheless, LCA would be incomplete without looking at the environmental impacts of other concrete raw materials such as admixtures, aggregates, supplementary cementitious materials (SCMs), and water. In general, most concrete LCAs do not go beyond the second step that is the compilation of life-cycle inventory. Those few that include the LCIA step cover only a few impact categories (mostly global warming potential). Other impact categories, including acidification potential, eutrophication potential, human-toxicity, and eco-toxicity, are mostly left out. Moreover, both LCI data and LCIA characterization factors are based on national data averages without geographical differentiation, mostly because of lack of regional data. Other concrete and building LCA application-related gaps include: lack of a clearly defined functional unit, lack of extensive LCI data coverage, exclusion of various environmental indicators such as water consumption, solid waste, toxic emissions, and waste water, and lack of a more structured interpretation of LCA results based on sensitivity and uncertainty analysis. All these limitations lead to the necessity of a new concrete manufacturing LCA methodology and tool. As the first step towards developing a new methodology, I addressed the question: how well do existing concrete LCA studies support environmentally holistic decision making for manufacturing of concrete and its applications in buildings? The answer was not satisfactory as the currents studies have been limited to generic LCIs of resources and emissions with little or no inclusion of supply-chain impacts of resources used in concrete manufacturing. Most of the existing concrete LCA tools in the markets are static without the consideration of regional variations, technological alternatives, and design mix properties of concrete products. Therefore, there is a need for a dynamic and flexible LCA tool that is accessible and user-friendly, based on scientific review of available life-cycle modeling data and techniques, allows for fine-tuning on how key modeling variables affect the results in LCA of cement and concrete, adaptable to different location, process, and technology variations. Based on these key factors, this dissertation provides a step-by-step roadmap to the development of a dynamic concrete LCA tool, namely GreenConcrete LCA. The tool has the capability to calculate the environmental life-cycle impacts of one type of concrete mixture and also compare and evaluate different concrete mixtures designed by the user. The integration of regional variations and technological alternatives in the material production processes within the tool offers a wide range of applicability and flexibility for cement and concrete manufacturers not only in the United States, but also worldwide.

1.3 Research Scope

The scope of the dissertation includes concrete manufacturing and its application in buildings, therefore, it is a cradle-to-grave analysis. For a full environmental assessment of concrete and buildings, it is essential to define major processes taking place within the system boundary. As given in Chapter 2, while Figure 2.1 demonstrates the cradle-to-gate system boundary of the concrete manufacturing, Figure 2.2 completes the life cycle of the concrete from its use in construction of a building frame to its end-of-life fate. Although both Figures 2.1 and 2.2 draw well-defined system boundaries, each with one end product (ready-mixed concrete and concrete building, respectively), the supply-chain impacts associated with inputs (e.g., materials, products, electricity, fuels, water, etc.) of varying regional specificity and production/generation technologies complicate the analysis.

1.4 Objectives of Research and Dissertation

Today, one of the biggest drivers for the construction industry is likely to be the use of low-carbon technologies and delivering a sustainable built environment. With this impetus in mind, the ultimate goal of this research is to develop an LCA methodology which can improve our understanding of the environmental burden of concrete and recommending ways of reducing its burden to eventually develop sustainable buildings. To reach this ultimate goal, the dissertation is structured around these major objectives: to review and synthesize the current concrete and building LCA literature to identify areas that need improvement, to design a dynamic decision support tool to evaluate life-cycle environmental impacts of concrete from extraction of raw materials to the end-of-life stage, to apply the new process-based LCA methodology to evaluate environmental impacts of concrete used in a building case study located in Istanbul; to estimate the overall LCA of a concrete vs. steel dormitory building from manufacturing of building materials, to end-of-life stage, including both direct and supply chain impacts. Additionally, the GreenConcrete LCA tool has been used to analyze and understand key parameters that can reduce GHG emissions from the Turkish cement and concrete manufacturing sector based on sectoral production statistics. Using the tool, scenarios that vary in manufacturing technology, alternative materials use, electricity grid mix, and transportation alternatives were developed. Findings from the scenario analysis stated the key contributors to GHG emissions from cement and concrete plants. Based on the building case study and scenario analysis, recommendations for developing sustainable building materials and improving the current practice in concrete manufacturing and buildings construction sectors were provided.

1.5 Structure of Dissertation

Chapter 1 of this dissertation has introduced the motivation, significance of the built environment, the problem statement, research scope, and objectives of the dissertation.

Chapter 2 provides a literature review of cement manufacturing, concrete manufacturing, and commercial buildings including all stages of materials extraction and production, construction, operation, maintenance, demolition, and end-of-life stages. For a credible review, the studies were selected from peer-reviewed journals and reports that follow systematic LCA guidelines, such ISO guidelines. The included studies are analyzed in three groups: the first group covers cement production LCA studies. The second group focuses on LCA of concrete and its raw materials other than cement. Finally, the third group is a compilation of commercial building

LCA studies. Each of the LCA studies were summarized in terms of regional representation, LCA approach, materials /products studied, functional unit, LCA phases included, and allocation. Finally, all studied are evaluated on the basis of goal/scope definition, life-cycle inventory analysis (LCI), and life-cycle impact assessment. Finally, this chapter summarizes those areas that deserve further discussion and research to fill in the major limitations of current materials and building LCA literature.

Chapter 3 includes a review of the life-cycle assessment (LCA) methodology, description and limitations of various LCA approaches, including process-based, I-O-based, and hybrid LCA, their strengths and weakness, as well as applications and significance of LCA in estimating environmental impact of buildings.

Chapter 4 describes the concrete production LCA tool, namely GreenConcrete LCA tool which has MS Excel and Web versions. The GreenConcrete tool is specifically designed for cement and concrete manufacturers for the purpose of quantifying and comparing environmental impacts of their products. This chapter addresses the details of each and every worksheet in the GreenConcrete LCA tool consisting of calculations and environmental inventories of data for concrete and its raw materials (cement, aggregates, admixtures, fly ash, slag, natural pozzolans, water, etc.). The data pool covers direct and supply chain life-cycle inventories of electricity generation, freight transportation, and fuel pre-combustion and combustion based on the databases from current studies. The Appendix is an integral part of this chapter with tables of direct and supply-chain LCI data for U.S. electricity grid mix by State and by energy source. This chapter can be considered as a handbook or a guidebook for users such as decision makers in the construction sector including construction managers, contractors, civil engineers, architects, owners, and consulting companies interested in LCA of a wide range of concrete products.

Chapter 5 is the case study application for the process-based LCA of concrete-framed and steel-framed versions of a dormitory building located in Istanbul. The case building was initially designed as a concrete frame, while a steel option was later developed for cost and seismic risk assessment (for earthquake zone type 1) and comparison purposes. Energy use and GWP results for all building phases provided in this chapter were based on the manufacturer’s product descriptions and technical specifications, and documents from both engineering and construction companies. The case study LCA results were used to define uncertainties stemming from variations in spatial and temporal differences as well as materials manufacturing, replacement, and construction technologies, operation phase impacts, end-of-life decisions, LCA calculation methods, and many other aspects. A pedigree matrix was applied to assess data quality. This chapter also emphasized the significance of certain technological/regional parameters on the LCA results of cement and concrete products, using sensitivity analysis. The Appendix is an integral part of this chapter as it provides the list of all building materials together with their descriptions and sources of data, LCI and LCIA factors for the materials, heavy-duty truck and construction equipment related manufacturing and LCI data, Turkish electricity grid mix LCI data, case study operation phase energy use data, as well as tabulated results of cement manufacturing sensitivity analysis.

Chapter 6 is the policy scenario analysis chapter developed for analyzing and understanding the key parameters that can abate GHG emissions from the Turkish cement and concrete manufacturing sectors. Scenarios that vary in technology, materials use, electricity mix, and transportation have been developed in order to identify which parameters are the major drivers of GHG variation across a range of circumstances for cement and concrete manufacturing. Results from the scenario analysis showed that CO_2 emissions can be lowered through four major strategies. The first improvement strategy involves the installation of more fuel-efficient cement kilns, more energy-efficient cooling, conveying, grinding, milling, and blending technologies that use considerable amount of electricity. In addition to the improvements in manufacturing technologies, partial substitution of SCMs, such as pozzolans (mainly fly ash), slag, limestone for portland cement in the finished cement products (such as blended cements) and in concrete can be promoted. Other measures include reducing transportation impacts by switching to low-environmental impact modes and/or transporting of materials, products, equipment, and labor for shorter distances. At the national level, change in electricity grid mix, such as converting major energy sources to renewable sources of energy should be considered.

Finally, interpretation and discussions of dissertation results, limitations and contributions of the research, and recommendations regarding the future research are provided in Chapter 7.

2 Background, Synthesis and Limitations of Life-Cycle Assessment of Concrete Manufacturing and Concrete Commercial Buildings

This chapter presents a critical review of the existing studies and tools on environmental assessment of cement manufacturing, concrete production, and concrete commercial buildings including their construction, operation, maintenance, and end-of-life stages. Following the review, studies are evaluated to discuss major findings and gaps in the research arena.

The included studies were selected from peer-reviewed journals and reports that follow systematic LCA guidelines, such as ISO 14040 framework [12, 13] for the purpose of enabling credible comparisons between studies. The review consists of three groups of studies: The first group covers cement production LCA studies. The second group is a compilation of concrete production LCAs. Finally, the third group of studies reviews concrete commercial building LCA studies conducted mainly in the United States and Europe. The LCA studies are evaluated based on the following three major LCA phases [12]:

- The scope and goal definition;
- The Life-Cycle Inventory (LCI) analysis;
- The Life-Cycle Impact Assessment (LCIA).

LCA studies are comparative by nature. These three LCA phases are selected for meaningful, equivalent, and transparent comparisons of the results from the literature. The assessment of the scope and goal definition stage examines functional unit, scope, and system boundary similarities as well as inconsistencies among studies. The LCI results compare the selected studies in terms of environmental inputs (materials, water, and energy use) and outputs (atmospheric emissions, waterborne emissions, and solid wastes) quantified within the LCA system boundary. The LCIA phase translates the emissions from LCI to impact categories like eco-toxicity, human toxicity or damage to human health, etc.

Within the context of these three LCA phases, the body of literature is assessed to understand how well it meets the needs of major players in the LCA research domain (described in Chapter 4 Description of GreenConcrete LCA Tool) along with three important dimensions: holistic decision-making across all environmental exchanges and associated impacts (via LCI and LCIA); ability to apply to regional and local decision making; and avoidance of truncation error (continual exclusion of some specific production processes) error [14, 15]. The findings from the literature review are summarized in three major tables (see Table 2.11, Table 2.30, and Table 2.67 for cement production, concrete production, and concrete commercial buildings, respectively).

2.1 Review scope

The scope of the review is limited to concrete production and its application in concrete commercial buildings, therefore, it is a cradle-to-grave analysis. For a full environmental assessment of concrete production and concrete commercial buildings, it is essential to define major processes taking place within the system boundary. While Figure 2.1 demonstrates the cradle-to-gate system boundary of the concrete production, Figure 2.2 completes the life-cycle of the concrete from its use in construction of a building frame to its end-of-life fate. Although both Figures 2.1 and 2.2 draw well-defined system boundaries, each with one end product (ready-mixed concrete and concrete building, respectively), the supply-chain impacts associated with inputs (e.g. materials, products, electricity, fuels, water, etc.) of varying regional specificity and production/generation technologies complicate the analysis. Throughout the literature review, major research findings and discrepancies are described.

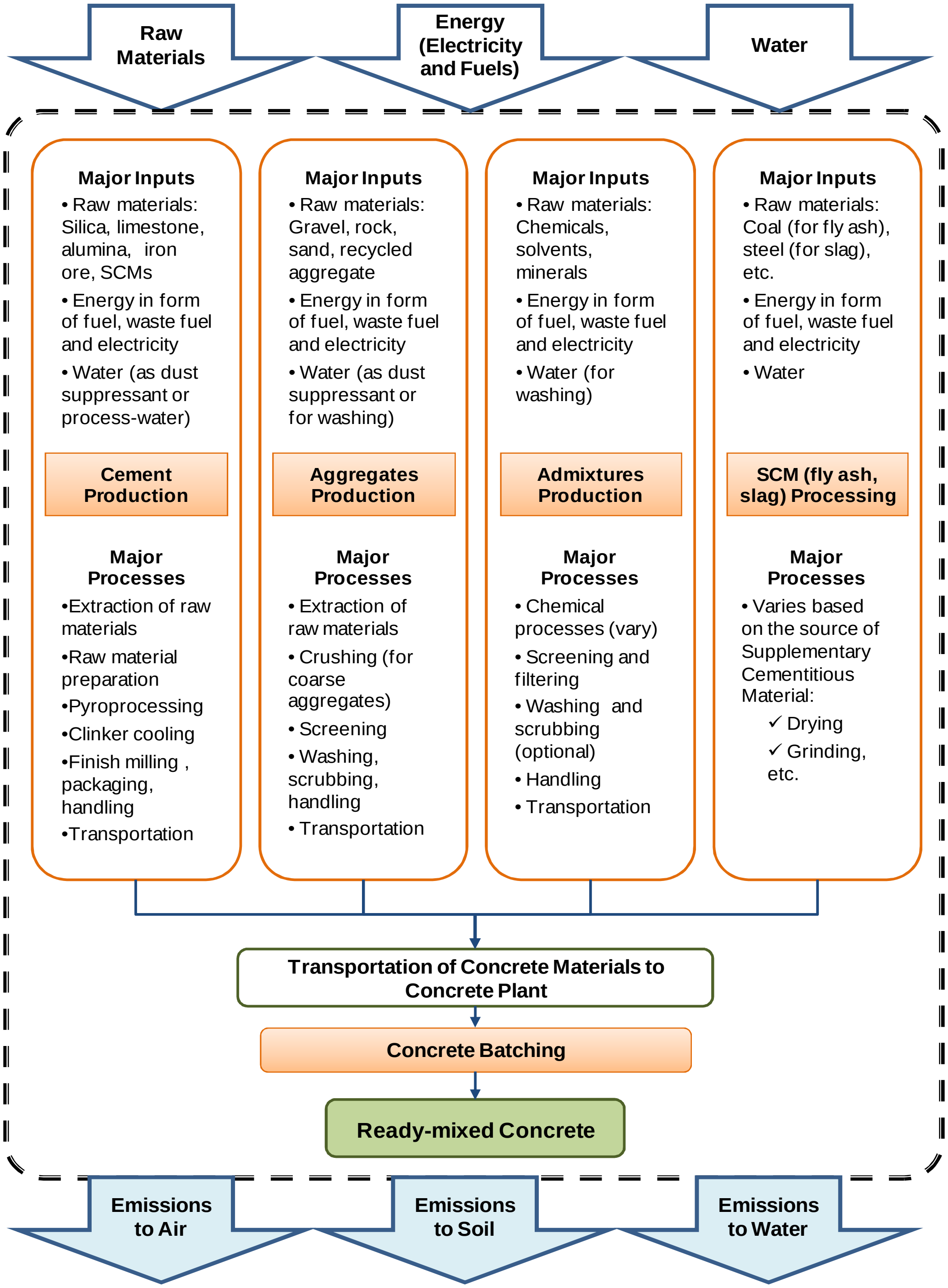

Figure 2.1: Scope of cradle-to-gate ready-mixed concrete production LCA representation

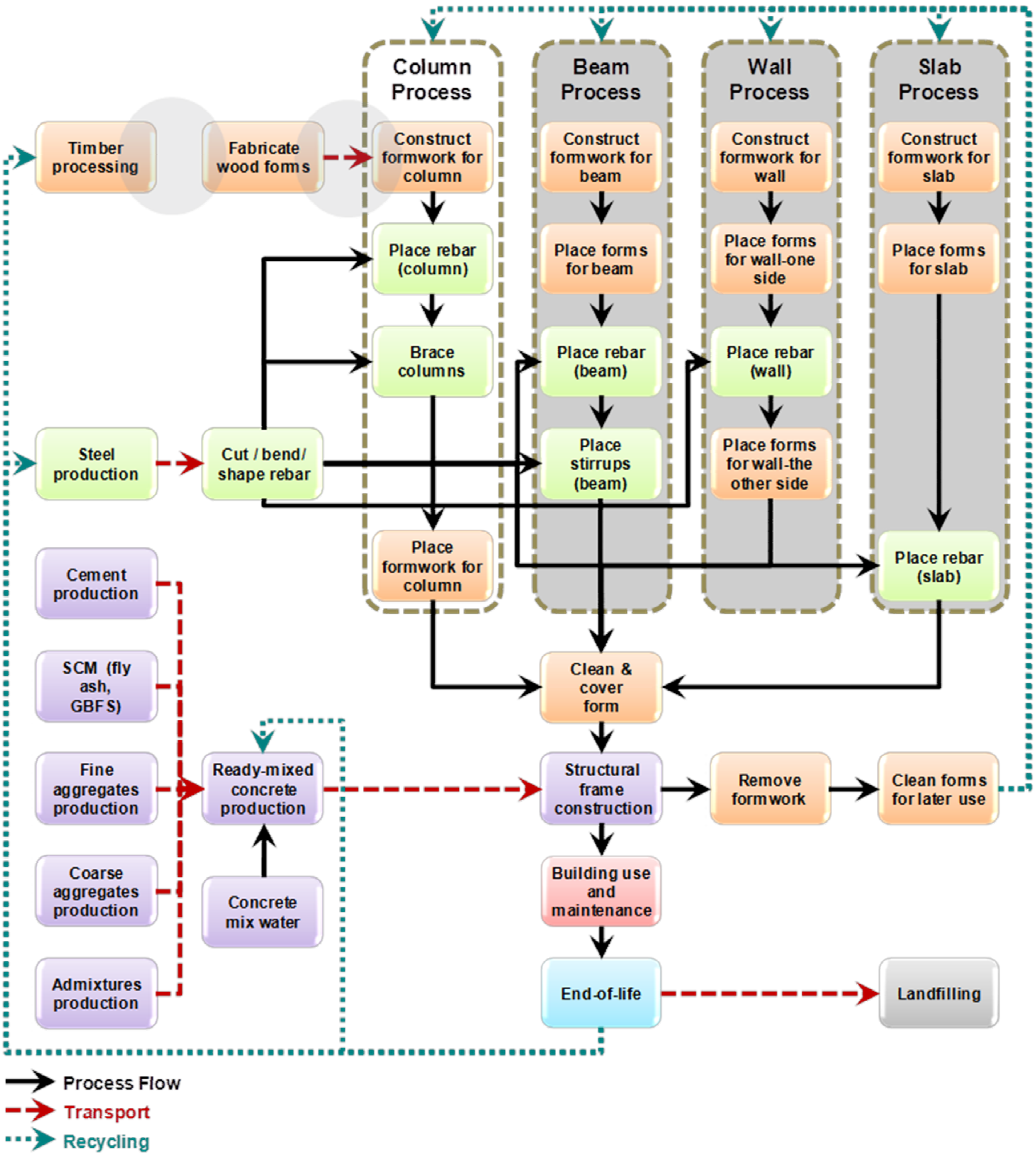

Figure 2.2: Scope of cradle-to-grave reinforced concrete commercial building LCA representation

2.2 Cement Manufacturing LCAs

For analysis and comparison purposes, first major LCA studies are summarized and then evaluated on the basis of their scope and goal definition, as well as LCI and LCIA phases' representation. Since most of the concrete manufacturing LCAs lack the LCIA step, cement and concrete LCIA are covered together in one section following the concrete LCI section (Table

2.32 and Table 2.33).

The purpose of the following chapter is to determine those areas that deserve further discussion and research to fill in the major limitations of cement production LCIs in current literature.

2.2.1 Background on Cement Manufacturing LCAs

Almost all concrete raw material LCAs focus on cement manufacturing [16-22]. However, cement LCA studies have their inherent shortcomings. Recent European cement LCA studies [16, 17] pinpoint to the inaccurate and non-representative data with regards to the representation of level of technology and the geographical setting of cement plants. For example, such data from technologically advanced plants or from countries with developed LCI database are not always representative of less advanced cement plants or countries. Differing system boundaries and modeling assumptions further complicate environmental assessment of the well-understood process of cement manufacturing. As waste fuels and alternative raw materials are increasingly being used in kilns, the environmental assessment of cement products gets more intricate. Of the major cement LCA studies, most are complete LCAs with inclusion of both life-cycle inventory (LCI) and life-cycle impact assessment (LCIA) phases. The related studies are summarized in reverse chronological order, starting with the latest one.

2.2.1.1 Valderrama et al. (2012)

Authors applied a cradle-to-gate LCA to evaluate and quantify the environmental impacts of the potential improvements in a cement plant where the production lines were upgraded. The former lines (L3, L4 and L5) were replaced by a new line (L6) which was designed and constructed based on the best available technologies (BAT) for the cement industry in Spain. The BAT for the cement industry was introduced by the European Commission. It covers the integrated pollution prevention and control (IPPC) technologies in cement manufacturing [23]. Major technology improvements took place in raw material grinding (from three-ball mill system to vertical roller mill), cyclone tower (from four- and two-cyclone systems with preheater to five cyclones with preheater stages and precalciner), reduction of NO_x emissions by introducing selective non-catalytic reduction (SNCR) system, and coolers (from satellite to grate). The system boundary included processes from raw material extraction to the finished clinker product, excluding the last step of blending and grinding of clinker and mineral components to produce the portland cement (Table 2.1). Therefore, the functional unit was selected as one kg of cement clinker. The related LCIA step was performed using SimaPro7.2 software, CML midpoint approach. The damage assessment was also considered. In the analysis, damage to human health was related to the categories of carcinogens, respiratory organics, respiratory inorganics, climate change, radiation and ozone layer and was expressed in disability-adjusted life years (DALY) units; damage to ecosystem quality was associated to the categories of ecotoxicity (expressed in potentially affected fraction (PAF) units), acidification/ eutrophication and land use (expressed in potentially disappeared fraction (PDF) units) and finally damage to resources were related to minerals and fossil categories, which were expressed as “surplus energy”.

Significant improvement was achieved in energy efficiency of the new kiln system by the replacement. Specifically, results indicated reduction of the environmental impacts for GWP (5%), acidification (15%), eutrophication (17%) and cumulative exergy demand (CED) (13%). For the damage assessment, the updated system resulted in reductions for human health (11%), ecosystem quality (11%), and resources damage (14%) compared to the former production line.

Table 2.1: Summary of Valderrama et al. (2012) [22]

Title	Implementation of best available techniques in cement manufacturing: a life-cycle assessment study
Region	Spain
LCA Approach	Process, both LCI and LCIA (both midpoint and endpoint damage approaches)
Materials/ products studied	Portland cement clinker
Functional unit	1 kg of clinker
Phases studied	Extraction/Production Transportation
Allocation	No

2.2.1.2 Chen et al. (2010a)

The authors assessed the environmental impacts of the French cement industry, using an LCA approach (see Table 2.2). Within the system boundary, cement manufacturing processes and associated impacts were analyzed based on three main processes: 1) Extraction and preparation of raw materials in the quarry (assuming the quarry is very close to the cement plant, no transportation); 2) Fine mixing of raw materials, cement kiln processes, production of traditional fossil fuels (waste fuels are not considered), transportation of both fossil fuels and alternative fuels to the cement plant; and 3) Grinding of clinker and its mixing with gypsum. Additionally, materials used in the construction of the industrial installations were considered and divided by the expected life time of the cement plant, assuming 50 years of life-time with a production of 340,000 tonne per year. Cement LCI data were generic (average), obtained from the French cement union (ATILH) while additional data for energy use, materials and transportation as well as all upstream products and processes were based on the EcoInvent. LCI results covered raw materials, fuels (fossil and waste fuels) use, water consumption, electricity use, solid waste, and a wide range of air emissions (GHG emissions, criteria air pollutants, heavy metals, and toxic emissions). LCIA results were calculated using CML 2001 indicators. Some of the indicators (i.e., GWP, photochemical oxidation) varied by 20-30% among cement plants, while others (i.e., acidification, eutrophication, terrestrial ecotoxicity) varied by more than 40%. The authors concluded that these variations were attributed to the lack of accurate measurements on both pollutant content and emission registry by the plant or due to the specificity of the technology and variability of industry practice of each cement plant.

Table 2.2: Summary of Chen et al. (2010a) [24]

Title	Environmental impact of cement production: detail of the different processes and cement plant variability evaluation
Region	France
LCA Approach	Process, both LCI and LCIA
Materials/ products studied	CEM I cement type
Functional unit	1 kg of ordinary portland cement (CEM I type)
Phases studied	Extraction/Production Transportation
Allocation	No

2.2.1.3 Boesch et al. (2010)

This study evaluated cement manufacturing in the European Union and the United States from a cradle-to-gate perspective and analyzed the sensitivity of various production options on the environmental impacts (Table 2.3). LCI comprised emissions of CO_2, CO, NO_x, SO_2, VOC, PM, and toxic emissions and resource consumptions for all cement types analyzed. LCIA methods included were climate change (IPCC Climate Change, 100 years), nonrenewable cumulative exergy demand (CExD), acidification (CML 2001), eutrophication (CML 2001), and human toxicity (CML 2001), where the focus was on climate change (GHG emissions) and CExD as an indicator for resource consumption. CExD takes into account not only the quantity but also the quality of energetic resources. Further, CExD also includes non-energetic resources such as minerals and metals. Results from the analysis were consistent with the rest of the literature. It was shown that CO_2 emissions are reduced with a combination of measures, such as the use of the best available technology and a thermal substitution for fuels. Since clinker production is the dominant pollution producing step in cement production, the substitution of clinker with mineral components (GBFS or fly ash) is an efficient measure to reduce the environmental impact. Blended cements exhibited considerably lower environmental footprints than portland cement, despite the requirement for additional grinding, drying and long transportation distances. These findings were supported with the sensitivity analysis.

Table 2.3: Summary of Boesch et al. (2010) [25]

Title	Model for cradle-to-gate life-cycle assessment of clinker production
Region	EU and United States
LCA Approach	Process, both LCI and LCIA
Materials/ products studied	<u>For Europe:</u> Portland cement (CEM I) Portland composite cement (CEM II) with GBFS, silica fume, pozzolan, fly ash, burnt shale, limestone Blast furnace cement (CEM III) with GBFS Pozzolanic cement (CEM IV) with silica fume, pozzolan, fly ash Composite cement (CEM V) with GBFS, pozzolan, fly ash <u>For United States:</u> Portland cement (Type I-V) Slag modified portland cement (Type I(SM)) Portland blast furnace slag cement (Type IS) Slag cement (Type S) Pozzolan modified portland cement
Functional unit	1 tonne cement
Phases studied	Extraction/Production Transportation
Allocation	No

2.2.1.4 Boesch et al. (2009)

A technology- and input-specific cradle-to-gate LCA model was developed to assess and compare the environmental impacts of waste co-processing and use of different kiln technologies in clinker production. The scope was the European clinker production based on the material-supply chain data from EcoInvent. The functional unit was selected as one tonne of clinker (Table 2.4). The model compared environmental performance of five types of cement kiln systems: precalciner, suspension preheater, lepol, long dry, and long wet (also known as wet kiln). The base case comprised of a precalciner kiln system that co-processes three alternative fuels (tires, prepared industrial waste, dried sewage sludge) and one alternative raw material (blast furnace slag). In the study, alternative fuels replaced hard coal, while slag substituted limestone and clay. Authors applied various LCIA approaches in the analysis: IPCC 2001, CED, and Ecoindicator'99. Results from the study were consistent with other LCA results concluding that alternative fuels and materials in the kiln system have generally positive environmental impacts (decreased GHG emissions, reduced resource use, etc.).

Table 2.4: Summary of Boesch et al. (2009) [20]

Title	Model for cradle-to-gate life-cycle assessment of clinker production
Region	Switzerland
LCA Approach	Process, both LCI and LCIA
Materials/ products studied	Cement clinker produced using various types of alternative fuels/raw materials and different kiln technologies
Functional unit	1 tonne clinker
Phases studied	~~Extraction~~/Production Transportation
Allocation	No

2.2.1.5 Huntzinger and Eatmon (2009)

Authors assessed the environmental impacts of producing four different types of cement (Table 2.5): 1) Traditional portland cement, 2) Blended cement (by mass, 25% of clinker is substituted with natural pozzolans), 3) Cement with recycled cement kiln dust (CKD) where 100% recycling of CKD was assumed, and 4) Portland cement with CKD to sequester a portion of the process related CO_2 emissions (with an assumption of 0.06 tonnes of CO_2 captured per tonne of finished product). Inventory data for raw material acquisition (mining of limestone, sand, iron ore, and clay) along with electricity production and heat generation by fuel type for each processing step as well as packaging and transportation data were obtained from SimaPro databases. The Ecoindicator95 in SimaPro was used for the LCIA calculations. Major impact categories included GWP, acidification, eutrophication, heavy metals, carcinogens, winter smog, summer smog, and use of energy resources.

Results again revealed that blended cements provided the greatest environmental benefits (in terms of CO_2 emissions) followed by the utilization of CKD for sequestration. The cement produced from the recycled CKD had little environmental advantage over the traditional portland cement. The authors believed that the high impact scores for heavy metals and acidification obtained from SimaPro were due to the incomplete representation of the chemical reactions occurring in the kilns. They found actual sulfur dioxide emissions to be much lower than those predicted in SimaPro because clinker and CKD could serve as partial scrubbers for SO_2. However, they didn't make any corrections for these two impacts as the focus of the assessment was GWP, not other impact categories.

Table 2.5: Summary of Huntzinger and Eatmon (2009) [19]

Title	A life-cycle assessment of portland cement manufacturing: comparing the traditional process with alternative technologies
Region	United States
LCA Approach	Process, both LCI and LCIA
Materials/products studied	Portland cement Blended cement (with natural pozzolans) Portland cement with recycled CKD PC with CO_2 sequestered in CKD
Functional unit	1 tonne cement

Phases studied	Extraction/Production Transportation
Allocation	No

2.2.1.6 Josa et al. (2007)

In a nutshell, the study is a comparative analysis of the environmental impacts of different cement types produced in the European Union (see Table 2.6). Authors compared the life-cycle impacts of cement inventories based on an earlier paper [16]. The functional unit of the analysis was one kg of portland cement with or without substitutes (such as blast furnace slag, pozzolanic ash, etc.). For LCIA, CML 1992 methodology based on SimaPro was used. CML is a mid-point LCIA approach. It is called because indicators are located between inventory interventions and endpoint effects and damages. Environmental impact categories for cement production included GWP, acidification, eutrophication, and winter smog. Characterization factors for photochemical ozone formation, heavy metals, and carcinogens were also presented in the study. Results from the analysis were highly scattered, and a correlation with the cement type or definition of representative values were unlikely. Authors linked this scatter, in part, to the criteria utilized in LCIA method or to the definition of the system boundaries in each case of cement manufacturing. However, it could also be attributed, in a decisive way, to the fuels utilized in the kiln, some of which might lead to these sorts of emissions. In summary, authors attributed the differences in results mostly to the variations in clinker content of cement and technologies/ materials used during manufacturing.

Table 2.6: Summary of Josa et al. (2007) [17]

Title	Comparative analysis of the life-cycle impact assessment of available cement inventories in the EU
Region	EU
LCA Approach	Process, only LCIA
Materials/products studied	Portland cement (with 95-100% clinker content) Portland slag cement (with 65-94% clinker content) Pozzolanic cement (with 45-64% clinker content) Blast furnace slag cement (with 20-34% clinker content)
Functional unit	1 kg cement
Phases studied	Extraction/Production Transportation
Allocation	No

2.2.1.7 Marceau et al. (2006)

The Portland Cement Association (PCA)'s report offers a framework for the environmental assessment of the U.S. portland cement manufacturing in compliance with ISO 14040 and ISO 14041 guidelines (Table 2.7). The functional unit was selected as one tonne of cement produced in the U.S. The LCI data were presented for each of the four cement plant kilns: wet, long dry, dry with preheater, and dry with preheater and precalciner for the key processes of portland cement manufacturing. Major processes included were: 1) Quarrying and crushing of raw materials, 2) Raw meal preparation, 3) Pyroprocessing, and 4) Finish grinding. Transportation of materials and fuels to the cement plant were also evaluated. Upstream activities of fuel production and electricity generation were excluded in the LCI analysis. Data were based on the industry-wide surveys and major national databases and sources [26-30]. Throughout the report, all emissions and inputs were attributed to the product itself, meaning that there was no allocation issue. LCI results were demonstrated under three major groups: 1) Material inputs, 2)

Energy input for cement manufacturing and transportation, and 3) Major emissions to air, land, and water. Finally, authors assessed the material and energy input data quality by applying SETAC's 18 criteria approach [31], which is a qualitative data assessment method. Furthermore, the quality of the input data was described according to the coverage, timeliness, representativeness, accuracy, precision, consistency, and reproducibility properties.

Table 2.7: Summary of Marceau et al. (2006) [18]

Title	Life cycle inventory of portland cement manufacture
Region	United States
LCA Approach	Process, only LCI
Materials/products studied	Portland cement
Functional unit	1 tonne (2,000 lbs) cement
Phases studied	Extraction/Production Transportation
Allocation	No

2.2.1.8 Navia et al. (2006)

Authors evaluated the utilization of spent volcanic soil in Chilean cement industry. Two scenarios were compared: existing cement manufacturing process as the base-case scenario versus the cement manufacturing with the addition of spent volcanic soil (Table 2.8). The volcanic soil was originally used to adsorb phenolics compounds, color from paper milling effluents, and heavy metals from contaminated water streams. Depending on its composition, volcanic soil could also be used as limestone or clay substitute or as correction material in clinker. The functional unit of the LCA was one tonne of clinker. The system boundary for the first scenario included limestone mining, raw meal grinding, transportation (by train) of limestone, and clinker production. In addition to these steps, the second scenario also included the transportation (by train) of the contaminated volcanic soil. The avoided emissions of landfill disposal of spent volcanic soil were considered in the system boundary. The LCI for the first scenario included raw materials (two types of limestone), fuels used in the transportation of materials, and fuels (pet coke, auxiliary liquid fuel, and tires) used in clinker production. Emissions were chromium, lead, zinc, CO_2. Inputs for the second scenario included all the inputs used in the first scenario plus the volcanic soil as SCM and the diesel fuel for transporting the volcanic soil to cement plant. Outputs were air emissions of chromium, lead, zinc, CO_2 plus the avoided emissions to soil (chromium, lead and zinc) and avoided emissions to air (CO_2 and CH_4) due to use of volcanic soil.

LCIA was based on Ecoindicator 99 methodology. Impact categories included carcinogens, respiratory organics, respiratory inorganics, climate change, radiation, ozone layer, ecotoxicity, acidification/eutrophication, land use, minerals, and fossil fuels. With the exception of carcinogens and minerals categories, second scenario was more favorable compared to the first scenario, especially in ecotoxicity category because of the avoided landfilling of the volcanic soil disposal. Damage assessment categories covered damage to human health (related to carcinogens, respiratory organics, respiratory inorganics, climate change, radiation, and ozone layer); damage to ecosystem quality (ecotoxicity, acidification/eutrophication, and land use); damage to resources (minerals and fossil fuels). Damage to ecosystem quality was the most relevant damage identified in both scenarios. The avoided emissions from the use of volcanic soil in the second scenario provided a significant reduction on the global environmental indicators. Finally, authors performed a sensitivity analysis to understand the influence of some parameters (transporting the contaminated soil, CO_2 emissions from the clinkerization process, and the estimated metals leaching) on the results of the assessment. It was proven that the use of spent volcanic soil would be beneficial in terms of sustainability, slightly improving the economy of the process.

Table 2.8: Summary of Navia et al. (2006) [32]

Title	Recycling contaminated soil as alternative raw material in cement facilities: Life-cycle assessment
Region	Chile
LCA Approach	Process, both LCI and LCIA
Materials/products studied	Traditional portland cement Cement with spent volcanic soil
Functional unit	1 tonne of clinker
Phases studied	Extraction/Production Transportation
Allocation	No

2.2.1.9 Gäbel and Tillman (2005)

Authors developed a cradle-to-gate LCA model to predict the environmental, operational, and economic performance of cement manufacturing by simulating nine different operational alternatives for Cementa-AB Company in Sweden. In each scenario, impacts from varying combinations of raw meals and cement mixes as well as fuel mixes were investigated (Table 2.9). For each scenario, authors picked from each mix to form an operational alternative. Parameters used in order to calculate the environmental load from cement manufacturing included: 1) Resource use of natural minerals, fossil fuels, bio-fuels, uranium ore, land area, and water, 2) Recovered materials and alternative fuels, 3) Emissions to air. Fossil fuel use and associated emissions from the production and transportation of fuels as well as alternative fuels and recovered materials use were also studied. Additionally, authors calculated product performance and cost of operational alternatives and products. Results from the simulation illustrated that emissions of CO_2, NO_x, SO_2, CO, VOC, CH_4 and dust could be mitigated up to 80% based on the extent of the quantity of recovered material and alternative fuel used in cement manufacturing.

Table 2.9: Summary of Gäbel and Tillman (2005) [33]

Title	Simulating operational alternatives for future cement production
Region	Sweden
LCA Approach	Process, only LCI
Materials/products studied	Combinations of : Two raw meal mixes Three fuel mixes Two cement mixes
Functional unit	1,000 kg cement
Phases studied	Extraction/Production Transportation
Allocation	No

2.2.1.10 Josa et al. (2004)

This paper is a comparative analysis of inventories of different cement types produced in Europe (Table 2.10). Input data included raw materials and energy use for the production of 1 kg of cement. Authors used ISO 14040 guidelines to determine the associated LCI factors for energy use and emissions of NO_x, SO_2, and dust. For GHG emissions, IPCC guidelines were applied [34]. Results from the study were consistent with the literature: Reductions in CO_2 emissions were linked to the amount of SCM addition. However, authors mentioned that other parameters, such as the mechanical strength of the concrete, could limit the reductions that could have been reached in practical situations. As to NO_x emissions, the higher the degree of clinker substitution (by GBFS and fly ash), the lower the NO_x emissions. Both SO_2 and PM emissions depended on the clinker content as well as the fuel type used during cement manufacturing. Therefore, emissions of SO_2 and PM varied considerably from one type of cement to another. Differences in system boundary definition, omission of certain emission sources or lack of homogeneity in data and emission control techniques were considered as among major reasons for the variations in LCI results.

Table 2.10: Summary of Josa et al. (2004) [16]

Title	Comparative analysis of available life-cycle inventories of cement in the EU
Region	EU
LCA Approach	Process, only LCI
Materials/ products studied	Portland cement (with 95-100% clinker content) Portland slag cement (with 65-94% clinker content) Pozzolanic cement (with 45-64% clinker content) Blast furnace slag cement (with 20-34% clinker content) Portland cement mix (with 82.2% clinker content) Portland limestone cement (with 90.6% clinker content)
Functional unit	1 kg cement
Phases studied	Extraction/Production
Allocation	No

2.2.2 Synthesis and Limitations of Goal Definition and Scope of Cement Manufacturing LCAs

Cement manufacturing LCAs in literature are cradle-to-gate LCAs with varying system boundaries as well as technological and geographical variations. A synopsis of the literature reveals that each study, in itself, has well-defined scope and goal definition despite limitations within the literature domain.

Conventional portland cement manufacturing processes in system boundary include: 1) Extraction of raw materials (quarrying and raw materials crushing); 2) Preparation of raw meal and blending; 3) Pyroprocessing; 4) Finish grinding (milling) with gypsum; 5) Packaging, handling, and shipment of the finished product [30, 35]. The inclusion of transportation impacts is also an essential step as it occurs over all life-cycle phases and the associated environmental burden can be considerable. A glance at Table 2.11 demonstrates that except for Josa et al. [16, 17], inventories associated with each cement production process (e.g. raw materials preparation and clinker production processes) are analyzed separately in literature. Noticeably, almost all studies focus on the most energy intensive stage of cement manufacturing, that is, pyroprocessing. This stage can use about 90% of the total energy [18, 36]. On the other hand, the extraction of raw materials is left out in some of the studies as it is either deemed insignificant in terms of energy consumption (about 2% of total) or simply because of lack of data. Raw materials preparation, finish grinding and blending, and transportation stages are often, but not always, included in the cement production LCAs. Energy use during these stages is comparably low, which corresponds to 2-5% of energy use of total production. However, as in the case of impacts from raw materials extraction, impacts from these three stages can add up to substantial amounts when considered globally. When the impacts are scaled up to global levels, even two percent of energy use during cement production can add up to unpredictably large numbers. A quick back-of-an-envelope calculation can give a rough estimation of the energy use during one of these three stages: USGS [28] estimates that an average of 5.2 GJ of energy per tonne of cement is required and two percent of it equals to one GJ which adds up to 2.3 billion GJ of energy use globally in year 2005 [37].

Except for one recent cement manufacturing LCA study [22], none specifically considers the variations in production technologies for major stages of cement manufacturing. This particular study compares older and updated versions of cement manufacturing lines in a cement plant with respect to the "Best Available Technologies" (BAT) in Europe [23].

Although it cannot be considered as deficiency, differences in types of cement products studied between Europe and the U.S. are noticeable. The European cement LCAs often include blended cements (cement with fly ash, slag, or pozzolan) in their analysis since about 70% of cements consumed are currently blended cements [21]. In the U.S., the market share of blended cements is below 3%. However, these numbers can be misleading as it is common practice in the U.S. to blend the supplementary cementitious materials during concrete mixing, not during cement production. Additionally, regulatory restrictions, slow adaptations of standards, and reluctance to use such new materials with less understood properties can be counted as some of the reasons for not including blended cements in the U.S. LCAs [21]. Therefore, while interpreting an LCA, one should also recognize the trends and regulations in a given location for an accurate assessment. However, none of the cement LCAs considered allocation in blended cements with fly ash or GBFS.

Overall, Table 2.11 clearly demonstrates that each cement LCA study complements one other; they all together cover major stages with varying details of technology, regional specificity and cement product types. However, as with many LCAs, these details are important for determining which study is appropriate for the purpose of the analysis and also for apple-to-apple comparison among studies.

Table 2.11: Scope of cradle-to-gate cement production LCAs

		Cement manufacturing processes						Cement products			
(Author, year)	**Region**	Extraction and crushing of raw materials	Raw meal preparation	Fuels and SCMs preparation	Pyroprocessing	Finish grinding and blending	Transportation (raw materials, fuels)	Clinker	Traditional PC	Blended cement	Other
Valderrama et al. (2012) **[22]**	Spain	*	*	*	*		*	*			
Chen et al. (2010a) **[24]**	France	*	*	*	*	*	*	*	*		
Boesch and Hellweg (2010) **[25]**	EU and US		*	*	*	*	*	*	*	*	
Boesch et al. (2009) **[20]**	Switzerland		*	*	*		*	*			
Huntzinger and Eatmon (2009) **[19]**[2]	US		*		*	*	*	*	*	*	*[1]
Josa et al. (2004, 2007) **[16, 17]**	EU							*	*	*	
Marceau et al. (2006) **[18]**	US	*	*		*	*	*	*	*		
Navia et al. (2006) **[32]**	Chile	*		*	*		*	*			
Gäbel and Tillman (2005) **[33]**	Sweden	*	*	*	*	*	*	*	*		

[1] PC with CKD and CO_2 sequestered in CKD in cement

[2] LCI for only traditional portland cement manufacturing but LCIA results are calculated for traditional PC, blended

2.2.3 Life Cycle Inventory (LCI) Representation in Cement LCAs

During cement manufacturing, considerable amount of energy is consumed in the form of fuels and electricity. The range of fuels is extremely wide. Fossil fuels used in the pyroprocessing represent the majority of fuels consumption. Most cement kiln operations in the United States are primarily powered by coal, coal and petroleum coke combination, and alternative fuels [27]. However, the specific mix of kiln fuels heavily depend on the manufacturing facility and can include a unique combination of fuels including natural gas, fuel oil, waste tires, liquid and solid wastes, as well as the more commonly used fuels [27, 28, 38]. To be able to use any of these fuels in a cement kiln, it is necessary to know the composition of the fuel. The choice is normally based on price and availability. The energy (heating values) and ash contents are also important, as are the moisture and volatile matter contents. All kinds of varieties from liquid to solids, powdered or as big lumps can be encountered when dealing with alternative fuels, requiring a flexible fuel feeding system. Somehow, they should all be fed into the burning chamber of the process. It may be fed directly into the burning zone in the kiln itself or into the pre-heating system for dissociating part of the carbonates from the meal before it enters the kiln for clinker formation [39]. Electricity is consumed during almost all production steps - crushing, grinding, rotating the kiln, conveying materials, and driving other electrical devices to clean exhaust gases and to cool clinker [35, 40].

Energy consumption data are mostly national averages in cement LCAs [16, 18-20, 22, 24, 25, 32] (see Table 2.12). Regional and technological variations in fuel use during production processes (mostly pyroprocessing) are not typically captured, which limits the applicability of these LCI data to regions or cement plants that differ substantially from the "national average" conditions. For example, some portland cement plants in the U.S. use imported clinker, which is later ground with gypsum to produce domestic portland cement. Some U.S. distributors also import portland cement itself. Portland cement and clinker imports constitute about eight percent of the total U.S. cement consumption [41]. However, the upstream inventories of the imported clinker and the corresponding energy use factors specific to the country of origin as well as the type of transportation mode/fuel associated with imported clinker are not taken into consideration in LCA. Instead, domestic and imported clinkers are assumed to be produced using similar technologies [18]. The energy-related nuances in production technologies are recommended to be considered in future LCIs for more accurate environmental assessment.

Contrary to the U.S. practice, most European cement studies consider the electricity use and related impacts associated with fuels and SCM preparation processes in their analysis [20, 22, 24, 25, 32, 33]. The exclusion of this step from cement LCIs can lead to underestimation of impacts from electricity consumption during cement production processes. The following back-of-the-envelope calculation reveals the magnitude of the problem. For example, coal provides 65% of the U.S. cement industry's heat requirement. As common practice, coal is ground before feeding into the kiln. Grinding of coal may require 30-40 kWh/tonne depending on the type of coal used in the kiln. According to USGS [42], about 5.5 million tonnes of coal was used for clinker production in 2009. This corresponds to an average of 190 million kWh of annual electricity consumption from coal preparation process only in the cement plant. In the same year, electricity consumption of U.S. cement plants was reported to be 9,020 million kWh. Assuming this number includes the electricity use for fuels preparation, about two percent of the electricity consumption can be attributed to coal preparation. Waste fuels are also prepared before used in the cement kiln. The most common type is tires (supplies 4% of the total U.S. cement kiln heat requirement). Process of shredding tires may require as much as 45 kWh/tonne [21]. It should be note that some cement kilns use whole tires while shredding may be required in others. When considered in global/national volumes, again impacts from waste fuel preparation can be significant. These arguments are valid for the preparation of alternative materials used for supplementing cementitious materials. Before blending with clinker, such supplementary materials must be dried, ground, and prepared. In comparison to other mineral components, the preparation of ground GBFS exhibits a higher environmental impact due to its lower grindability and possible additional drying requirement. It requires about 95 kWh of electricity per tonne of slag to prepare prior to mixing with cement clinker [43]. Fly ash preparation, which requires no grinding as opposed to GBFS processing, takes about 7 kWh per tonne of fly ash [44].

Generally, studies left out parts of the system that were deemed insignificant, but even 1% of the energy use of the concrete cradle-to-gate system can add up to significant levels when considered in global volumes of production. The same argument is true for other environmental exchanges (e.g. emissions to air, water, and land) at global production levels.

The portland cement industry is a major contributor to global GHG emissions. Other key emissions associated with portland cement manufacturing are particulate matter (PM), nitrogen oxides (NO_x), and sulfur dioxide (SO_2) [23]. Additionally, carbon monoxide (CO), volatile organic compounds (VOCs), and toxic emissions (e.g. heavy metals, dioxins and furans) may be of concern. The type and amount of air pollutants vary with the composition of raw materials and fuels used in cement making process, as well as the choice of manufacturing technology and other parameters. GHG emissions, mostly in the form of CO_2, are included in the inventories of cement manufacturing LCAs considered in this section. There are two major sources of direct CO_2 emissions from production: fuel combustion- and calcination-related. Table 2.12 summarizes the studies analyzing CO_2 from fuel combustion and calcination separately. In most cement LCAs, CO_2 emissions from the pyroprocessing stage are generally based on national averages for the fuel composition and kiln technologies without the consideration of varying technology and material options [16-19, 22, 24, 32].

Although electricity consumption (in kWh or in MJ of fuels) per tonne of cement or clinker is included in cement LCI studies [18-21, 24, 33], most of the LCI databases and studies [18, 45] do not provide the supply-chain inventories for electricity and associated fuel production. Inevitably, comparison of different cradle-to-gate inventory data is not realistic and results from such comparisons are inconsistent. Two European studies [22, 33] included supply chain impacts associated with the fuel production and electricity generation in their analysis. However, one of these two studies [22] applied the electricity grid mix LCI developed for Switzerland to a cement plant located in Spain due to data restrictions in the model (e.g., SimaPro) used. A holistic LCA approach ideally incorporates supply chains of all materials and fuels used in the system. It is important to note that the amount of CO_2 and other air emissions would depend on the mix of fuels used to generate the electricity and would vary nationally and regionally [28]. For a complete assessment, the source of emissions associated with electricity use and production of associated fuels used in the grid mix and in other processes should be considered within a regional context.

Like any other fuel-burning production process, cement manufacturing generates major common air pollutants: SO_2, NO_x, CO, PM, VOC, and CH_4 in addition to CO_2 emissions. Marceau et al. [18] is the only U.S. LCI source that includes these air pollutants in its inventory, and does so for four different types of cement kilns. Additionally, all the EU studies [16, 17, 20, 22, 24, 25, 33] provide some or all of the criteria air pollutants for different cement types.

PM requires scrupulous attention as it is generated during almost all stages of portland cement manufacturing [36, 46, 47]. Both of the U.S. portland cement LCAs in literature [18, 19] provide PM emissions for major processes, including raw meal preparation, pyroprocessing, and finish grinding. Additionally, Marceau et al. [18] provide PM from quarrying activities and transportation of raw materials to the portland cement plant. Generally, 90% of cement raw materials (limestone, clay, marl, shale, etc.) are quarried. Particulates emissions, water consumption, water effluents, and use of explosives are major concerns during quarrying. Specifically, PM from quarrying can cause about 90% of the total particulates emissions during cement manufacturing. Water consumption during quarrying is about 60% of the total use [18]. When we consider the global volumes of cement production [42], the magnitude of emissions and water use from quarrying can become significant.

Organic carbon content in natural raw materials can cause elevated amounts of hydrocarbon

(HC) and carbon monoxide (CO) emissions. Hydrocarbon emissions during pyroprocessing are mostly composed of VOC and CH_4 [18]. Emissions of VOCs and other HCs from traditional cement production processes are generally found at insignificant levels. Cembureau [48] explains why these pollutants are at such low levels as: "...other substances entering the kiln system which could give rise to undesirable emissions are either effectively destroyed in the high temperature combustion process or almost completely incorporated into the product."

In the surveyed literature, a number of portland cement LCA and non-LCA studies provide data for toxic emissions of VOC, benzene, dioxin/furans, heavy metals (Ar, Cr, Pb, Hg, Ni, Thallium, Zn), HF, and HCl as part of their environmental analysis [18, 20, 32, 33, 48-54]. Looking at the data sources, one can conclude that those portland cement LCAs which focus on alternative/waste raw materials and fuels also provide toxic air emissions in their LCIs as it is one of the concerns for using such materials. Waste used as alternative fuel or as a substitute for raw material may contain varying concentrations of trace elements. Certain conditions, such as burning waste fuels in an inefficient wet kiln, can result in higher toxic emissions. For example, in [25] study, elemental analysis of scrap tires, solvents, and waste oils show considerably higher amounts of Zn, Pb, Cr, Cd, and other trace elements compared to other traditional fuels. Although some studies were conducted on the criteria pollutant and hazardous air pollutant (HAP) emissions associated with tire-derived fuel, these studies [49, 50] examine fuels that are a combination of scrap tires and conventional fuels. Therefore, these studies do not isolate the criteria air pollutants or HAPs associated with scrap tires alone [55] and for that reason, the LCI results cannot be used for other fuel mixes. For an accurate assessment, fuel burning and emission control technologies need to be considered while calculating emissions from the pyroprocessing stage in an LCI.

Water consumption was rarely covered in cement LCIs. Investigated studies provided only the quantity of water consumed in cement manufacturing [16-18, 22, 24]. About 60% of it is consumed during extraction of cement raw materials [18]. None of the cement LCAs quantified related environmental impacts of water consumption because the available water consumption data was not sufficient.

Table 2.12: LCI categories included in cement LCA literature

LCI in cement LCAs	**[22]**	**[24]**	**[25]**	**[20]**	**[19]**	**[16, 17]**	**[18]**	**[32]**	**[33]**
Raw materials use	*	*	*	*	*	*	*	*	*
Energy use	*	*	*	*	*	*	*	*	*
Water consumption	*	*				*	*		
GHG (CO_2) emissions, calcination			*	*			*		*
GHG (CO_2) emissions, fuel use			*	*			*		*
GHG (CO_2) emissions, total	*	*	*	*	*	*	*	*	*
SO_2 emissions	*	*	*	*		*	*		*
NOx emissions	*	*	*	*		*	*		*
PM emissions	*	*	*	*	*	*	*		*

CO emissions		*	*				*		
VOC emissions		*	*	*			*		*
Toxic emissions		*	*	*			*	*	
Solid waste		*			*		*		
Waste water		*					*		

2.3 Concrete Manufacturing LCAs

This section is a synthesis of concrete and its components manufacturing LCA studies shown in Table 2.30. Similarly to the cement manufacturing LCA literature, concrete studies are also evaluated on the basis of their scope (in terms of concrete raw materials covered and functional units involved) and LCI and LCIA representation.

2.3.1 Background on Concrete Manufacturing LCAs

The main literature sources for concrete LCA studies include industry organizations such as Portland Cement Association, scientific and consulting institutions (i.e., ATHENA^{TM} - Sustainable Materials Institute, NIST), and peer reviewed journals (i.e., Journal of Cleaner Production, Environmental Impact Assessment Review, International Journal of LCA, Building and Environment, Journal of Resources, Conservation, and Recycling, Cement and Concrete Research). Concrete LCAs reviewed in this section go back to early 1990s. Most of the earlier studies were limited to LCI stage [47, 56-60]. More recent studies [6, 44, 61-63] applied both LCI and LCIA, among which only one is a U.S. study [6]. This study is the “BEES- Building for Environmental and Economic Sustainability” tool which assesses the environmental impacts of concrete and other building elements on the basis of a process-based LCA methodology. Others are European and Australian studies [44, 61-65]. Among these non-U.S. concrete LCAs, four of them [44, 61, 64, 65] compare different types of “green concrete”. Except for Habert et al. [65], the remaining three are limited to LCAs of ordinary portland cement vs. substitutions of cement with slag, fly ash or geopolymer in concrete pastes. Therefore, these three studies do not include aggregates, admixtures, and concrete plant batching processes and associated environmental interventions in the scope of the LCAs reviewed. On the other hand, only Habert et al. [65] evaluated the full environmental impacts of concrete ingredients (cement, gravel, sand, admixtures, fly ash, slag, sodium silicate, NaOH, silica fume, etc.) for both fly ash-based and slag-based concrete mixes, compared to ordinary portland cement concrete mix designs with similar mechanical properties. Different from the earlier research, allocation (in terms of mass and economic for concrete types with fly ash or GBFS) procedure was applied in a number of concrete LCA studies, including Van den Heede and De Belie (2012) [61], Habert et al. (2011) [65], and Chen et al. (2010b) [44]. Additionally, Zabalza Bribián et al. (2011) [62] analyzed not only cement and concrete but also different building materials. Finally, Blengini et al. (2012) described guidelines on application of LCA methodology in aggregates production.

The following sections provide a more detailed review of major concrete LCAs in literature.

2.3.1.1 Van den Heede and De Belie (2012)

This recent study is a comprehensive literature review based on the compilation of energy and emissions data for both traditional and “green” concrete manufacturing. Authors provided details on various aspects of concrete such as durability, service life, production processes, LCI data for concrete ingredients (portland cement, fine and coarse aggregates, admixtures, fly ash, and GBFS) as well as allocation procedures within the context of concrete production (Table 2.13). Additionally, the study demonstrated the link between the most relevant LCI factors (fossil energy use, CO_2, NO_x, PM_{10}, and SO_x) and problem-oriented LCIA (CML 2002) and damage-oriented LCIA (Ecoindicator 99) data for concrete products with ordinary portland cement, with GBFS substitution (economic and mass allocation), and with fly ash substitution (economic and mass allocation). Results indicated that the impact of concrete with blast-furnace slag and fly ash substitution was about an order of magnitude lower compared to ordinary portland cement in concrete.

Table 2.13: Summary of Van den Heede and De Belie (2012) [61]

Title	Environmental impact and life cycle assessment (LCA) of traditional and ‘green’ concretes: Literature review and theoretical calculations
Region	Europe-Belgium
LCA Approach	Process, both LCI and LCIA
Materials/products studied	Traditional and “green” concrete mixes
Functional unit	1 kg of ordinary portland cement, 1 kg of fly ash, or 1 kg of GBFS
Phases studied	Extraction/Production Waste Treatment Transportation
Allocation	Economic and mass allocation

2.3.1.2 Blengini et al. (2012)

This is one of the only-aggregates production LCA studies known in literature since aggregates are mostly analyzed as part of concrete manufacturing LCAs. The implementation of LCA methodology in aggregates was initiated by a project, namely SARMa (www.sarmaproject.eu), developed for South Eastern Europe. The EU-funded SARMa (Sustainable Aggregates Resource Management) project focused on promoting sustainable management and use of aggregates in the construction industry as well as increasing the construction and demolition waste (C&DW) recycling rates. The implemented LCA methodology is a cradle-to-gate LCA including mining, transportation, and extended to C&DW recycling and the production of recycled aggregates (plus avoided landfill impacts). The functional unit is one tonne of natural aggregates or recycled aggregates. However, no LCI or LCIA were provided as the project comprised a guideline for aggregates production LCA.

Table 2.14: Summary of Blengini et al. (2012) [66]

Title	Life Cycle Assessment guidelines for the sustainable production and recycling of aggregates: the Sustainable Aggregates Resource Management project (SARMa)
Region	Europe – South Eastern Europe
LCA Approach	Process, guidelines, no LCI/LCIA results
Materials/products studied	Natural aggregates Recycled aggregates
Functional unit	1 tonne of aggregate
Phases studied	Extraction/Production Transportation End-of-life (recycling)
Allocation	No

2.3.1.3 McLellan et al. (2011)

This study is a comparison of the cost and GHG emissions of ordinary portland cement (OPC) concrete and geopolymer concrete in Australia. In the article, authors provided geopolymer concrete mix data based on typical Australian feedstock (materials including fly ash, slag, sodium hydroxide (NaOH), gibbsite (uncalcined alumina), sodium silicate, metakaolin, silica fume) and the associated LCI data from literature (Table 2.15). Results from these sources indicated potential for a 44-64% reduction in GHG emissions while the production costs varied between 7% lower to 39% higher compared with the cost of OPC mixes. In addition to GHG emissions (in CO_2-eq) and cost evaluations, results were also compared on the basis of energy use (direct fuel use and electricity use) per tonne of ordinary portland cement and geopolymer feedstock (sodium hydroxide and sodium silicate). In the interpretation, authors assumed that "… wastes (fly ash, GBFS, silica fume etc.) would not be generated without the production of their associated commercial product (e.g. electricity in the case of fly ash and silicon in the case of silica fume), and hence the emissions should be allocated to their respective commercial products." This assumption means that, apart from any post-collection processing, these materials come with no "embodied impacts" and therefore allocation is not considered in LCA calculations.

Table 2.15: Summary of McLellan et al. (2011) [64]

Title	Costs and carbon emissions for geopolymer pastes in comparison to ordinary portland cement
Region	Australia
LCA Approach	Process, only LCI
Materials/products studied	Ordinary portland cement concrete vs. Geopolymer concrete mixes
Functional unit	1 tonne of ordinary portland cement vs.1 tonne of geopolymer feedstock for comparable performance in concrete
Phases studied	Extraction/Production Transportation (collection)
Allocation	No

2.3.1.4 Habert et al. (2011)

Environmental impacts of geopolymer and blended cement concrete mix designs are evaluated and compared to ordinary portland cement concrete (OPC) for the 3 allocation procedures. These procedures included: no allocation, mass allocation, and economic allocation. Authors used geopolymer concrete mix-designs found in the literature. A distinction was made between three types of geopolymer concrete made from different materials: fly ash, blast furnace slag and metakaolin (Table 2.16). The functional unit for the LCA was chosen as one cubic meter of concrete with a given compressive strength in the hardened state. Furthermore, based on standard concretes made with an average substitution of 30% of OPC by mineral additions (such as fly ash) in Europe, geopolymer based concrete from literature were similarly compared with cement based concrete with the same mechanical strength and with binding material options either only OPC or 30% clinker substitution. Different from McLellan et al. study [64], this LCA study provided results from different components of concrete (i.e., gravel, sand, filler, NaOH powder, silicate solution, water, admixture) in addition to impacts from binders (i.e., OPC, fly ash, slag, metakaolin) in geopolymer concretes. Therefore, the scope is comparably larger.

Finally, environmental impacts were evaluated according to the baseline method of CML01 that evaluates 10 environmental impacts (abiotic depletion, global warming, ozone layer depletion, fresh and marine water ecotoxicity, terrestrial ecotoxicity, human toxicity, eutrophication, acidification and photochemical oxidation). The production of geopolymer concrete resulted in slightly lower GWP compared to the production of standard OPC concrete. However, other impact categories were higher for the geopolymer type. Authors attributed these results to the sodium silicate solution used in the mixes. Geopolymer concrete mixes with fly ash or GBFS required less of the sodium silicate solution in order to be activated. They, therefore, had lower environmental impact than geopolymer concrete made with pure metakaolin. On the other hand, when an economic or a mass allocation procedure was applied to the fly ash and slag production, it appeared that geopolymer concrete had similar GWP impact as OPC concrete.

Table 2.16: Summary of Habert et al. (2011) [65]

Title	An environmental evaluation of geopolymer based concrete production: reviewing current research trends
Region	France
LCA Approach	Process, only LCIA
Materials/products studied	Ordinary portland cement concrete vs. Geopolymer concrete mixes with fly ash, GBFS, metakaolin
Functional unit	1 m^3 concrete with a given compressive strength
Phases studied	Extraction/Production Transportation (collection)
Allocation	Economic and mass allocation

2.3.1.5 *Zabalza Bribián et al. (2011)*

This study evaluates primary energy demand (in MJ-eq), GWP (in kg CO_2-eq), and water demand (in liters) associated with different building materials during manufacturing, transportation, and end-of-life stages. Primary energy demand was calculated based on CED (Cumulative Energy Demand) method which has been used as an indicator [67, 68] for energy systems; distinguishing between non-renewable and renewable primary energy use. GWP was evaluated based on 2007 IPCC [69] characterization factors considering a 100-year time horizon. For water demand, no specific method was applied. For this study, water indicator was an aggregation of all fresh water extractions (from river, lakes, ocean, soil, and wells) including water used for cooling processes. The functional unit was selected as one kg of material. In analysis, SimaPro v7.1.8 software was used. Inventories were selected from EcoInvent v2.0 database [70-72]. For all building materials (see Table 2.17 for the list of products), density and thermal conductivity data were also provided. Proposed improvements in the manufacturing of materials (e.g. energy efficiency) were based on the BREF – the Best Available Techniques Reference documents (http://eippcb.jrc.es/reference/). Results from the study can be used for improving the performance of building materials by providing guidelines for material selection.

Table 2.17: Summary of Zabalza Bribián et al. (2011) [62]

Title	Life cycle assessment of building materials: Comparative analysis of energy and environmental impacts and evaluation of the eco-efficiency improvement potential
Region	Spain
LCA Approach	Process, LCI and LCIA (energy, GWP, water)
Materials/products studied	Bricks and tiles: Ordinary brick Light clay brick

	Sand-lime brick Ceramic tile Quarry tile Ceramic roof tile Concrete roof tile Fiber cement roof slate Insulation: Expanded polystyrene foam slab Rock wool Polyurethane rigid foam Cork slab Cellulose fiber Wood wool Cement and concrete products: Cement Cement mortar Reinforced concrete Concrete Wood products: Sawn timber, softwood, planed, kiln dried Sawn timber, softwood, planed, air dried Glued laminated timber, indoor use Particle board, indoor use Oriented strand board Other common building products Reinforcing steel Aluminum Polyvinylchloride Flat glass Copper
Functional unit	Per kg of building material
Phases studied	Materials Production Transportation EOL
Allocation	No

2.3.1.6 *Chen et al. (2010b)*

This process-based concrete LCA study evaluated the influence of three allocation procedures on the environmental impacts of blast furnace slag and fly ash in concrete, namely, no allocation, allocation by mass and allocation by economic value. The latter two approaches resulted in the calculation of mass and economic allocation coefficients. These coefficients were used to calculate the amount of energy use, CO_2, SO_x, NO_x, and PM emissions attributable to the fly ash and GBFS (Table 2.18) production. The binding equivalent (BE) value was chosen as the functional unit, in order to compare concrete products with similar concrete strength properties according to the EN 206-1 standards. The EN 206-1 standard defines an equivalent binding capacity for SCM additions when they substitute type I cement. It is calculated as follows:

$$\boxed{BE = cem + k \times SCM}$$

Where;

BE = the binding equivalent value (eq.kg/m^3), based on the targeted strength properties of the cement concrete,

cem = CEM I cement dosage (kg/m^3),

SCM = dosage of supplementary cementitious material (kg/m^3), and

k = coefficient specific to the additive (no unit).

Accordingly, 1 kg of CEM I cement was compared to 1.11 kg of GBFS, and to 1.67 kg of fly ash in concrete.

For the LCIA, the CML-based method was chosen. Impact categories included were: abiotic depletion, GWP, ozone layer depletion, human toxicity, fresh water aquatic ecotoxicity, marine aquatic ecotoxicity, terrestrial ecotoxicity, photochemical oxidation, acidification, eutrophication, and energy (see Table 2.33).

The paper concluded with the advantages and disadvantages of each allocation method. Mass allocation imposed substantial environmental impacts to the industrial by-products which may discourage the concrete industry to continue applying them as cement replacement. Besides, the economic allocation method presented the advantage of lowering impacts of by-products when compared to the mass allocation. It enhanced the fact that the alternative resources were primarily waste and should therefore not have the same environmental burden as the main products. However, this method had the disadvantage of price instability which could make the LCA outcome subject to significant fluctuations over time.

Table 2.18: Summary of Chen et al. (2010b) [44]

Title	LCA allocation procedure used as an incitative method for waste recycling: An application to mineral additions in concrete
Region	Europe-France
LCA Approach	Process, both LCI and LCIA
Materials/products studied	Concrete with CEM I Concrete with GBFS substitution Concrete with fly ash substitution
Functional unit	Binding equivalent value (strength) based on EN 206-1
Phases studied	Production Waste treatment Transportation
Allocation	Economic, mass, and no allocation

2.3.1.7 O'Brien et al. (2009)

The purpose of this study was to develop an equation for quantifying the GHG emissions (in kg CO_2-eq.) and embodied water in concrete as a function of fly ash content and determine the critical fly ash transportation distance, beyond which the fly ash use in concrete would start increasing the embodied GHG emissions. The functional unit for the analysis was one cubic meter of concrete. The system boundary included GHG emissions during manufacturing and transportation of concrete (Table 2.19). The fly ash content varied from 0 percent to 40 percent for a concrete mixture of 32-MPa compressive strength. Three modes of transportation: road, sea, and rail were analyzed to determine the "critical fly ash transportation distance". Total GHG emissions embodied in concrete were estimated as the sum of the emissions associated with the production of cement, aggregates, and fly ash, and the emissions associated with the transportation of raw materials to the batching plant and transportation of concrete to the construction site. Authors assumed that no energy use was associated with the fly ash production but only for its collection. Based on the LCA results, no predictable relationship was determined between fly ash content and embodied water in concrete.

Table 2.19: Summary of O'Brien et al. (2009) [56]

Title	Impact of fly ash content and fly ash transportation distance on embodied greenhouse gas emissions and water consumption in concrete
Region	Australia
LCA Approach	Process, only LCI
Materials/ products studied	Concrete with fly ash content
Functional unit	1 m^3 concrete
Phases studied	Extraction/Production Transportation
Allocation	No

2.3.1.8 *Flower and Sanjayan (2007)*

Authors evaluated the CO_2-eq emissions associated with concrete production in Australia. LCI data was collected from two coarse aggregate quarries, one fine aggregate quarry and six concrete batching plants for the assessment. The CO_2-eq emission factors involved emissions from diesel, electricity, explosives (bulk emulsion, heavy ANFO), and LPG. The study summarized CO_2-eq emissions generated from typical commercial concrete mixes, which include two different strengths (25 MPa and 32 MPa) of concrete with 100% portland cement, with 25% of the portland cement replaced by fly ash, and 40% replaced by GBFS; resulting in six different mixes (see Table 2.20). In comparisons, 100% portland cement concretes (with 25 MPa and 32 MPa) were considered as benchmark. Besides concrete production, structural concrete elements of a sustainable medium-rise apartment complex in Melbourne were studied as a case study. Authors calculated GHG emissions associated with concrete used for footings (32 MPa), slabs (32 MPa), in-situ columns and walls (40 MPa), and precast walls (40 MPa).

Results showed that: 1) During coarse aggregate production, crushing was the most significant source of CO_2 emissions; 2) Diesel and electricity contributed almost equally to the CO_2 emissions from production and transportation of fine aggregates; 3) CO_2 emissions from cement production was the highest; 4) The electricity used for mixing was significant source of emissions during concrete batching process (but much less compared to other components of the concrete). Based on the results, authors recommended "*passive design measures, which enhance the operational energy performance of a building, have the potential to make a greater impact on the overall greenhouse gas emissions of a building than using fly ash substitution in concrete mix designs.*"

Table 2.20: Summary of Flower and Sanjayan (2007) [57]

Title	Greenhouse gas emissions due to concrete manufacture
Region	Australia
LCA Approach	Process, only LCI (GHG in CO_2-eq.)
Materials/products studied	Coarse aggregates: Granite or hornfelts Basalt Fine aggregates (sand) Portland cement Fly ash (F-type)

	GBFS Admixtures Concrete types: 100% Portland cement concrete (25 MPa vs. 32 MPa) 25% fly ash concrete (25 MPa vs. 32 MPa) 40% GGBFS concrete (25 MPa vs. 32 MPa) Concrete structural elements: Blinding (15 MPa) Footing (32 MPa) Slabs (32 MPa) In-situ columns and walls (40 MPa) Precast walls (40 MPa)
Functional unit	Per unit mass or volume of each product/material
Phases studied	Extraction/Production Construction Use Transportation
Allocation	No

2.3.1.9 *Marceau et al. (2007)*

Authors presented LCI data for three types of concrete products: ready mixed concrete (for seven different mix designs with varying strength), concrete masonry, and precast concrete (Table 2.21). The functional unit was chosen as the unit volume of concrete produced in the U.S. from domestic portland cement, SCMs, and aggregates. For ready-mixed and precast concrete, the unit volume was one cubic meter (or one cubic yard) of concrete, and for the concrete masonry, it was 100 standard 8x8x16-in.concrete masonry units, which contain about one cubic yard of concrete. The system boundary included both upstream activities and concrete plant operations such as; cement and slag cement production; aggregates production; transportation of fuel, cement, SCMs, and aggregates to the concrete plant; plant operations (including truck mixer wash-out in case of ready-mixed concrete). Energy used for heating, cooling, and lighting the plant building was also included in plant operations and examined as part of the manufacturing energy. Inputs to LCI (for all concrete products) included raw materials, ancillary materials (e.g. explosives, refractory materials, grinding media, grinding aids, filter bags, oil & grease, solvent, cement bags, and chains), fuel, electricity use, and their energy equivalents (for coal, gasoline, LPG, middle distillates, natural gas, petroleum coke, residual oil, wastes and electricity). Outputs (from all concrete products studied in the report) include emissions to water (aluminum, ammonia (-um), COD, chlorides, copper, DOC, iron, nitric, nitrites, oil and grease, pH, phenolics, phosphorus, sulfates, sulfides, suspended solids, water that leaves site, and zinc), emissions to air (CO_2, CO, SO_2, NO_x, CH_4, VOC, PM, heavy metals, dioxins and furans, carcinogens, and others),and emissions to land (CKD, slag reject, other solid waste).

Study results indicated that newer plants replacing older ones, use of more energy efficient technologies, and more accurate data (particularly for concrete plants and aggregate production), LCI results were lower for most of the flows compared to those reported in the previous edition of the PCA report [73]. For example, for a typical 20-MPa (3,000-psi) concrete mix, embodied energy is 30% lower and CO_2 emissions are about 7% lower.

Table 2.21: Summary of Marceau et al. (2007) [58]

Title	Life-cycle inventory of portland cement concrete
Region	United States
LCA Approach	Process, only LCI

Materials/products studied	Coarse aggregates: Natural quarried Crushed stone Fine aggregates (natural quarried) Portland cement SCMs Ready-mixed concrete (seven different mixes) Concrete masonary units Precast concrete (three different mixes)
Functional unit	per unit mass or volume of each product/material
Phases studied	Extraction/Production Transportation
Allocation	No

2.3.1.10 *Pade and Guimaraes (2007)*

This paper covers CO_2 uptake by concrete based on theoretical and laboratory studies, surveys and calculations in Denmark, Iceland, Norway, and Sweden (Table 2.22). Authors developed a new methodology for estimating the CO_2 uptake by concrete in a 100-year period (with an assumption of 70 years of service life and 30 years of secondary life after demolishing). Estimations were based on Nordic ready-mixed concrete and pre-cast concrete elements/products data for differing exposure conditions (indoor vs. outdoor exposed, painted vs. covered, etc.) and thicknesses of structural elements. For ready-mixed concrete, authors used the results from a survey conducted by European Ready-Mix Concrete Organization (ERMCO). On the other hand, they used their personal judgments for data on exposure conditions and structural dimensions (thickness) of products as such data were not readily available. Authors concluded that the effect of carbonation on the net CO_2 emissions from concrete can significantly be influenced by the way concrete is handled after demolition (e.g., crushing can maximize CO_2 uptake).

Table 2.22: Summary of Pade and Guimaraes (2007) [74]

Title	The CO_2 uptake of concrete in a 100 year perspective
Region	Nordic countries
LCA Approach	Process, only LCI, limited to CO_2 emissions and uptake
Materials/products studied	Ready-mixed concrete elements and products Precast concrete elements and products
Functional unit	1 m^2 for ready-mixed concrete and 1 m^3 for precast
Phases studied	Production Use End-of-life
Allocation	No
Note that CO_2 uptake by concrete was considered in the calculations	

2.3.1.11 *Petersen and Solberg (2005)*

This study is a collection of Norwegian and Swedish LCA studies that compare the environmental impacts of wood and alternative building materials, including concrete and steel (Table 2.23). The focus is on GHG emissions, cost, and methodological issues. All of the reviewed studies concluded that wood is a better alternative in terms of GHG emissions, waste generation, and SO_2 emissions, depending on the waste management technique and the way carbon fixation on forest land was applied. However, studies showed that using “preservative treated (using creosote)” wood might have toxicological impacts on human health and ecosystems. It is necessary to mention that, because of different assumptions, system boundaries and functional units applied in each study, results were hardly comparable. All studies included raw material extraction and manufacturing, a cradle-to gate inventory, but the remaining stages in the life-cycle that were included differed from one study to another. In some of the LCAs, electricity was measured as direct energy, in others as both direct and indirect energy (including energy sources needed to produce the used energy or electricity). Allocation between life cycles was also handled differently, along with different product durability. Moreover, comparisons between some studies [75] were based on different evaluation methods (e.g. EPS method[1], the Environmental Theme method[2], and the Ecological Scarcity-method[3]). Each of these methods combined different environmental impacts into one value while weighting factors were subjectively determined. Therefore, results obtained using these methods should carefully be assessed.

Table 2.23: Summary of Petersen and Solberg (2005) [76]

Title	Environmental and economic inputs of substitution between wood products and alternative materials: a review of micro-level analyses from Norway and Sweden
Region	Sweden and Norway
LCA Approach	Process, both LCI and LCIA
Materials/products studied	Wood/ Steel/Concrete elements/products (roof, walls, floor, dwelling, beams, warehouse frame, multi-storey building)
Functional unit	Varies from study to study
Phases studied	Extraction/Production Construction Use M&R EOL
Allocation	Varies by each study: None, Cut-off[4] , 50/50[5], and Quality[6]

Notes:

[1] EPS Method: Environmental priority strategies in product design. It is based on willingness to pay for restoration of biodiversity, production, human health, resources and aesthetic values to their normal status.

[2] Environmental Theme method: Data on emissions and use of resources are calculated as contributions to environmental problems. These environmental problems are then weighted against each other according to political goals.

[3] Ecological Scarcity method: Actual emissions are set in relation to critical emission limits (for instance legal emission limits).

[4] All emissions from raw material extraction, manufacturing and landfill are allocated to the product.

[5] Half of the emissions from manufacturing and waste handling are allocated to the product.

[6] Emissions from manufacturing and waste handling are divided on several life cycles according to reduction in quality.

2.3.1.12 Sjunnesson (2005)

The author assessed two types of concrete: Ordinary and frost-resistant concrete, with emphasis on the superplasticisers as admixtures. LCA system boundary included raw materials production, concrete production, transportation, and demolition (Table 2.24). Results from the study were consistent with other concrete LCA studies and showed that production of raw materials; mainly cement manufacturing and transportation are among major contributors to the total environmental load. The environmental impact of frost resistant concrete was calculated as 24 to 41 percent higher than that of ordinary concrete because of its higher cement content.

Superplasticisers contributed to 0.4 to 10.4 percent of the total environmental impact of the concrete, the least to the GWP and the most to the photochemical ozone creation potential (POCP). In terms of toxicity, superplasticisers constituted a low risk for the environment and the human beings due to its minimal leakage from concrete during its use and end-of-life phases.

Table 2.24: Summary of Sjunnesson (2005) [63]

Title	Life-cycle assessment of concrete
Region	Sweden
LCA Approach	Process, both LCI and LCIA
Materials/products studied	Concrete raw materials: cement, aggregates, admixtures (superplasticisers) Ordinary concrete vs. frost-resistant concrete
Functional unit	per unit mass or volume of each product/material
Phases studied	Extraction/Production End-of-life
Allocation	No

2.3.1.13 Prusinski et al. (2004)

This study provides life-cycle inventory for concrete manufacturing with slag cement replacing a portion of portland cement. In general, slag cement substitution for portland cement ranges from 25 percent to 80 percent by mass. The U.S. State Department of Transportation allows up to 50 percent substitution for paving and structural concrete. This percentage varies between 65 to 80 percent for mass concrete structures to reduce heat generation.

Authors considered five types of concrete in their study: 20 and 35 MPa ready-mixed concrete; 50 and 70 MPa precast concrete; and a concrete block mix. For each concrete type, three versions of cement were analyzed (Table 2.25): 100 percent portland cement, 35 percent and 50 percent substitution of slag cement for the portland cement. The functional unit was one cubic yard of concrete. The LCI data covered raw materials, energy use (in terms of fuels and electricity), and air emissions of CO_2, CO, H_2S, metals, CH_4 , NO_x, VOC, PM, and SO_2 from extraction of raw materials, production of cement (both portland cement and slag cement), processing of aggregates, transportation, and production of concrete. The upstream profiles for producing fuels and generating electricity were not included in the LCI. Authors assumed that one tonne of slag yielded one tonne of slag cement although some amount was lost as PM and suspended solids (which are less than one tenth of one percent). Water consumption in slag manufacturing was not incorporated in the analysis. Results revealed that slag cement mixtures, in general, used about 21.1 to 36.5 percent less energy and 4.3 to 14.6 percent less virgin materials. Their use also reduced CO_2 emissions by 29.2 to 46.1 percent.

Table 2.25: Summary of Prusinski et al. (2004) [59]

Title	Life-cycle inventory of slag cement concrete
Region	United States
LCA Approach	Process LCA, only LCI
Materials/products studied	Ready-mixed concrete (20 MPa, 35 MPa) [100% portland cement, 65% portland cement - 35% slag, and 50% portland cement - 50% slag] Precast concrete (50 MPa, 70 MPa) [100% portland cement, 65% portland cement - 35% slag, and 50% portland cement - 50% slag] Concrete block mix [100% portland cement, 65% portland cement - 35% slag, and 50% portland cement - 50% slag]

Functional unit	1 cu.yd of concrete
Phases studied	Extraction/Production
Allocation	No
Note: For comparison purposes, ten slag cement mixes were compared to five portland cement - only mixes and one portland cement and fly ash mix (20 percent fly ash mix concrete. The high performance 70 MPa precast concrete mix included 11 percent silica fume.	

2.3.1.14 Lippiatt and Ahmad (2004); Lippiatt (2007)

Building for Environmental and Economic Sustainability (BEES) [77] model was developed to estimate environmental and economic performance of construction products using the LCA approach. The BEES was initiated by the NIST Healthy and Sustainable Buildings Program in 1994. Two approaches were applied in the software: LCA as specified in the ISO 14040 series of standards for measuring the environmental performance of concrete products and ASTM's international standard life-cycle cost (LCC) for the economic performance part. These two performance measures were synthesized into one performance measure by using a Multi-attribute Decision Analysis (MADA) of ASTM standard. The later version by Lippiatt (2007) [6] constitutes the BEES® 4.0 technical manual and user guide. Data requirements included geographic, time-related, and technological coverage.

Authors assumed that all product alternatives meet the minimum technical performance requirements (e.g. hydration, strength development). The LCI included inputs of raw materials, energy use, and water consumption and emissions to air, water, and land. Environmental impacts were normalized based on the TRACI impact assessment method developed by the U.S. EPA Office of Research and Development and included: global warming, acidification, eutrophication, fossil fuel depletion, indoor air quality, habitat alteration, water intake, criteria air pollutants, human health, smog, ozone depletion, and ecological toxicity. The interpretation stage evaluated the normalized impacts. The LCC section included initial and future costs for estimating the economic performance score. Finally, two performance scores (LCA and LCC) were combined into one overall score by taking a weighted average of each score depending on their relative importance.

Table 2.26: Summary of Lippiatt and Ahmad (2004) [77]; Lippiatt (2007) [6]

Title	Measuring the life-cycle environmental and economic performance of concrete: The BEES approach
Country	United States
LCA Approach	Process LCA, both LCI and LCIA
Materials/products studied	Both generic and manufacturer-specific concrete mixes and products. These include concrete walls/slabs/paving and concrete beams/columns
Functional unit	0.09 m^2 (1 ft^2) for walls/slabs/paving and 0.76 m^3 (1 cu.yd) for beams and columns with service life of 50 years
Phases studied	Extraction/Production
Allocation	No

2.3.1.15 ATHENA™ (1999, 2005, 2010)

The ATHENA™ Cement and Structural Concrete LCI model provides data for concrete raw materials by region and by type of process and energy source. The first part of the tool is reserved for cement and its associated LCI. Cement manufacturing processes within the system boundary include primary crushing, secondary crushing, raw grinding, pyroprocessing, and finish grinding. Energy sources for cement plants cover choices of natural gas, coal, oil, petcoke, waste fuels, and electricity. Energy efficiencies of four different pyroprocessing methods (wet, dry long, dry preheater, dry precalciner) are specified on Canadian national weighted average basis. Finished product transportation data include average haul distances (in km) by mode of transportation with options of truck, rail, and ship. Transportation energy is estimated based on the average distance by mode which consists of diesel-road, diesel-rail, and heavy fuel oil-marine. Major air emissions considered in the tool are CO_2, SO_2, NO_x, VOC, CH_4, CO, and total PM. Liquid effluents of suspended solids, aluminum, phenolics, oil and grease, nitrate, nitrite, DOC, chlorides, sulphates, sulphides, ammonia (-um), phosphorus, and zinc per unit mass of cement are also provided in the LCI. Major sources of effluents cover cement plant effluents (mostly from water used to clean equipment and yards as well as rain water washing away cement dust), quarrying water, and storm water. Authors state that solid waste from cement raw materials extraction is minimal. However, the degree of land disturbance can be significant. During the cement manufacturing stage, CKD is the major solid waste generated. Another solid waste from cement manufacturing is spent refractory brick (SRB) from cement kiln lining. If higher than limits, volatilized metals concentrated in SRBs can be considered hazardous. But no current data are available on SRBs.

The second part of the tool covers raw material requirements, energy use and water consumption, as well as atmospheric emissions, liquid effluents and solid wastes per unit of concrete. Concrete products specialized in the tool vary by strength and structural use purpose (see Table 2.27). In the second half, information provided are: 1) Number and location of ready-mixed, block and precast concrete plants across Canada; 2) Product characteristics and raw material requirements (cement, coarse aggregates, fine aggregates, and water) for each concrete product type. Steel requirement for precast products are calculated as well; 3) Average haul distances and modes for raw material transportation to the concrete plants; 4) Average energy use estimates for raw material extraction (diesel use), processing (electricity) of coarse and fine aggregates as well as transportation energy data for coarse aggregates, fine aggregates, and steel; 5) Fuel use in concrete manufacturing in the form of diesel (road), diesel (rail), heavy fuel oil (marine), natural gas, coal, oil, coke, waste, and electricity; 6) Estimated water consumption (batch water, truck washout, truck wash off, etc.) for ready-mixed concrete manufacturing; 7) Air emissions of CO_2, SO_2, NO_x, VOC, CH_4, CO, and total PM associated with fine and coarse aggregate extraction/processing and transportation as well as SCM transportation and processing, and concrete batching; 8) Liquid effluents from concrete manufacturing involve effluents from cement manufacturing, aggregates production, and concrete batching; 9) Finally, total solid waste from aggregates and concrete batching are provided. In terms of wastes involved, aggregates quarrying and cement raw material extraction exhibit similar trends. Solid waste from concrete batching involves mixer washout, sludges from settling basins and ponds, and returned excess ready-mixed products, unless reprocessed. Currently, the Canadian concrete industry disposes solid wastes in one of three ways: backfilling into quarries, long-term storage on-site, and reprocessing. Table 2.27 provides a summary of the tool.

Table 2.27: ATHENA^{TM} (1999, 2005, 2010) [36, 46, 47]

Title	Cement and Structural Concrete Products: Life Cycle Inventory Update #1 and #2 - ATHENA^{TM}

Region	Canada
LCA Approach	Process LCA, only LCI
Materials/products studied	Cement Concrete Products Ready Mixed (15 MPa, 20 MPa, 30 MPa, 60 MPa) Block Double T Beam Hollow Deck Cement Mortar
Functional unit	1 tonne of cement 1 unit of concrete product (m^3 of ready-mixed concrete, block of concrete, meter of concrete slab or beam)
Phases studied	Extraction/Production Construction End-of-life Transportation
Allocation	No

2.3.1.16 Kuhlman and Paschmann (1996)

The authors considered leaching as one of the major concerns over the life-cycle of concrete manufacturing. The source of this concern is traces of heavy metals (Pb, Cd, Cr, Hg, thallium, and Zn) as well as organic constituents found in chemical admixtures and additional organic compounds used in concrete. Based on the literature provided in the study, significant leaching of heavy metals, except for chromium (Cr), is not generally expected due to their low solubility in the alkaline medium of ready-mixed concrete. In case of organic constituents, the sorption properties of sodium naphthalene sulphonate (SNS) and calcium lignosulphonate (CLS) in cementitious suspensions were studied. Superplasticisers in concrete are the sources of these substances. As these substances are assumed to be strongly sorbed by cement and other ultra-fine particles, they do not constitute threat to environment. Therefore, these materials are not of a much concern in case of leaching. It is also known that freshly mixed concrete can cause irritations on skin if in contact due to high alkalinity and water soluble chromate content. But this problem can be minimized by using gloves and protective clothing. During the use phase of concrete, emissions of heavy metals and volatile organic matter are considered insignificant. Finally, at the end-of-life stage, no leaching of environmentally significant contaminants is expected from storage of crushed concrete (Table 2.28). The authors concluded that concrete is an environmentally compatible material through all its life-cycle phases but there is still a need for further investigation.

Table 2.28: Summary of Kuhlman and Paschmann (1996)[78]

Title	Environmental compatibility of concrete from the starting materials through its re-utilization (both in German and English)
Region	Germany
LCA Approach	Not an LCA, examines major environmental concerns through life-cycle stages of concrete, focus is on leaching, toxic emissions, radioactivity, and emissions of volatile and organic substances
Materials/products studied	Concrete, including ready-mixed concrete and pre-cast concrete
Functional unit	-
Phases studied	Production Construction Use End-of-life
Allocation	No

2.3.1.17 Cole and Rousseau (1992)

In this study, authors focused on direct environmental impacts of building production and operation. Energy intensity data (energy used in the production of building material and components) of selected building materials for Canada, United States, New Zealand, and Finland were provided (Table 2.29). Data varied significantly from one country to another due to differences in selection of system boundaries, data source reliability, fuel type, raw material imports, different accounting methods as well as thermal energy content of feedstock materials. Authors estimated emissions of CO_2, particulates, SO_2, NO_x, and CO associated with energy use and processes for load bearing wall assemblies used in commercial building construction. Results showed that: 1) Low mass construction has low environmental consequences; and 2) Walls with high embodied energy figures (steel, aluminum) have consequentially higher CO_2 production emissions and air emissions index. But recycling potential of these materials was not considered and if considered results would have differed.

Table 2.29: Summary of Cole and Rousseau (1992) [60]

Title	Environmental Auditing for Building Construction: Energy and Air Pollution Indices for Building Materials
Region	Canada
LCA Approach	Process LCA, only LCI
Materials/products studied	Non-load bearing wall assemblies in commercial building construction: Precast concrete panel clad wall with polystyrene board insulation and gypsum board interior finish. Brick clad construction with lightweight steel framing containing fiberglass insulation and gypsum board finishes. Exterior insulation and finish system using acrylic stucco, polystyrene board insulation and lightweight steel framing with gypsum board finish. Aluminum curtain wall with three alternative cladding panels: porcelain steel, aluminum, and glass. This system incorporates fiberglass insulation and gypsum board interior finish.
Functional unit	Varies; per kg of building material and per m^2 of wall assembly
Phases studied	Production Construction
Allocation	No

2.3.2 Synthesis and Limitations of Goal Definition and Scope of Concrete Manufacturing LCAs

Concrete LCAs in literature vary in terms of scope, geography, and type of concrete products (see Table 2.30). As opposed to the cement manufacturing LCAs, there are not many stand-alone LCAs of other concrete raw materials (including aggregates, admixtures, and water consumption) in literature except for one aggregate production study [66] which is limited to the LCA guidelines with no associated LCI/LCIA data. Concrete constituents other than cement are generally observed in concrete manufacturing LCAs. A few studies provided LIC/LCIA results for not only cement and concrete but also for other building materials such as bricks, aluminum, ceramic, insulation materials, wood, and steel products [62] and structural elements made of either concrete, steel or wood [6, 36, 46, 47, 57, 60, 76, 77].

A number of concrete LCA studies in literature focus on environmental impacts of recently developed “green” concrete products such geopolymer, fly ash, or GBFS concrete mix designs [44, 59, 61, 64, 65]. The recent LCAs incorporated by-product allocation in geopolymer and “green” concrete manufacturing [44, 61, 65]. For instance, both Van den Heede et al. [61] and Chen et al. [44] solely focused on allocation procedures that were considered for the addition of fly ash and GBFS into concrete. They examine the LCI data for iron production and processing of by-product GBFS and electricity generation from coal power plant and the processing of by-product fly ash. Authors suggested future research in LCAs of industrial by-products by applying either mass or economical allocation procedures in cases industrial by-products are not considered waste and used in concrete for substituting portland cement. Habert et al.[65] focused on geopolymer concrete mix-designs and also performed the allocation analysis on three types of geopolymer concrete made with fly ash, blast furnace slag and metakaolin. On the other hand, other two “green” concrete studies did not consider allocation issues. Of these two studies, McLellan et al. [64] focused on GHG emissions from geopolymer pastes while Prusinski et al. [59] specifically studied LCI data for concrete with slag substitution without any allocation procedure.

Except for three concrete LCAs [57, 63, 65], LCA of admixture production is limited in literature. Because of smaller quantities of admixtures in concrete (less than 1% by mass of concrete), their impacts are assumed to be negligible on the basis of common LCA guidelines [31].

For precise and transparent comparison of LCAs, consistency in concrete functional unit is necessary. The common functional unit used for concrete mixture designs and precast concrete is one cubic meter (or one cubic yard). The most commonly used functional unit for concrete slabs and walls is per one square meter (or one square feet). It is one cubic meter (one cubic feet) for beams and column structural elements [6].

Compared to other major construction materials, concrete is a complex composite with varying mixture designs. Depending on the designer’s requirements and type of concrete application, concrete mixture designs and properties vary considerably. To be able to assess accurately, certain concrete properties should be defined prior to LCAs. These properties include 7-day, 28-day, and 90-day compressive strength, unit weight, permeability, workability, thermal conductivity, etc. Each of these properties vary considerably depending on the mixture design [9, 79]. This variability offers an infinite range of concrete mixes, each of which will have its own life-cycle inventory. Despite the substantial amount of literature about the LCA of concrete, none of these studies provided systematic details about mixture proportions of concrete ingredients and properties (e.g. strength, permeability) of resulting concrete products and their associated life-cycle inventories. Generally, concrete production LCAs offered LCI data in terms of single values [63, 80, 81] or a range of values [56-59, 82] per unit volume of concrete. Of all the concrete studies, the recent ones [44, 56, 59, 61, 65] included different mixture designs to formulate the effect of fly ash, GBFS, metakaolin, and other cement substitutions in reducing the concrete’s environmental impacts but the results are still limited to the given concrete mix designs with no systematic recipe.

As previously mentioned, transportation of materials/products/equipment/machinery from one location to another is a critical issue in LCA as environmental impacts of transportation are significant. Except for a few [62, 66, 74, 78], all other remaining concrete LCA studies incorporate various aspects of transportation impacts in their analysis.

In addition to concrete LCAs in literature, a few earlier studies evaluated environmental impacts of concrete manufacturing from different perspectives. For example, Petersen and Solberg (2005) [76] reviewed environmental impacts of European building materials (wood, steel, and concrete) in a cradle-to-grave setting based on literature data. Kuhlman and Paschmann [78] studied problems of leaching, toxic emissions, and radioactivity through life-cycle stages of ready-mixed and precast concrete. Also, Cole and Rousseau (1992) reviewed direct environmental impacts (energy use and air emissions) associated with building materials and assemblies for the extraction, production, and construction stages. The Pade and Guimaraes [74], Kjellsen et al.[83], and Gajda [84] analyzed the carbonation process (carbon uptake) from exposed surfaces of concrete products. Gajda [84] is the only U.S. study but is limited to the materials production phase while other two studies covered use and end-of-life phases of Nordic concrete. The most recent one [74] is the most detailed and representative of the other two carbon uptake studies. Therefore, only Pade and Guimaraes study is provided in the following Table 2.30.

Table 2.30: Scope of cradle-to-gate concrete production LCAs

		Concrete and Raw Materials Production							**Concrete Products**			
(Author, year)	**Region**	Cement production	Fine aggregates production	Coarse aggregates production	Admixtures production	SCM production	Concrete batching	Transportation	Concrete mixes with 100% PC	Concrete mixes with varying % slag	Concrete mixes with varying % of fly ash	Other
Van den Heede and De Belie (2012) [61]	Belgium	*				*		*	*	*	*	
Blengini et al. (2012) [66]	Europe		*	*								*[0]
McLellan et al. (2011) [64]	Australia	*				*		*	*			*[1]
Habert et al. (2011)[65]	France	*	*	*	*	*	*	*	*	*	*	*[1]
Zabalza Bribián et al. (2011) [62]	Spain											*[2]
Chen et al. (2010b) [44]	France	*								*	*	
O'Brien et al. (2009) [56]	Australia	*	*	*				*	*	*		
Flower and Sanjayan (2007) [57]	Australia	*	*	*	*		*	*	*	*	*	
Marceau et al. (2007) [58]	U.S.	*	*	*			*	*	*	*	*	*[3]
Pade and Guimaraes (2007) [74] [4]	Nordic						*		*			
Petersen and Solberg (2005) [76][5]	Norway, Sweden						*	*				*
Sjunnesson (2005) [63]	Sweden	*	*	*	*		*	*	*[6]			*[7]
Prusinski et al. (2004) [59]	U.S.	*	*	*			*	*	*	*	*	*[8]
Lippiatt and Ahmad (2004) [77]; Lippiatt (2007) [6]	U.S.	*	*	*			*	*	*	*	*	
ATHENA™ (1999, 2005, 2010) **[36, 46, 47]**	Canada	*	*	*			*	*	*			*[9]
Kuhlman and Paschmann (1996)[78]	Germany						*		*			*[9]
Cole and Rousseau (1992) [60]	Canada	*					*					*[10]

[0] Recycled aggregates

[1] Geopolymer

[2] In addition to cement and concrete, other common building products, e.g., bricks, tiles, insulation materials, mortar, wood products, steel, aluminum, PVC, glass, copper.

[3] Concrete masonry block and precast concrete mixes (reinforcing steel impacts excluded)

[4] CO$_2$ emissions and uptake during concrete manufacturing, use, and end-of-life phases

[5] Concrete, steel, and wood structural elements
[6] Ordinary PC concrete with the addition of superplasticizers
[7] Frost-resistant concrete with the addition of superplasticizers and air-entraining admixtures
[8] Precast concrete = mixes with silica fume in addition to slag and PC (reinforcing steel impacts excluded)
[9] Concrete masonry, cement mortar, and precast concrete units (reinforcing steel included)
[10] Four different non-load bearing wall assemblies

2.3.3 Life-Cycle Inventory (LCI) Representation in Concrete LCAs

Environmental interventions associated with the manufacturing of concrete materials and batching processes are mostly attributed to the use of electricity and fossil fuel use. Energy consumption in ready-mixed concrete plant operations constitute about 4% of the total embodied energy of concrete [58]. Electricity and fuel are required for mixing, conveying, pumping of concrete, as well as heating and cooling of the concrete batching plant. The environmental impacts of primary energy use in the concrete plant are very much dependent on the electricity-grid mix within the region.

Most of the reviewed LCAs in this section applied national average factors for mass and energy flows in the LCI calculations without the consideration of regional and technical variations. Table 2.31 demonstrates that both GHG emissions and criteria air pollutants are well-covered in the literature. The most commonly reviewed factor in concrete LCA and non-LCA studies is CO_2 (or can be in the form of CO_2-eq) emissions. Recent “green” concrete and geopolymer concrete LCAs specifically focused on the GHG emission aspects of manufacturing new types of concrete mixes [44, 61, 64, 65] in addition to other life-cycle impacts. O’Brien et al. [56] derived an equation for quantifying the GHG emissions and embodied water in concrete as a function of fly ash content. They also determined the critical fly ash transportation distance, beyond which use of fly ash increased the embodied GHG emissions in concrete. Flower and Sanjayan [57] focused on CO_2-equivalent (CO_2-eq) emissions associated with the concrete manufacturing, construction as well as production of related materials including portland cement, fine and coarse aggregates, GBFS, fly ash, and admixtures in Australia. Petersen and Solberg [76] compared various Nordic LCA studies in terms of GHG emissions from wood, concrete and steel products. In addition to CO_2 emissions from concrete manufacturing, Pade and Guimaraes [74], Kjellsen et al. [83] and Gajda [84] studied the topic of carbon (dioxide) uptake by concrete.

VOCs (mostly from additives in concrete and organic substances) that are emitted during or shortly after the concrete manufacturing processes need further attention, especially for those concrete products with chemical admixtures [78]. Five of the concrete LCAs included VOCs in their analysis [6, 46, 58, 59, 76].

Only five out of sixteen concrete studies [6, 44, 58, 59, 78] examined heavy metals, dioxins and furans, and other carcinogens associated with concrete manufacturing. Among these five studies, Prusinski et al. [59] provided emissions data particularly for the manufacturing and transportation of slag cement concrete. Similarly, Chen et al. [44] offered toxic emissions LCI associated with the production of GBFS and fly ash as well as pig iron production and electricity generation sectors which produce the related SCMs used in concrete. The non-LCA study by Kuhlman and Paschmann [78] analyzed explicitly toxic emissions from concrete manufacturing, use and end-of-life stages. Marceau et al. [58] and Lippiatt [6] provided toxic emission LCI for traditional cement concrete mix designs manufactured in the United States.

Solid waste from concrete manufacturing was provided in a number of studies including two of the concrete LCA tools, BEES and ATHENA [6, 36, 46, 47, 58, 77, 82]. Solid wastes are generated during cement manufacturing (mostly in the form of CKD), as well as during aggregates production, SCM preparation, and concrete batching processes. Moreover, solid waste may include mixer washout, sludge from settling basins and ponds, returned ready-mixed products which are not re-processed. Specifically, there is lack of data about disposal rates of such wastes, as well as their constituents which can vary considerably with concrete mix design and concrete ingredients.

In most of the concrete LCAs, environmental impacts of form oils are generally overlooked. Accordingly [85], hydrocarbons have been detected in concrete slurries from rinsing mixers, in concrete waste, and in waste from demolished concrete. Such occasions can increase the risk of hydrocarbon leaching (to the groundwater). The major source of hydrocarbons is estimated to be form oils used to grease the concrete mixers and mixer trucks. A back-of-an-envelope calculation can estimate the dimensions of the problem. Typically, about 180 ml form oil per m^3 of concrete is used. Global concrete production is estimated to be roughly 25 billion tonnes annually [7]. For a typical unit weight of 2,370 kg/m^3 normal concrete, this translates into about 1.9 billion liters of form oil consumption globally. A further research on the quantity and chemical composition of form oils used in concrete production and the associated inventory of emissions from such products would be beneficial for a complete assessment of concrete. Chemical substances used in concrete admixtures could be a major concern in terms of their toxicological properties. These problems are generally not addressed in concrete production LCIs. Concrete admixtures have only been used for the last 30-40 years. So far, we can assume that the majority of demolished concrete has been free of admixtures. In order to be able to estimate emissions from leaching of admixtures in concrete, tests need to be performed regarding admixture content. Knowledge and research discrepancies still exist in admixtures production LCAs compared to other concrete constituents [86]. A non-LCA study by Kuhlman [78] specifically focuses on leaching issues from both ready-mixed and precast concrete through life-cycle stages of concrete. During the processing of ready-mixed concrete, the leaching of environmentally significant substances is of major concern. The source of this concern is predominantly the alkalis which contain traces of heavy metals (Pb, Cd, Cr, Hg, thallium, and Zn) as well as organic constituents in the additive agents and additional organic compounds found in concrete. Study results showed that, except for chromium (Cr), leaching of other heavy metals was not observed due to their low solubility in the alkaline medium of ready-mixed concrete. Throughout the concrete use phase, leaching of heavy metals and organic constituents from conventional concrete were shown to be extremely low. Throughout the end-of-life stage, leaching of environmentally significant contaminants was not expected from crushed concrete.

In addition to the previously mentioned deficiencies, water consumption and withdrawal impacts during cement and concrete manufacturing are generally excluded in literature, mostly because of lack of data and research. Electricity is used when pumping the source water prior to its use. Environmental impacts associated with water withdrawal require a methodical analysis. The study by Kenny et al. [87] provides a guideline for water related considerations.

Overall, solid and liquid wastes data from concrete batching plants and water consumption data during concrete and cement manufacturing are major areas that lack the LCI data. In literature [88-91], data availability and quality are identified as one of the significant problems encountered during collection of inventory analysis data. In most of the LCAs, data gaps go unnoticed, assumed or estimated [91, 92] which end up as incomplete assessments. Filling these gaps would require close collaboration between the industry and academia. Moreover, there is still an existing need for more peer-reviewed, standardized inventory databases for concrete and its constituents' manufacturing processes [61, 91].

Table 2.31: LCI categories included in concrete LCAs

	Life-cycle Inventory							
Source	Raw materials use	Energy use	Water	GHG (CO_2) emissions	Criteria Air Pollutants	Toxic emissions	Solid waste	Waste water
[61]		*		*	*			
[66]								
[64]		*		*				
[65]				*				
[62]		*	*	*				
[44]		*		*	*	*	*	*
[56]	*		*	*				
[57]				*				
[58]	*	*	*	*	*	*	*	*
[74]				*				
[76]		*		*	*		*	
[63]	*	*	*	*	*			*
[59]	*	*		*	*	*		
[6, 77]	*	*	*	*	*	*	*	*
[36, 46, 47]	*	*	*	*	*		*	*
[78]						*		
[60]		*		*	*			

2.3.4 Life-Cycle Impact Assessment (LCIA) Representation in Cement Manufacturing and Concrete Manufacturing LCAs

The main aim of LCIA is to connect each LCI result to the corresponding environmental impact. In general, LCIA consists of classification of impact categories, each with a category indicator. The majority of cement LCAs includes LCIA step while concrete LCAs with LCIA are mainly a few recent studies (see Table 2.32 and Table 2.33). Studies which estimate and interpret environmental impact assessment stage often refer to the software program or method used for these calculations. These methods are described in Chapter 3, in more details. In general, two major approaches for impact assessment are distinguished:

1) Traditional by the first approach, known as mid-point (also known as pressure-oriented or problem-oriented) analysis, groups LCI results into a related environmental problem, into mid-point categories. Therefore, these methods are considered to be problem oriented. For example, a material's impact on climate change can be expressed in kg of CO_2-eq. Major problem-oriented

methods include CML [93], TRACI [94] or EDIP [95] that restrict quantitative modeling to relatively early stages in the cause-effect chain to limit uncertainties.

2) The second approach focuses much more on the actual effect. So-called damage oriented (end-point) methods (e.g. Ecoindicator 99 [96] or IMPACT 2002+ [97]) model the actual environmental damage, sometimes with high uncertainties. With respect to climate change, the damage on human health is quantified in terms of disability-adjusted life years (DALYs). This unit counts as a measure for the years lived disabled (YLD) and the years of life lost (YLL) due to this damage.

In addition to these two common schools and methods (CML, TRACI, Ecoindicator 99) mentioned above, energy consumption has also been calculated with the cumulative energy demand method (CED) that quantifies the energy required during the life cycle of a product [44]. Although both CML and TRACI cover the climate change (GWP) impact category, some studies applied IPCC 2002 or 2007 GWP impact method [34, 69]. According to this method, the corresponding GWP index is calculated for every emitted GHG.

CML evaluates 10 environmental impacts: abiotic depletion, GWP, ozone layer depletion, human toxicity, fresh water aquatic ecotoxicity, marine aquatic ecotoxicity, terrestrial ecotoxicity, photochemical oxidation, acidification, and eutrophication. The U.S. EPA’s TRACI (Tool for the Reduction and Assessment of Chemical and other environmental Impacts) was applied only by the BEES model. TRACI impact categories include: GWP, acidification, eutrophication, fossil fuel depletion, habitat alteration, criteria air pollutants, human health (cancer, non-cancer), smog, ozone depletion, ecological toxicity, and lastly water intake. Indoor air quality is also assessed for the BEES model but this factor is not included in TRACI. In Table 2.32 and Table 2.33, not all impact factors are displayed. For example, all human health impacts are covered in “human toxicity” category while “eco-toxicity” refers to all types of ecological toxicity problems defined in both TRACI and CML methods.

On the other hand, damage-oriented impact categories include: damage to human health, damage to ecosystem quality, damage to fossil and mineral resources, and surplus energy (coal, gas, and oil). In the last four rows of both Table 2.32 and Table 2.33, other categories of impact (EF, ES, ET, and EPS) scoring methods are displayed. These methods are subjective in nature and not as in-depth and systematic as other common LCIA methods.

In general, the majority of LCIAs in Table 2.32 and Table 2.33 were calculated based on various versions of CML (1992, 2000, 2001, and 2002) approach using SimaPro software. The impact assessment categories represented in the literature were provided in the first column of both tables. A few of the cement and concrete studies used the Ecoindicator 99 method to model the effects of resource use and emissions on human health, ecosystem quality. Only one U.S. concrete LCA study (BEES tool) applied TRACI impact assessment method [6].

As observed in Table 2.32 below, 7 out of 9 reviewed cement LCA studies carried out a detailed impact assessment. While two [20, 22] of these studies applied both CML and Ecoindicator 99, four [17, 19, 24, 25] applied only CML, and one [32] applied only Ecoindicator 99. Additionally, reference [20] applied two other impact scoring methods (EF and ES). Three of the most recent cement LCAs [20, 22, 25] also calculated the CED rate for cement manufacturing. Turning to Table 2.33, one can observe that only 7 out of 16 concrete LCAs incorporated the LCIA step. Of these seven LCAs, only one recent study [61] applied both CML and Ecoindicator 99, three of them [44, 62, 65] used only CML, one U.S. study [6] applied TRACI, while in one reference [63] the type of LCIA approach was not stated clearly.

In both cement and concrete manufacturing LCAs, GWP was clearly the most commonly assessed impact, likely due to the accessible data on embodied energy and carbon content of construction materials, and the recent status of global climate change. GWP therefore becomes an easily calculated and understandable metric over which material alternatives may be compared**.** Similar to the GWP impact, the regional impact categories such as acidification (in SO_2-equivalent) potential is also modeled with well-inventoried NO_x and SO_2 emissions which are commonly included in cement and concrete LCAs. In addition to NO_x and SO_2 while some studies [24, 25] consider HCl and ammonia (NH_3) emissions, others [17, 22, 32, 44, 62] do not include these emissions in developing acidification impact categories. Mostly because these emissions are not of major concern for cement and concrete production. In case of eutrophication, NO_x is the major source during cement manufacturing. Again as in the case of acidification, other relevant sources of eutrophication such as NH_3, total nitrogen (N-tot), and chemical oxygen demand (COD) are omitted in most LCIs of cement and concrete manufacturing. Such inconsistencies in development of impact factors have to be considered while interpreting the results. The minimal emphasis on ecological and human toxicity, photochemical oxidation, etc. points to the lack of data and inventorying of associated emissions.

It is, generally, not clear how toxic emissions are translated into impact categories like human toxicity or damage to human health. Other less studied impact categories such as human toxicity, ecotoxicity and resource consumption are developed using different classification and characterization methods and factors. While only three cement LCA studies [20, 22, 32] and just one concrete LCA [61] applied damage-oriented impact assessment methodology, the remaining LCAs were limited to traditional problem-oriented LCIA. Traditional LCIA approach reduces the amount of assumptions and the complexity of the modeling and results compared to damage-oriented assessment. However, the traditional approach makes the interpretation of absolute results more difficult since they do not refer directly to the damages produced [17]. In Navia et al. [32], for example, damage to health is related to the categories of carcinogens, respiratory organics and inorganics, climate change, radiation, and ozone layer. One important problem with human toxicity and ecotoxicity categories is the lack of exposure data. From one study to another human or environment exposure to pollutants vary considerably depending on the proximity, concentration of pollutant, existence of other sources of pollutant as well as regional differences in climate, geography, population density and so on. It would be good to report results in ranges of possible values. Additionally, due to lack of information about chemical composition of some common air pollutants from cement manufacturing (PM, VOC, etc.), it is almost impossible to categorize some pollutants provided in the inventory in terms of their toxicity, carcinogenicity, and so on. Impacts from heavy metals and other toxic emissions are mostly omitted in LCIA since their quantities are deemed insignificant however it is their severity that could be of significance in terms of damage to human health and environment.

Finally, a building materials review study by Petersen and Solberg [76] applied various evaluation methods such as EPS, Environmental Theme, and EcoScarcity. These methods combine different environmental impacts into one value whereas weighting factors are subjectively determined. In addition to the subjectivity issue, as one moves along the cause-effect chain of inventory analysis to problem-oriented, then to the damage-oriented impact categories to finally the single impact score, the scientific precision specific to this single information (e.g., the single score) decreases. Therefore, caution is required while comparing results from LCA studies with single impact scores. Concluding results from Tables 2.32 and 2.33 below show that more and more studies are involved with the LCIA stage recently as the information and data associated with this stage are growing and more LCAs are performed.

Table 2.32: LCIA categories included in cement manufacturing LCA literature

LCIA Sources:	**[22]**	**[24]**	**[25]**	**[20]**	**[19]**	**[16, 17]**	**[18]**	**[32]**	**[33]**
a) Methodology/software applied: Midpoint approach (also known as pressure oriented approach)									
CML v. 92, 00, 01, 02 (in SimaPro)	√	√	√	√	√	√	-	-	-
TRACI	-	-	-	-	-	-	-	-	-
Acidification	*	*	*	*	*	*			
Eutrophication	*	*	*	*	*	*			
GWP (see IPCC climate change row if based on IPCC guidelines)[1]	*	*	*	*	*	*			
Depletion of raw materials/ fossil fuels									
Ozone layer depletion	*								
Abiotic depletion	*								
Eco-toxicity	*	*							
Human toxicity		*	*	*	*	*			
Photo-oxidant Formation (POCP)	*					*			
b) Methodology/software applied: Endpoint approach (also known as damage assessment)									
Ecoindicator 99 (E)	√	-	-	√	-	-	-	√	-
Human health (E)	*			*				*	
Ecosystem quality (E)	*			*				*	
Resource (E)	*			*				*	
c) Other approaches (not considered as LCIA method)									
Cumulative Exergy Demand (CExD, CED)	*		*	*					
[1]IPCC Climate change (IPCC-GWP)	*		*	*					
Ecological Footprint (EF) method				*					
Ecological Scarcity (ES) method				*					
Environmental Priority Strategies (EPS) method									

LCIA Sources:	**[22]**	**[24]**	**[25]**	**[20]**	**[19]**	**[16, 17]**	**[18]**	**[32]**	**[33]**
Environmental Theme (ET) method									

Table 2.33: LCIA categories included in concrete manufacturing LCA literature

LCIA Sources	**[61]**	**[64]**	**[65]**	**[62]**	**[44]**	**[56]**	**[57]**	**[58]**	**[74]**	**[76]**	**[63]**	**[59]**	**[6]**	**[46]**	**[78]**	**[60]**
a) Methodology applied: Midpoint approach (also known as pressure oriented approach)																
CML v.00, 01, 02 (in SimaPro)	√	-	√	√	√	-	-	-	-	-	?	-	-	-	-	-
TRACI	-	-	-	-	-	-	-	-	-	-	?	-	√	-	-	-
Acidification	*		*		*						*		*			
Eutrophication	*		*		*						*		*			
GWP (see IPCC climate change row if based on IPCC guidelines)[1]	*		*	*	*						*		*			
Depletion of raw materials/ fossil fuels													*			
Ozone layer depletion	*		*		*								*			
Abiotic depletion	*		*		*											
Eco-toxicity			*		*											
Human toxicity	*		*		*								*			
Photo-oxidant Formation (POCP)	*		*		*						*					
b) Methodology/software applied: Endpoint approach (also known as damage assessment)																
Ecoindicator 99	√															
Human health (E)	*															
Ecosystem quality (E)	*															
Resource (E)	*															
c) Other approaches (not considered as LCIA method)																
Cumulative Exergy Demand (CExD, CED)				*	*											

LCIA Sources	**[61]**	**[64]**	**[65]**	**[62]**	**[44]**	**[56]**	**[57]**	**[58]**	**[74]**	**[76]**	**[63]**	**[59]**	**[6]**	**[46]**	**[78]**	**[60]**
IPCC Climate change (IPCC-GWP)				*												
Ecological Footprint (EF) method										*						
Ecological Scarcity (ES) method										*						
Environmental Priority Strategies (EPS) method										*						
Environmental Theme (ET) method																

2.4 Concrete Commercial Building LCAs

This section reviews commercial building LCA studies demonstrated in Table 2.67 Similar to the cement and concrete manufacturing LCA literature, existing commercial building LCA literature has been organized and compared on the basis of their scope and in terms of LCI and LCIA categories analyzed. Additionally, current building and construction materials LCA tools have been evaluated briefly.

2.4.1 Background on Concrete Commercial Building LCAs

In literature, several commercial building LCAs have been performed both nationally and internationally. Major sources for building LCAs include peer-reviewed journals (including Energy and Buildings, Construction and Building Materials, Environmental Science and Technology, Journal of Infrastructure Systems, Journal of Cleaner Production, International Journal of LCA, Journal of Building and Environment, and Journal of Construction Engineering and Management, and so on).

The existing literature identifies the major cradle-to-grave building life-cycle phases as: extraction of raw materials, production of building materials, construction of building system, operation and maintenance of built environment, end-of-life (demolition/deconstruction of building system, disposal or reuse of materials), and transportation at proper stages.

The synthesis of literature reveals that several studies diverge in their scope and functional unit definition, LCA approach designated, life-cycle phase inclusion, type of building elements, building envelope materials, or structural frame analyzed, the climate zone where the building system is operated, the purpose of use (office, university, hospital, etc.), environmental loads addressed, the choice of method used in impact assessment, interpretation of results, and so on. This creates a challenge for comparing building LCAs. For example, wall systems may be compared by either their thermal or structural properties while building structural frames maybe compared by their resistance to earthquake or fire, or other structural properties. Furthermore, the existing body of work exhibits methodological incompatibilities that serve as barriers to the widespread utilization of LCA by policy makers. Gaps in data availability and representation of life-cycle phase and associated inventory and impact categories should be resolved before an accurate comparison of construction material life-cycle impacts is achieved.

Following sections first summarize the major studies in this group and the synthesis of the literature reveals major data and research gaps, areas of uncertainty, and opportunities for further research.

2.4.1.1 Zhang et al. (2013)

This study is a cradle-to-grave building LCA applied to a construction case study in Hong Kong. Life-cycle stages included were: materials manufacturing, materials transportation, construction, operation and maintenance, demolition, and construction waste disposal stages. The LCI covered emissions of CO_2, CH_4, N_2O, SO_2, CO, NO_x, NMVOC and PM over the life-cycle of the building. Based on major data sources in literature, authors provided the emission factors associated with manufacturing of major building materials (i.e., concrete, cement, steel, aluminum, glass, sand, and timber) and transportation of these materials to the construction site. Transportation modes covered deep sea transportation-heavy fuel, coastal vessel-heavy fuel, road freight-diesel, and railroad-diesel. The construction related emissions were calculated on the basis of electric power use, fuel use (diesel) in construction equipment, and transportation of construction waste from site to the disposal area. Building operation emissions were largely from various devices such as boilers, heaters, electricity generators, lift, and any other equipment or machinery. Maintenance-associated emissions were assumed to be 0.2 percent of the total amount of emissions from construction stage. Electricity and diesel use during demolition process and associated impacts were also quantified. Finally, waste disposal stage involved transportation of demolition waste to the landfill area and related emissions calculations. Table 2.34 describes the properties of the building case study. Results from the study are aligned with other building LCAs in literature. Of all the life-cycle stages of the building, operation stage contributes the most to air emissions.

Table 2.34: Summary of Zhang et al. (2013) [98]

Title	Life cycle assessment of the air emissions during building construction process: A case study in Hong Kong
Region	Hong Kong
LCA Approach	Process, only LCI (GHG, criteria air emissions)
Materials/products studied	30-storey, reinforced-concrete commercial building 43,120 m^2 floor area, 50-year life span
Functional unit	Whole building
Phases studied	Materials Production Transportation Construction O&M EOL

2.4.1.2 Wu et al. (2012)

In this paper, authors developed an LCA model for a university office building in China to quantify the related energy consumption and CO_2 emissions. The system boundary includes major building materials production (i.e., concrete, cement, brick, steel, timber, glass, and plastic), transportation of these building materials to the site, construction, operation, and demolition of the building and transportation of the waste to the landfill (Table 2.35). A service life of 50 years was assumed. The case study is a 13-storey reinforced concrete university building of 36,500 m^2 floor area with internal and external walls constructed of brick and mortar. Electricity grid and water supply data represented the national average. Heating system was coal-fired (about 6 months a year, 6 days per week, and 14 hours a day). The results, again consistent with the rest of the literature, showed that the operation stage (especially, cooling and heating system) consumed the largest amount of energy and contributed to most of the CO_2 emissions.

Table 2.35: Summary of Wu et al. (2012) [99]

Title	Life cycle energy consumption and CO_2 emission of an office building in China
Region	Liaoning, China
LCA Approach	Process, only LCI (limited to energy use and CO_2)
Materials/products studied	13-storey, reinforced-concrete university building with 36,500 m^2 floor area, 50-year life span
Functional unit	per square meter of usable floor area
Phases studied	Materials Production Transportation Construction O&M EOL

2.4.1.3 Audenaert et al. (2012)

Authors performed an LCA on a three-storey, low-energy timber frame building with 19 flats, using the Ecoindicator 99 (damage-oriented LCIA method). Three categories of damages ("human health", "ecosystem", and "resources") are combined into one single score. Within this setting, authors analyzed and quantified the eco-scores associated with alternative material choices for external walls, and internal and external insulation materials. Additionally, end-of-life scenarios were investigated. The insulation materials and non-bearing building elements were assumed to be free of the type of structural frame. For flat roof insulation and floor insulation, originally, 0.09 m and 0.06 m thick polyurethane (PUR) was used, respectively. Alternative insulation materials included rock wool, glass wool, polystyrene foam, and vermiculite. Exterior wall was made of 0.15 m thick oriented strand board (OSB) and insulated with 0.14 m rock wool while interior wall consists of 0.015 m OSB plate, 0.09 m rock wool insulation, and 0.012 m plasterboard. Alternatives for rock wool also included PUR, glass wool, polystyrene, and vermiculate. Alternatives to both external and internal wall materials are listed in Table 2.36. Materials (see Table 2.36) were chosen on the basis of (at least) equal insulation performance. Authors used the following equation to calculate the minimal thickness of the alternative material with the same degree of insulation: $D = R \times \lambda$ where D is the material thickness in m, R is the heat resistance in m^2 K/W, and λ is the coefficient of heat conductivity.

Authors additionally compared waste disposal vs. recycling options of the building materials on the basis of eco-score over the life-cycle stages of material production, use, and EOL.

Table 2.36: Summary of Audenaert et al. (2012) [100]

Title	LCA of low-energy flats using the Ecoindicator 99 method: Impact of insulation materials
Region	Belgium
LCA Approach	Process, only LCIA (limited to energy use and CO_2)
Materials/products studied	Material alternatives for: Flat roof and external wall insulation: PUR Rock wool Polystyrene foam Vermiculate External wall OSB MDF Particle board Soft board Interior wall Wooden framing - OSB, rock wool, plaster board Plaster blocks
Functional unit	per unit of insulation material with equal performance
Phases studied	Materials Production EOL

2.4.1.4 *Williams et al. (2012)*

This paper is a description of a methodology that includes the influence of climate change in the LCA of buildings with respect to GHG emissions. The methodology encompasses all life cycle stages of a building as opposed to current practice that focuses only on annual operational GHG emissions. Authors, in particular, considered the life-cycle GHG emissions due to operation of the HVAC system. To be able to develop the case building's (see Table 2.37) response to changing climate conditions, authors used a “dynamic thermal model” with inputs of heating and cooling demands (all together named as HVAC energy demand and all provided by electricity). For all demands, respective fuel consumption associated with HVAC was converted to equivalent CO_2 (in CO_2-eq) emissions. Finally, authors determined GHG emissions from extraction and manufacturing of common construction materials based on EcoInvent database v2.0, transportation of materials, construction processes, construction site waste, and component replacement rate. Various data sources were utilized in the calculations. The LCA was truncated at the end of the operational phase based on the justification that the long operational life would introduce considerable uncertainty over the final deconstruction methods. Moreover, the current literature has shown that the GHG from deconstruction processes were relatively negligible in comparison to other life-cycle phases.

Results from the study showed that energy embodied in materials outside the building operation impacts were large enough to be significant. For a life-span of 60 years, it was found that embodied GHG emissions were 20% of the life-cycle total. However, in case of 25 years of life span, embodied emissions increased to 25% of the total under similar climate conditions. The replacement of components over 60 years was found to be the major source of GHG emissions, being responsible for 44% of the total embodied emissions. Overall, GHG emissions due to building lighting were the major cause of emissions at 54% of the lifecycle total.

Table 2.37: Summary of Williams et al. (2012) [101]

Title	Climate change influence on building life cycle greenhouse gas emissions: Case study of a UK mixed-use development
Region	UK
LCA Approach	Process, only LCI (limited to GHG emissions)
Materials/products studied	Mixed-used development with 3-levels of basement parking, retail outlets on the ground floor and office space in the 14 floors above ground.
Functional unit	per building system per year over 60-year life span
Phases studied	Materials Production Transportation Construction O&M

2.4.1.5 Tingley and Davison (2012)

In this study, a web-based life-cycle carbon analysis tool, named Sakura is described (see Table 2.38). One of the important aspects of this tool is its ability to provide different end-of-life options for the purpose of comparing environmental impacts of reuse, recycling or landfill for different building material components. Results from the tool are demonstrated in terms of embodied energy (in MJ per m^2 of a building structure) and embodied carbon (in kg CO_2-eq per m^2 of a building structure) associated with major building materials at the end-of-life stage. In terms of graphical outputs, embodied carbon and energy related to a component can be demonstrated in a couple of ways. In the first option, total amount of embodied carbon (or energy) can be demonstrated so that the impact is spread out between different lives (no reuse, reused once with first life, second life, reused twice with first life, second life, etc.) for a specific building element. The second graphical option demonstrates embodied carbon (energy) occurred at each life-cycle stage of a building. In the last option, a project where the structure has been designed for deconstruction can be compared with the same project without the deconstruction.

Table 2.38: Summary of Tingley and Davison (2012) [102]

Title	Developing an LCA methodology to account for the environmental benefits of design for deconstruction

Region	UK
LCA Approach	Process, only LCI (limited to energy intensity and GHG emissions)
Materials/products studied	Structural building materials (concrete, steel, and timber) – default building with 50 years of life-span.
Functional unit	per square meter of usable floor area per year
Phases studied	Materials Production Transportation Construction O&M EOL

2.4.1.6 Marshall et al. (2012)

The focus of the study is the quantification of air emissions from the utilization of on-site non-road equipment during construction of commercial buildings. In the past, much work was done about the environmental impacts associated with on-road vehicles. However, due to growing concerns about GHG emissions, non-road equipment now are becoming more of focus recently in parallel with the regulations on improving fuel efficiency and also contractual and project requirements (e.g. LEED certifications, incentives for contractors to upgrade their equipments for reduced fuel use, etc.).

This study provided a methodology to understand and estimate what construction equipment and activity contribute to what type of pollutant and in what quantities. For conducting the activity or equipment level emissions analyses, two major data sources were used to link cost estimates and quantity takeoffs from RS Means to the emission factors based on EPA's NONROAD software. Emissions factors involved CO_2, CO, PM_{10}, NO_x, SO_2, and total HCs from non-road equipment use. Case study was a 13,400 ft^2 church with on-site parking lot which involved use of diverse construction equipment with differing horsepower (varying from 1-3 HP gas engine vibrator to 175-300 HP diesel bulldozer, grader, etc.) and engines (diesel vs. gasoline). In conclusions, authors suggested practical methods such as applying value engineering approach with respect to optimization (with minimal or no added cost) of construction equipment performance while reducing emissions. Moreover, similar analyses on other construction projects are needed to validate the results from the applied methodology in the study.

Table 2.39: Summary of Marshall et al. [103]

Title	Methodology for estimating emissions inventories for commercial building projects
Region	United States
LCA Approach	Process, only LCI (limited to six major air pollutants)
Materials/products studied	On-site non-road equipment use during commercial building construction
Functional unit	per construction activity or per hour of construction activity
Phases studied	Construction (non-road equipment only)

2.4.1.7 Malmqvist et al. (2011)

The paper describes a set of building LCA guidelines and the European ENSLIC (Energy Saving through Promotion of Life Cycle Assessment in Buildings) Project which was developed to promote the use of LCA for buildings (case study is based on housing project) over their life-cycle.

Table 2.40: Summary of Malmqvist et al. (2011) [104]

Title	Life cycle assessment in buildings: The ENSLIC simplified method and guidelines

Region	Sweden
LCA Approach	Process, only LCI (simplified version: CO_2-eq emissions) plus LCIA (longer version)
Materials/products studied	EU buildings with 50-year life span
Functional unit	per square meter of usable floor area per year
Phases studied	Materials Production O&M

2.4.1.8 *Wallhagen et al. (2011)*

Authors examined a new office building in Gävle, Sweden from a life-cycle perspective as a basis for improvements using the ENSLIC tool described in Table 2.41. This tool calculates energy use and CO_2-equivalents from operational energy and building material production. Therefore, it doesn't include impacts from the construction and end-of-life stages based on the assumption that energy use during these two stages is considerably smaller. Additionally, the study estimated relative impacts from materials production and building operation, as well as the relative importance of the impact contributions from these two life-cycle stages at various conditions. These 21 pre-designed improvement measures included building form (2), building envelop (7), energy saving equipment (5), energy supply (6) and building life time (1). Default values were applied for electricity and hot water consumption. The contribution to climate change was calculated based on the 100-year GWP values from IPCC.

The office building studied covered 3,314 m^2 of office space (total heated area 3,537 m^2). It was a four-storey building with a load bearing structure of reinforced concrete and steel and roof beams made of glue-laminated wood. Its external walls were curtain walls made of lightweight steel beams with mineral wool insulation mainly covered with plaster but with some parts covered with wooden paneling. The roof was covered with polyester-coated steel sheets and the foundation was made of concrete and polystyrene insulation on a layer of crushed rock ('ballast'). The internal walls were mainly of glass, with wooden frames, or lightweight walls and module walls made of steel beams, insulation material and gypsum boards. Windows were made of steel, aluminum and wood. The most important measures that would improve the environmental impacts included converting to cleaner electricity mix, changing slabs from concrete to wood, using windows with better U-values, insulating the building more efficiently and installing low energy lighting and equipment. This study highlighted the consequences of different material choices and building operation options.

Table 2.41: Summary of Wallhagen et al. [105]

Title	Basic building life cycle calculations to decrease contribution to climate change – Case study on an office building in Sweden
Region	Sweden
LCA Approach	Process, only LCI (limited to energy use and GHG emissions)
Materials/products studied	4-storey office building with total heated floor area of 3,537 m^2, 50-year life span, with a load bearing structure of reinforced concrete and steel and roof beams made of glue-laminated wood
Functional unit	per square meter of usable floor area
Phases studied	Materials Production O&M

2.4.1.9 *Ortiz et al. (2009)*

This paper reviews existing LCA applications and literature in the construction industry from

2000 to 2007 in Europe and the U.S (see Table 2.42). The focus of the review consists of two major areas: construction materials and components and the whole process of construction (for dwellings, commercial buildings and civil engineering constructions). Results from the review demonstrated that a large number of LCAs considered a specific part of the building life cycle, while only a few studies dealed with the whole life cycle. Another finding from the review was the concentration of LCA applications in developed countries in Europe and the U.S. Consequentially, in all EU scenarios, environmental loads during operation phase was found to be the most critical because of the high-energy requirement for HVAC, hot water and lighting systems. The outcome from this review pinpoints to the necessity of application of LCA practice not only in developed countries but also in developing countries for the purpose of preserving the environment worldwide and contributing to the principles of sustainable construction.

Table 2.42: Summary of Ortiz et al. (2009) [106]

Title	Sustainability in the construction industry: A review of recent developments based on LCA
Region	Worldwide
LCA Approach	Review of LCA studies
Materials/products studied	Building materials and components Construction processes
Functional unit	Vary with the study reviewed
Phases studied	Materials Production Transportation Construction O&M EOL

2.4.1.10 Dodoo et al. (2009)

Authors compared the carbon balance of a four-storey reinforced concrete frame building to that of a functionally equivalent wood-frame building with usable floor area of 1,190m^2. In the study, carbon balance calculations included: 1) Carbon emissions from fossil fuels used in the production of building materials; 2) Carbon emissions avoided by substituting fossil fuels by recovered wood residues; 3) Changes in carbon stock attributed to using wooden building materials; and 4) The net carbon emissions resulting from calcination during cement production and carbonation of concrete during and after its service life.

The life-cycle phases covered building construction (including material extraction, processing and transportation, construction, and forest harvesting activities), service period (including carbonation of concrete in the building frame, forest re-growth, and demolition of buildings), and end-of-life phases (including recovery and crushing of concrete, recycling of steel, energy recovery of wooden material and carbon uptake of demolished concrete and cement mortar over 100 years). Service life covers a 100-year time span. In the analysis, it was assumed that 90% of concrete was recovered after demolition. For wood-framed building, 90% of wood was assumed to be recovered for energy after demolition. For steel, 90% was also recovered. These rates represented current European practice. In the results, it was shown that: "*The carbon benefit in the post-use phase is substantially greater than the carbon emissions in the construction stage of the wood-frame building as opposed to the concrete-frame building. Because wood-frame building has much lower emissions from fossil fuel use and cement calcination. Wood also provides bio-fuel to substitute fossil fuels.*" Obviously, higher clinker content resulted in elevated calcination emissions. Finally, carbon emission was the highest for the concrete-framed buildings. Even the consideration of carbon uptake by concrete during the post-use phase did not change the results from the study. Similar conclusions were drawn by other studies including: Upton et al. [107], Gustavsson and Sathre [108], and Petersen and Solberg [76] that compared carbon emissions from wood buildings versus concrete buildings.

Table 2.43: Summary of Dodoo et al. (2009) [109]

Title	Carbon implications of end-of-life management of building materials
Region	Europe
LCA Approach	Process, only LCI (limited to carbon balance)
Materials/products studied	4-storey, 1,190 m^2 floor area functionally equivalent reinforced concrete or wood framed buildings, with 100-year life span
Functional unit	Building over its whole life-cycle
Phases studied	Materials Production Transportation Construction O&M EOL
Note that: CO_2 uptake by concrete is considered in the calculations.	

2.4.1.11 López-Mesa et al. (2009)

This study compares environmental impacts of two types of slab systems commonly used for internal floor structures: in-situ cast floor and precast concrete floor. One important aspect of this study was the consideration of local construction practice so that inventory inputs were assessed according to local construction methods. Authors used an LCA approach and applied EPS 2000 method for their analysis. EPS 2000 includes all impact categories described in ISO 14042 standards. It applies objective environmental cost method for final weighting step of the impact assessment. This type of method considers *"the costs society needs to pay to avoid environmental damage and restore deteriorated areas."* For a fair comparison of two floor systems, environmental load of columns and foundation was also considered as the hollow core slabs in precast concrete floor system allows for higher spans between beams meaning that, the number of columns and spread footings will be lower. The 7-storey case building consisted of two basements, a ground floor and four floors each with 430 m^2 of floor surface, the total area corresponding to 3,010 m^2. The 430 m^2 floor area represented the mean value obtained from 20 recent residential buildings provided by local Developers and Construction Companies Association. For the output data, SimaPro 7.0 and EcoInvent v1.1 database were used. Results showed that precast concrete floors had 12% less environmental impact compared to in-situ cast floors for the defined functional unit. However, precast floors were 18% more expensive. Authors conclude that the cost is the main reason why precast concrete floors have less market share in residential buildings despite their environmental, quality and easy installation advantages.

Table 2.44: Summary of López-Mesa et al. (2009) [110]

Title	Comparison of environmental impacts of building structures with in situ cast floors and with precast concrete floors
Country	Spain
LCA Approach	Process, both LCI and LCIA
Materials/products studied	7-storey, 3,010 m^2 structure with in-situ concrete cast floor 7-storey, 3,010 m^2 structure with precast concrete floor
Functional unit	430 m^2 floor surface
Phases studied	Construction

2.4.1.12 Kellenberger and Althaus (2009)

This paper determines the relevance of materials and processes that are often neglected in simplified LCA of building components (e.g. wooden wall, concrete roof, etc.). Generally, simplified LCA studies were assumed to provide results of similar quality as do the comprehensive assessments with less effort. Simplifications include transportation of building materials from factory gate to the building site, ancillary materials (e.g. joints, surface treatments, formwork, etc.) which are not obvious in the component, the building process itself (mainly use of equipment, machines) and the associated waste as well as the disposal/recycling processes during the construction phase. Levels of detailing may range from all-inclusive to fully-reduced.

In the introduction of the paper, authors compared LCA studies covering whole buildings or parts of buildings to find the major contributors to buildings' environmental impacts and to identify opportunities for improvement. The functional unit for the assessment was selected as one square meter of an opaque building component with equivalent heat transfer rate (0.25-0.30 W/m^2K) over a life-span of 80 years. The system boundary included production of building materials, construction of the building component, operation of the building component, and the disposal/recycling of the building materials/component. Within this boundary, the focus of the study was the processes/products mentioned as the simplifications in the first paragraph plus the heating energy required for the operation of the building component. Studied building components included: horizontal concrete roof with external polystyrene insulation, wooden roof with glass wool insulation, calcareous sandstone wall with glass wool insulation, double masonary wall with intermediate glass wool insulation, and masonary with expanded polystyrene insulation. As the study focused only on components, not the whole building, a simplified approach was used to give a "rough indication on the effect of material related impact versus overall impact." For this reason, burdens of all-inclusive building components were compared to the burdens for replacing the heat energy losses through the respective components over the 80 year life-span. The calculations in this study were performed with the LCA-based building assessment tool called "*LTE-OGIP" which was developed in Switzerland. "OGIP" stands for "Optimization of Global demands in terms of costs, energy and environment within an integrated Planning process" and it is based on LCIA results from the EcoInvent database v1.1.*

Study results showed that transportation of materials and ancillary materials with high environmental impact should be included obviously. The other two, namely the building process and cutting waste, could be neglected. Also, the heavier the building materials and the longer the transportation distances the larger the influence of transportation would be on the LCA results. In case of wooden components, impact of ancillary materials was larger as more screw nails and other connectors were used. However, more components should be analyzed to identify systematic patterns of impact reduction by excluding certain processes or materials. This would introduce a practical guidance on what materials/processes to be included and what simplifications could be acceptable in the LCA of building components. Moreover, this methodology would be useful for defining cut-off rules for the additional materials that must be considered because of their high environmental impact.

Table 2.45: Summary of Kellenberger and Althaus (2009) [72]

Title	Relevance of simplifications in LCA of building components
Region	Switzerland
LCA Approach	Process, LCIA (limited to CED and EcoIndicator99 total score)
Materials/products studied	Five types of roof and interior wall building components including: Horizontal concrete roof with external polystyrene insulation Wooden roof with glass wool insulation

	Calcareous sandstone wall with glass wool insulation Double masonary wall with intermediate glass wool insulation Masonary with expanded polystyrene insulation
Functional unit	One square meter of opaque building component with similar heat transfer rate properties
Phases studied	Materials Production Transportation Construction O&M EOL

2.4.1.13 Kofoworola and Gheewala (2009)

Authors performed life-cycle energy analysis (LCEA) to study an office building in Thailand. Results indicated that although the operating phase consumed the largest percentage of energy, the embodied energy of building materials is a non-negligible fraction. Application of a combination of energy saving measures, showed that 40–50% of energy (electricity) used in a typical office building in Thailand could be saved. Additionally, authors estimated that the recycling building materials could also contribute to the additional energy savings (about 9%).

Table 2.46: Summary of Kofoworola and Gheewala (2009) [111]

Title	Life cycle energy assessment of a typical office building in Thailand
Region	Thailand
LCA Approach	Process LCI (limited to energy use)
Materials/products studied	Office building with 50 years of life: Reinforced concrete, 38-storey, 60,000 m^2 floor area
Functional unit	per square meter of overall floor area
Phases studied	Materials Production Transportation Construction O&M EOL

2.4.1.14Dimoudi and Tompa (2008)

In this paper, authors investigated and quantified the impacts of different construction materials in terms of embodied energy and emissions of CO_2 and SO_2 in Greek office buildings. The case study involved two office buildings in Athens, Greece, with 50 years of life-span. The first one is a five-storey reinforced concrete building with two basements and a flat r/f concrete roof with a total usable area of 1,892 m^2. The second examined building is a three-storey reinforced concrete building with one basement and a flat r/f concrete roof with a total usable area of 400 m^2. For both cases, external and internal walls were brick and mortar. Authors provided bill of materials (structural concrete, steel, brick, mortar, aluminum insulation materials, floor tiles, plaster, etc.) and their associated impacts for each of the office building. Insulation of external brick walls, flooring materials, and façade cladding materials differed in two buildings despite similarities in all other materials. The data for the environmental parameters of these materials were based on literature as no regional data existed for Greece. Results indicate that reinforced concrete represents the largest component in the building's total embodied energy for both cases. Among the building envelope materials, bricks have the higher embodied energy in the conventional building (first case). In case of the modern building (second case), aluminum claddings have the higher embodied energy despite its small weight compared to other envelope materials. Embodied energy related to insulation materials, paints, floor tiles is comparably lower. Again, CO_2- and SO_2-equivalent emissions of structural materials (concrete and r/f steel) represent a dominant portion of both buildings' total emissions. Among the envelope materials, bricks contribute to both CO_2- and SO_2-equivalent emissions in greater proportions in both building cases.

Authors also examined the embodied energy and emissions of the building structural elements (beams, columns, shear walls, slabs, flat roof, staircase, and foundation). Among these elements, slabs have the higher contribution (35-25%) for both buildings, followed by shear walls. This result is attributed to the higher quantities of reinforced concrete. As to the envelope elements, external walls contribute the most in the embodied energy (12-14%) of the two buildings. Finally, authors compared the embodied energy of the building materials with the energy required for the operation of an office building. For a life-cycle of a building with 50 years, the embodied energy varied between 13.05%-19.24% of the overall energy consumption of buildings 1 and 2, respectively, for the Athenian climatic zone. This study emphasizes the importance of material-related criteria on building's life-cycle environmental impacts. Such criteria include choice of materials, lifetime of materials, maintenance and compatibility of the lifetime among the layers' building materials, the assembly techniques required for different materials and so on.

Table 2.47: Summary of Dimoudi and Tompa (2008) [112]

Title	Energy and environmental indicators related to construction of office buildings
Region	Athens, Greece
LCA Approach	Process LCI (limited to embodied and operational energy use, CO_2, SO_2)
Materials/products studied	Two contemporary office buildings with 50 years of life: Reinforced concrete, 5-storey, 1,892 m^2 floor area Reinforces concrete, 3-storey, 400 m^2 floor area
Functional unit	per square meter of overall floor area per kg of building materials
Phases studied	Materials Production Transportation O&M

2.4.1.15 Vieira and Horvath (2008)

This paper analyzes the end-of-life stage of a building's life from an environmental point of view. Following a background on different types of LCA and critical issues in allocation and discounting techniques, authors discussed how new and traditional end-of-life (EOL) methods tackle with these issues when assessing buildings. Finally, a new method based on hybrid LCA was proposed to assess the EOL of buildings and its validity was tested by a case study.

The new method was developed on the basis of consequential LCA (CLCA) approach, which assesses "not only the cradle-to-grave chain, but all interlinked processes that will be affected by a decision." Authors compared the attributional LCA (ALCA) model - the traditional cradle-to-grave analysis - to the CLCA model based on a case study of a typical 5-storey, 4,400 m^2 U.S. office building. The structural frame was a reinforced concrete beam-and-column system with shear walls at the core. Within the system boundary, the CLCA model included alternative uses for each of the products used in building frame as well as complementary products. Alternative uses are defined as "potential applications for a product other than in the concrete frame." Complementary products are defined as "products that need to be used together with the alternative products to create a final product for alternative use." The final product can also be manufactured through competing products.

Data requirements (both in terms of ideal data set and data used) and their sources used for the CLCA of concrete building frame were tabulated for processes/activities of all building frame products as well as alternative and complimentary products. In the results section, energy use, GWP, and critical air pollutants (SO_2, CO, NO_x, PM_{10}) for ALCA and CLCA of concrete building frame were tabulated. Results showed that cement and concrete production contribute most to the total emissions. Inclusion of market behavior and recycling loops resulted in lower impact values for the CLCA model. *"The sensitivity analysis for both ALCA and CLCA showed that results were most sensitive to the price of cement and concrete, and the ratio of cement in concrete."*

As a summary: "Regardless of the type of LCA conducted, results show that recycling of concrete can have significant impact on the reduction of the overall environmental burden of buildings." For example, increasing the concrete recycling rate from 27% to 50% could yield a 2% to 3% reduction of GHG from buildings, equivalent of removing 408,000-847,000 typical cars from the U.S. highways.

Table 2.48: Summary of Vieira and Horvath (2008) [113]

Title	Assessing the end-of-life impacts of buildings
Region	United States
LCA Approach	Hybrid, LCI (comparison of ALCA to CLCA)
Materials/products studied	5-storey, 4,400 m^2 gross floor area, reinforced concrete office building
Functional unit	Typical reinforced concrete building frame
Phases studied	Materials Production Construction Transportation EOL

2.4.1.16 Xing et al. (2008)

The paper compares energy use and emissions during life-cycle phases of one concrete-framed and the other one steel-framed typical office buildings in Shanghai. The steel building was covered with glass walls, while the concrete was covered with both glass and aerated concrete walls outside the building. The useful life for both buildings was assumed to be 50 years. The system boundary included materials production, use, and end-of-life with transportation and distribution of materials/fuels in between stages. The functional unit was one square meter of building floor area. In addition to LCI inputs of mineral consumption, energy consumption, fossil fuel consumption major emissions included PM, SO_x, NO_x, CO, Non-Methane hydrocarbons, CH_4, N_2O, and CO_2. Authors used a model called BIN method (developed by Weiding 1992) to calculate the building energy use. During the use phase, air conditioning (chillers) and heating (fuel oil boilers) were the major emission sources. In the calculations, for example, the total annual energy consumption from A/C was the sum of annual energy consumption of A/C, upstream energy, and related transportation energy. Even though results showed that the life-cycle energy consumption of steel was 75% as that of concrete, concrete performed much better (steel buildings used about 8% more per area) during the use phase due to its better thermal conductivity. On the other hand, mineral consumption of steel-framed building was only 22% that of concrete-framed building. Except for PM emission (steel buildings emitted about 59% less compared to concrete buildings) air emissions were more or less the same for both building types.

Table 2.49: Summary of Xing et al. (2008) [114]

Title	Inventory analysis of LCA on steel- and concrete-construction office buildings
Region	China
LCA Approach	Process, only LCI
Materials/products studied	Steel-framed and reinforced concrete-framed office building

Functional unit	One square meter of office floor
Phases studied	Materials Production Transportation O&M EOL

2.4.1.17 Favre and Citherlet (2008)

In this paper, a recently developed tool, called Eco-Bat was described. It evaluates the life-cycle environmental impacts of a building (including family houses, rental buildings, offices, schools, etc.) or part of it. The tool is compatible with ISO 14040 standards.

Eco-Bat uses the impact data from Eco-invent 1.3. About 60 construction materials are included in the Eco-Bat. In the paper, only four indicators were applied for the environmental impact assessment of buildings, which are non-renewable energy (NRE), global warming potential (GWP), acidification potential (AP), and photochemical ozone potential (POCP).

Manufacturing, transportation, replacement, and elimination (all three different methods – recycling, incineration, and landfill- of elimination) were the life cycle stages considered. Additionally, material life spans and the number of material replacements during the building's life were considered in calculations. The building's life span was estimated to be 50 years.

Two application examples were presented in the paper. The first one was the comparison of three different variants of light-weight ventilated façade and a heavy weight element (brick). For the evaluation of building elements in Eco-Bat, the user has to define its composition as a multi-layer construction. The area of the element, for each layer of the element the material used, and the layer thickness have to be specified. A non-uniform layer can also be defined.

The second application example was the analysis of a whole building, including both construction materials and the energy consumed during its life cycle. The energy consumption categories for a building were: heating, cooling, domestic hot water, lighting, ventilation, and electrical equipment. Eco-Bat provides "electricity data for all European countries, which include both local production mixes with electricity importation". The example building was a seven-storey rental property in Switzerland with a heated floor area of 4,460 m^2.

Detailed results for different levels: the building, elements, and materials were obtained in Eco-Bat (see Table 2.50). Graphical representation of environmental impacts allowed comparison of building phases over its life cycle, its elements and materials. Energy consumption by the building had already been calculated by another simulation tool and inserted in Eco-Bat. Authors suggested the future development of integrated software which would allow the simultaneous assessment of energy consumption, environmental impacts, and the air quality of buildings and building parts.

Table 2.50: Summary of Favre and Citherlet (2008) [115]

Title	Eco-Bat: A design tool for assessing environmental impacts of buildings and equipment
Region	Switzerland
LCA Approach	Process, LCIA
Materials/products studied	Building elements (made of terra cotta brick, wood, flat fiberglass panel, and corrugated fiberglass panel Seven-storey building with 4,460 m^2 heated floor area.
Functional unit	Varies
Phases studied	Materials Production Transportation Construction O&M EOL

2.4.1.18 Haapio and Viitaniemi (2008)

The paper provides a brief background on environmental assessment tools for evaluating the performance of building materials and whole buildings, as well as life-cycle costing and service life planning of buildings (based on ISO 15686 Building and Constructed Assets - Service life planning).

Environmental impacts of 78 single family houses were evaluated using the LCA-based tool ATHENA™ Environmental Impact Estimator (EIE) Software Version 3.0.2. Authors used Excel to perform additional calculations since the EIE software could only compare five buildings at a time. As part of the study, authors assessed how variations in time-span of a building's service life could change the LCA results. Results from the software were specified in six major environmental criteria: embodied primary energy use, solid waste emissions, pollutants to air and water, GWP, and natural resource use (in kg, weighted). In the study, main structure of the analyzed buildings was assumed to be the same. Differences were within wall insulations, cladding materials, window frame materials, and roof materials. Results were demonstrated for two different lives: 60 years and 160 years. Interpretation and evaluation of the results influenced the "order of superiority" of different materials or structural solutions. As suggested, LCA tools must be used simultaneously with design tools for a better environmental evaluation. Factors such as choice of materials/components, the service life of components, or workmanship in different life cycle stages, etc. are to be considered for a detailed environmental impact assessment of a building.

Table 2.51: Summary of Haapio and Viitaniemi (2008) [116]

Title	Environmental effect of structural solutions and building materials to a building
Region	Europe
LCA Approach	Process, LCI (for two time periods: 60 years vs. 160 years)
Materials/products studied	Wall insulation: Exterior (cellulose/fiberglass/rock wool) and Interior (fiberglass/rock wool) Cladding materials: Brick; Stucco; Steel; Wood tongue-and-siding Window frame: Wood and Aluminum Roof material: Concrete tile; Clay tile; Steel roof
Functional unit	Varies with building component
Phases studied	Materials Production Construction O&M EOL

2.4.1.19 Sharrard et al. (2008)

This paper is a demonstration of an input-output-based hybrid LCA model that covers not only on-site construction activities but also economy wide effects of these activities. The model is developed on the basis of Carnegie Mellon University's (CMU) Economic Input-Output Life-Cycle Assessment (EIO-LCA) tool and combines "a new EIO-LCA hybrid interface with updated and reformulated environmental effect vector for EIO-LCA's 13 constructions sectors" (see http://www.eiolca.net/aurora-hybrid.html for 13 construction sector definitions). Eight construction project case studies were selected to validate the accuracy and comprehensiveness of results from the model (see Table 2.52).

Results from all case studies (including one-unit and multi-family residential housing, commercial building, asphalt paving, bridge repair, commercial renovation and others) showed that existing EIO-LCA have underestimated construction industry's impacts compared to reformulated I-O based hybrid estimates of major air emissions (NO_x, PM_{10}, VOCs, SO_2). Energy use (and GWP that is linked to energy use) results were mixed – with some estimates increasing and others decreasing due to reformulation and or hybridization of LCA.

Table 2.52: Summary of Sharrard et al. (2008) [117]

Title	Estimating construction project environmental effects using an input-output-based hybrid life-cycle assessment model
Region	United States
LCA Approach	Hybrid, input-output-based
Materials/products studied	Eight different construction project case studies from literature
Functional unit	Per square meter for energy use and per project or per million US $ for air emissions
Phases studied	Construction

2.4.1.20 Vieira (2007)

This dissertation was based on a compilation of various tools for studying the environmental impacts of buildings. These tools include both LCA tools and building assessment schemes, including environmental impact assessment (EIA) and certification (rating) schemes. The author described 29 building LCA tools and 13 assessment schemes briefly. The dissertation covered literature on the magnitude and significance of the environmental impacts of construction in general and buildings in particular. Results from the literature were compared with those obtained from the newly developed building LCA tool, BuiLCA. Prior to BuiLCA, several LCA tools were developed to assess the impacts of different types of buildings. Three of these studies are among the most important: Hendrickson and Horvath [118] estimated impacts associated with resources and energy used, emissions and wastes from four U.S. construction sectors (heavy civil, industrial, commercial and office buildings, and residential one-unit buildings) using the EIO-LCA tool. Guggemos [119] developed the Construction Environmental Decision Support Tool (CEDST) and focused on the "construction process of steel and concrete building frames". Sharrard [120] focused on the "construction and ancillary support activities" and assessed the construction activities by developing a hybrid LCA model based on the EIO-LCA tool.

BuiLCA is a hybrid tool; it is process-based and complemented with EIO-LCA data. It includes a common database of materials, flow diagrams, and methodologies for assessing the critical processes in the design, materials production, construction, maintenance, and end-of-life phases. The EOL effects, which could account for up to 8% of the building's life-cycle emissions of certain pollutants, were generally neglected in literature. As part of this study, a practical method for environmental assessment of the building's EOL phase was also developed and the methodology was applied to a specific case of concrete recycling. The case study was based on an office building (CITRIS) constructed in University of California, Berkeley campus.

Table 2.53: Summary of Vieira (2007) [4]

Title	Environmental assessment of office buildings
Region	United States
LCA Approach	Hybrid LCA (process-based and complemented with EIO-LCA data)
Materials/products studied	6-storey, 13,378 m^2, mixed-use building with labs, offices and conference rooms, with structural steel frame and a glazed façade
Functional unit	Building
Phases studied	Materials Production Transportation Construction O&M EOL

	In addition to above phases, design phase was also considered

2.4.1.21 Sharrard (2007)

The dissertation provides background on construction industry, LCA methods, environmental data sources, and methodologies used in development of the I-O-based hybrid LCA model for construction. The focus of the research was on-site construction activities and their associated direct and supply-chain impacts. The author studied a great number of criteria in developing the hybrid model, including; economics, on-site activities, equipment, transportation, construction waste, water use, energy use, equity, and support services. The hybrid LCA tool was applied to various new residential (non-farm multifamily or one-unit housing), farm housing and office building construction case studies as well as highway, street, bridge, and tunnel construction, water, sewer, and pipelines construction, and their maintenance and repair from literature [1, 121-123]. Each process-based study from literature represented one I-O construction sector and these studies were reformulated and hybridized by the new methodology described in the study. As a result, this study constitutes a roadmap in the development of a new hybrid LCA model for the construction processes.

Table 2.54: Summary of Sharrard (2007) [120]

Title	Greening construction processes using input-output-based hybrid life cycle assessment model
Region	United States
LCA Approach	Hybrid LCA (I-O-based)
Materials/products studied	On-site construction activities and their supply chain
Functional unit	U.S. Construction sector
Phases studied	Construction

2.4.1.22 Bilec et al. (2006)

This paper is an application of hybrid LCA approach to assess the environmental impacts of a precast concrete parking garage construction. As part of their study, authors compared and contrasted process-based LCA, EIO-LCA and hybrid LCA methods. The Hybrid models combine the advantages of two LCA models and they differ depending on the proportions of input-output and process LCA data used. For example, tiered hybrid analysis developed by Bullard et al. [124] consisted mainly of I-O (input-output data). Suh et al. [15], Hondo et al. [125], and Munksgaard et al. [126] are among the major literature focusing on tiered approach. I-O based hybrid developed by Joshi [127], integrated hybrid analysis developed by Suh [15], and augmented process-based are other three approaches that combine process and I-O processes.

Tiered and I-O based are similar as the I-O data dominates in both models. Integrated hybrid analysis may be comprehensive but it is time and data intensive. Augmented process-based approach “relies heavily on process data and I-O data is used for unit processes that cannot be modeled with process data efficiently. Among all four hybrid LCAs, the augmented process-based LCA is the most applicable one to construction processes because of the lack of LCA data for construction and the nature of the construction industry”. For example, Guggemos [119] used this model to assess the life cycle environmental impacts of commercial buildings. The author used both EIO-LCA and process data in the analysis. When the process data was missing, the author considered the EIO-LCA for determining the life-cycle inventory for materials manufacturing phase, as well as for the temporary materials in the construction phase, fossil fuel and electricity for operation phase, and maintenance of materials.

In this paper, Bilec et al. developed a hybrid LCA to analyze the construction phase of a precast parking garage based on the augmented process-based LCA approach. By using this approach, authors reduced the time and cost inherent in process LCAs while developing an inclusive system boundary. For this study, construction and design phases of a U.S. parking garage were studied within the LCA system boundary. The LCI focused on the GHG emissions and six criteria air pollutants. Results showed that: transportation had the highest GHG followed by the equipment (diesel) use and construction services. Transportation also caused the highest impact in terms of SO_2, NO_2, VOC, lead, and PM_{10}. The construction processes generated the highest amount of CO. In the conclusions, authors suggested additional research on externalities, bidding processes, and project delivery methods (esp. the relation between the environmental costs and submitted bid prices). In summary, this study provided a conceptual model for a hybrid LCA of design/construction processes.

Table 2.55: Summary of Bilec et al. (2006) [3]

Title	Example of a hybrid life-cycle assessment of construction processes
Region	United States
LCA Approach	Hybrid (augmented process type), only LCI
Materials/products studied	Parking facility (with 377 spaces) with a deep foundation construction
Functional unit	A precast parking structure
Phases studied	Design Transportation Construction

2.4.1.23 Zhang et al. (2006)

This study is a description of a building environmental performance analysis system (BEPAS) which is based on the LCA approach. The case study was a seven-floor office building in Beijing (Table 2.56). Bill of materials provided quantities of steel, wood, cement, glass, aluminum, and PVC. Other information included as part of the case study was the amount of solid waste after the building was demolished, reclaimed water supply, annual water consumption, annual electricity use, coal use for heating, and water consumption for heating. The LCIA results were demonstrated in units of Chinese currency (Yuan) per the unit of environmental impact (e.g. MJ for energy use; kg for solid waste; kg CO_2-eq for GWP, etc.). Results once again indicated that the operation stage caused about 97 percent of the total environmental impacts.

Table 2.56: Summary of Zhang et al. (2006) [128]

Title	BEPAS—a life cycle building environmental performance assessment model
Region	Beijing, China
LCA Approach	Process LCI (limited to energy use and CO_2)
Materials/products studied	6-storey above and 1-storey below ground, reinforced-concrete university building with 50-year life span
Functional unit	35,682 m^2 total floor area over 50-year life span
Phases studied	Materials Production Transportation Construction O&M EOL

2.4.1.24 Junnila et al. (2006)

Authors evaluated environmental impacts of two comparable office buildings, one in Finland and the other one in the United States (Midwest) with 50-year life span (Table 2.57). Within the system boundary, materials production, construction, use, maintenance, and end-of-life energy use, as well as CO_2, SO_2, NO_x, and PM_{10} emissions were analyzed. Transportation impacts were also considered.

Despite the difference in the location, the use phase impacts dominated (about 70%) in energy use and all emissions except for PM_{10}. Especially in the United States, materials production and maintenance phases were responsible for most of the PM_{10} emissions. In general, maintenance phase resulted in higher environmental impacts compared to the construction phase. End-of-life phase was only somewhat relevant in terms of NO_x and PM_{10} emissions.

All in all, it was found that Finnish building used one third less energy, and emitted less GHG and criteria air pollutants compared to the U.S. building. Difference in electricity mix of these two regions was the main source of different emission intensities between two case studies.

Table 2.57: Junnila et al. (2006) [121]

Title	Life-cycle environmental effects of office buildings in Europe and the United States
Region	Southern Finland and Midwest United States
LCA Approach	Process, only LCI
Materials/products studied	Finnish office building: 4,400 m^2 of gross floor area and a volume of 17,300 m^3 with four floors in Southern Finland. U.S. office building: 4,400 m^2 of gross floor area and a volume of 16,400 m^3 with five floors in Midwest region.
Functional unit	Office building with a structural frame of steel-reinforced concrete beam and column system over 50 years of service life.
Phases studied	Materials Production Transportation Construction O&M EOL

2.4.1.25 Li (2006)

The author developed a “region-type life cycle impact assessment” method that calculates the total environmental burden (EB) of a building and its infrastructure on a global scale as well as regional scale. In case of “attached environmental burden (EB_a)”, more than one building is served by the infrastructure facility, “EB_a of this facility” is allocated among the buildings in proportion with the number of people using them. The case study involved a Japanese store building and mixed-use development with its infrastructure facility. Three cases were developed by changing the effects of the location (two alternative regional development), structural frame (steel structure vs. reinforced concrete structure), and the energy system (ordinary system vs. photovoltaic energy system). The system boundary covered the construction of building or infrastructure, use and maintenance, and demolition/disposal stages. Functional unit was selected per year per square meter. Ina addition to air emissions, the direct social cost of the store building itself and the attached social cost caused by the infrastructure facilities were demonstrated in the results. The operation of construction machines, service (vehicle traveling), and waste disposal were among the major sources of local environmental burden. Especially for the large-scale buildings, the attached environmental burden caused by the supporting facilities was found to be significant.

Table 2.58: Summary of Li (2006) [129]

Title	A new life cycle impact assessment approach for buildings
Region	Japan
LCA Approach	Process LCA- Regional LCI

Materials/products studied	Mixed use development and its infrastructure facilities and three variations based on the location, energy source, and structural frame
Functional unit	One square meter of a building and its infrastructure facilities
Phases studied	Materials Production Transportation Construction O&M EOL

2.4.1.26 Guggemos and Horvath (2005) and Guggemos (2003)

Authors performed an LCA to understand the construction-related environmental impacts of two commercial building case studies, one with steel- and the other one with a cast-in-place concrete frame. Both of them were 4,400 m^2, five-story office buildings located in the Midwestern United States with an expected life of 50 years (Table 2.59). Two LCA methods (process-based and input-output analysis-based) were used together to evaluate the environmental life-cycle impacts of each building type from materials extraction/production phase through construction, use, maintenance, and end-of-life. Construction phase-related emissions and resource use was assessed by a tool called “Construction Environmental Decision Support Tool (CEDST)” developed by Guggemos [119]. Within the scope, in addition to the direct material and energy use and associated emissions from construction and operation of the building, the indirect or supply-chain environmental effects of production of construction materials and building use phases were assessed by the EIO-LCA method. Therefore, a hybrid LCA approach was used. Construction phase involved trucks used for transportation of construction materials and equipment to the site in addition to the electricity and fuel used in construction equipment. Use phase impacts covered electricity and natural gas use for heating, cooling, lighting and power outlet use over a 50-year life span. EIO-LCA was applied to obtain environmental effects of electricity and natural gas consumption. The results showed no difference in the use-phase impacts between steel and concrete buildings. Maintenance phase covered impacts from interior materials, equipment, and related transportation over 50 years. Since the focus of maintenance phase was the interior materials, no difference was found between steel- and concrete-framed buildings. The end-of-life phase considered only the demolition process and the removal of the demolished materials off-site without further consideration of end-of-life options, e.g. landfilling or recycling. Concluding, construction phase impacts were relatively small (0.4-11%) compared to the overall life cycle energy use and emissions. The maintenance and end-of-life phases had also smaller impacts. Consistent with the other LCA study results discussed so far, building use phase contributed most to the energy use impacts which would lead to the energy-efficient design of buildings.

Table 2.59: Summary of Guggemos and Horvath (2005) [122] and Guggemos (2003) [119]

Title	Comparison of environmental effects of steel- and concrete-framed buildings
Region	United States, Midwest
LCA Approach	Hybrid, LCI (but process-based for construction while others EIO-LCA)
Materials/products studied	Typical five-storey cast-in-concrete frame office building Typical five-storey steel frame office building
Functional unit	4,400 m^2 office building, with 50 years
Phases studied	Materials Production Transportation Construction O&M EOL

2.4.1.27 Scheuer et al. (2003)

Authors conducted an LCA of a six-storey, 7,300m^2 mixed-use university building with a projected 75-year life span, located on University of Michigan campus (see Table 2.60). The lower three floors and basement were classrooms and open-plan offices; the top three floors were used as hotel rooms. Authors used a computer model (DOE's eQuest 2.55b version [130]) to determine primary energy consumption for heating, cooling, ventilation, lighting, hot water and sanitary water consumption during the use phase.

Results were consistent with the literature findings: 2% of total life-cycle primary energy consumption was due to the production of building materials, their transportation to the site as well as the construction of the building. HVAC and electricity consumed about 95% of life-cycle primary energy. Water heating (used in hotel rooms in the top floors of the building) accounted for about 3% of life-cycle primary energy consumption. Building demolition and transportation of waste to the landfill consumed only 0.2% of life-cycle primary energy. LCIA categories (GWP, ozone depletion potential, acidification potential, eutrophication potential and solid waste generation) were associated directly with the primary energy demand. LCIA method was vaguely described in the paper.

Table 2.60: Summary of Scheuer et al. (2003) [131]

Title	Life cycle energy and environmental performance of a new university building: modeling challenges and design implications
Region	United States, Michigan
LCA Approach	Process, LCI and LCIA
Materials/products studied	7,300 m^2 six-storey building with steel column and girder structural frame
Functional unit	One square meter of a university building
Phases studied	Materials Production Transportation Construction O&M EOL

2.4.1.28 Junnila and Horvath (2003)

The paper is an LCA application on a Finnish office building with 50-year life span (see Table 2.61). The structural frame was made of cast-in-place concrete. Authors obtained major material and energy flows associated with the building from plans and design specifications. Related emissions data were obtained from the Finnish manufacturers. For the LCIA part of the study, Finland's KCL-ECO 3.0 life-cycle calculation program was used. Five main phases were covered within the LCA scope: building materials manufacturing, construction processes, use, maintenance, and demolition. Transportation of materials was included in appropriate life-cycle phases. Results from the analysis once more demonstrated that electricity use (lighting, HVAC systems, and outlets during use phase) and building materials manufacturing phases (steel cast iron manufacturing followed by the concrete manufacturing) contributed most to the overall building environmental impacts. The operational energy use accounted for 65-75% of the total and was consistent with other studies. Results were given in energy use, climate change, acidification, summer smog, eutrophication and heavy metal impacts for different life-cycle elements of the building over 50 years. As a final note, authors suggested that the assessment tools must be used simultaneously with the design tools for a better environmental evaluation. Moreover, factors such as material choice, service life of building elements or workmanship in different life-cycle stages should be considered for a detailed impact assessment of buildings in general.

Table 2.61: Summary of Junnila and Horvath (2003) [1]

Title	Life-cycle environmental effects of an office building
Region	Finland

LCA Approach	Process, LCI and LCIA
Materials/products studied	15,600 m^2 medium-sized, cast-in-place concrete office building with five stories in Finland.
Functional unit	Medium-sized office building with 50 years of service life
Phases studied	Materials Production Transportation Construction O&M EOL

2.4.1.29 Lenzen and Treloar (2002)

In this study authors analyzed the same wood and concrete building frames described in a preceding study by Börjesson and Gustavsson [132]. Differently, authors extended the previous process-based LCA study with an input-output framework in a tiered hybrid LCA approach. In a tiered hybrid LCA, “direct and downstream requirements (for construction, use, and end-of-life phases) and some important lower-order upstream requirements of the functional unit are examined in a detailed process analysis, while remaining higher-order requirements (for materials extraction and manufacturing) are covered by input-output analysis.” As a result, advantages of both LCA models were combined in a hybrid model. In their analysis, authors demonstrated the “…complexity of the inter-industry supply chains underlying the energy requirements for the building options.” Generally, after the second and higher order paths, impacts are difficult to capture in process-based LCAs in which case systematic truncation errors are inevitable. Authors covered energy intensities of materials used in buildings and energy contents of wood and concrete frame buildings in three ways: Börjesson and Gustavsson, Australian input-output multipliers for two production layers, and Australian input-output multipliers and extrapolated Börjesson and Gustavsson’s values towards upstream production layers. Finally, results showed that energy and GHG emissions embodied in building materials were underestimated by a factor of “2” in the study. However, in both studies the general result which was the concrete -framed buildings emitted higher amount of GHG emissions compared to wood buildings – was still valid. Since Börjesson and Gustavsson covered the similar case study, [132] is not included here in the literature body.

Table 2.62: Summary of Lenzen and Treloar (2002) [133]

Title	Embodied energy in buildings: wood versus concrete - reply to Börjesson and Gustavsson
Country	Australia
LCA Approach	Tiered hybrid, LCI
Materials/products studied	Concrete vs. wooden building frame materials (including concrete, iron, wood, particleboard, plywood, insulation, plasterboard, paper, and plastic)
Functional unit	1 kg of building material
Phases studied	Materials Production

2.4.1.30 Hendrickson and Horvath (2000)

Authors estimated resource and energy use, environmental emissions and waste generation in four major U.S. construction sectors defined by Department of Commerce (DOC): 1) Highway, bridge and other horizontal construction; 2) Industrial facilities, commercial and office buildings; 3) Residential one-unit buildings; 4) Other construction (towers, water, sewer and irrigation systems, railroads, and so on.). An economic input-output analysis-based life-cycle assessment (EIO-LCA) model was used to account not only for the economic and environmental impacts from the sector alone, but also those from the entire supply chain sectors associated with the construction industry. The model was based on 1992 detailed input-output model of the U.S. economy which included 485 commodity sectors. As a first step, gross sales of those four major construction sectors were determined. Following, major direct and indirect sector inputs were determined on the basis of $100,000,000 economic activity in each of the four construction sector. The most of the purchases were from the construction material supply industries expectedly.

Resource input requirements included electricity use, total fuels, total ores, fertilizers, and water (water intake and recycled/reused water) for construction sectors considered in the study. Emissions included SO_2, CO, NO_2, VOC, PM, GWP, hazardous waste, toxic releases to air, five largest toxic emissions (chlorine, ammonia, methanol, toluene, and hydrochloric acid), total toxic releases (TRI), CMU-ET equivalent toxic air releases (H_2SO_4 equivalent), and CMU-ET equivalent total toxic (H_2SO_4 equivalent) releases. Results from the analysis showed that the four major U.S. construction sectors used smaller amount of resources and generated less emissions and waste than their share of GDP compared to other sectors.

Table 2.63: Summary of Hendrickson and Horvath (2000) [118]

Title	Resource use and environmental emissions of U.S. construction sectors
Region	United States
LCA Approach	EIO-LCA
Materials/products studied	Four major U.S. construction sectors
Functional unit	Each of the four U.S. construction sectors
Phases studied	Construction

2.4.1.31 Cole (1999)

This is one of the earliest LCAs that assessed the energy use and GHG emissions associated with the construction of Canadian buildings with three major structural systems: concrete, steel, and wood. The analysis performed in this study was the foundation of the ATHENA™ project, an LCA tool developed for comparing and contrasting "the relative merits, amounts of energy, air emissions, liquid effluents, and solid waste associated with the production and installation of alternative designs." Major data sources involved RS Means Catalogue (1992) and interviews/ surveys performed with Canadian contractors. Sources of energy use and GHG emissions were: "1) Transportation of workers to and from the construction site during their construction task; 2) Transportation of materials from a distribution center to the site; 3) Transportation of equipment specific to the construction task to and from a central depot to the site; d) The use of on-site equipment specific to the construction task; and e) Supporting processes like formwork and temporary heating (especially important in colder regions during curing of concrete and its strength gain)." Results demonstrated that concrete construction caused the highest energy use and GHG emission values compared to the construction of steel and wood frames. Among three different forms of concrete construction, cast-in-place assemblies consumed the highest amount of energy in overall followed by the transportation of workers. Energy use was less for tilt-up wall construction, followed by the on-site equipment use. Pre-cast concrete results were the lowest and about 75-80% of the total precast construction was associated with the transportation of materials and equipment to the site.

Table 2.64: Summary of Cole (1999) [134]

Title	Energy and greenhouse gas emissions associated with the construction of alternative structural systems

Region	Canada
LCA Approach	Process, LCI
Materials/products studied	Structural assemblies used in wood, steel, and concrete building frames
Functional unit	1 m^2 of either wall or floor area
Phases studied	Construction

2.4.1.32 Jönsson et al. (1998)

Authors assessed the environmental impacts of structural concrete and steel frames in buildings by performing an LCA based on SETAC guidelines. Seven types of structural frames were studied: 1) In-situ cast concrete frame (office); 2) In-situ cast concrete frame (dwelling); 3) Precast concrete frame (office); 4) Precast concrete frame (dwelling); 5) Steel/concrete frame (office); 6) Steel/concrete frame (dwelling); and 7) Steel/steel frame (dwelling). The functional unit was selected as one square meter of floor area. In the study, all frame structures were assumed to have the same average lifetime of 50 years. LCI covered use of raw materials, energy use, emissions to air, emissions to water, and waste generation from building production phase (including raw materials, building materials, building components and building frames), service for 50 years, demolition and final disposal phases. At the disposal stage, all building materials (except for steel beams and columns) were either treated as filling material or waste after demolition. Steel elements were recovered after demolishing the building.

For the environmental impact assessment part, three methods, each resulting in one single value were used and compared: 1) Environmental Priority Strategies (EPS), focusing on the use of scarce resources; 2) Environmental Theme Method developed, based on environmental policy targets, 3) Ecological Scarcity Method. Results showed that fossil fuels, CO_2, electricity, SO_X, NO_X, alloys, and waste parameters were weighed more heavily compared to other parameters, depending on the type of the method used. End-of-life phase had considerably lower impact, based on the assumption that all demolition materials were used as filling material without any waste. Energy use during the 50 years of service life caused the largest impact regardless of the choice of the frame construction. Therefore, reduction in energy use was highly recommended.

Table 2.65: Summary of Jönsson et al. (1998) [135]

Title	LCA of Concrete and Steel Building Frames
Region	Sweden
LCA Approach	Process, LCI and LCIA
Materials/products studied	In-situ cast concrete (office and dwelling) Precast concrete frame (office and dwelling) Steel/concrete frame (office and dwelling) Steel/steel frame (dwelling)
Functional unit	One square meter of floor area
Phases studied	Materials Production Transportation Construction O&M EOL

2.4.1.33 Cole and Kernan (1996)

Authors calculated total life-cycle energy of a generic, 3-story, 4,620 m^2 (50,000 ft^2) office building constructed with three alternative building materials: wood, steel and concrete. Energy values were estimated in terms of initial embodied energy, the recurring embodied energy associated with maintenance and repair, and operating energy. Operating energy represented the largest share of the total life-cycle energy use. Building elements that required the most energy for maintenance and repair were the building services such as HVAC and interior finishes.

Results showed that "depending on the effective life of a building, the initial embodied energy may be greater or less than the recurring energy associated with refurbishment and repair." Over a typical 50 year building life, the initial embodied energy of the structure represented a relatively small portion of life-cycle embodied energy (i.e. less than 5%), and as a consequence, the distinction between wood, steel and concrete systems was less marked.

Table 2.66: Summary of Cole and Kernan (1996) [136]

Title	Life-cycle energy use in office buildings
Region	Canada
LCA Approach	Process, LCI (embodied energy use)
Materials/products studied	4,620 m^2 of three-story generic office building for wood/steel/concrete structural systems, with or without underground parking
Functional unit	One square meter or one building
Phases studied	Materials Production Transportation Construction O&M EOL

2.4.2 Synthesis and Limitations of Goal Definition and Scope of Concrete Commercial Building LCAs

The current state of commercial building LCA research is demonstrated in reverse chronological order from 2013 back to 1996 in Table 2.67. Of the 33 LCA studies reviewed, most of them are geographically concentrated in Europe and the United States while a few were developed in Asia-Pacific region and none of them included LCAs from developing countries. In order to achieve sustainability-related goals worldwide and recognize the scale of both global and regional problems (GWP, energy use, human health concerns, etc.), researchers need to conduct studies beyond developed countries. With the ongoing global shift of industrial activities [137] from developed countries and China to more and more developing regions of the world (e.g. India, China, Middle Eastern countries, etc.) due to lower supply and higher costs of energy, materials and labor, more research is inevitable for this part of the world.

Moving forward, building case studies in LCA literature differ considerably in terms of estimated life-span and total usable area (from 400 m^2 to 60,000 m^2, see Table 2.67). Buildings and building components have longer life spans (on average 50-100 years) compared to most of the building materials and products (such as insulation materials, tiles, paints, carpets which require replacement and maintenance over the life of the buildings. Looking at the lifetime selection criteria in building LCAs, one noticeable thing is its arbitrary selection without the consideration of the uniqueness of a building in terms of its geographical setting (is it in a seismically risky area? Or is it in a highly flooded zone?, position and proximity with respect to the sea level, etc.), climate (tropical vs. dry, wear and tear due to UV light, location with higher chances of precipitation or with little precipitation, etc.). Moreover, factors such as social acceptability or change are customer needs/dissatisfaction would be more important than durability or structural factors in determining the lifetime [138, 139]. As suggested by Aktas and Bilec [140], the use of statistical distributions instead of discrete lifetime values for buildings and building products would improve the accuracy of building LCAs and provide sound quantitative results.

Another issue in building LCAs is the building area selection. Except for a few studies [100, 117, 120, 141] functional unit was selected as per square meter of usable floor area of a building or per the whole building system with variations in design, type of structural frame (concrete, steel, or wood), building type (in terms of use purpose, architectural style, number of floors, number of residents, construction method), indoor and outdoor climate, source of data (calculated vs. measured) and so on. Therefore, full building LCA studies differ considerably from manufacturing related LCAs of building materials in terms of functional unit selection. In case of building material (product) LCAs, functional unit is de facto the final material (product) itself (see sections on Cement and Concrete Manufacturing LCAs) which is the outcome of somewhat series of simpler, more controllable processes. On the other hand, construction and building projects are unique with complex processes and these processes may require participation of different parties, different equipment, and practices while many assumptions have to be made for estimating the environmental impacts. Inevitably, functional units in building LCAs vary because of the complexity/variability of projects studied: About half (15 out of 33) of the studies [4, 72, 99, 104, 105, 111, 112, 114, 116, 128, 129, 131, 134-136] selected one square meter (or square feet) of building floor area as the functional unit. Majority of remaining LCAs used functional unit of a whole building [1, 4, 98, 101, 102, 109, 110, 113, 121, 122, 128, 136] with few exceptions. Among these exceptions, Audenaert et al. [100] chose one unit of building insulation material with equal performance and function, Bilec et al. [3] used precast concrete parking garage as their functional units. Based on the focus of the LCA, the U.S. construction sector was the functional unit for both Sharrard et al. [120] and Hendrickson and Horvath [118] whereas it was per unit of building material for Lenzen and Treloar [133]. In order to make apple-to-apple comparisons, functional unit for building LCAs can be demonstrated in units of per square meter per year. This would counterbalance the differences in size and life-time estimations.

The comparison of LCA methods used in literature is illustrated in Figure 2.3: A number of studies [15, 142, 143] demonstrated the benefits of hybrid analysis, with Dixit et al. [143] stating that ‘input-output based hybrid analysis is considered complete and nearly perfect in the life cycle analysis of buildings”. However, despite the benefits of hybrid analysis, majority of commercial building LCA literature was comprised of process-based LCAs (25 out of 33). Only one study by Hendrickson and Horvath [118] applied I-O based (CMU’s EIO-LCA) approach to study the environmental burden of the total U.S. construction sector. 7 out of 33 studies are hybrid building LCAs with variations of process-based and I-O-based approaches. For example, Vieira and Horvath [113] proposed a new hybrid LCA method to assess the end-of-life impacts of buildings. The new hybrid method was a consequential LCA (CLCA) approach, which assessed “not only the cradle-to-grave chain, but all interlinked processes that will be affected by a decision.” They compared CLCA results to attributional (traditional) LCA (ALCA) results. Sharrard et al. [117] developed an I-O-based hybrid LCA model that covered not only on-site construction activities (process) but also economy-wide effects of these activities. In this study authors reformulated existing process-based construction case studies with the extension of supply-chain impacts using EIO-LCA method. Again, in earlier studies, Sharrard [120] and Bilec et al. [3] applied hybrid LCA and complemented their assessment with nationwide EIO-LCA data in addition to using process-based LCA data in their assessments. Moreover, Vieira (2007) [4] used a hybrid LCA methodology for a cradle-to-grave assessment of commercial buildings. Earlier in 2003, Guggemos [119] applied both process-based and input-output approach to quantify and compare environmental impacts of cast-in-place concrete and steel frame office buildings. Finally, Treloar and Lenzen [133] analyzed the embodied energy value associated with wood and concrete buildings assessed in an earlier study conducted by Börjesson and Gustavsson [132] in 2000. Treloar and Lenzen employed an “environmentally extended input-output framework in a tiered hybrid life cycle assessment” for comparison purposes. Their results varied with the inclusion/exclusion of upstream production layers. Authors discussed effects of system-boundary truncation on the primary energy values embodied in wood and concrete structural frames. Their results showed that emissions and embodied energy values of building materials calculated by process-based LCAs (as in the case of Börjesson and Gustavsson [132]) were underestimated because of the truncation error, which is an inherent problem in process-based LCAs.

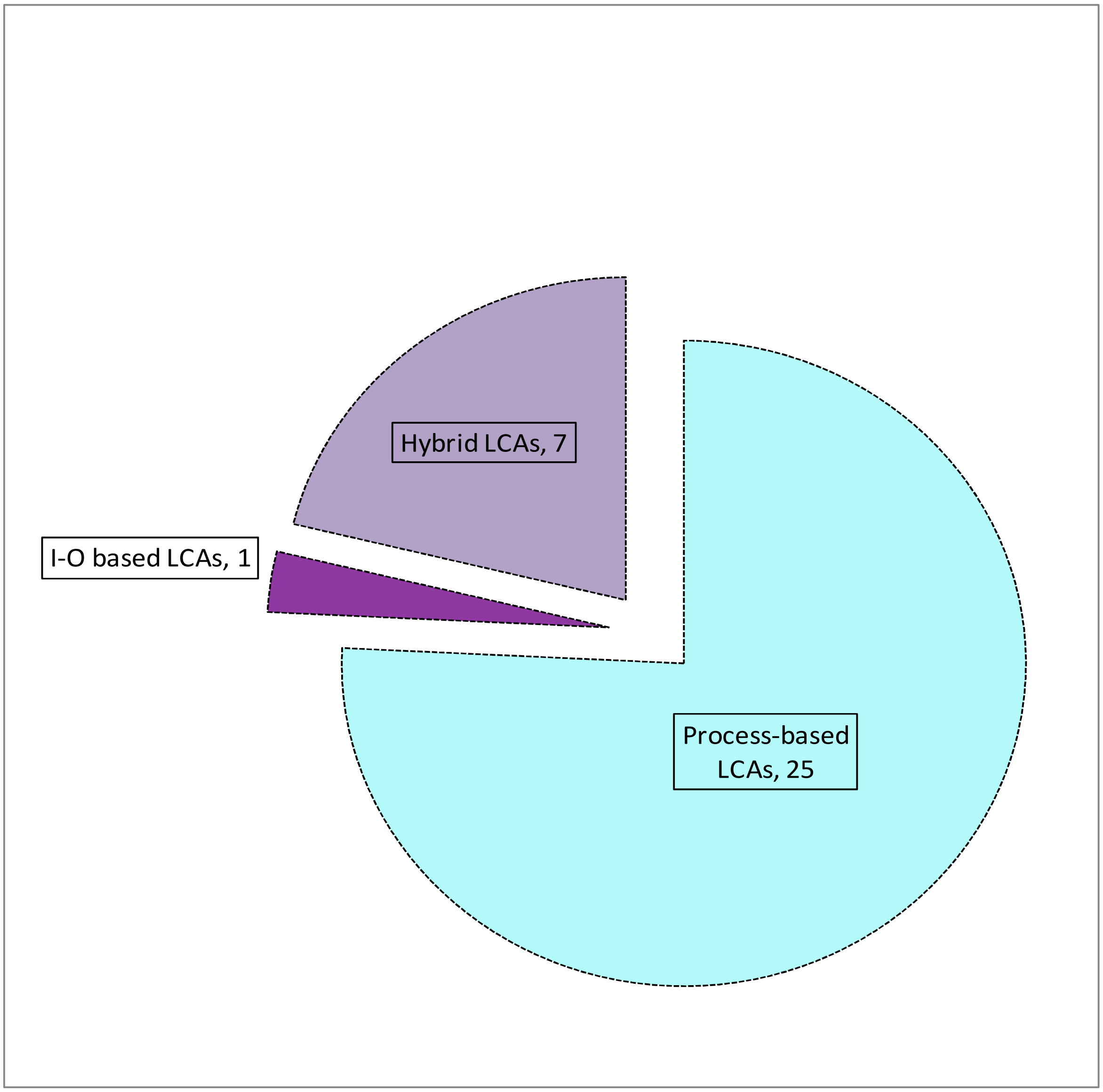

Figure 2.3: Comparison of LCA methods applied in commercial building LCA studies

Table 2.67: Summary (scope, type of LCA, functional unit, etc.) of Concrete Commercial Building LCAs

(Author, year)	Region	Type of LCA	Material Comparison	Functional Unit	Building Type	Life Span (Years)	Floor Area (m^2)	Notes
Zhang et al. (2013) [98]	Hong Kong	Process, only LCI	N	One Building	30-storey Office, Reinforced concrete	50	43,210 m^2	
Wu et al. (2012) [99]	China	Process, only LCI	N	One square meter	13-storey Office, Reinforced concrete	50	36,500 m^2	With brick and mortar walls
Audenaert et al. (2012) [100]	Belgium	Process, only LCIA	Y[1]	One unit of insulation material with equal performance (K, E values)	3-storey Residential	-	-	Building with 19 flats. External and internal walls, roof and floor insulation materials.
Williams et al. (2012) [101]	UK	Process, only LCI	N	One mixed-use development	18-storey Office and Residential	60	-	3-storey underground parking, ground-level retail, 14-storey office. Focus on climate change and influence of HVAC system.
Tingley and Davison (2012) **[102]**	UK	Process, only LCI	Y (concrete, wood, steel)	One Building	No specification	50	-	Focus of the tool is on EOL phase of structural components, materials.
Marshall et al. (2012) [103]	United States	Process, only LCI	N	One construction activity or per one hour	Church building with on-site parking lot	-	1,245 m^2	Methodology to link between RS Means and NONROAD tool to estimated non-road equipment use related emissions
Malmqvist et al. (2011) **[104]**	Sweden	Process, LCI and LCIA	N	One square meter	No specification (office or housing)	50	-	Description of the ENSLIC building project
Wallhagen et al. (2011) **[105]**	Sweden	Process, LCI and LCIA	N	One square meter	4-storey Office	50	3,537 m^2	Application of the ENSCLIC tool
Ortiz et al. (2009) **[106]**	EU, United States	Review	-	-	-	-	-	Review of building materials and

								construction LCAs
Dodoo et al. (2009) **[109]**	Sweden	Process, only LCI	Y (concrete and wood)	One building	4-storey building with wood frame vs. reinforced concrete frame	100	1,190 m^2	Carbon balance (both emissions and uptake)
López-Mesa et al. (2009) **[110]**	Spain	Process, LCI and LCIA	N	One typical floor surface (430 m^2)	7-storey Residential, Either with precast concrete or in-situ cast concrete slab.	-	3,010 m^2	Both environmental and cost analysis
Kellenberger and Althaus (2009) [72]		Process, LCIA	N	One square meter	Building components	80	-	Results involve CED and Ecoindicator 99 total points associated with building components described on five different levels of detailing
Kofoworola and Gheewala (2009) **[111]**	Thailand	Process, energy only	N	One square meter	38-storey Office, Concrete	50	60,000 m^2	Life-cycle energy analysis
Dimoudi and Tompa (2008) **[112]**	Greece	Process, LCI	N	One square meter One kg for building materials	5-storey and 3-storey Office	50	5-storey: 1,891 m^2 3-storey: 400 m^2	Contribution of different building materials and building elements over the life of buildings were assessed. Only SO_2, CO_2, and energy use
Vieira and Horvath (2008) **[113]**	United States	Hybrid, LCI	N	One building frame	5-storey Office, Steel reinforced concrete beam and column system with shear walls at the core	-	4,400 m^2	Comparison of CLCA and ALCA of concrete. CLCA includes alternative uses of materials as well as complementary materials
Xing et al. (2008) **[114]**	China	Process, LCI	Y (concrete and steel)	One square meter	Office, Reinforced concrete or Steel-framed	50	Reinforced Concrete: 34,620 m^2 Steel: 46,240 m^2	BIN method was used to calculate the building energy use and emissions of direct and

								indirect sources
Favre and Citherlet (2008) **[115]**	Switzerland	Process, LCI and LCIA	Y (envelope elements)	Varies	Residential building and components		4,460 m^2	Description of a new LCA tool, BAT
Haapio and Viitaniemi (2008) **[116]**	Finland	Process, LCI and LCIA	Y	One square meter	Residential	60 160	-	78 single-family houses. Assessment tool ATHENA® Environmental Impact Estimator (EIE) was used. No operational energy use included
Sharrard et al. (2008) [117]	United States	I-O-based hybrid	N	One project /one square meter/ one million US$	Varies with construction case study	-	-	Description of I-O based hybrid LCA based on CMU's EIO-LCA method.
Vieira (2007) **[4]**	United States	Hybrid, LCI	Y (concrete and steel)	One building	Office, Steel-framed	50	13,378 m^2	Dissertation on BuiLCA building LCA tool. Case study is a 6-storey mixed use of labs, offices, and conference rooms,
Sharrard (2007) **[120]**	United States	Hybrid, LCI	N	U.S. Construction Sector	Construction phase of Residential, Office, Bridges and highways	-	Varies	Description of an I-O based Hybrid LCA for US construction industry. Case studies were taken from literature
Bilec et al. (2006) **[3]**	United States	Hybrid, LCI	N	One parking garage facility	Design and construction of a parking garage facility with deep foundation	-	-	Augmented process-based hybrid LCA approach.
Zhang et al. (2006) **[128]**	China	Process, both LCI and LCIA	N	One square or one building	7-storey (one below ground) Office, Reinforced concrete	50	35,685 m^2	Description of Building Performance Analysis system (BEPAS) approach

Junnila et al. (2006) [121]	Finland United States	Process, LCI	N	One building	Finland: 4-storey Office U.S.: 5-storey Office, Reinforced concrete	50	4,400 m^2	Data quality assessment was performed.
Li (2006) [129]	Japan	Process, LCI	Y (concrete and steel)	One square meter per one year	Regional development including infrastructure	35	Varies	Location, structural frame, and energy source impacts on LCA of a mixed use building and its infrastructure. Social cost was considered.
Guggemos and Horvath (2005) [122], Guggemos (2003) [119]	United States	Hybrid, LCI	Y (concrete and steel)	One building	Two 5-storey Office, Cast-in-place or Steel-framed	50	Both are 4,400 m^2	Process-based CDEST LCA tool – application in the construction of office buildings.
Scheuer et al. (2003) [131]	United States	Process, LCI and LCIA	N	One square meter	6-storey Office, Steel column and girder structural frame	75	7,300 m^2	Use phase impacts were calculated based on DOE's eQuest.
Junnila and Horvath (2003) [1]	Finland	Process, LCI and LCIA	N	One building	5-storey Office, Cast-in-place concrete	50	15,600 m^2	Used Finnish *KCL-ECO* 1999 for LCIA step.
Lenzen and Treloar (2002) [133]	Australia	Tiered hybrid vs. Process, LCI	Y (concrete and wood)	One kg of building material	Walludden building [132]	-	-	Effects of system boundary truncation – associated with supply chain
Hendrickson and Horvath (2000) [118]	United States	EIO-LCA	N	Major construction sector	-	-	-	EIO-LCA application to the U.S. construction industry
Cole (1999) [134]	Canada	Process, LCI	Y (concrete, steel, and wood)	One square meter of either wall or floor area	Structural assemblies – walls, floors, beams, columns, and slabs	-	-	The basis of ATHENA project
Jönsson et al. (1998) [135]	Sweden	Process, LCI and LCIA	Y (concrete and steel)	One square meter	Structural frames	50	-	LCIA represented by single score approaches, such

								as EPS, ETM, ESM.
Cole and Kernan (1996) [136]	Canada	Process, LCI	Y (concrete, steel, and wood)	One square meter One building	3-storey generic Office, with or w/o underground parking	50 100	4,620 m^2	Alternative structural materials and systems with similar performance. Part of ATHENA project.

[1] Alternative material choice for external walls and internal and external insulation materials

2.4.2.1 Commercial Building Life-Cycle Phase Representation in Literature

As observed in Figure 2.4, building life-cycle phases encompass materials (extraction) production, construction, operation and maintenance (O&M) and ends up with the demolition (cradle-to-grave) followed by landfilling or recycling/ reusing (EOL). 12 out of 33 commercial building LCAs covered all five phases including the transportation phase [1, 4, 98, 102, 104, 109, 111, 115, 119, 121, 122, 129, 131, 135]. It should be noted that Figure 2.4 excludes those studies when LCA phases were vaguely included or not indicated clearly, demonstrated in "question mark" or were aggregated without any distinction between phases, shown in "ND" in Table 2.68

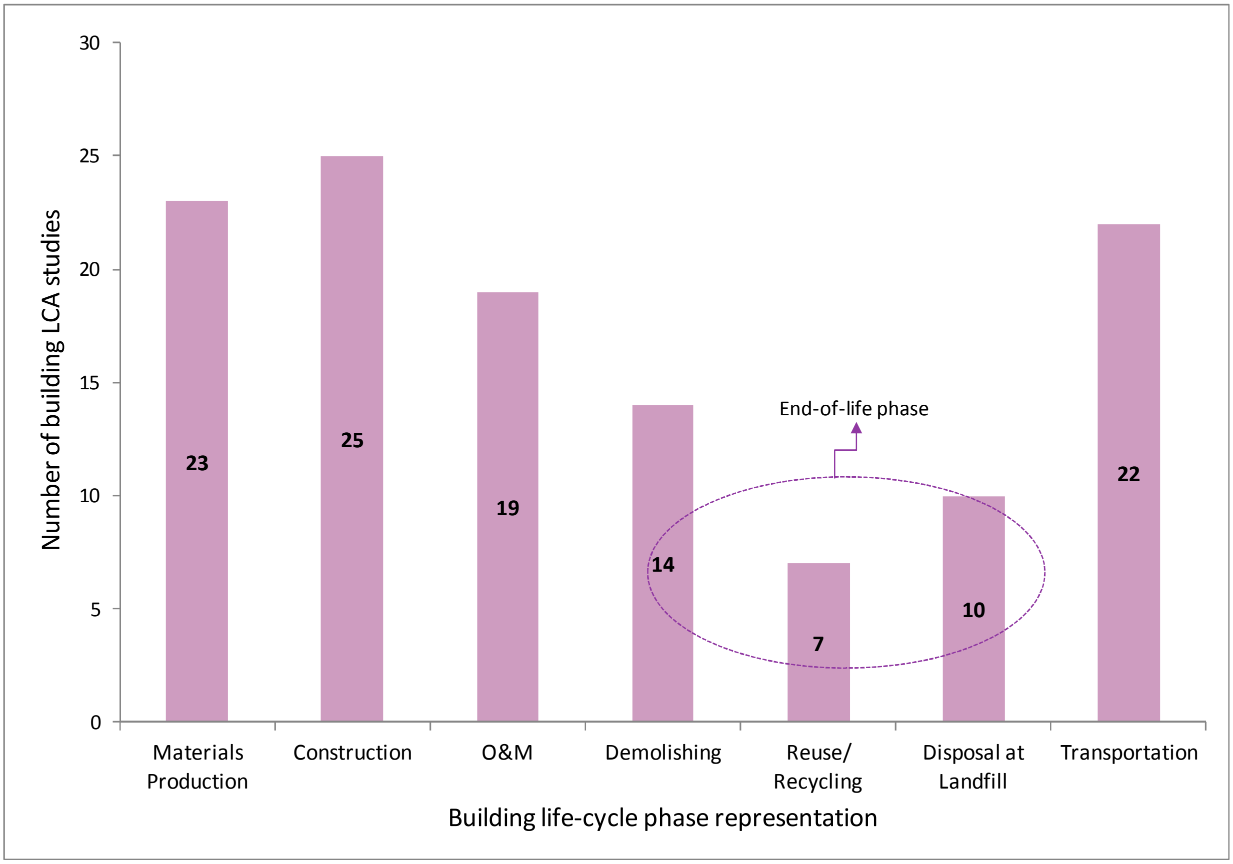

Figure 2.4: Life-cycle phase representation for commercial building LCAs

Transportation phase involves transportation of extracted materials to the production facility, then building products and equipment to construction site, and finally transportation of waste streams to disposal land or to recycling/reuse facilities. However, not all of the commercial building LCAs have covered these details in their assessment. Number of studies with transportation phase details is illustrated in Figure 2.5. The "vaguely-included" means that transportation impacts were covered but vaguely either accounted in EIO-LCA results [113, 122] or in the database (e.g. EcoInvent) [109, 115] where the raw data was taken from and without explicitly showing the calculations in the related study [134, 135].

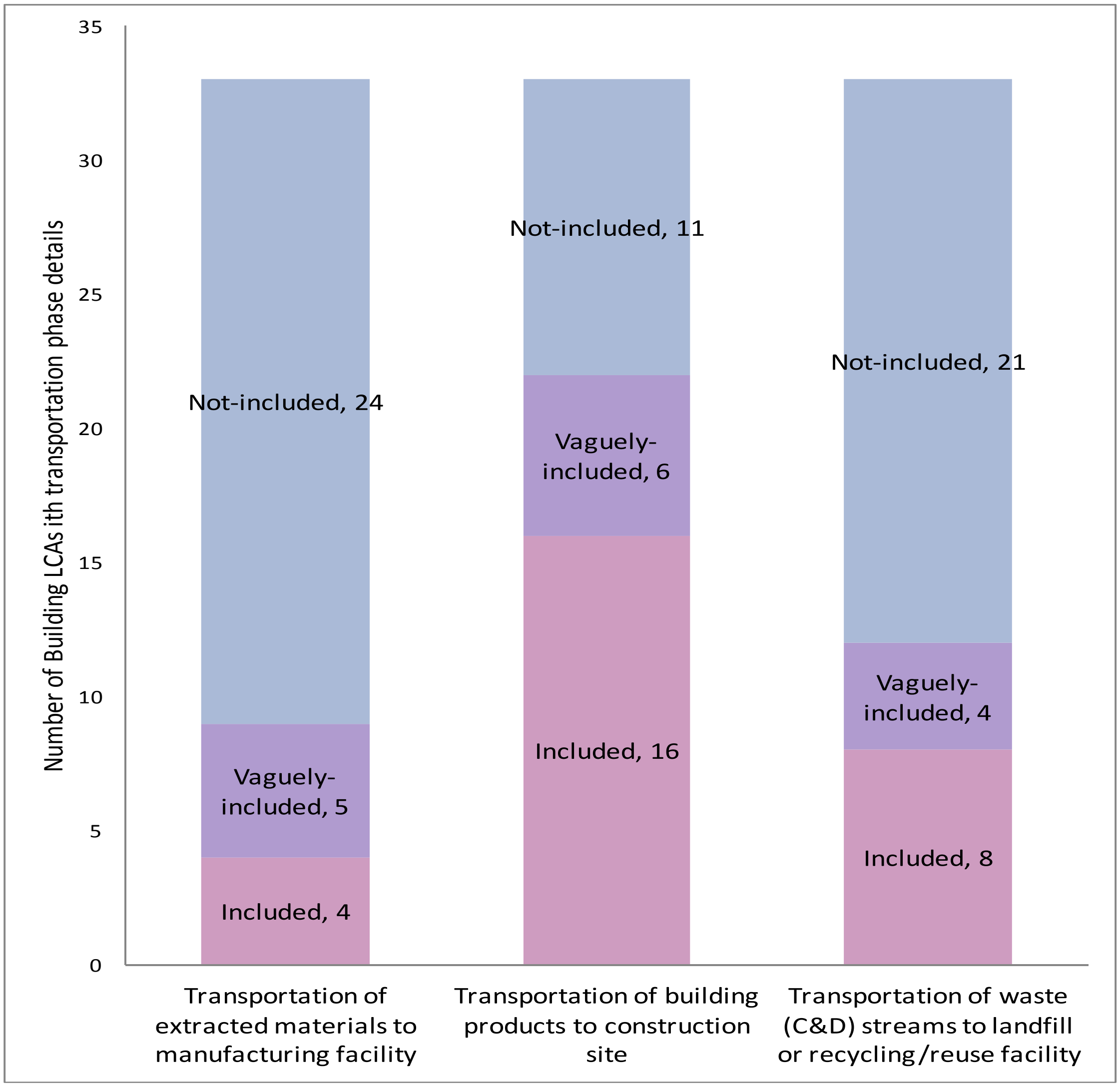

Figure 2.5: Transportation phase details documented in commercial building LCAs

Table 2.68: Life-cycle phases included in commercial building LCAs

	Life-cycle Phases						
				End-of-Life			
(Author, year)	**Materials Extraction/ Production**	**Construction**	**Operation (O) & Maintenance (M)**	**Demolishing**	**Reuse/ Recycling**	**Disposal at Landfill**	**Transportation**
Zhang et al. (2013) [98]	*	*	O,M	*		*	*
Wu et al. (2012) [99]	*	*	O	*	*	*	*
Audenaert et al. (2012) [100]	*				*	*	
Williams et al. (2012) [101]	*	*	O,M				*
Tingley and Davison (2012) **[102]**	*	*	O,M	*	*	*	*
Marshall et al. [103]		*					
Malmqvist et al. (2011) **[104]**	*	ND	O	ND	ND	ND	ND
Wallhagen et al. (2011) **[105]**	*		O				
Ortiz et al. (2009) **[106]**							
Dodoo et al. (2009) **[109]**	*	*		*	*	*	*
López-Mesa et al. (2009) **[110]**		*					*
Kellenberger and Althaus (2009) [72]	*	*	O	ND			*
Kofoworola and Gheewala (2009) **[111]**	*	*	O,M	*			*
Dimoudi and Tompa (2008) **[112]**	*		O				
Vieira and Horvath (2008) **[113]**	*	*		*	*	*	*
Xing et al. (2008) **[114]**	*	*	O	ND	ND	ND	*
Favre and Citherlet (2008) **[115]**	*	*	O,M	*	*	*	*

Haapio and Viitaniemi (2008) **[116]**	?	*	?	ND	ND	ND	?
Sharrard et al. (2008) [117]		*					
Vieira (2007) **[4]**	*	*	O,M	*	*	*	*
Sharrard (2007) **[120]**		*					*
Bilec et al. (2006) **[3]**		*					*
Zhang et al. (2006) **[128]**	ND	ND	ND	ND	ND	ND	ND
Junnila et al. (2006) [121]	*	*	O,M	*		*	*
Li (2006) [129]	*	*	O,M	*			*
Guggemos and Horvath (2005) [122], Guggemos (2003) [119]	*	*	O,M	*		*	*
Scheuer et al. (2003) [131]	*	*	O	*			*
Junnila and Horvath (2003) [1]	*	*	O,M	*	*	*	*
Lenzen and Treloar (2002) [133]	*						
Hendrickson and Horvath (2000) [118]	ND	*					ND
Cole (1999) [134]		*					*
Jönsson et al. (1998) [144]	*	*	O	*	?	?	*
Cole and Kernan (1996) [136]	*	*	*	*			*

? : Vaguely included, not clearly indicated

ND: Aggregated impacts of LCA stages with no distinction (of inputs, outputs or stages)

Moving forward, extraction and manufacturing of building materials is considerably well-covered, mainly due to the availability of embodied energy and associated emissions data from production processes and transportation. Quantity and cost of materials data are generally extracted from bill of materials (from contractors or engineering companies) when a building case study is analyzed. Data may include all structural and non-structural materials/components as well as temporary materials (such as formwork, oil form release, shoring for concrete, lubricants, templates for steel, etc.) used in construction of a building or building element. Generally, LCI data of building materials have been obtained from major data sources such as NIST's BEES [6], EcoInvent, Ecoindicator and SimaPro databases and software [6, 72, 101, 115], CMU's EIO-LCA [4, 111, 113, 119, 122, 133] with adjustments made for electricity grid mix. Table 2.69 is an overview of the materials with brief description of LCA approaches and methods applied in manufacturing phase over the building life-cycle. While some studies solely focused on one specific building material, such as insulation material alternatives for exterior walls, roof, and floors, most of them included all major building materials (as taken from bill of materials) in their LCA scope. Therefore, materials are generally covered in substantial depth and breadth in building LCA literature.

Shifting focus to the construction phase, 25 out of 33 studies, while 5 of them solely [103, 110, 116-118] studied this phase. Construction phase covers all types of activities including the construction site preparation, structural and building envelope installation, mechanical, electrical equipment installation, exterior and interior finishing applications as well as renovating the buildings [131]. During this stage, emissions occur from the electric power use and fuel combustion of construction equipment. Transportation of materials and equipment to the construction site and waste from the site produce additional emissions. To estimate what construction equipment and activity contribute to what type of pollutant and in what quantities, a link between project quantity takeoff values and emission factors associated with the corresponding activity/equipment is set. Starting with the RS Means Cost Data [145], one can determine/predict the equipment horsepower and model, total number of hours the equipment used and total number of equipment required based on the quantity takeoff input. RS Means provides materials (plus markup percentage for material handling) and labor costs (plus markup for overhead and profit) for building components and construction activities per unit area or per unit of construction activity. Emission factors associated with construction equipment and activities are obtained from sources such as U.S. EPA's NONROAD model [103, 146]. For example, Guggemos et al. [119, 122] used NONROAD model to estimate pollutants of HCs, CO, NOx, and PM from construction of a concrete- and steel-framed building. The emission factors in the model are reported by engine power, model year, and technology type (tier number) and in units of g/hp-hr On the other hand, authors calculated CO_2 and SO_2 emissions based on diesel fuel-related data (see CDEST tool in [119] for details). CO_2 and SO_2 calculations require BSFC (Brake Specific Fuel Consumption, in units of lb/hp-hr) rates for non-road construction equipment (provided in NONROAD as well). The following Equation 2.1 box shows how CO_2 and SO_2 emissions from diesel construction equipment are calculated Diesel fuel higher heating values and carbon content can be obtained from sources including EPA's MOVES energy and emission inputs document [147]:

Energy consumption is calculated based on diesel heating value of 19,300 Btu/lb

Energy consumption = (BSFC lb/hp-hr)* (19,300 Btu/lb)*(1,055.056 J/Btu)/(1*10^6

J/MJ)

CO_2 emission rate = (BSFC lb/hp-hr)*(1/7.099 lb/gal)*(2,770 g C/gal diesel fuel)*(44/12 g CO_2/ g C)

SO_2 emission rate = (BSFC *453.6 *(1-0.02247)-HC)*0.0033*2

Equation 2.1: CO_2 and SO_2 emissions from diesel use by non-road construction equipment

Similar to the approach described above in Guggemos et al. [119, 122], other U.S. LCA studies by Cole [134], Junnila et al. [1, 121], Vieira [113], and Marshall [103] applied process-based approach in estimating construction-activity related emissions. In addition to process-based, other couple of U.S. studies applied either economical I-O-based or hybrid LCA approach. Only one U.S. study by Hendrickson and Horvath [118] applied EIO-LCA to estimate the environmental impacts from four major U.S. construction sector as described by Department of Construction (see Table 2.63). On the other hand, Sharrard [120] developed I-O-based hybrid approach to I-O construction sectors (including eight case studies from residential, commercial, and heavy construction projects and five related maintenance and repair projects) to fully understand both direct and supply-chain impacts of the sector. In a word, the author fine-tuned the construction sector vectors in the I-O matrix. By looking beyond the aggregated EIO-LCA, project cost items were utilized as "process-level input for the I-O-based hybrid LCA model" and supply-chain activities that were mostly ignored in process-based LCAs were considered in the hybrid approach. The author selected various process-based construction LCAs from literature and applied to validate the new I-O-based hybrid approach. Lastly, Bilec et al. [3] applied hybrid LCA to the construction of a U.S. parking lot. Except for Lenzen and Treloar [133] which applied Australian I-O matrix, all other remaining non-U.S. studies applied process-based approach in assessing the construction-related environmental burden. These studies obtained data from either commonly-used databases including EcoInvent, Ecoindicator, EMEP/CORINAIR, IPCC, SimaPro or other national databases, such as LCAiT for Sweden, KCL-EC3 for Finland, BEPAS LCA for China, Thai EIO-LCA, etc.

As part of the construction phase, to account for the construction waste, Williams et al. [101], Kofoworola et al. [111], Vieira [4], and Guggemos and Guggemos et al. [119, 122] added a small percentage to major material quantities based on literature findings [148-150]. Moreover, burden from transportation of materials and equipment (and also workers as in the case of Cole [134] and Williams et al. [101]) to the construction site from the suppliers were considered in all 25 but 3 [103, 110, 116, 117] studies that included the construction phase impacts. Transportation distance from material supplier to the site and heavy truck usage information are two pieces of data required to calculate transportation related impacts. For the U.S., major data sources included: U.S. EPA's MOVES (Motor Vehicle Simulator) model and AP-42 database [147, 151], Transportation Energy Data Book by Davis et al. [152]. Non-U.S. studies obtain data from EcoInvent and SimaPro databases [102, 110] and organizations such as UK's Department for Environment, Food and Rural Affairs (DEFRA) [101].

The operation and maintenance phase includes all activities related to the use of the building over its life-span which can be 50-100 years. In their review, Sartori and Hestnes [153] found that use phase would represent 80-90% of the life-cycle energy consumed. According to CEN/TC 350 standard (Sustainability of construction works by European Committee for

Standardization) [154], building use phase activities are: maintenance, repair and replacement, refurbishment, operational energy use including heating, cooling, ventilation, hot water and lighting, and operational water use. Although operation phase is comparably well-studied (19 out of 33 commercial building LCAs), maintenance of buildings is generally underrepresented (11 out of 19 studies covered both operation and maintenance while 8 of them focused only on operation phase impacts), especially with components (such as paint, carpeting, etc.) other than the structural frame, where the life expectancy is 50-100 years. This is because of the uncertainty regarding the replacement frequency of building materials and the building's lifespan. In general, building operation-related energy use and emissions either involved ranges of data from literature [135, 136] or actual thermal and electrical energy consumption records or calculated on the basis of energy use patterns [98, 99]. In another study, Malmqvist et al. [104] applied Excel-based "ENSLIC Basic Energy & Climate Tool" to estimate a building's energy use and associated environmental impact on the basis of building design features such as building size, type, material u-values, location, and indoor air quality, thermal climate, etc. requirements. Williams et al. [101] focused on the operation phase more in depth by specifically studying the HVAC system in commercial buildings. Authors used a Dynamic Thermal Model and UK Climate Projections '09 Weather Generator (a climate model) software to establish potential building performance in each of the weather scenarios defined. This study allowed "the influence of climate change to be included in the LCA of building GHG emissions." Additionally, various other energy use simulations were applied by other commercial building LCAs. For example, Junnila and Horvath [1] estimated heat and energy consumption values on the basis of IDA 2001 – Indoor Climate and Energy software by Equa (http://www.equa-solutions.co.uk/). Junnila et al. [121] performed energy calculations using the WinEtana energy simulation program for the Finnish building case study, while U.S. building energy use was calculated based on data from CMU's EIO-LCA, EIA, EPA, and other sources. Similarly, Vieira [4] approached the operation phase in a broader perspective and calculated the amount of electricity and fuel consumption based on literature, including EIA's Building Energy Consumption Data for the average U.S. building (see Commercial Buildings Energy Consumption Survey from: http://www.eia.doe.gov/emeu/cbecs/contents.html Tables b1, c1 and c2.). The author also used U.S. EPA's eGRID to estimate emissions from electricity grid mix and EIO-LCA to estimate all other impacts from natural gas consumption, and use of office supplies, paper, computers, office waste, photocopiers, fax machines, and so on. Another U.S. study by Scheuer et al. [131] modeled a university building's HVAC and electrical services using eQuest, developed by the U.S. Department of Energy [130]. Therefore, each study focused on different aspects of the operation phase, with varying degrees of depth and breadth.

Only one third of the building LCAs incorporated maintenance and replacement of building materials. Environmental impacts from this phase are calculated based on the service life of building materials/elements and followed similar approaches as used for materials manufacturing. Literature is the major data source for building material service life. Zhang et al. [98] and Li [129] assumed maintenance-related energy use and emissions were 0.2% and 3% of the construction impacts, respectively, based on the literature. Kofoworola and Gheewala calculated a similar percentage (the construction stage contributed 4% of the life-cycle GHG emissions while maintenance caused about 0.1% of total, which is about 0.2% of the construction impacts). Junnila et al. [121], Junnila and Horvath [1], and Guggemos and Horvath [119, 122] all used the literature and expert opinion as the source for material service life (replacement) rates. For the U.S. commercial building LCA case studies, CMU EIO-LCA was applied to calculate the energy use and emissions related to maintenance of materials [4, 119, 121, 122] over their service life. Two UK studies by Williams et al. [101] and Tingley and Davison [102] used the replacement factors from Building Cost Information Services (BCIS) [155] and Building Research Establishment (BRE) [156] databases, respectively. Finally, the earliest Canadian study by Cole and Kernan [136] covered the maintenance phase impacts by describing the significance of recurring embodied energy over a 25, 50 and 100 year building life. For a building with 50-year service life, results showed that the embodied energy for replacement and repair was almost equivalent to that of the initial embodied energy, which was corresponding to 5-10% of building life-cycle energy use. Authors found the percentage of recurring energy was lower for shorter life spans, while for longer building life (100 years), it was found to be 2-3 times greater than the initial embodied energy. Accordingly, Williams et al. [101] demonstrated that the replacement of components could produce as high as about 44% of total embodied GHG emissions over a service life of 60 years, being in line with Cole and Kernan [136] results.

End-of-life (EOL) phase is the least studied phase (14 out of 33) as some studies indicated that demolition and following EOL impacts can be ignored, because they tend to contribute insignificantly to the total life-cycle impacts [101, 132, 133]. Moreover, as of today, the degree of uncertainty is high as it would be difficult to predict impacts that will occur in about 50 years or more in the future [101, 136]. Indeed, a number of LCAs calculated that end-of-life activities caused about 0.2-1.3% of total life-cycle energy use and related emissions according to a number of LCAs worldwide [4, 98, 119, 121, 122, 131]. The demolition covers the destruction of the building with the use of heavy construction equipment (mostly diesel use). Energy use and emissions are calculated as similar to construction-related impacts. Then, the demolished materials are transported to landfill areas and/or recycling plants. In none of the studies, allocation of environmental impact to recycled or reused materials was neglected. This is mostly because of the uncertainty associated with what allocation would be more appropriate (mass or economic allocation) for a specific component or material and if economic allocation is used, which scrap price to use now for an activity taking place 50 years in the future. ISO 14040 guidelines [12, 13] and BRE [156] are two major sources of allocation issue in recycling/reusing of building materials.

Once again, Table 2.68 and Table 2.69 summarize the major life-cycle phases together with the overview of building materials and components covered in the literature. Moving forward, LCI representation of commercial building LCAs comes next. More than half of the 33 building LCA studies reviewed included both LCI and LCIA steps, while the remaining half covered LCI only, the focus being energy use and GHG emissions.

Table 2.69: Overview of building products and materials covered in commercial building LCAs

Sources:	**Building products/materials**	**Referenced**	**Calculated**	**Notes**
Zhang et al. (2013) [90]	Concrete, cement, steel, aluminum, glass, sand	Yes (journal articles, EMEP/CORINAIR, California EPA, etc.)		Emission factors of CO_2, CH_4,N_2O, SO_2, CO, NO_x, NMVOC, PM_{10} for materials used in a reinforced concrete structure
Wu et al. (2012) [91]	Concrete, cement, brick, steel, timber, aluminum, glass, plastic	Yes (IPCC, journal articles, etc.)		Embodied energy and emission factors for CO_2 for materials
Audenaert et al. (2012) [92]	Insulation material alternatives for exterior walls, roof, and floors as well as materials used for external and internal walls	Yes (EcoIndicator99: A damage- oriented method)		Non-bearing elements used in wooden frame for different alternatives. Results given in eco-score
Williams et al. (2012) [93]	Aluminum, brass, ceramic, concrete, copper, galvanized steel, glass, glass reinforced plastic, plywood, polypropylene, PVC, reinforcing steel, stainless steel	Yes (EcoInvent v2.0, IPCC, UK-Construction Resources and Waste Platform, Chau et al. 2007)		Embodied GHG emissions (except for HVAC energy demand, all respective fuel use was converted to CO_2-eq) as well as waste production rates for major typical materials
Tingley and Davison (2012) [94]	Superstructure (columns, beams for concrete, steel, or timber) and upper floor system (precast slab or timber-joist floor). Focus is on deconstruction, future reuse of components	Yes (based on Guide to PAS2050 by British Standards Institution, Carbon Trust and DEFRA)	Yes (by Sakura, an LCA tool described in the paper)	Embodied energy (in MJ per m^2 of a building structure) and embodied carbon (in kg CO_2-eq per m^2 of a building structure) associated with major building materials used in structural components (concrete, steel, wood) and upper floor systems (precast vs. timber joists). Results in CO_2-eq
Marshall et al. (2012) [95]	N/A		RS Means and NONROAD database	Only non-road equipment use for construction phase
Malmqvist et al. (2011) [96]	Slabs, external walls (incl. doors and windows), attic and roof, internal walls	?	Yes	CO_2-eq

Sources:	**Building products/materials**	**Referenced**	**Calculated**	**Notes**
Wallhagen et al. (2011) [97]	Improvement measures for building components e.g. slabs (concrete to wood), extra insulation, windows, etc. Materials: concrete, aluminum, glass, gypsum, insulation (cellulose fiber, EPS, rockwool), polyethene, steel, wood	Yes, EcoInvent, EcoEffect (Swedish LCA program for buildings) and BEAT (Danish LCA program for buildings), IPCC	Yes (ENSLIC tool, drawings, specifications)	CO_2-eq
Ortiz et al. (2009) [98]	N/A			Building LCA review
Dodoo et al. (2009) [101]	Concrete-framed and wood-framed building			Carbon-balance, EOL implications
López-Mesa et al. (2009) [102]	Materials (concrete, reinforcing bars, mesh reinforcement, plastic, wooden formwork, release agents, etc.) for reinforced concrete structural frame with in-situ cast-in-place concrete floor vs. precast concrete floor	Yes (EcoInvent v1.1 and SimaPro 7.0)		Only construction phase inventory and LCIA results in EPS score points
Kellenberger and Althaus (2009) [62]	Material alternatives (insulation, wood vs. concrete structure, sandstone vs. brick wall, etc.) for roof, exterior and interior wall components in buildings	Yes (EcoIndicator99: A damage- oriented method)		Ecoindicator cumulative score, CED (non-renewable, renewable, and biomass) scores for determining impacts from transportation, construction, additional materials, waste cutting for five types of building components
Kofoworola and Gheewala (2009) [103]	Bill of materials (ceramic tile, granite, vinyl tile, brick, plaster, gypsum, aluminum, paint, wood, terrazzo, precast concrete, glass, stainless steel, ready mixed concrete, structural steel, steel wire, steel reinforcement, cement sand screed)		Yes (Thai EIO-LCA model data for materials manufacturing and maintenance)	Emissions factors of tonnes of CO_2-eq, SO_2-eq, C_2H_4-eq per monetary units of materials

Sources:	**Building products/materials**	**Referenced**	**Calculated**	**Notes**
Dimoudi and Tompa (2008) [104]	Mortar, cement flooring tiles, light concrete, concrete (structural frame), reinforcement steel, extruded polystyrene, mineral wool, brick, ceramic tiles, internal and external plaster, PVC membrane, aluminum sheet, polyethylene, vinyl tiles	Yes (journal articles, Centre for Building Performance Research database - New Zealand)		Embodied energy, CO_2-eq, SO_2-eq, and lifetime values per kg of major building materials were provided. Comparison of two office building
Vieira and Horvath (2008) [105]	Major building materials (concrete, cement, sand, crushed stone, PVC pipe, bitumen, asphalt) and complementary/alternative uses (scrap concrete, recycled concrete, etc.)		Yes (EIO-LCA for materials, BuiLCA for construction, demolition, and debris separation, EPA-WARM for landfilling, Guggemos 2003 for recycling)	Total (direct and indirect) energy use, CO, SO_2, NO_x, PM_{10}, GHG, GWP, CFCs per 1,000,000 USD value of building material
Xing et al. (2008) [106]	Steel- vs. concrete-framed buildings. Materials include concrete, steel, glass (walls)	Yes (Building energy consumption analysis by BIN tool, China industry reports for materials production)		Energy use, CO_2-eq, CO, SO_2, NO_x, PM_{10}, NMHC for materials production and use phases
Favre and Citherlet (2008) [107]	Comparison of building envelope elements (e.g. façade, floors, roof, etc.) and related materials (brick, glass wool, polystyrene, fiberglass panel, wood panel, vapor barrier, etc.)		Yes (Eco-Bat, tool developed by the same authors based on EcoInvent database and information from industry)	Non-renewable energy (NRE), GWP, AP, POCP impacts for variations of building elements for whole life-cycle phases
Haapio and Viitaniemi (2008) [108]	Wall insulation (cellulose, fiberglass, rock wool), cladding (brick, stucco, steel, wood), window frame (wood, aluminum), roof (concrete tile, clay tile, steel roof)		Yes (ATHENA^{TM} Environmental Impact Estimator v3.02)	Primary energy consumption, air pollution, water pollution, GWP, solid waste, weighted resource use for variations of building elements for lifetime of 60, 80, 100, 120, 140, 160 (for the whole life-cycle)
Sharrard et al. (2008) [109]	Different construction projects (residential, office, paving, bridge repair, etc.)		Yes (EIO-LCA for various construction projects)	Comparing energy use, GHG, criteria air pollutants from different LCA approaches (hybrid, EIO-LCA, process)

Sources:	**Building products/materials**	**Referenced**	**Calculated**	**Notes**
Vieira (2007) [113]	Detailed bill of materials for a structural steel frame and a glazed façade mixed-use office building		Yes (EIO-LCA data for materials manufacturing, CDEST (Guggemos 2003) for the construction, literature and industry)	Energy use, CO_2-eq, CO, SO_2, NO_x, PM_{10}, VOC for all life-cycle phases, including building design
Sharrard (2007) [112]	Various construction projects – focus on the construction phase		Yes (EIO-LCA, other major data sources from EPA, DOE, DOT, etc.)	Direct and total energy input, GWP, criteria air pollutants, TRI (toxic releases), RCRA (hazardous waste)
Bilec et al. (2006) [122]	Limited to construction (processes and supply-chains) and related transportation processes. Materials were not considered.		Yes (EIO-LCA, SimaPro v5.0, drawings and specs.)	CO_2, CH_4, N_2O and CFC; and SO_2, CO, NO_2, VOC, lead, and PM_{10}.
Zhang et al. (2006) [123]	Quantities of steel, wood, cement, glass, aluminum, and PVC for a reinforced concrete building		Yes (BEPAS -LCA model for buildings in China)	LCI and LCIA results are aggregated over the whole life-cycle of the building
Junnila et al. (2006) [114]	Detailed bill of materials for concrete-framed building (one in Finland and the other one in the U.S.)		Yes (Contractors and architects, WinEtana energy simulation program for Finnish building use phase, EIA for U.S. use phase, EIO-LCA and literature)	Total energy use, CO_2, SO_2, NO_x, and PM_{10} for whole life-cycle phases
Li (2006) [124]	Steel-framed store buildings and infrastructure		Yes (Japanese version of damage-oriented LCIA method named LIME and an LCA program developed for Japan)	Emission factors of CO_2, SO_2, NO_x, PM, COD, solid waste, total-Nitrogen, and total-Phosphorus for three steel building case studies
Guggemos and Horvath (2005) [116], Case study is from Guggemos (2003) [111]	Detailed bill of materials (concrete, aluminum, carpet, steel, glass, paint) for concrete- and steel-framed building		Yes (RS Means, EIO-LCA, IPCC, EPA)	Embodied energy and CO_2, CO, NO_x, PM_{10}, SO_2 (aggregated for materials manufacturing, construction, and transportation to site)

Sources:	**Building products/materials**	**Referenced**	**Calculated**	**Notes**
Scheuer et al. (2003) [126]	Concrete, cement, sand, steel, exterior and interior wall materials, flooring, roof, window, ceiling, etc.	Yes (EcoBilan, SAEFL, SimaPro, Franklin Assoc., eQuest by USDOE)		Both initial and replacement quantities and embodied energy values for major building materials.
Junnila and Horvath (2003) [115]	Detailed bill of materials (cast iron steel, concrete, aluminum, copper, masonary, glass, etc.) for a cast-in-place concrete building		Yes (KCL-ECO 3 life-cycle calculation program, IDA indoor climate and energy simulation program, data from industry)	Electricity and fuel use for construction, use, maintenance, and demolition (materials and replacement not included). Climate change, AP, summer smog, EP, heavy metals
Lenzen and Treloar (2002) [128]	Concrete and wood structural frame comparison (materials include: concrete, iron, wood, particle wood, insulation, plasterboard, paper, plastic)	Yes (Börjesson and Gustavsson 2000 paper)	Yes (Australian I-O matrix)	Energy content by materials in concrete and wood frames on the basis of LCA methods applied
Hendrickson and Horvath (2000) [110]	Major direct and indirect inputs (ready-mixed concrete, steel mills, sand and gravel, electricity, banking sectors, etc.) to U.S. construction sectors		Yes (EIO-LCA)	Direct and total energy input, GWP, criteria air pollutants, TRI (toxic releases), RCRA (hazardous waste)
Cole (1999) [129]	Concrete, steel, wood structural frame comparison - construction and transportation only		Yes (RS Means, interviews with contractors)	Energy use and GHG emissions from construction and transportation (of materials, equipment, and workers to site)
Jönsson et al. (1998) [130]	In-situ cast concrete, precast concrete and steel frames. Also aggregates, limestone, iron-ore, gypsum, fossil fuels, scrap, alloy materials, chemicals, minerals, etc.	Yes (literature for materials other than steel and concrete)	Yes (LCAiT tool and data from Swedish building industry)	Feedstock energy of fossil materials used as raw materials (e.g. coal/coke in steel production as raw material) included. Emissions of CO_2, NO_x, SO_x, COD, hazardous and non-hazardous waste
Cole and Kernan (1996) [131]	Concrete, steel, wood		Yes (part of ATHENA^{TM} tool, BRE, Forintek, CANMET)	Initial embodied, replacement, and operating energy values for wood, steel, and concrete frames with or without underground parking place.

2.4.3 Life-Cycle Inventory (LCI) Representation in Commercial Building LCAs

A few studies are comprehensive in terms of inventories covered over the life-cycle of a building. Walking through the Table 2.70, it is observed that air emissions (especially GHG and criteria air pollutants), energy use and materials (from quantity takeoff and cost estimates) were covered in more than half of the building LCAs. On the other hand, the literature rarely included the inventory of water consumption, toxic and hazardous waste, solid waste, and waste water.

Table 2.70: LCI categories included in concrete commercial building LCAs

	Life-cycle Inventory							
Source	Raw materials	Energy use (F:fuel, E:electric)	Water	GHG (CO_2)	Criteria Air P.	Solid Waste	Waste Water	Toxic Emissions
[98]	*	F,E		*	*	*		
[99]	*	*		*				
[100]	*							
[101]	*			*				
[102]		*		*				
[103]				*	*			
[104]			*	*		*		
[105]	*	*		*				
[106]				*				
[109]	*			*				
[110]	*	*	*					
[72]								
[111]	*	*						
[112]	*	*		*	*			
[113]	*	*		*	*			
[114]	*	*		*	*			
[115]	*							
[116]	?[1]	*		*	?[1]	*	*	
[117]		*		*	*			
[4]	*	*	*	*	*			
[120]		*		*	*			
[3]				*	*			
[128]	*	*	*	*	*	*		
[121]		*		*	*			
[129]	*			*	*	*	*	
[122], [119]	*	*		*	*			*
[131]	*	*	*	*	*	*		

[1]	*	*	*					
[133]		*		*				
[118]	*	*	*	*	*	*	*	*
[134]		*		*				
[144]	*	*		*	*	*	*	
[136]		*						

[1] Indicators are from building environmental assessment tool ATHENA™ Environmental Impact Estimator (EIE), including: Weighted resource use, energy consumption, solid waste, GWP, and air and water pollution.

2.4.3.1 Energy use in Commercial Building LCAs

As mentioned before, energy consumption (as in the form of fuel and electricity) is addressed commonly in existing building LCAs. After the synthesis of literature, a clarification is necessary regarding the energy use terminology for adequate comparisons between studies. Based on Cole and Kernan [136]'s definitions, there are four major categories of building's life-cycle energy use:

> *The **initial embodied energy** of a building is the energy used to acquire raw materials and manufacture, transport and install building products in the initial construction of a building.*
>
> *The **recurring embodied energy** is the energy required to refurbish and maintain the building over its effective life.*
>
> *The **operation energy** is the energy required to operate the building - i.e. the energy required to condition (heat, cool and ventilate) and light the interior spaces and to power equipment and other services.*
>
> *The **demolition energy** is the energy to demolish and dispose of the building at the end of its effective life.*

Figure 2.6 is a demonstration of the four major energy categories described above. Based on this figure, the life-cycle embodied energy is the sum of initial embodied energy, recurring energy and demolition energy. Therefore, total life-cycle energy is the sum of operation energy and life-cycle embodied energy. As observed in Figure 2.6, at year = 0, when the building's life starts just after construction, the initial embodied energy reached at its maximum value. The energy value before "0" time slot represents the material-related energy use before the construction starts. The operation energy starts at "0" and grows cumulatively till the end of building's life. The slope of the cumulative operating energy line can be more or less steeper depending on the efficiency of energy use over the life of the building. At year = 25, the embodied energy increases due to maintenance and refurbishment of building materials (carpet, paint, windows, doors) which involves recurring energy used for materials/components manufacturing and installations. It is assumed that maintenance occurs once at year 25 with nothing in between. At year 50, demolition takes place and it is shown with a small upward spike on the Figure.

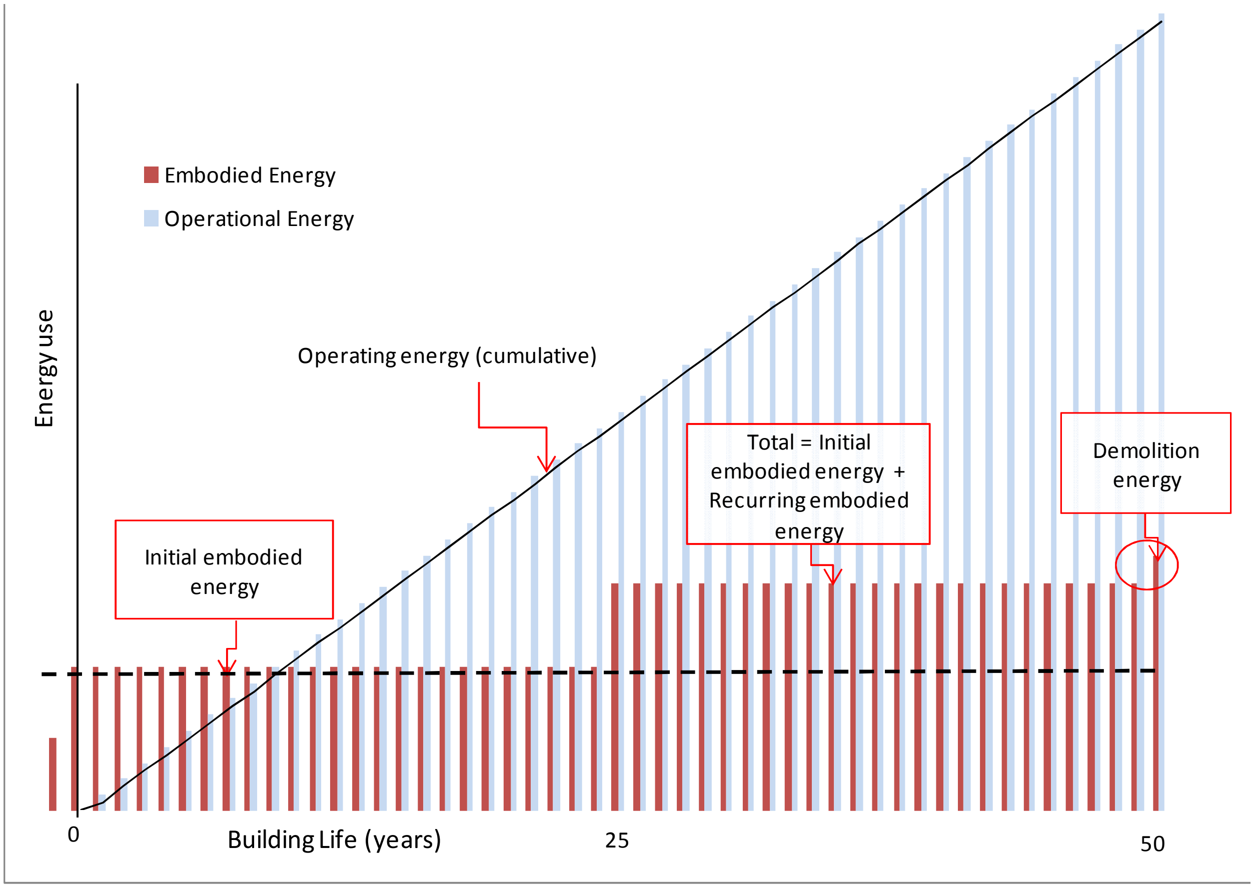

Figure 2.6: Demonstration of embodied and operational energy over the life-cycle of a commercial building, based on Yohanis and Norton [157]

Additionally, primary energy vs. end-use energy terminology was seldom observed in building LCAs. In most of the studies, these two are undifferentiated and the term “energy” is used to refer to overall energy use without any distinction. As stated in Sartori and Hestnes [153], energy carriers for thermal purposes and/or sources of electricity generation could be different when we consider the primary energy while the end-use energy can have similar figures for identical buildings in different countries with similar climate properties and associated emissions vary as well. Table 2.71 briefly summarizes building LCAs with respect to life-cycle embodied and operational energy coverage as well as primary vs. end-use energy representation. About half of the studies (16 out of 33) included initial embodied energy values (3 of them were limited to only construction-related and one was only materials-related embodied energy) while 9 of them provided total embodied energy numbers. Recurring embodied energy and demolition energy use were the least studied categories.

For comparison purposes, Figure 2.7 was prepared based on energy consumption percentages by building life-cycle phases. In the figure, capital letters “A” and “B” refer to different building cases. For example, [114]A and [114]B percentages correspond to concrete and steel structural frames, [121]A and [121]B to the U.S. and Finnish office buildings, and [119]A and [119]B to concrete and steel structural frames, respectively. The difference between case study percentages can be explained by the system boundary studied, inclusion/exclusion of supply-chain effects, energy sources, electricity grid mix differences, variations in production technologies, building use patterns, building service life, differences in climate and assumptions made. However, despite these variations, as observed in Figure 2.7, there is consistency in building life-cycle energy consumption percentages.

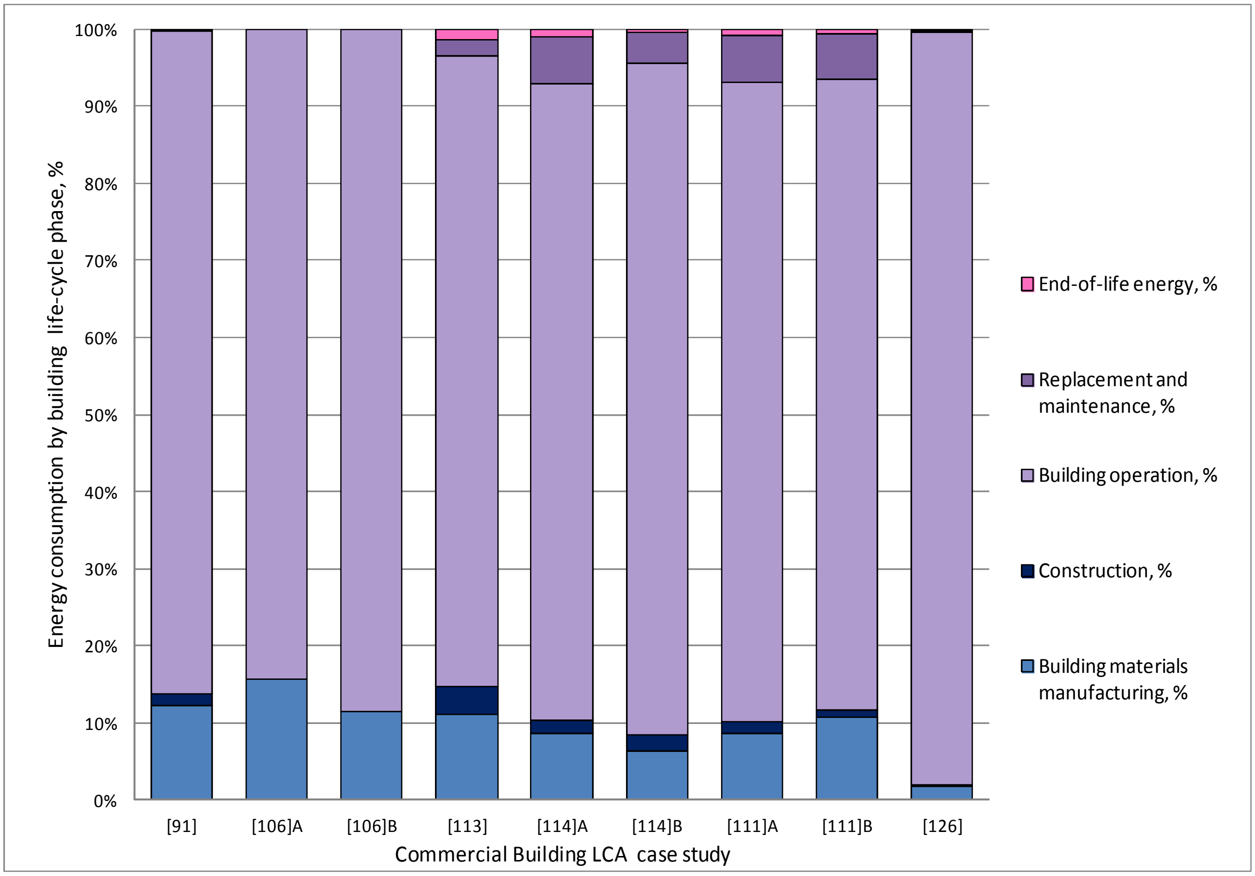

Figure 2.7: Comparison of energy consumption by building life-cycle phases (based on literature)

Table 2.71: Representation of energy use in commercial building LCI

	Embodied Energy Use				**Operation Energy Use**			**Notes**
Source	Initial	Recurring	Feedstock	Total (I+R)	Primary	End-use	Demolition	
[98]								GHG, criteria emissions
[99]	I			T		E	D	Energy use and CO_2
[100]								Eco-score,
[101]								GHG emissions
[102]				T		E		Embodied CO_2-eq
[103]								
[104]						E		
[105]						E		Electricity use and water heating in kWh/m^2 but all others in CO_2-eq
[106]								Carbon uptake, emissions
[109]								
[110]	I (only C)							Construction equipment and transportation to site
[72]				T	P			Non-renewable CED in MJ/m^2 and Ecoindicator points
[111]						E		Only annual operating (end-use) energy
[112]	I			T		E		Initial to total embodied energy ratio: 60-70%, that is 13-19% of life-cycle energy use
[113]	I			T				Aggregated results
[114]	I					E		
[115]								Non-renewable energy (NRE), GWP, AP, POCP
[116]					P			Aggregated results
[117]	I							
[4]	I	R		T	P	E		
[120]								
[3]								
[128]								Aggregated results
[121]	I	R		T	P	E		
[129]						(?)	D	
[122], [119]	I						D	I: Steel frame with concrete slabs: 9,500 MJ/m^2, Cast-in-

								place concrete frame: 8,300 MJ/m^2
[131]	I	R	F	T	P	E	D	
[1]	I (only C)				P	E		Limited to construction and operation
[133]	I				P			Energy use values from original process-based LCA, I-O with two production layers, complete I-O application
[118]	I							
[134]	I (only C)							Construction: 7-10% of initial embodied energy
[144]	I		F		P	E		Bar charts are hard to interpret. Results in eco-points
[136]	I (only M)	R		T		E		I includes only materials manufacturing energy use

2.4.3.2 GHG emissions and criteria air pollutants in Commercial Building LCAs

Similar to the cement and concrete manufacturing LCIs, the most commonly studied LCI factor in commercial building LCAs (26 out of 33 studies) is CO_2 emissions (or in the form of CO_2-eq). In proportion to amount of energy consumed, most of the CO_2 is emitted during the building operation phase, varying between 98.8% [98] and 81.3% [99], as illustrated in Figure 2.8. The high percentage in Zhang et al. [98] study is noticeable. It is important to note that 98.8% figure includes both operational and maintenance CO_2 emissions. However, there could be other causes regarding poor energy efficiency of building's operation phase or energy sources of electricity generation with high carbon content. Also, other life-cycle phases may cause much lower emissions due to use of advanced technologies in building materials manufacturing or construction. In general, materials extraction/manufacturing phase is the second highest source of CO_2 emissions, causing 10-20% of total life-cycle emissions, in general [153]. Compared to concrete frame buildings, steel frame buildings emit slightly higher amount of CO_2 as a result of higher CO_2 emissions during steel extraction/production stage. In Figure 2.8, it is observed that, CO_2 emissions associated with materials extraction/manufacturing vary between 1% [98] -10% [4, 119]. In Guggemos study, both concrete and steel buildings were assessed causing 8.3% and 10% of total building CO_2 emissions, respectively. The one percent value is again from Zhang et al. study and is an outlier when other LCA results are considered. The construction (including transportation) and end-of-life related CO_2 emissions are considerably low: 0.2%-3.4% of total emissions. In one study by Wu et al. [99], the end-of-life emissions are comparably high at 13.7% , mostly because of waste disposal in landfilling. Studies, except for Wu et al. [99] compared in Figure 2.8 calculated CO_2 from only demolition. Maintenance phase causes 2%-5% of total CO_2 emissions. In addition to CO_2 emissions, Dodoo et al. [109] investigated and compared the carbon balance of reinforced concrete frame and wood frame buildings over their life cycle. Authors calculated carbon flows (in units of tonnes of carbon) associated with fossil fuel use in materials production, calcination emission from cement manufacturing, carbonation of concrete during and after its service life, substitution of fossil fuels recovered by wood residues, recycling of steel, and fossil fuel used for post-use material management. *Despite the carbonation of concrete in the post-use stage, results of the study confirm the validity of earlier studies and favor wood-frame buildings in terms of carbon emissions.*

In Figure 2.8, major criteria air pollutants are compared on the basis of concrete commercial buildings through their whole life cycle. In these six studies, except for VOC emissions, SO_2, NO_x, PM_{10}, and CO emissions are all addressed. VOC emissions are included in Zhang et al. [98] and Vieira [4] for all major building phases. However, in literature, VOC from only construction activities, mainly from painting process was considered in Guggemos [119] and Bilec et al. [3]. As observed in Figure 2.8, SO_2 and NO_x emissions are comparably higher during the use phase, followed by materials production, construction, and end-of-life phases. Materials extraction/production and operation phases are equally responsible from most of the PM_{10} emissions during the life-cycle of buildings. CO emissions are again primarily from materials extraction/production and operation stages of concrete buildings (but on average, slightly higher for the materials production compared to the use phase). In steel framed buildings, CO associated with steel production is estimated to be higher compared to CO from concrete production and also exceeds the amount emitted during the use phase (see the Figure 2.8 for steel frame and concrete frame building comparisons from Guggemos [119] study). In summary, similar to energy consumption profile, the use phase dominates majority of air emissions except for CO and PM_{10} which spread at different life cycle stages of buildings, including materials manufacturing, buildings operation and maintenance.

Results from Guggemos [119] provided sources of GHG and criteria air pollutants for each of the building life-cycle phase. For example, during materials manufacturing phase, steel elements (reinforcement, studs, frames, grid, etc.) used in concrete were found to be responsible from most of the CO, NO_x, CO_2, and SO_2 emissions. Major source of PM_{10} emissions was estimated to be the insulation-fiber glass. Concrete was the second major source of PM_{10} following the insulation materials during the materials extraction/ manufacturing phase. The author estimated construction equipment use as the leading source of construction-related emissions. During the building operation phase, in line with the literature results, electricity was the major source of emissions while the replacement of carpets dominated emissions for the maintenance phase. Finally, construction equipment used in building demolition contributed most to air emissions during the end-of-life phase.

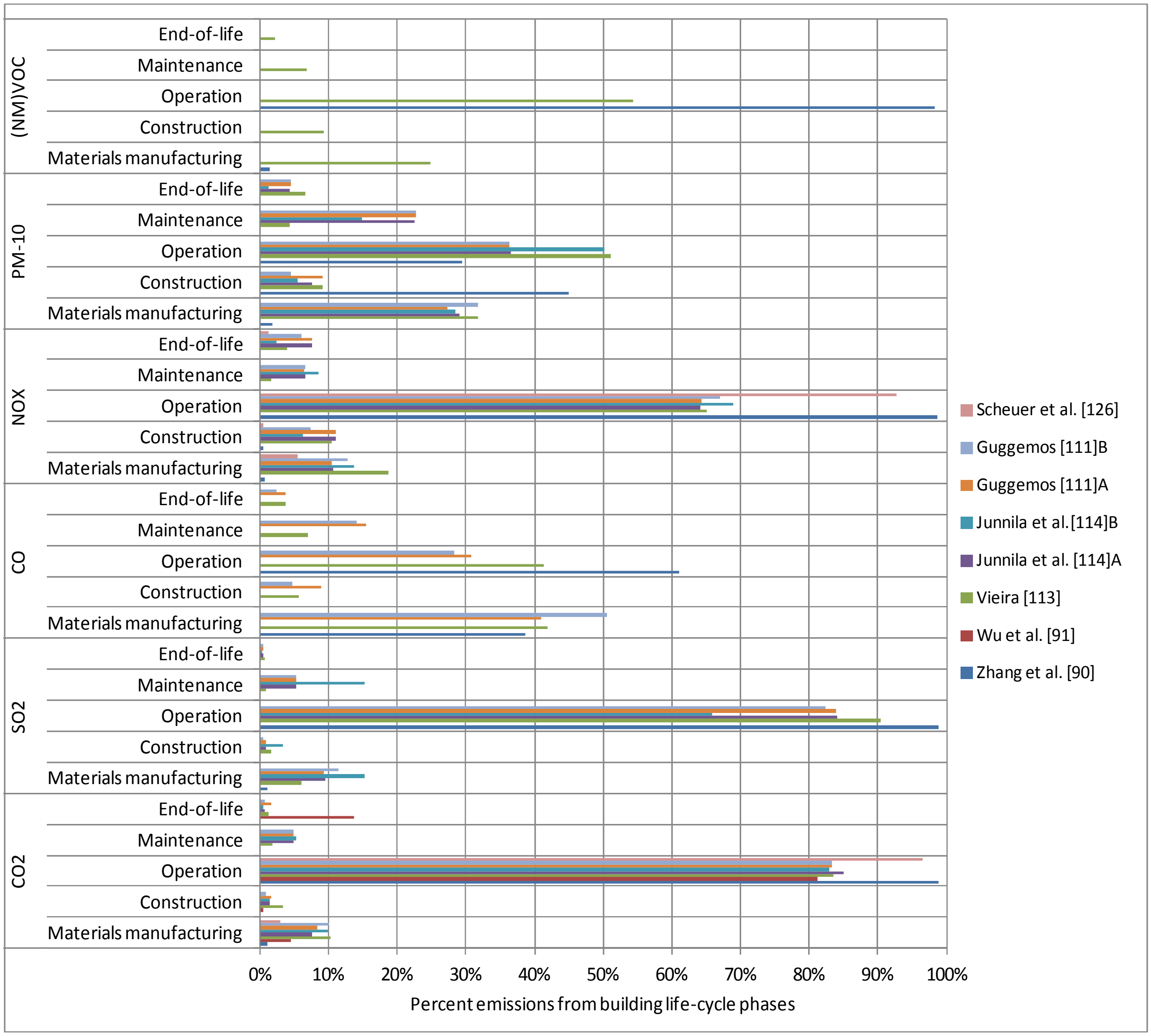

Figure 2.8: Percent CO_2 emission and criteria air pollutants by building life-cycle phases (based on literature)

2.4.3.3 Water consumption, toxic emissions, solid waste, and waste water Commercial Building LCAs

Limited number of building LCAs estimated water consumption, toxic emissions, solid waste, and waste water from commercial buildings (Table 2.70). Only seven out of 33 LCAs considered water consumption in their analysis. However, it is limited to the quantity of water consumed during building life-cycle stages (mostly construction and operation) without the consideration of energy use and associated environmental impacts of water supply options.

Among building LCA studies covered in this section, only Guggemos [119] and Hendrickson and Horvath [118] included the toxic emissions in their results. However, it was limited to the construction only. Guggemos [119] provided waste factors generated for the different materials used on-site for the structural frame from waste data sources including R.S. Means, Björklund et al. [75], ATHENA [36, 46], contractor input, and others. For steel frames, construction-related solid waste included cardboard, concrete, fireproofing, grout, paint at the fabrication shop, paint at the job site, steel, and wood. For concrete frames, construction waste was from cardboard, concrete, and wood. In the same study, construction-related toxic emissions covered heavy metals Cr (VI), Ni, Cr, and Mn, where the majority of impacts were caused by painting, welding, and torch cutting. By applying EIO-LCA, Hendrickson and Horvath also [118] provided hazardous waste (RCRA), toxic air releases (TRI) and CMU-ET (H_2SO_4) equivalent toxic releases to air and water based on the monetary value of major four U.S. construction sectors.

Haapio and Viitaniemi [116] estimated water pollution (index) and solid waste from buildings with different cladding materials over different spans of service life. Authors used ATHENA^{TM} Environmental Impact Estimator (EIE) Software Version 3.0.2. Li [158] also considered LCI for waterborne releases of suspended particulate matter, COD (chemical oxygen demand), total nitrogen, and total phosphorus, as well as solid waste of wasted plastics, sludge, wood chip, slag, and other wastes from building materials (including crushed gravel, portland cement, blast furnace slag cement, fly ash cement, ready mix concrete, etc.). But the data was limited to Japanese building applications. Jönsson et al. [135] estimated COD and hazardous/non-hazardous waste for different types of building frames but the calculations were not transparent. The non-hazardous waste usually consisted of mineral, building and industrial waste. Authors found that steel wires caused the hazardous waste, such as sulfuric acid with dissolved metals, primarily iron. Scheuer et al. [131] quantified the total amount of solid waste generated through the life-cycle of a university building. Results showed that materials manufacturing waste accounted for 22% of the total amount, whereas 5.5% was construction-related, 66% from the operation phase (2.8% of from water services), and the remaining 6.8% of the waste was from the demolished building. Material manufacturing-related waste was derived from “slag and fly ash” occurring during energy use while producing materials and wastes from manufacturing processes themselves. Waste from building operation phase was the result of electricity generation waste. Authors assumed that waste after building demolition was minima as most of the major building materials (e.g. concrete, sand, gravel, brick, all metals, carpets etc.) would either be recycled or reused. Both Zhang et al. studies [98, 128] also provided solid waste generated during demolition stage on the basis of literature data.

Overall, results from the literature point to a lack of data or research in inventory flows such as waste water, solid waste or toxic emissions in building LCAs. These should be considered in future LCAs of concrete commercial buildings.

2.4.4 Life-cycle impact assessment (LCIA) Representation in Commercial Building LCAs

Results from the critical literature review on commercial building LCAs reveal the same problem encountered in cement and concrete production LCA literature review: most of the studies either partially or wholly excluded the LCIA step of the LCA methodology. Studies which do estimate and interpret environmental impacts often cited the software program or method used for these calculations. As seen in Figure 2.9 (see Table 2.72 and Table 2.73 for more details), while three studies applied damage-oriented impact assessment methodology, five studies limit LCIA to midpoint analysis (that provides only characterization factors but no damage assessment). Two out of five midpoint analysis by Malmqvist et al. and Favre and Citherlet [104, 115] used different versions of CML by SimaPro software. Additionally, Junnila and Horvath [1] applied mid-point approach using KCL-ECO 3.0 life-cycle calculation program for the classification and characterization of inventory data within impact categories. Other two mid-point LCAs by Zhang and Scheuer et al. [128, 131] adopted LCIA factors from ISO/SETAC guidelines [159, 160]. It is important to note that mid-point analysis is based on traditional LCIA characterization and normalization methods as indicators located between inventory interventions and endpoint effects and damages. Mid-point analyses reduce the amount of assumptions and the complexity of the modeling and results in comparison with end-point analyses. However, they make the interpretation of absolute results more difficult since they do not refer directly to the damages produced [17] More information on CML method can be found in Section 2.3.4.

Due to higher data requirements and complexity, end-point (damage) approach was applied in only three studies [72, 100, 110]. Audenaert et al. [100] and Kellenberger and Althaus [72] estimated the effects of building- and materials-related resource use and emissions on human health, ecosystem quality based on software Ecoindicator 99. As stated in Audenaert et al.:

> *Of all the emissions, extractions and land use in all processes, the damage they cause to human health, ecosystem quality and resources is calculated. At the end, these three categories are combined into a single score [96]. To do this, weighting factors are used to indicate the importance of each part (damage to resources 20%, human health 40%, and ecosystems 40%). One of the advantages of the single score output of the Ecoindicator 99 method is that it makes it relatively easy to compare different building components. At the same time, the subjectivity of the weighting factors is one of the main weaknesses of this method.*

Both studies provided and compared their results in units of eco-score. On the other hand, López-Mesa et al. [110] covered both midpoint and endpoint analysis. Impact categories involved life expectancy, crop growth capacity, degrees of morbidity (severe to less severe), nuisance (sever to less severe), soil acidification, fish and meat production, wood growth capacity, species extinction and others that are related to human toxicity and eco-toxicity. Authors used EPS 2000 method for the LCIA step of their analysis.

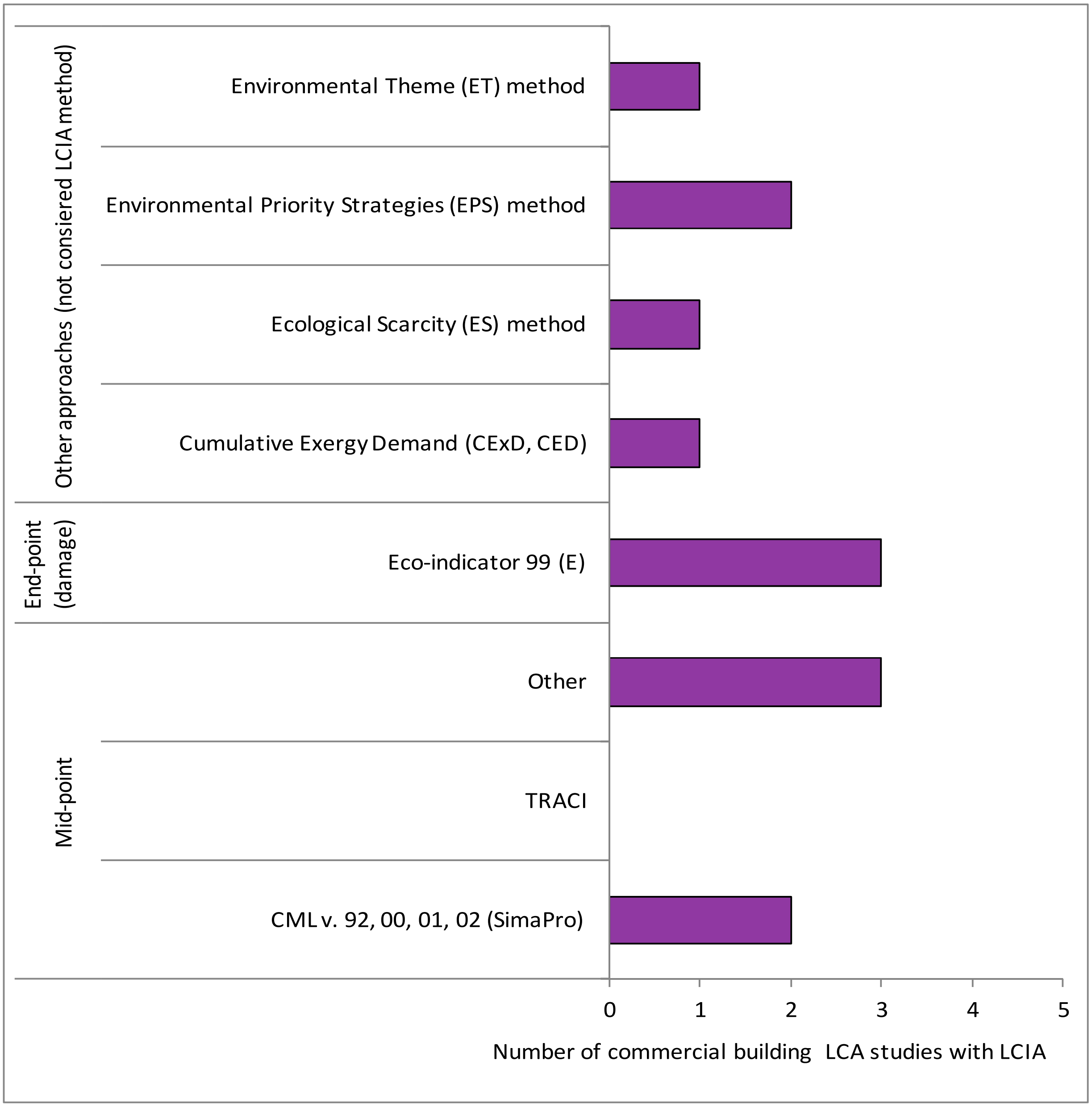

Figure 2.9: LCIA methodology or software applied in commercial building LCA studies

Throughout the literature, the following impact assessment categories were represented in the literature: land use, eco-toxicity, human toxicity, photo-oxidant formation, eutrophication, acidification, ozone depletion, depletion of raw materials including fossil fuels, and global warming potential (GWP). GWP was clearly the most commonly assessed impact, likely due to the accessible data on embodied energy and carbon of construction materials, and the recent status of global climate change. GWP, therefore, becomes an easily calculated and understandable metric over which material alternatives may be compared. As seen in Figure 2.10, 12 out of 33 LCAs included GWP from commercial building frames. In calculating GWP, diverse number of techniques was applied, such as: IPCC guidelines, SETAC/ISO guidelines, EIO-LCA model, in addition to CML (SimaPro). Acidification (6 studies), eutrophication (5 studies), and POCP (5 studies) were somewhat estimated by application of either CML database or ISO guidelines. The minimal emphasis on ozone layer depletion, eco-toxicity, human toxicity, and abiotic depletion points to the lack of data and inventorying of polluted runoff. One important problem with human toxicity and eco-toxicity categories is the lack of exposure data – from one study to another human exposure to pollutants vary considerable depending on the proximity, concentration of pollutant, existence of other sources of pollutant as well as regional differences in climate, geography, population density and so on. It would be good to report results in ranges of possible values. Additionally, due to lack of information about chemical composition of some common air pollutants throughout the life of the building, it is almost impossible to categorize these pollutants provided in the inventory in terms of their toxicity, carcinogenicity, and bioaccumulation and so on. Above all, impacts from heavy metals and other toxic emissions are mostly omitted in building material (especially for concrete) LCIAs since their quantities are deemed insignificant however it's their severity that could be of significant in terms of damage to human and environment.

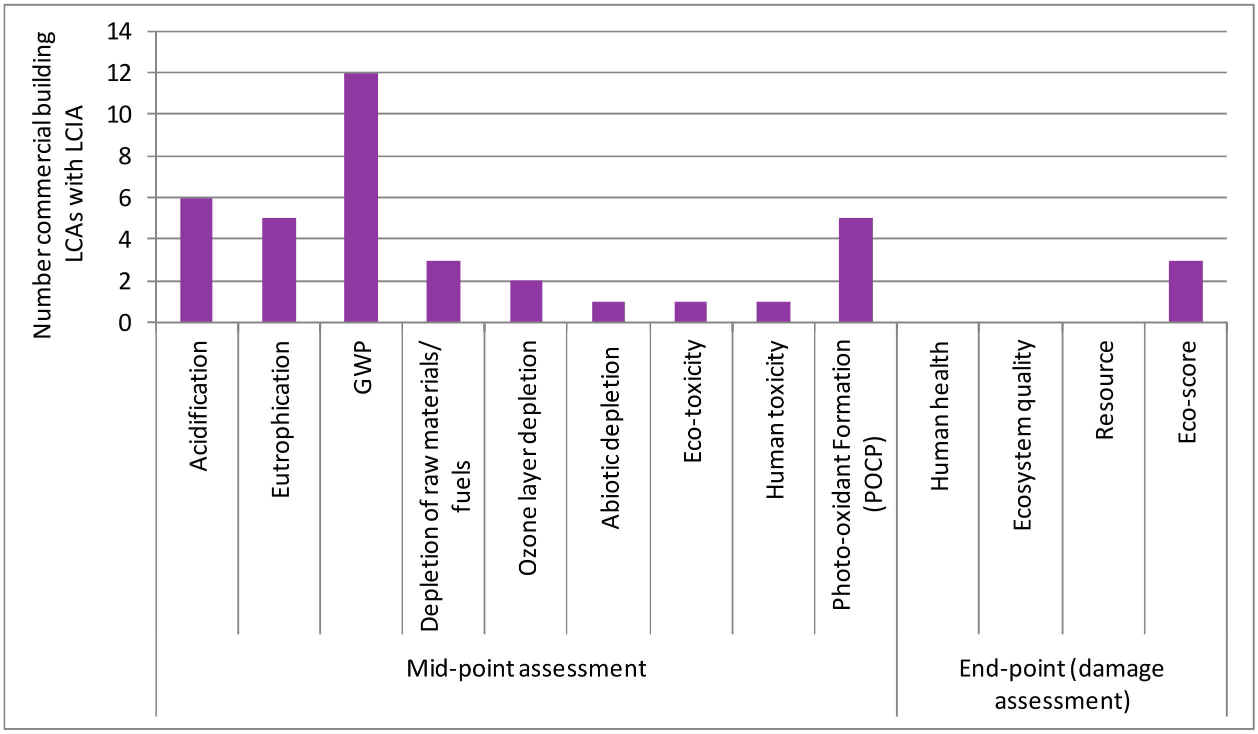

Figure 2.10: LCIA impact categories included in commercial building LCA studies

All things considered, the synthesis of concrete raw materials, concrete manufacturing, and concrete commercial buildings LCA literature shows that as the system, such as buildings, gets more complex, it is more difficult to obtain consistent results within a specific system boundary. It is also difficult to present LCA results of a complex structure as they have many components within or outside the boundary. Drawing the system boundary - what processes to include and what to exclude- can underestimate the LCA outcomes in traditional approaches which can omit the supply-chain impacts that can have considerable environmental impacts over the life cycle of commercial buildings. Moreover, the interpretation of the LCA results is usually incomparable because of the ambiguity/inconsistency in determination of LCIA factors and aggregation of environmental impact data in a single score without a quantitative approach. For example, some studies applied different evaluation methods such as EPS, Environmental Theme, and

EcoScarcity and combined various environmental impacts into one value whereas weighting factors were subjectively determined. Therefore, transparent, detailed inventories and impact characterization based on such inventory and quantitative assessments would lead to more meaningful results. Factors such as choice of materials/components, energy use and other critical inputs as well as emissions to air/water/land and wastes from different life cycle stages should be considered for complete life-cycle assessment of commercial buildings.

Table 2.72: LCIA categories included in concrete commercial building LCAs

LCIA Sources:	[98]	[99]	[100]	[101]	[102]	[103]	[104]	[105]	[106]	[109]	[110]	[72]	[111]	[112]	[113]	[114]	[115]
a) Methodology/software applied: Midpoint approach (also known as pressure oriented approach)																	
CML v. 92, 00, 01, 02 (SimaPro)	-	-	-	-	-	-	√	-	-	-	?	-	-	-	-	-	√
TRACI	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Other	-	-	-	-	-	-	-	-	-	-	-	-	ISO	-	-	-	-
Acidification							*						*				*
Eutrophication							*										*
GWP (see IPCC climate change row if based on IPCC guidelines)[1]							*	*					*		*		*
Depletion of raw materials / fossil fuels							*				*						
Ozone layer depletion							*										
Abiotic depletion																	
Eco-toxicity																	
Human toxicity																	
Photo-oxidant Formation (POCP)							*						*	*			*
b) Methodology/software applied: Endpoint approach (also known as damage assessment)																	
Ecoindicator 99 (E)	-	-	√	-	-		-	-	-	-	√	√	-	-	-	-	-
Human health																	
Ecosystem quality																	
Resource																	

LCIA Sources:	[98]	[99]	[100]	[101]	[102]	[103]	[104]	[105]	[106]	[109]	[110]	[72]	[111]	[112]	[113]	[114]	[115]
Eco-score			*								*	*					
c) Other approaches (not considered as LCIA method)																	
Cumulative Exergy Demand (CExD, CED)												√					
[1]IPCC Climate change (IPCC-GWP)								√					√				
Ecological Footprint (EF) method																	
Ecological Scarcity (ES) method																	
Environmental Priority Strategies (EPS) method											√						
Environmental Theme (ET) method																	
EIO-LCA																	

Table 2.73: LCIA categories included in LCA literature (continue)

LCIA Sources:	[116]	[117]	[4]	[120]	[3]	[128]	[121]	[129]	[122]	[119]	[131]	[1]	[133]	[118]	[134]	[144]	[136]
CML v. 92, 00, 01, 02 (in SimaPro)		-	-	-	*	-	-	-	-	-	-	-	-	-	-	-	-
TRACI		-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Other		-	-	-	-	ISO	-	-	-	-	ISO	KCL ECO	-	-	-	-	-

LCIA Sources:	[116]	[117]	[4]	[120]	[3]	[128]	[121]	[129]	[122]	[119]	[131]	[1]	[133]	[118]	[134]	[144]	[136]
Acidification						*					*	*					
Eutrophication						*					*	*					
GWP (see IPCC climate change row if based on IPCC guidelines)[1]			*	*		*				*	*	*		*			
Depletion of raw materials / fossil fuels						*											
Ozone layer depletion											*						
Abiotic depletion						*											
Eco-toxicity						*											
Human toxicity						*											
Photo-oxidant Formation (POCP)						*											
Ecoindicator 99 (E)		-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Human health																	
Ecosystem quality																	
Resource																	
Eco-score																	
Cumulative Exergy Demand (CExD, CED)																	
[1]IPCC Climate change (IPCC-GWP)																	
Ecological Footprint (EF) method																	

LCIA Sources:	[116]	[117]	[4]	[120]	[3]	[128]	[121]	[129]	[122]	[119]	[131]	[1]	[133]	[118]	[134]	[144]	[136]
Ecological Scarcity (ES) method																*	
Environmental Priority Strategies (EPS) method																*	
Environmental Theme (ET) method																*	
EIO-LCA			*	*	*					*				*			

? : The approach was not specified or not clear

2.5 Summary and Conclusions for Building LCAs

The synthesis of literature concludes that variances in the definition of goal and scope, LCI, and LCI of building materials and buildings may induce important differences in the LCA results. Cement manufacturing LCA literature reveals that studies still lack data reflecting variations in technological and regional nuances; mostly limited to the energy use and GHGs emissions despite it is the most commonly studied material. Impacts from toxic emissions, water effluents, solid waste (e.g. cement kiln dust), and water consumption are generally overlooked either because of the expertise, time, and data constraints or these effects are assumed insignificant (without a thorough analysis). These limitations preclude robust environmental analysis of cement production across the full range of energy and emissions issues that should be considered.

Regarding concrete manufacturing, environmental impacts from the production of concrete materials other than portland cement; such as, admixtures, and water consumption are rarely analyzed in concrete LCAs. Functional unit choice in concrete LCAs is seen as one of the most influencing factors in interpretation of LCA results. This unit, preferably (but very rarely in literature) includes all relevant concrete aspects, such as strength, durability, unit weight, etc. To take into both strength and durability account, it should involve the concrete amount needed to manufacture a structural element or even a whole building with a predefined service life (to determine the life-span of concrete for future end-of-life scenarios) and design load. As developed into “GreenConcrete LCA” tool, the concrete mix must be defined on the basis of its cement content and strength according to the applicable standards so that different concrete types can be compared for “green” concrete design requirements. Besides concrete material aspects, LCA system boundary (cradle-to-gate, gate-to-gate, and cradle-to-grave) selection is also important. Especially for durability properties and carbon uptake by concrete surface issues, building use, maintenance, and EOL phases are preferably considered within the system boundary. With respect to concrete LCI coverage, there is still need for further investigation of toxic emissions in addition to GHG emissions and criteria air pollutions within an LCA context. Similar to cement production LCIs, concrete production LCIs also lack data reflecting variations in technological and regional nuances. There is a clear need for current regionally specific data when compiling life cycle inventories. In all phases, especially manufacturing and processing, technology resolution should be represented in the data to assure more exact inventories. Lastly, for both cement and concrete manufacturing, the choice of the impact assessment method should be carefully considered. The method used must cover more than only the impact on climate change and should be damage-oriented (end-point analysis).

Finally, in commercial building LCAs, there is significant inconsistency in the assumption of building life-span (ranging between 25 to 100 years) and system boundary coverage. The life-span assumption critically influences the relative impact of embodied energy versus operational energy. The criterion also affects the maintenance and replacement considerations with respect to building material life-span considerations. Therefore, in addition to the comparably well-studied operation phase, the system boundary should be inclusive of maintenance and repair phases. Also, more research is necessary to compare end-of-life scenarios after the demolition of the buildings. As part of the future research, integration of LCA tools with CAD tools, BIM programs or cost estimating programs is advisable for accurate and timely assessment of building projects, given their one-of-a kind and complex nature.

3 Research Methodology

In recent years, climate change and other environmental hazards have become the focus of many research areas and parties. To understand the reasons behind those threats and take precautions to reduce their impacts require information on environmental aspects of different systems. Consequently, many tools and indicators have recently been developed for assessing environmental impacts. Among these tools, Life-Cycle Assessment (LCA) has the unique feature of analyzing the environmental impacts of products (goods and services) in a life-cycle perspective. It is a comprehensive approach that considers all attributes and aspects of environmental impacts and resources used throughout the product's life-cycle, i.e., from raw material acquisition, via production and use phase, to end of life [12]. Therefore, LCA is particularly crucial for a methodical analysis and quantification of the overall environmental impacts of concrete production given the high volumes of concrete use, the growing importance of environmentally sustainable infrastructure decisions, and the fact that once concrete is put in a structure, its impacts are locked in for many years.

The following sections describe the LCA methodology, types, and guidelines applied in concrete and building LCAs.

3.1 Background

3.1.1 Environmental and Technical Data Collection

One of the major tasks prior to life-cycle assessment is the collection, organization and reporting of information and data pertaining to production processes and associated environmental inputs and outputs to/from these processes. The International Organization for Standardization (ISO)'s 14044 series of standards [13] suggest data to be collected from specific sites or from published sources.

Major data sources include journal papers that follow systematic LCA guidelines, such as the ISO 14040 framework, for the purpose of enabling credible comparisons between studies, and publicly available building material LCA tools (e.g., BEES, ATHENA^{TM}) and databases from government and private organizations.

3.1.2 Application of LCA Approach to Concrete Production

3.1.3 Process-Based LCA

Process-based LCA (also known as the SETAC-EPA approach) was initially developed by the Society of Environmental Toxicology and Chemistry (SETAC) and is supported by SETAC and the U.S. Environmental Protection Agency [161]. This type of LCA typically requires a detailed inventory of resource inputs and environmental outputs for the analysis period and processes considered [162]. An example of the process model-based approach that has been used in a number of industrial applications is the Life-Cycle Engineering model developed by the Institute for Polymer Science and Polymer Testing (IKP) of the University of Stuttgart (Germany), which is implemented in the software system called GaBi (2009) [163]. Most of the cement and concrete production LCAs [6, 18, 36, 58] are process-based models that identify and quantify resource inputs and environmental outputs at each life-cycle stage based on mass-balance calculations [31, 162, 164].

The International Organization for Standardization (ISO)'s 14040 - 14044 [12, 13] standards define four phases in an LCA study: Goal and Scope Definition, Life-Cycle Inventory Analysis (LCI), Life-Cycle Impact Assessment (LCIA), and Interpretation.

3.1.3.1 Goal and Scope Definition

This first step is the description of the product system in terms of the goal and scope of the LCA study. The goal includes the intended applications, reasons for carrying out the study, and the target audience [13]. Concrete LCA tool was developed with a goal to understand and lower the environmental impacts of concrete as well as to accurately compare the overall environmental impacts of traditional concrete to concrete mixes produced with unconventional materials, e.g. concrete with blast furnace slag. There is a diverse audience of decision makers and manufacturers who are interested in understanding and lowering the environmental impact of concrete and buildings built with concrete. These decision makers include policy makers and urban planners, developers of green building standards (e.g., LEED rating system), and construction/engineering companies. Another audience is the manufactures who are interested in lowering their concrete production footprint and also the footprints of the raw materials they procure while they stay competitive markets as the demand for greener products increase. The LCA approach is mainly important for this audience in understanding the full range of impacts of concrete and its ingredients in a cradle-to-gate life-cycle setting.

The scope of the LCA is the step where the functional unit is defined and system boundaries are described. LCA has a comparative nature and functional unit is the basis that enables the equivalent comparison of concrete to its alternatives [15], i.e., one cubic meter of ready-mixed concrete with a given water/cementitious material ratio, strength, and durability conditions, whereas it is a square meter of a commercial building (dormitory building in the case study) in the case of a cradle-to-grave LCA of reinforced concrete commercial building. Figure 3.1 demonstrates the major process flows occurring over the life-cycle of a concrete building. Although not shown in the figure, each of the processes requires inputs of raw materials, energy, and water and associated supply-chain impacts of these inputs.

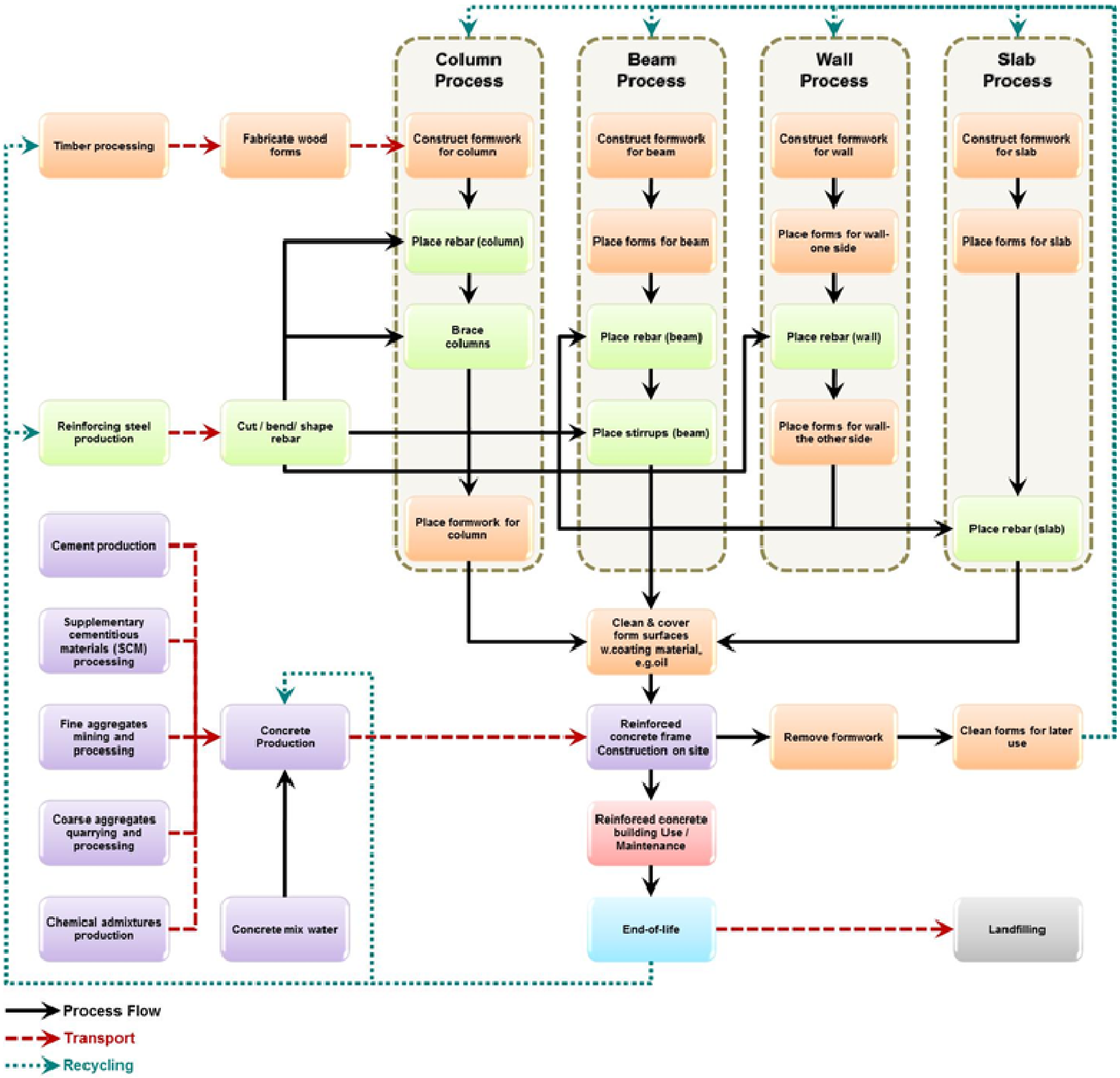

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Figure 3.1: Cradle-to-grave reinforced concrete process-based LCA representation [122, 165, 166]

In defining system boundaries, it is important to include every major step that could affect the overall analysis. Only in certain well-defined instances can life-cycle phases (such as raw materials quarrying) be excluded [161]. Since the focus of the tool for this dissertation is concrete and its raw materials, the quarrying impacts of each raw material are also quantified.

Additionally, the goal/scope definition step describes the allocation procedures (consideration of economic allocation when by-products such as fly ash, slag are used in concrete), impact categories and the impact model (e.g., impact categories defined by TRACI), data assumptions and limitations, data quality requirements, peer review, and type of reporting. Since data quality has a major influence on the results, it is essential. ISO Guidelines [167, 168] provide a checklist for data quality validation.

In relation to the Goal and Scope Definition, Section 3.2.1 further discusses the distinction between attributional and consequential LCA approach as this distinction is pertinent when defining the system boundaries, especially when the LCA includes multi-functional processes that requires allocation.

In recent years, allocation and the distinction between attributional and consequential LCAs are among the mostly discussed methodological issues in LCA world [15, 160]. Chapter 3.2 briefly describes and discusses these emerging issues and develops a framework to handle allocation problems taking place in multi-functional processes over the life-cycle of concrete.

3.1.3.2 Life-Cycle Inventory Analysis (LCI)

Life-cycle inventory analysis (LCI) involves collecting and describing the quantities of resources (in the form of materials, energy) required as well as the generation of waste flows and emissions associated with a product's life cycle. The result of an LCI analysis is an inventory of environmental exchanges related to the functional unit within a defined product system. Consumption of resources and generation of waste/emissions can occur at multiple locations; as different fractions of total emissions at any one site (allocation amongst related and non-related co-products, etc.); at different times of product/service life (construction phase vs. use phase); and over different periods of time (e.g., carbonation impacts from crushed and landfilled concrete after 20 years) [15].

In the case of concrete production LCA, major inputs are constituents of concrete in the form of raw materials (limestone, sand, and gravel, natural pozzolan), products (cement, admixtures), by-products (fly ash, granulated blast furnace slag), water, and energy use as fuel and electricity. Outputs are emissions to air, water, and land. In most of the cases, LCI data are taken from publicly available data sources (e.g., NREL LCI database) rather than being collected from the field. As a consequence, most concrete and cement production LCIs [18, 58, 73] are based on average national data with little or no consideration of regional and technological variations in the production. It is essential to assess the LCI data quality and the associated uncertainty and variability. To validate the reliability of data, it is common practice to conduct sensitivity analysis.

3.1.3.3 Life-Cycle Impact Assessment (LCIA)

The characterization of life-cycle inventory data into impact categories such as human toxicity, eutrophication, or acidification would create meaningful results in comparing and understanding the environmental impacts of concrete, cement, and other materials regardless of the life-cycle inventory which provides useful insight about these materials.

Most of the cement and concrete LCAs either keep out LCIA stage or limit the analysis to Global Warming Potential impact because there is consensus on acceptable characterization factors of GWP. However, for other impact categories, such as resource depletion, human toxicity, a consensus is still being developed as the analysis of these impacts requires extensive research and time. For example, human health cancer and non-cancer impact assessment requires determining the relationship between emissions and exposure to these emissions, intake fraction (is the fraction of a pollutant emitted that is actually inhaled), and other factors such as age, gender, the frequency/intensity of exposure as each of this information [94].

The ISO 14044 lists impact category selection, classification, and characterization as three mandatory steps for an LCIA [13] while other steps are optional depending on the goal and scope of the study. The reference [161] lists both the mandatory and optional LCIA steps in the "LCA Principles" document.

1. *Selection and Definition of Impact Categories:* identifying relevant environmental impact categories (e.g., global warming, acidification, terrestrial toxicity).
2. *Classification:* assigning LCI results to the impact categories (e.g. classifying carbon dioxide emissions to global warming).
3. *Characterization:* modeling LCI impacts within impact categories using science-based conversion factors (e.g., modeling the potential impact of carbon dioxide and methane on global warming).
4. *Normalization:* expressing potential impacts in ways that can be compared (e.g. comparing the global warming impact of carbon dioxide and methane for the two options).
5. *Grouping:* sorting or ranking the indicators (e.g. sorting the indicators by location: local, regional, and global).
6. *Weighting:* emphasizing the most important potential impacts.
7. *Evaluating and Reporting LCIA Results:* gaining a better understanding of the reliability of the LCIA results.

There are two internationally-recognized operational approaches to LCIA: "problem-oriented" approach (e.g. CML 1992, 2002) [159] and "damage-oriented" (e.g. EcoIndicator99) [96]. They adopt different impact categories, characterization models (factors) and indicators:

1. Problem-oriented (also known as mid-point) approach, first presented by Heijungs et al. [169], is a commonly used and widely accepted method [17]. This approach is based on traditional LCIA characterization and normalization methods as indicators are located between the inventory interventions and endpoint effects and damages. The problem-oriented method provides more reliable results as there are less assumptions and modeling complexity compared with the damage-oriented (end-point) approach. However, the interpretation of the results is more difficult since they do not directly refer to the damages produced due to lack of weighting factors covering all impact categories [17, 159, 170]. For example, all greenhouse gases can be expressed in terms of CO_2 equivalents by multiplying the relevant LCI results by a CO_2 characterization factor and then combining the resulting impact indicators to provide an overall indicator of global warming potential. The characterization step can put different quantities of chemicals (e.g. methane, CFCs, etc.) on an equal scale to determine the amount of impact each one has on e.g., global warming. This approach does not consider the actual effects of damage. The GreenConcrete LCA tool utilizes TRACI, short for "Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts" as the LCIA methodology. It is mid-point oriented which draws simple cause-effect chains to show the point at which each impact category is characterized [94].

2. Damage-oriented (also known as end-point) approach focuses on the actual effect of interventions from the inventory. With respect to climate change, the damage on human health is quantified in terms of disability adjusted life years (DALYs). This unit counts as a measure for the Years Lived Disabled (YLD) and the Years of Life Lost (YLL) due to this damage.

Figure 3.2 shows the framework developed by the UNEP-SETAC life-cycle initiative [97] with a list of suggested mid-point impact categories and their relationship to damage impact categories. Note that "waste" is not to be considered an impact category, but another process of the system that will lead to a certain amount of LCI results.

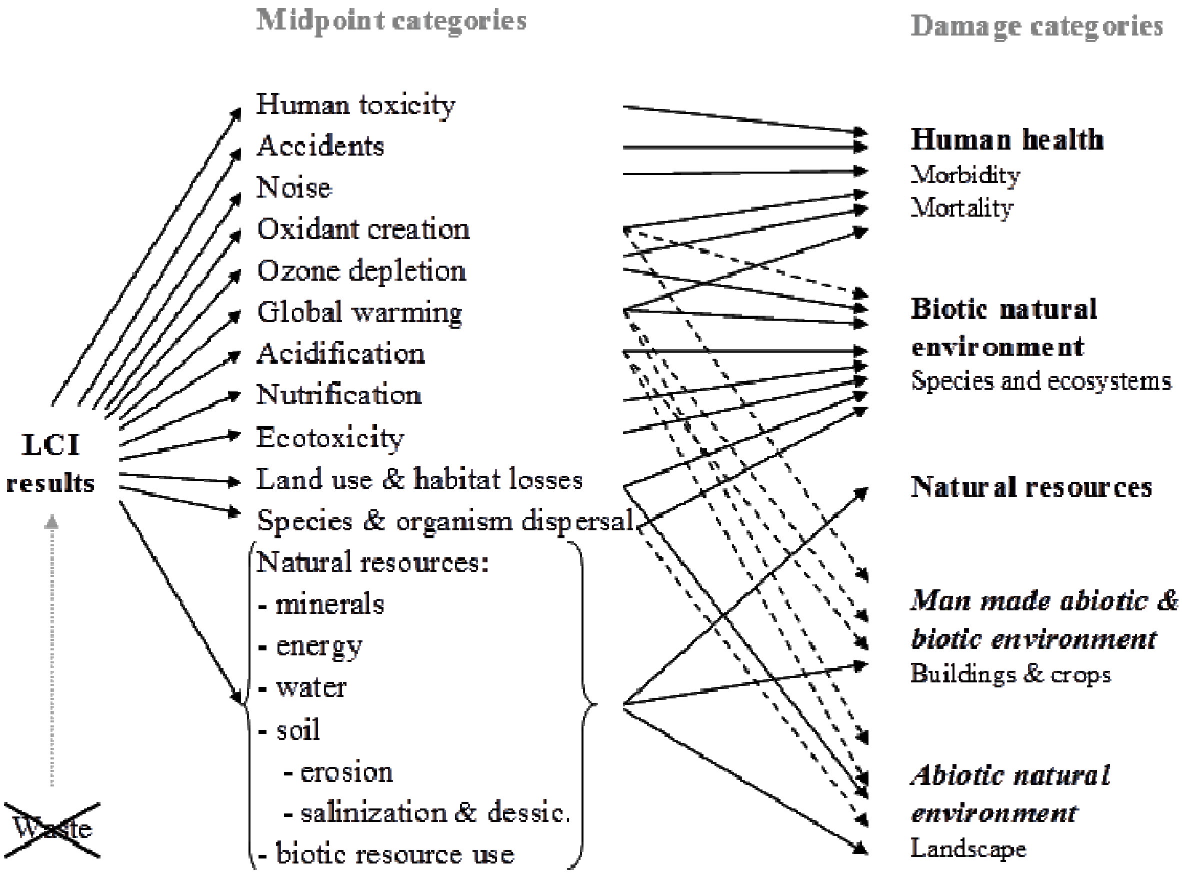


Figure 3.2: Overall framework linking LCI results via the midpoint impact categories to damage impact categories [97]

3.1.3.4 Life-Cycle Interpretation

Interpretation occurs at every stage of LCA and consists of analyzing results from LCI and LCIA stages, drawing conclusions from these results, identifying limitations and significant issues in the analysis, evaluating these issues, and finally providing recommendations for improving the analysis [13, 15, 161] After significant issues in the study are identified, they can be evaluated by completeness, sensitivity, and consistency checks.

Completeness check ensures that all relevant information and data needed for the interpretation are available and complete. A checklist can be developed to indicate each significant area represented in the results. For example, cement kiln fuel mix data is a significant issue in quantifying the energy use and associated emissions from cement production. It is essential that major kiln fuel combustion and pre-combustion related data are complete and reflective of the cement kiln use conditions. In some cases data may not be currently available (e.g. combustion data for most of the waste fuels used in the cement kilns are lacking) but it is still important to report these deficiencies for fair comparison of results from different LCA studies.

Sensitivity check evaluates the robustness of the results by determining whether the uncertainty in the significant issues identified in the completeness check affect the decision-makers' ability to confidently draw comparative conclusions. As part of the LCI and LCIA phases, a sensitivity, uncertainty, and/or contribution analysis may have been conducted. These results can be used as the sensitivity check. For example, one can measure the extent that changes in the mix of kiln fuel data affect the energy use results of the cement production life-cycle assessment. Moreover, the sensitivity check is used to verify if LCA goals (defined in the first stage) have been met.

Finally, a consistency check can be performed to understand whether the assumptions, methods, and data used throughout the LCA process are consistent with the goal and scope of the study, and for each product/process evaluated. A checklist with some common types of information categories can be useful in determining inconsistencies throughout the analysis. These categories include:

1. Data source (from literature or measured on the field),
2. Data accuracy (availability of detailed process flows or limited process information when developing the LCI),
3. Data age (e.g. older cement production data not reflecting the current practice),
4. Technological representation (consideration of full cement production processes vs. only clinker pyroprocessing process),
5. Temporal representation (e.g. inclusion of a recently developed cement grinding practice in addition to older technologies used in the plant),
6. Geographical presentation (consideration of electricity grid mix by State),
7. System boundaries, assumptions, and models (use of 500-year GWP model vs. 100-year GWP).

At the end of the analysis, it is important to provide conclusions and recommendations, as well as uncertainties and limitations of the LCA study. This informs and cautions decision-makers about the use of LCA results by helping them understand the gaps and well-established areas of the study and the relative magnitude of each type of impact in comparison to alternatives proposed in the study.

3.1.3.5 Pros and Cons of Process-Based LCA Approach

Process-based LCA has the advantage to examine the desired inputs and outputs for a particular product and process in great detail. This method can especially be useful for process improvements and weak point analysis. On the other hand, attention to detail is considered as the major weakness of this approach although it is also considered as its major advantage. Hendrickson et al. and Curran [162, 164] have criticized the process LCA model for being relatively tedious, expensive and slow to generate results, especially when trying to include all the upstream components, working through the hierarchy of process models in the supply chain. Since this approach generally uses proprietary data, it is sometimes hard to compare results because of ambiguity in assumptions and boundary conditions used in the assessment.

In the process-based LCA, for practical reasons, the boundary around the problem is often drawn tightly, excluding potentially important life-cycle components, both upstream and downstream. Thus, an LCI compiled using process flow diagram exhibits inherent system incompleteness. As a consequence of the omission of processes outside a tight system boundary, a particular systematic truncation error is inevitable in most traditional process-based LCAs. Depending on data availability and/or significance, the magnitude of error can be above 50 percent and it apparently decreases with the increasing order of production stages considered in the process analysis [15, 171].

3.1.4 Economic Input-Output Analysis-based LCA

Input-output (I-O) analysis is a top-down economic approach that "uses sectoral monetary transactions data to account for the complex interdependencies of industries in modern economies" [15, 171]. The I-O model of the United States economy was first developed by Wassily Leontief in the 1930s. By assembling all the sectors of the economy, it is possible to trace all the direct and indirect inputs to produce outputs in each sector of the economy [162]. The United States Department of Commerce has been publishing I-O tables for the U.S. economy since 1947, and has updated these tables once every five years based on the Economic Census conducted by the Census Bureau. The most recent publication is based on the 2002 data (released in 2007) and breaks the economy into 426 industries and 428 commodities [172].

3.1.4.1 Pros and Cons of Economic Input-Output Analysis-Based LCA

The major advantage of this model is its ability to include all the direct and indirect environmental effects of suppliers without a need for the definition of a system boundary for the upstream processes as in the case of process-based LCA [162]. However, this approach has some intrinsic limitations. The EIO-LCA model can only provide averages, without the consideration of differences between marginal and average impacts. Consequently, major sources of limitations and uncertainties in the EIO-LCA model are described as [171]:

- Data source uncertainty – resulting from unreliable data sampling, collection, and reporting;
- Aggregation uncertainty – grouping different producers (by technology, geography, and production scale) within one industry;
- Imports assumption uncertainty – assuming same factor multipliers for domestic and imported goods;
- Allocation uncertainty – resulting from aggregation of input-output data over different products supplied by one industry and ignoring product diversity;
- Gate-to-grave truncation error – resulting from considering only the cradle-to-gate period but omitting the use, maintenance, disposal, or recycling components of the full life-cycle.

Therefore, process-based and economic I-O based models have their own advantages and drawbacks. Each could provide quite different results and the analyst would need to examine the reasons for these differences to come up with the best model choice (including the combination of two). Strengths and weaknesses of the two LCA models are listed in Table 3.1.

Table 3.1: Advantages and Disadvantages of Two Life-Cycle Assessment Approaches [162]

	Process models	**EIO-LCA**
Advantages	Detailed process-specific analyses	Economy-wide, comprehensive assessments (all direct and indirect environmental effects included)
	Specific product comparisons	System LCA: industries, products, services, national economy
	Process improvements, weak point analyses	Sensitivity analyses, scenario planning
	Future product development assessments	Publicly available data, reproducible results
		Future product development assessments
		Information on every commodity in economy
Disadvantages	System boundary setting subjective	Aggregated data
	Time intensive and costly	Process assessments difficult
	New process design difficult	Difficulty in linking dollar values to physical units
	Use of proprietary data	Economic and environmental data may reflect past practices (I-O tables are released every five years and data used can even be older than five years)
	Cannot be replicated if confidential data are used	Imports treated as U.S. average products
		Difficult to apply to an open economy (with substantial non-comparable imports)
		Non-U.S. data availability a problem

3.1.5 Hybrid LCA

As stated in Hendrickson et al. [162], process-based LCA and EIO-LCA have comparative advantages and disadvantages. A hybrid model eliminates the disadvantages of each approach, while combining the strengths of both. The development of a hybrid model depends on which existing LCA model's structure is adopted. In one option, process-level data are substituted for EIO-LCA's missing data while keeping the EIO-LCA's structure, or in another type, EIO-LCA data are used to expand the coverage of environmental impacts of process model-based LCAs. Hybrid LCA models show variations depending on the proportions of input-output and process LCA data used. Bilec et al. [3] present a review of existing hybrid models and have used this approach to assess construction processes. Tiered hybrid analysis [124] consists mainly of I-O data. References [15, 125, 126] studied the tiered approach. I-O-based hybrid analysis by Joshi (2000) [127], integrated hybrid analysis [15] and augmented process-based are other approaches that combine process and I-O methods.

The tiered and I-O-based approaches are similar as the I-O data dominate in both models. Integrated hybrid analysis may be comprehensive but it is time and data intensive. The augmented process-based approach relies heavily on process data, and I-O data is used for unit processes that cannot be modeled with process data efficiently [3]. Figure 12 illustrates the application of an augmented hybrid LCA to ready mixed concrete production.

It is important to note that most of the cement and concrete production LCAs [6, 18, 36, 58] are process-based models that identify and quantify resource inputs and environmental outputs at each life-cycle stage based on mass-balance calculations [31, 162, 164].

3.2 Impact Allocation

In the LCA literature, allocation is one of the mostly discussed methodological problems but still not resolved completely. Impact allocation over the life-cycle of concrete is inevitable. Concrete production (as well as all other industrial production) processes have multiple input streams and most of the processes generate multiple output streams in the form of products, co-products or by-products (that are mostly treated as waste despite their economical and material values, as in the case of fly ash from coal combustion) or these processes recycle intermediate or discarded products (cement kiln dust, crushed concrete) as raw materials into other production systems. When dealing with systems involving multiple products and recycling systems, one needs to elaborate on the allocation procedures. When this is the case, the inputs and outputs of the system should be partitioned between its different products or functions in a way that reflects the underlying causal relationships between them, e.g. allocation by energy content, mass or by economic value. However, in most of the LCA studies, allocation of inputs (energy, water, raw materials) and associated emissions from these processes to multiple output streams is either done arbitrarily (e.g. on an equal basis (50/50) or on an “all or none” basis (100 % to one product) or without being justified by any “causal” relationship.

The following sections describe the impact allocation in a detailed way, starting with the explanation of attributional LCA (ALCA) versus consequential LCA (CLCA) since the distinction between these two approaches has a significant effect on the selection of allocation procedure applied within the system. Subsequently, applications of impact allocation in concrete manufacturing are described based on the literature findings.

3.2.1 Consequential (Change-oriented) vs. Attributional (Descriptive) LCA

The term “attributional life cycle assessment” was defined as an attempt to answer “how are things (i.e. pollutants, resources, and exchanges among processes) flowing within the chosen temporal window?” while “consequential life cycle assessment” attempts to answer “how will flows beyond the immediate system change in response to decisions?” [173]. Within the LCA research field, it has recently been recognized that choices concerning data and methodology may depend on the intended goal of the study based on whether it is used for attributional (also known as descriptive, accounting studies, or retrospective) and consequential (also known as change-orientated, effect-orientated, or prospective) purposes.

Attributional (ALCA) approach describes a product system and the system-wide flows and environmental impacts “associated with” or “attributed to” the delivery of a specific amount of functional unit of a product. Here the system is linearly modeled. Therefore, all results will scale linearly with the functional unit. [15, 160]. On the other hand, the consequential approach (CLCA) studies the consequences of a choice [174, 175]. This type of LCA exists to describe “how the environmental exchanges of the system could be expected to change as results of actions taken in the system”. As opposed to ALCA, the consequences in CLCAs do not scale linearly with the magnitude of the change [15].

The distinction between ALCA and CLCA may have repercussions for other parts of the LCA methodology, including impact assessment methodology. Although in most cases consequential studies are generally of the largest interest, in practice many LCAs have been performed using data and methodology appropriate for attributional studies.

There have been different points of view on when different types of LCA would be appropriate for decision-making and understanding the product systems. Several authors [176-178] argue that CLCAs should be used for decision-making with the exception that the difference between two approaches is small and when the uncertainties in the consequential approach outweigh the insights gained from it. Additionally, reference [176] asserts that the consequential approach is more relevant in understanding the product chain and for identifying the processes and relations that need improvement. On the other hand, both approaches are legitimate for both the purposes of decision-making and gaining information [179].

Both the ALCA and CLCA approaches can be applied for modeling future systems, as well as past or current ones [179, 180]. Vieira and Horvath [113] used the same product showing the applicability of both approaches in modeling the systems.

As mentioned before, the distinction between ALCA and CLCAs has consequences for the methodological choices made in LCA, including choice of data, system boundaries, temporal effects, and so on. Data choice can be average or marginal data based on the choice of LCA approach. For example, authors [113] demonstrate the effects of the distinction between ALCA and CLCA approaches in the selection of data, as well as allocation procedures within a building LCA (focus being the end-of-life stage) context. Accordingly, average data (representing the average environmental burdens for producing a unit of a product) is associated with ALCA and the attributional approach excludes the use of marginal data. Allocation is done based on either physical flows (e.g., mass) or economic value. In an electricity generation LCA example, attributional LCA results describe the environmental interventions of the average electricity production in a certain geographic area (e.g., national-wide, county-wide, limited to one public utility, etc.) [15]. On the other hand, in CLCA, marginal data are used for the purpose of understanding the consequences of decisions on processes/technologies selected. For example, technologies affected by an incremental increase or reduction on electricity production can change emission results. Such technologies are known as marginal technologies. A large change can have substantial consequences for the structure of the whole electricity generation system [15, 181]. In CLCA, allocation is preferably avoided by expanding the boundaries of the analysis as demonstrated in Figure 3.3.

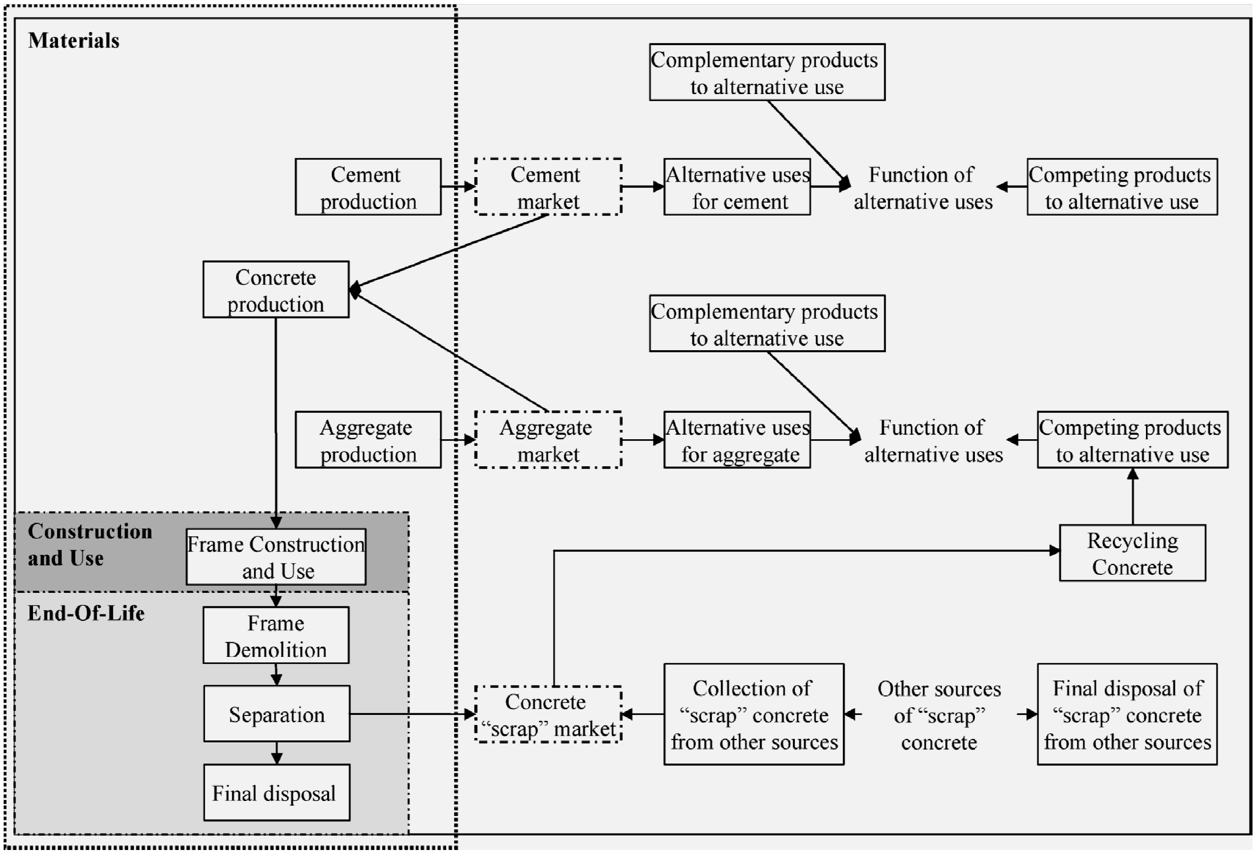


Figure 3.3 Representation of ALCA and CLCA approaches in a building LCA study. ALCA (dotted boundary) and CLCA (solid boundary) models of concrete used in a building frame. Markets are identified by dash-dot lines [113]

When identifying which processes to include in the product system, it is important to note the difference between ALCA and CLCA approaches. In ALCA, both the upstream supply (of raw materials to a product) and the downstream demand (to the final disposal of waste) are assumed to be fully elastic. In case of supply, this means that the induced demand for one unit of product leads to the production and supply of one unit of product, with associated emissions and resource use. Other customers/applications of the product of same functional unit are assumed to be unaffected. In the case of downstream demand, the induced supply for one unit of product leads to the consumption of one unit of product whereas other producers of the same product are assumed not to be affected [15].

In the CLCA, the system boundaries are defined on the basis of the market's reaction to the studied change, and references [176, 182] suggest considering the following factors:

- *Neither production nor demand are always fully elastic, which means that the demand for one unit of product in the life cycle investigated affects not only the production of this product but also the consumption of the product in other systems.*

- *Individual suppliers or markets may be constrained, which means that they are unaffected by an increase in demand for the product.*

- *A change in demand for a product is so small, compared to the total market for that product, that it only affects the marginal upstream production processes.*

Results from Vieira's and Horvath's [113] building end-of-life analysis demonstrate an insignificant difference between the results of two LCA approaches and concludes that the choice between the use of ALCA or CLCA for buildings may not be a critical decision. For the purpose of this dissertation, the concrete production system is analyzed using an attributional LCA approach as the focus is the development of a comprehensive concrete LCA tool. With the available database, a CLCA approach can be complicated for modeling concrete life-cycle impacts as the system involves use of many different materials, products, energy sources, production technologies, equipment, and so on. Moreover, when placed in the building, impacts from concrete have been locked in for many years (even centuries). A number of CLCAs focusing on short and long-term marginal effects state that the uncertainty associated with marginal effects can grow with the time horizon, exceeding the uncertainty associated with the marginal effect itself [160, 183].

3.2.2 Impact Allocation in Multi-Function Production Systems

Since ISO guidelines are commonly applied in many LCA studies worldwide, it would be the first source [13] to refer once in this section. Based on the guidelines, as an initial step in allocation, processes shared with other product systems are identified. Following the identification of such processes, the quoted steps are taken (as in the ISO document):

> *" a) Step 1: Wherever possible, allocation should be avoided by:*
>
> > *1) Dividing the unit process to be allocated into two or more sub-processes and collecting the input and output data related to these sub-processes, or*
> >
> > *2) Expanding the product system to include the additional functions related to the co-products, taking into account the requirements of reuse and recycling situations.*
>
> *b) Step 2: Where allocation cannot be avoided, the inputs and outputs of the system should be partitioned between its different products or functions in a way that reflects the underlying physical relationships between them; i.e. they should reflect the way in which the inputs and outputs are changed by quantitative changes in the products or functions delivered by the system.*
>
> *c) Step 3: Where physical relationship alone cannot be established or used as the basis for allocation, the inputs should be allocated between the products and functions in a way that reflects other relationships between them. For example, input and output data might be allocated between co-products in proportion to the economic value of the products.*
>
> *Some outputs may be partly co-products and partly waste. In such cases, it is necessary to identify the ratio between co-products and waste since the inputs and outputs shall be allocated to the co-products part only.*
>
> *Allocation procedures shall be uniformly applied to similar inputs and outputs of the system under consideration. For example, if allocation is made*

> *to usable products (e.g. intermediate or discarded products) leaving the system, then the allocation procedure shall be similar to the allocation procedure used for such products entering the system.*
>
> *The inventory is based on material balances between input and output. Allocation procedures should therefore approximate as much as possible such fundamental input/output relationships and characteristics."*

Accordingly, whenever possible, one obvious solution to handling processes with multiple outputs is to divide the unit process into separate processes, each associated with only one product. Other than subdividing, another recommended option is to expand the studied systems "to include the additional functions related to the co-products", yielding comparable product outputs. The second option describes causal relationships that exist when the co-products can be independently varied. The third option is analogous to the second one and economic value is the only causal relationship emphasized. In a nutshell, ISO 14044 allocation steps funnel down to two methods of treating the problem of allocation [181]:

1. Avoid by expanding the system boundaries or disaggregating the given process into different subprocesses (applicable to consequential LCAs).
2. Solve using a method based on the real behavior of the product system; i.e. on causal relationships, such as mass, economic value, etc. (attributional LCAs).

Based on Azapagic et al. [181] and the ISO 14044 guidelines, one can define three types of multi-function systems. This classification evolves from the argument [181] stating that "… allocation is an artifact of applying LCA to individual products rather than to the whole productive system". Accordingly, three multi-function production systems where allocation of environmental burdens can be relevant are:

1. Multiple-input systems (e.g. waste treatment processes, cement kilns burning different types of fuels),
2. Multiple-output systems (e.g. co-production), and
3. Multiple-use or "cascaded use" systems (e.g. "open-loop recycling")

Allocation is of particular importance when industrial by-products (fly ash, granulated blast furnace slag or silica fume) are used as supplementary cementitious materials in concrete mixes. Except for few studies [44, 64, 65], no environmental impact was attributed to the production of fly ash and GBFS as they are considered as waste products in general. The following sections cover the limited number of concrete LCA literature with the application of impact allocation.

3.2.3 Application of Impact Allocation in Concrete Production LCAs with Supplementary Cementitious Materials Use

The utilization of industrial by-products (or wastes) contributes both to reducing wastes and conserving resources while reducing landfilling and associated environmental impacts. Byproducts, such as granulated blast furnace slag (GBFS) and fly ash have lower environmental impact than cement if they are considered as waste from other industries, with no impacts allocated to these components [25, 184]. In LCA applications, their impacts are reduced to the energy consumption required for their processing and transportation to cement or concrete plant [25, 185]. However, based on a recent European Union directive [186], a question arises whether these byproducts are to be treated as waste or coproducts:

> *“A substance or object, resulting from a production process, the primary aim of which is not the production of that item, may be regarded as not being waste but as being a byproduct only if the following conditions are met:*
>
> *a) Further use of the substance or object is certain;*
>
> *b) The substance or object can be used directly without any further processing other than normal industrial practice;*
>
> *c) The substance or object is produced as an integral part of a production process; and*
>
> *d) Further use is lawful, i.e. the substance or object fulfils all relevant product, environmental and health protection requirements for the specific use and will not lead to overall adverse environmental or human health impacts.”*

This directive corresponds exactly to the context of use of SCMs such as GBFS and fly ash in concrete mixes and also applies to the U.S. markets when we consider the increasing rates of recycling of wastes into products instead of landfilling. Going back to the EU directive, one can check the above three conditions to understand whether the use of GBFS and fly ash as SCMs can also be met in the U.S. market conditions. Actually, their future use is certain. It fulfils condition (a) The U.S. power plants produce millions of tons of coal fly ash annually – it was about 70.8 million tons in 2004. More than 35 percent of the annual production is utilized in variety of applications, while the remainder is landfilled. Of the 70.8 million tons of fly ash, 16.5 million tons were used as replacement for portland cement in concrete manufacturing. It was also utilized in road and other construction applications [187]. National data from the PCA Economic Research Department [26, 27] indicate that, of the 113 cement plants, more than 50 of them use fly ash or bottom ash as SCMs.

It should be noted that GBFS are made from the extraction of iron from iron ore in blast furnace, whereas it is not possible to produce iron without producing GBFS. Fly ash is, on the other hand, made of the unburnt particulates (mainly siliceous components) that are released in exhaust gas when coal is burnt in coal power plants. For sanitary reasons, these gases have to be cleaned from ashes which are removed and concentrates to form FA. Thus both materials are produced as an integral part of a production process and then fulfill condition.

When all the above conditions are considered, these SCMs must then be considered as by-products and not waste anymore according to the EU directives. This consideration has important consequences in analyzing the impacts of SCMs and once again brings in the concept of allocation. Indeed, as mentioned in the prior section, in LCA when a production system produces several products, material and energy flows and the associated environmental burdens must be partitioned between them in order to accurately reflect their individual contribution to the environmental impacts. In the studies that applied allocation procedures, there does not seem to be any consensus about any specific method that is considered the “correct” one [160].

A recent study has evaluated the influence of different allocation procedures on the environmental impact of GBFS and fly ash when they are used as a replacement of clinker in blended cement [44]. As no specific method seems to be fully adequate [188] and as the ISO standard for LCA [12, 13]) states that when several alternative allocation procedures seem applicable, a sensitivity analysis should be conducted to illustrate the influence of each procedure on the results. Therefore, authors have tested the influence of the three allocation procedures: i) in the first one, fly ash and GBFS are respectively considered as waste from coal power and iron industries. Their environmental burdens are therefore limited to the specific treatments needed for their use in concrete (including grinding, drying and stocking). Although not realistic, this method has been used in most of the recent studies dealing with environmental evaluation of fly ash and GBFS used as SCMSs in concrete [57, 184, 185]; ii) The second allocation procedure is based on the relative mass ratio between the products and the co-products. Although SETAC guidelines [31] recommend to rely for the allocation procedure primarily on physicochemical considerations this procedure is not always usable as co-products have often similar impacts as the main product; iii) The third allocation procedure is based on the economic values of products and by-products. This procedure is the one that is often preferred in allocations studies [189] as it reflects the reality of the industrial process where the main products (iron and electricity) are the ones that form the main purpose of the industrial processes compared to the by-products (GBFS and fly ash respectively). With this allocation procedure, the major share of the environmental impact is allocated to the main products and a small portion to the by-products.

In summary, the current cement and concrete LCAs generally do not consider the allocation on the inventory results associated with such by-products. When applied, economic allocation is suggested to guarantee the use of GBFS and FA as cement replacing materials in the future. In case of mass allocation, environmental impacts of GBFS and FA are calculated to be an order of magnitude higher. As a consequence, their environmental burdens, especially when FA is used as SCM, become higher than the burden of traditional cement.

4 Description of GreenConcrete LCA Tool

4.1 Goal

One of the important deliverables of this dissertation is a concrete production LCA tool (hereafter named as GreenConcrete tool) and its web version to assess the environmental profiles of different concrete mixes defined by the user. The tool is developed to calculate environmental life-cycle impacts of one type of concrete mix as well as to compare and evaluate different concrete mixes based on the user's purpose. The tool is not a conventional database of inventory of resources (materials, energy, and water) and some emissions from manufacturing concrete that only considers direct impacts, e.g., only tailpipe emissions during transportation of concrete materials or direct emissions from electricity generation. In GreenConcrete, the supply chain impacts of each process during the production of concrete and its materials are evaluated. For example, the transportation section considers not only tailpipe emissions from transporting materials to concrete plant but also supply-chain emissions associated with vehicles production, infrastructure construction, and fuels extraction and production. Similarly, when a process involves use of electricity, the tool provides not only direct electricity generation impacts but also supply-chain impacts that encompass the construction and operation of a power plant, as well as the life-cycle impacts of the major resources used in the construction of the plant, the operation of the plant and so on.

Additionally, integration of regional variations and technological alternatives in the material production processes within the tool offers a wide range of applicability and flexibility for cement and concrete manufacturers in the U.S. and worldwide.

4.2 The Brief Structure of the Tool

The GreenConcrete tool is specifically designed for cement and concrete manufacturers for the purpose of quantifying and comparing environmental impacts of their products. Decision makers in the construction sector including construction managers, contractors, civil engineers, architects, and owners can also make use of the output of the GreenConcrete as a decision-support tool for the selection of materials or concrete mixes based on their calculated environmental impacts. The GreenConcrete consists of Microsoft Excel worksheets that can be grouped into four major sections, each connected to one another either by feeding in to or getting data from the other: "User Input" worksheet, "Reference Data Pool" worksheets, "Process and Calculation" worksheets, and "Results" worksheet with life-cycle inventory (LCI) and life-cycle impact assessment (LCIA) result The Web version consists of two major sections: "User Input" and "Results" that are visible to the user whereas "Reference Data Pool" and "Processes and Calculations" sections are not visible in the Web tool. In addition to the "Reference Data Pool" pages, each "Process and Calculation" worksheet accommodates smaller databases from literature. The "Reference Data Pool" worksheets consist of life-cycle inventories of electricity generation, freight transportation, and fuel pre-combustion and combustion based on the databases from current studies (see section for Databases). Life-cycle inventories of electricity, fuel, and materials are organized for each materials production phase in "Process and Calculation" worksheets within the tool. Emission factors from the "Reference Data Pool" worksheets are multiplied with the phase inventories (in "Process and Calculation" worksheets) to calculate the total phase impacts. These emission inventories are summed and collected in the "Results" page together with LCIA results that are calculated by multiplying the emission inventories with corresponding TRACI impact category weighting factors.

GreenConcrete tool users are asked to provide information about the concrete mix proportions per unit volume of the concrete mix, which in turn requires input for quantities and types of materials used in the mix. The second type of input requires information about the quarry or plant location for quantifying the energy use and emissions associated with electricity use and for quarrying/producing/ processing of cement raw materials (limestone, gypsum, etc.), portland and blended cements, fine and coarse aggregates, and supplementary cementitious materials (SCMs) that include limestone natural pozzolan, fly ash, granulated blast furnace slag (GBFS). Only admixtures production worksheet does not need electricity input from the user since the database [190] that provides the admixture inventory lacks the production-related electricity and fuel use quantities. The user also provides input for transportation distances and modes for delivering materials to cement plant and concrete batching plant. The third type of input involves data for production technologies used in cement and concrete plants. In case of lack of input data, the user has the option to proceed with the default values defined in the tool and can still run the analysis successfully. The details of each and every worksheet in the GreenConcrete are addressed in the following sections. Figure 4.1 illustrates the GreenConcrete structure briefly.

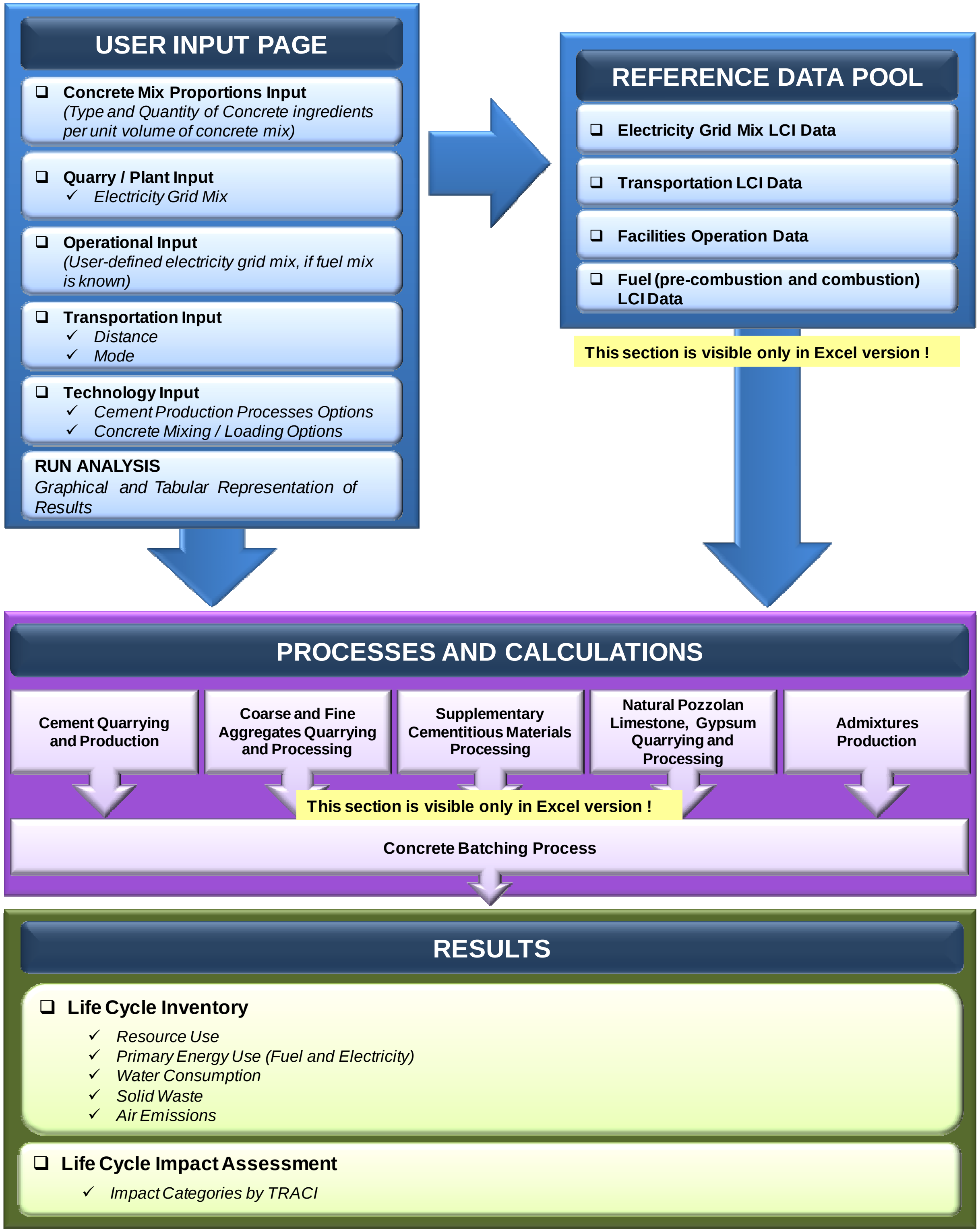


Figure 4.1: GreenConcrete tool structure

4.3 Functional Unit and System Boundary

The functional unit defined in the GreenConcrete is the unit volume of ready-mixed concrete that is exiting the concrete plant gate. The scope of the analysis encompasses environmental impacts associated with several different processes such as: cement raw materials quarrying and cement production, fine aggregates and coarse aggregates quarrying and processing, processing of supplementary cementitious materials (SCMs), production of major chemical admixtures, and electricity generation impacts associated with the processes considered and transportation of materials within the system. See Figure 4.2 and Figure 4.3 below for the scope of the analysis.

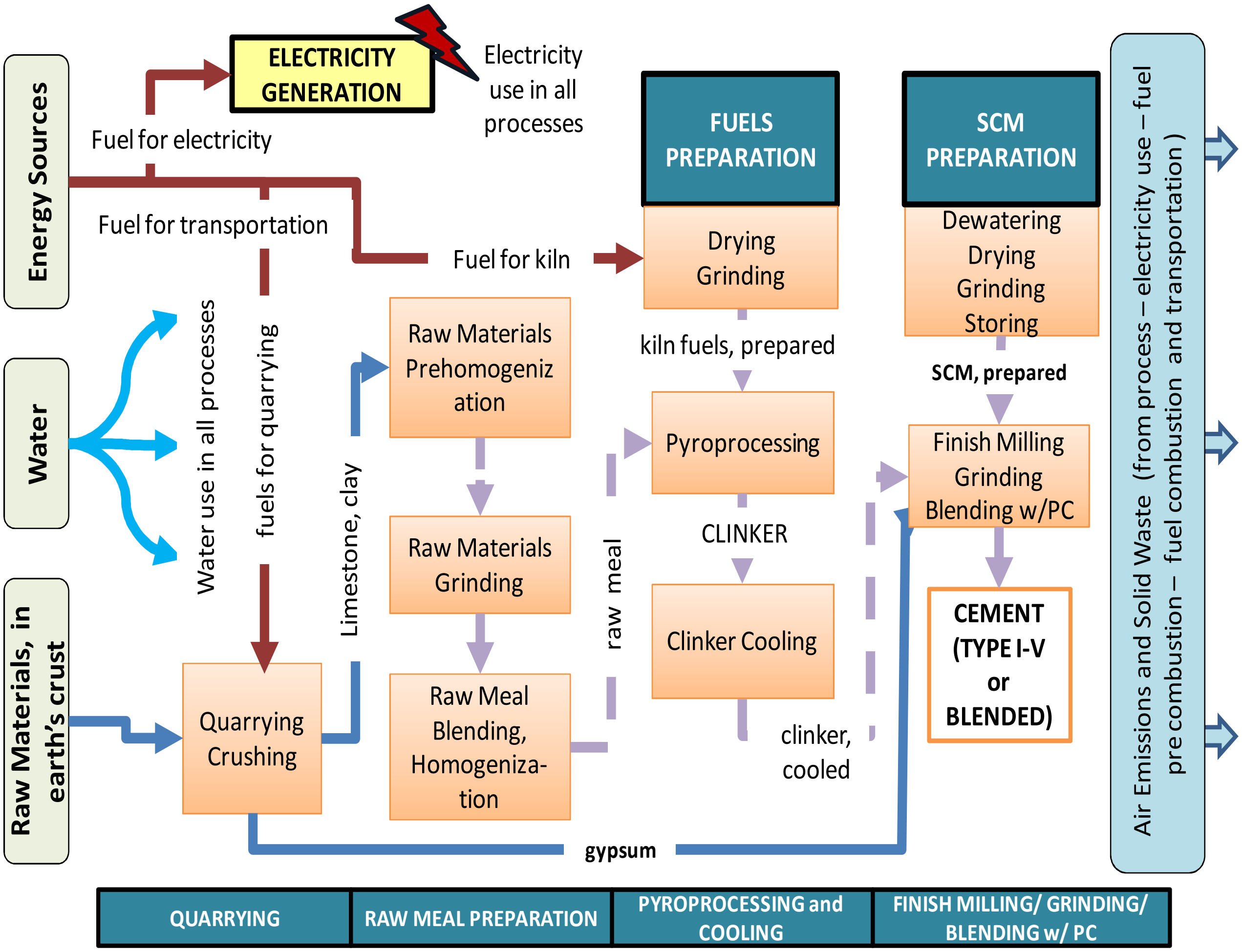


Figure 4.2: Cement production processes and associated life-cycle impacts

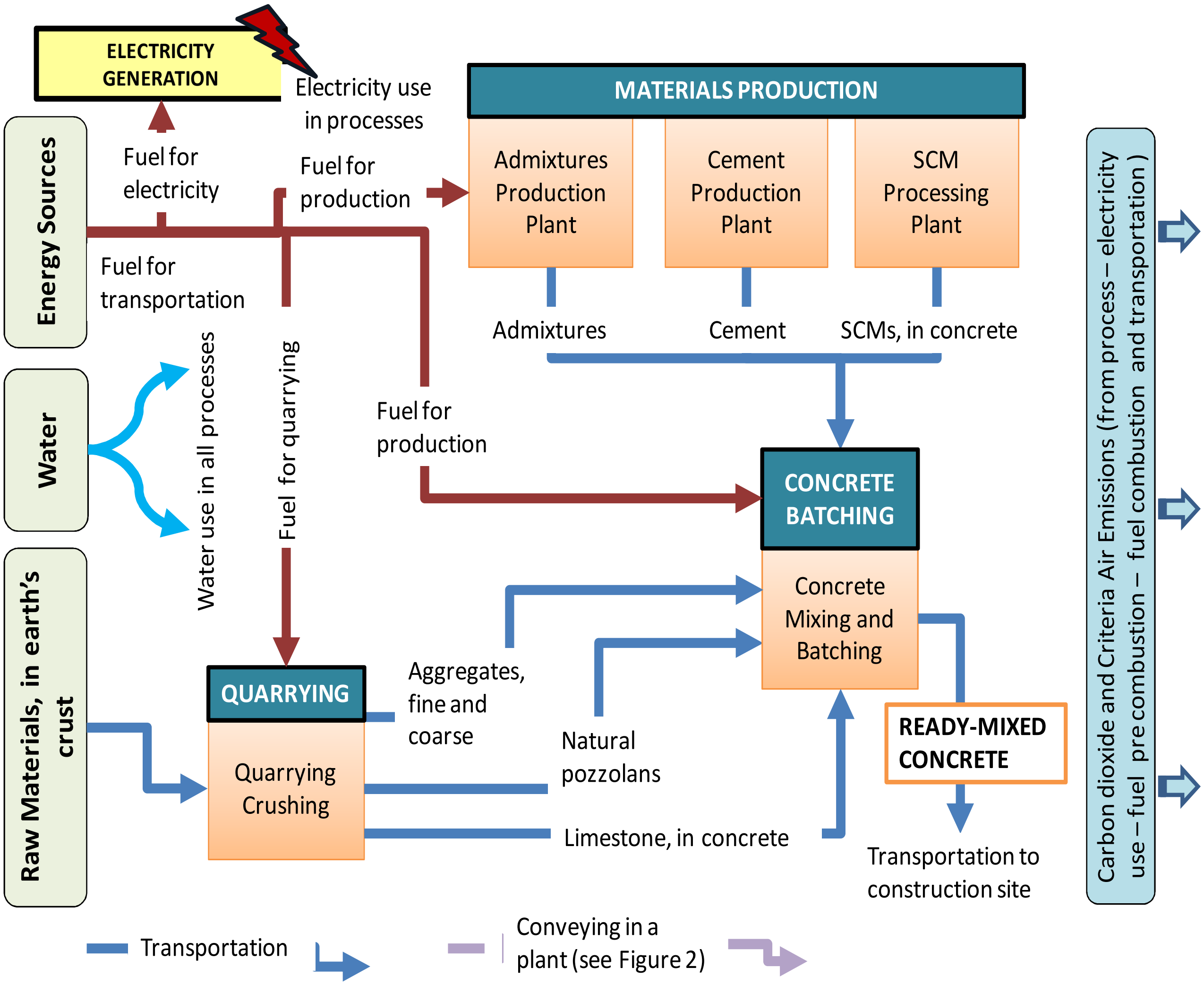


Figure 4.3: Concrete production processes and associated life-cycle impacts

4.4 Environmental Impacts to Assess

To quantify and analyze environmental impacts of the processes within the defined system boundary, different types of environmental metrics are estimated in the form of inputs of resources, energy (as fuel use and electricity use), and water as well as environmental outputs of solid waste and air emissions associated with the use of these resources, energy sources, and transportation of these resources.

The resource use input for concrete production encompasses a spectrum of extracted raw materials including limestone, clay, gypsum, sand, and gravel (as fine aggregates), crushed stone (as coarse aggregate), natural pozzolan; products of cement (traditional and blended); admixtures; and industrial by-products including fly ash, and GBFS. Quantities of raw materials used in different cement products and aggregates are estimated in the life-cycle inventory of concrete. Nonetheless, the resource use associated with admixtures production is not provided in the tool as the available LCI data source [190] lacks the details about the quantities and sources of active ingredients in chemical admixtures.

Amount of water consumption associated with most of the production processes of concrete and its major materials is also tabulated in the tool.

Energy used (in the form of fuel use and electricity) in the production and transportation of concrete and its materials is one of the main environmental impacts analyzed throughout the tool. More details about the calculation of energy and associated environmental impacts will be given in the following sections.

Throughout the tool, air emissions released from major processes (fuel pre-combustion, fuel combustion, electricity generation, transportation, and process-specific) that take place within the defined system boundary are listed below. Data sources and calculations of these emissions are described in more details in upcoming pages.

- Antimony (Sb) and Antimony compounds,
- Arsenic (As) and Arsenic compounds,
- Beryllium (Be),
- Cadmium (Cd) and Cadmium compounds,
- Carbon Dioxide (CO_2),
- Carbon Monoxide (CO),
- Chromium (Cr) and Chromium compounds,
- Cobalt (Co),
- Copper (Cu) and Copper compounds,
- Formaldehyde,
- Lead (Pb) and Lead compounds,
- Manganese (Mn),
- Mercury (Hg) and Mercury compounds,
- Methane (CH_4),
- Nickel (Ni) and Nickel compounds,
- Nitrogen Oxides (NO_x),
- Nitrous Oxide (N_2O),
- Non Methane Volatile Organic Compounds (NMVOC),
- Particulates (PM_{10}),
- Particulates (total),
- Selenium (Se) and Selenium compounds,
- Sulfur Dioxide (SO_2),
- Volatile Organic Compounds (VOC),
- Zinc (Zn) and Zinc compounds.

Solid waste from fuel pre-combustion and combustion, electricity generation, and raw materials quarrying and production processes are also estimated in the tool. Additionally, the tool conducts a life-cycle impact assessment based on TRACI Impact Category Weighting Factors for twelve environmental impact indicators, namely;

- Acidification (air),
- Ecotoxicity (air),
- Ecotoxicity (water),
- Eutrophication (air),

- Eutrophication (water),
- Global Warming Potential (air),
- Human Health Cancer (air),
- Human Health Cancer (water),
- Human Health Non-Cancer (air),
- Human Health Non-Cancer (water),
- Human Health Criteria (air),
- Photochemical Smog (air).

The output from the GreenConcrete tool can later be fed as an input to an overall environmental LCA of concrete buildings, and other structures, since the tool has the flexibility to allow user enter as many variations of concrete mix designs as possible that can be applied in different construction projects in different geographical locations both in the United States and worldwide.

The following chapters provide details about the tool.

4.5 **User Input Page**

The user input page provides information to the remaining worksheets of the tool, which consists of color-shaded and drop-down cells with input data entered or selected by the user. Table 4.1 provides the summary of inputs and associated worksheets. There are seven sections on User Input Page. The first section asks for information about modeling parameters used throughout the tool; such as, functional unit of concrete mix, unit type, and quantity of concrete produced. Other sections require input for concrete mix proportions; quarry/plant location details for state electricity grid mix selection; electricity grid mix percentages for user-defined options; transportation options; and technology options (for cement plant and concrete batching plant processes).

Table 4.1: Summary of user inputs (on 'Input_Page' tab) and associated “Process and Calculation” Worksheets

Related Worksheets / **User Inputs**	Cement_ Raw Meal	Cement _ Pyroprocessing	Cement _ Clinker Cooling	Cement_ Finish Mill_ Grind_ Blend	Gypsum_ Production	Limestone _ Production	SCM (fly ash and GBFS) _ Preparation	Aggregates _ Production	Admixtures _ Production	Natural Pozzolan _ Production	Concrete Mixing
Total volume of concrete produced	*	*	*	*	*	*	*	*	*	*	*
Type of cement	*	*	*	*	*		*				
Mass of cement	*	*	*	*	*		*				*
Mass of fine aggregates								*			*
Mass of coarse aggregates											
Mass of admixtures									*		*
Type of admixtures									*		
Mass of fly ash							*				*
Mass of granulated blast furnace slag							*				*
Mass of natural pozzolan										*	*
Mass of limestone (in concrete)						*					*
Electricity grid mix	*	*	*	*	*	*	*	*	*	*	*
Distance for transportation of cement raw materials to the cement plant	*										
Transportation mode for cement raw materials	*										
Distance for transportation of concrete materials to concrete plant					*	*	*	*	*	*	
Transportation mode for concrete materials					*	*	*	*	*	*	
Cement raw materials prehomogenization technology	*										

Cement raw materials grinding technology	*										
Raw meal blending / homogenization technology	*										
Pyroprocessing (cement kiln) technology		*									
Clinker cooling technology			*								
Cement plant PM emission control technology			*								
Finish milling and grinding technology				*							
SCM type in blended cement							*				
Percent fuel input to pyroprocessing (by % energy)		*									
Conveying technology option within cement plant	*	*	*	*			*				
Concrete batching plant loading/mixing technology											*
Concrete batching plant PM emission control technology											*

4.5.1 Modeling Parameters

In this section, the user is asked to enter the amount of concrete exiting the ready-mixed concrete plant (Table 4.2). This value, eventually, feeds in all “Process and Calculation” worksheets and “Results” page. The functional unit is constant throughout the tool, defined as per unit volume of ready-mixed concrete and expressed in cubic meter (m^3). If necessary, the user can convert metric units to US units by using the conversion factors in the “Data_Lists_Descriptions” worksheet, which provides unit conversions (for mass, volume, energy) for calculations throughout the tool.

Table 4.2: GreenConcrete User Input Page – Modeling Parameters

Modeling Parameters	
Functional Unit	Unit volume of ready-mixed concrete exiting the plant
Unit Type	Volume
Unit	m^3
Enter Total Amount of Concrete Produced	User Input

4.5.2 Concrete Mix Proportions

The second user input section, namely “Concrete Mix Proportions”, is broken down into three parts. The first part provides the information pertaining to the name of the concrete mix and type of cement used in the defined concrete mix (Table 4.3). The remaining cells in this part are calculated values that are specific to the concrete mix properties; such as, unit weight of concrete per its volume, total weight of cementitious (binding) materials (that is sum of portland cement and other binding materials added to concrete mix, e.g. fly ash, GBFS, natural pozzolan, and limestone) per unit volume of concrete, water/binder ratio of concrete mix based on the user-input data in the second part of this section.

First, the user can type in the name of the concrete mix design in the designated cell. The user-defined name will appear in the results and is practical specifically for sorting out and comparing different types of concrete mixes at the end of the analysis. In the second row, the user is required to select one of the six cement types from the drop-down list. These ASTM C595-defined six cement types are described in details in Section 4.10.3.

Table 4.3: GreenConcrete User Input Page – Concrete Mix Proportions

Concrete Mix Proportions – Calculated based on the user input for material quantities	
Enter Concrete Mix Design Name	User Input
Enter Cement Type	Selection from Dropdown List
Unit Weight of Concrete (kg/m^3)	Calculated
Total Cementitious (Binding) Materials (kg)	Calculated
Water/Binder Ratio	Calculated

The unit weight of concrete, which is listed in Table 4.3 above, is calculated as follows:

$$Unit\ Weight\ of\ Concrete\ (kg/m^3) = \sum Mass\ of\ Concrete\ Materials\ (kg)/(\,m^3\ of\ concrete)$$

Equation 4.1: Calculation of unit weight of concrete

$$Total\ Cementitious\ Materials\ (kg) = \sum Mass\ of\ Cementitious\ Materials\ (kg)$$

Equation 4.2: Calculation of total mass of cementitious materials used in unit volume of concrete mix

$$\left(\frac{Water}{Binder}\right) Ratio = \frac{Total\ Mass\ of\ Water\ (kg)}{Total\ Cementitious\ Materials\ (kg)}$$

Equation 4.3: Calculation of ratio of mass of mix water to total mass of cementitious materials in concrete mix

Equations 4.1 through 4.3 above search out the variables from the input page section demonstrated in Table 4.4 with the list of materials used per unit volume of concrete. In this part, the user is required to enter the weight of materials in the concrete mix.

Major concrete raw materials include cement, water, fine aggregates, and coarse aggregates. Typically, a concrete mixture is about 7-15 percent cement, 60-80 percent aggregates, and 15-20 percent water (by weight). Entrained air bubbles in many concrete mixtures may also take up another 5-8 percent of volume. Based on the concrete-mix design requirements, supplementary cementitious materials (SCMs) can also be introduced in the concrete mix. In recent years, concrete producers acquire SCMs to supplement the portland cement used in concrete [9]. Equation 4.2 calculates total mass of cementitious materials used in concrete which include mainly cement and other binding materials such as fly ash, GBFS, natural pozzolan, and limestone. The result from Equation 4.2 is used in calculating the water/binder ratio defined by Equation 4.3. Water/binder ratio, also called as water/cementitious materials (w/c) ratio is the mass ratio of free water (not contained in the aggregates) to the total amount of cementitious materials, such as cement, pozzolan, and slag in a paste, mortar, or concrete [165]. Workability and compressive strength of concrete are significantly influenced by various mixing properties including the water-binder ratio [191].

Additionally, if required, chemical admixtures are added to the concrete mix and may constitute less than two percent by weight of concrete. The tool provides the life-cycle inventory for major types of admixtures, namely: plasticiser, superplasticiser, retarder, accelerating admixture, air entraining admixture, and waterproofing (Table 4.4).

Table 4.4: GreenConcrete User Input Page – Concrete Mix Proportions: Material Quantities

Concrete Material Quantities

Material	**Unit Weight (per m^3 of concrete)**	**Total Weight**	**Unit Type**	**Unit**
1 Cement	User Input	Calculated	Mass	kg
2 Water	User Input	Calculated	Mass	kg
3 Fine Aggregates	User Input	Calculated	Mass	kg
4 Coarse Aggregates	User Input	Calculated	Mass	kg
Supplementary Cementitious Materials (also known as Mineral Admixtures). If blended cement is used,				

subtract the amount of fly ash and GBFS in cement from the entered amount				
5 Fly Ash	User Input	Calculated	Mass	kg
6 Granulated Blast Furnace Slag	User Input	Calculated	Mass	kg
7 Natural Pozzolan	User Input	Calculated	Mass	kg
8 Limestone	User Input	Calculated	Mass	kg
Total Cementitious Materials (Sum of 1,5,6,7,8)	*Calculated (Equation 4.2)*	*Calculated*	*Mass*	kg
Admixtures (Chemical)				
9 Plasticiser	User Input	Calculated	Mass	kg
10 Superplasticiser	User Input	Calculated	Mass	kg
11 Retarder	User Input	Calculated	Mass	kg
12 Accelerating admixture	User Input	Calculated	Mass	kg
13 Air entraining admixture	User Input	Calculated	Mass	kg
14 Waterproofing	User Input	Calculated	Mass	kg

In Table 4.4 above, total weight of a material required in concrete mix is calculated by multiplying the weight of that material per unit volume of concrete with the total amount of concrete produced at a batching plant. For each of the materials used in the mix, the following calculations take place on the user input page:

$$Total\ Mass\ of\ Cement\ (kg) = Mass\ of\ Cement\ per\ Unit\ Volume\ of\ Concrete\ (kg/m^3\ of\ concrete) \times Total\ Volume\ of\ Concrete\ Produced\ (m^3)$$

Equation 4.4: Calculation of total mass of cement in the concrete mix

$$Total\ Mass\ of\ Water\ (kg) = Mass\ of\ Water\ per\ Unit\ Volume\ of\ Concrete\ (kg/m^3\ of\ concrete) \times Total\ Volume\ of\ Concrete\ Produced\ (m^3)$$

Equation 4.5: Calculation of total mass of water in the concrete mix

$$Total\ Mass\ of\ Fine\ Aggregates\ (kg) = Mass\ of\ Fine\ Aggregates\ per\ Unit\ Volume\ of\ Concrete\ (kg/m^3\ of\ concrete) \times Total\ Volume\ of\ Concrete\ Produced\ (m^3)$$

Equation 4.6: Calculation of total mass of fine aggregates in the concrete mix

$$Total\ Mass\ of\ Coarse\ Aggregates\ (kg) = Mass\ of\ Coarse\ Aggregates\ per\ Unit\ Volume\ of\ Concrete\ (kg/m^3\ of\ concrete) \times Total\ Volume\ of\ Concrete\ Produced\ (m^3)$$

Equation 4.7: Calculation of total mass of coarse aggregates in the concrete mix

$$Total\ Mass\ of\ Fly\ Ash\ (kg) = Mass\ of\ Fly\ Ash\ per\ Unit\ Volume\ of\ Concrete\ (kg/m^3\ of\ concrete) \times Total\ Volume\ of\ Concrete\ Produced\ (m^3)$$

Equation 4.8: Calculation of total mass of fly ash in the concrete mix

$$\begin{aligned} &Total\ Mass\ of\ GBFS\ (kg) \\ &\quad = Mass\ of\ GBFS\ per\ Unit\ Volume\ of\ Concrete\ (kg/\,m^3\ of\ concrete) \\ &\quad \times Total\ Volume\ of\ Concrete\ Produced\ (m^3) \end{aligned}$$

Equation 4.9: Calculation of total mass of GBFS in the concrete mix

$$\begin{aligned} &Total\ Mass\ of\ Natural\ Pozzolan\ (kg) \\ &\quad = Mass\ of\ Natural\ Pozzolan\ per\ Unit\ Volume\ of\ Concrete\ (kg/\,m^3\ of\ concrete) \\ &\quad \times Total\ Volume\ of\ Concrete\ Produced\ (m^3) \end{aligned}$$

Equation 4.10: Calculation of total mass of natural pozzolan in the concrete mix

$$\begin{aligned} &Total\ Mass\ of\ Limestone\ (kg) \\ &\quad = Mass\ of\ Limestone\ per\ Unit\ Volume\ of\ Concrete\ (kg/\,m^3\ of\ concrete) \\ &\quad \times Total\ Volume\ of\ Concrete\ Produced\ (m^3) \end{aligned}$$

Equation 4.11: Calculation of total mass of limestone in the concrete mix

$$\begin{aligned} &Total\ Mass\ of\ Plasticiser\ (kg) \\ &\quad = Mass\ of\ Plasticiser\ per\ Unit\ Volume\ of\ Concrete\ (kg/\,m^3\ of\ concrete) \\ &\quad \times Total\ Volume\ of\ Concrete\ Produced\ (m^3) \end{aligned}$$

Equation 4.12: Calculation of total mass of plasticiser in the concrete mix

$$\begin{aligned} &Total\ Mass\ of\ Superplasticiser\ (kg) \\ &\quad = Mass\ of\ Superplasticiser\ per\ Unit\ Volume\ of\ Concrete(kg/\,m^3\ of\ concrete) \\ &\quad \times Total\ Volume\ of\ Concrete\ Produced\ (m^3) \end{aligned}$$

Equation 4.13: Calculation of total mass of superplasticiser in the concrete mix

$$\begin{aligned} &Total\ Mass\ of\ Retarder\ (kg) \\ &\quad = Mass\ of\ Retarder\ per\ Unit\ Volume\ of\ Concrete\ (kg/\,m^3\ of\ concrete) \\ &\quad \times Total\ Volume\ of\ Concrete\ Produced\ (m^3) \end{aligned}$$

Equation 4.14: Calculation of total mass of retarder in the concrete mix

$$\begin{aligned} &Total\ Mass\ of\ Accelerating\ Admixture\ (kg) \\ &\quad = Mass\ of\ Accelerating\ Admixture\ per\ Unit\ Volume\ of\ Concrete\ (kg/\,m^3\ of\ concrete) \\ &\quad \times Total\ Volume\ of\ Concrete\ Produced\ (m^3) \end{aligned}$$

Equation 4.15: Calculation of total mass of accelerating admixture in the concrete mix

$$\begin{aligned} &Total\ Mass\ of\ Air\ Entraining\ Admixture\ (kg) \\ &\quad = Mass\ of\ Air\ Entraining\ Admixture\ per\ Unit\ Volume\ of\ Concrete\ (kg/\,m^3\ of\ concrete) \\ &\quad \times Total\ Volume\ of\ Concrete\ Produced\ (m^3) \end{aligned}$$

Equation 4.16: Calculation of total mass of air entraining admixture in the concrete mix

$$\begin{aligned} &Total\ Mass\ of\ Waterproofing\ (kg) \\ &\quad = Mass\ of\ Waterproofing\ per\ Unit\ Volume\ of\ Concrete\ (kg/\,m^3\ of\ concrete) \\ &\quad \times Total\ Volume\ of\ Concrete\ Produced\ (m^3) \end{aligned}$$

Equation 4.17: Calculation of total mass of waterproofing admixture required in the concrete mix

The next section on the user input page (see Table 4.5) demonstrates the calculated quantities of major ingredients that are blended in the cement. Calculations are based on information about the type of cement selected by the user (see Table 4.3). Details of these calculations are in "Cement_ Finish Mill_ Grind_ Blend" tab of the tool whereas finish grinding, milling, and blending of portland cement processes are analyzed. In the table below, max/min or min/max quantities of cement ingredients needs further explanation. When the user selects one of the blended cement types, cement is composed of clinker, gypsum, and one type of SCM (either fly ash or GBFS) as opposed to the traditional portland cement which consists of clinker and gypsum. In this case, when the "clinker + gypsum" amount is of maximum amount, SCM (fly ash or slag) is at minimum level based on ASTM standard definitions. Assumptions and calculation details are explained in Sections 4.10.3 and 4.10.6, which are SCM Preparation and Cement Finish Milling and Grinding tabs in the GreenConcrete LCA tool worksheets.

Table 4.5: GreenConcrete User Input Page – Concrete Mix Proportions: Cement Raw Materials

Cement Raw Material (based on ASTM)					
	Average	**Max /Min**	**Min/Max**	**Unit Type**	**Unit**
Cement clinker	Calculated	Calculated	Calculated	Mass	kg
Cement gypsum	Calculated	Calculated	Calculated	Mass	kg
Cement kiln dust (CKD)	Calculated	Calculated	Calculated	Mass	kg
Fly ash, blended in cement	Calculated	Calculated	Calculated	Mass	kg
Granulated blast furnace slag, blended in cement	Calculated	Calculated	Calculated	Mass	kg
Portland cement (clinker + gypsum), which may be different from the total mass of cement if it is blended type.	Calculated	Calculated	Calculated	Mass	kg

4.5.3 Quarry/Plant Location and Electricity Grid Mix Input

Most LCI data in the public domain are reported on a national average basis, which may not be realistic for local and regional plant operations that differ significantly from national average conditions. The third user input section, namely "Quarry/Plant Location and Grid Mix" (see Table 4.6) allows users to select among the default values defined for the U.S. states and custom-defined electricity grid mixes used in the following locations:

- Cement raw materials quarrying and production plant,
- Fine and coarse aggregates quarrying and processing plant,
- Gypsum quarry and processing plant,
- Limestone quarry and processing plant,
- Natural pozzolan quarry and processing plant,
- Fly ash processing plant,
- Granulated blast furnace slag (GBFS) processing plant, and
- Concrete batching plant.

For each of the above quarry/plant locations, the corresponding electricity grid mix drop-down list consists of the States, the U.S. average, and three user-defined grid mix options. The user-defined option requires the user's custom fuel mix input for electricity generation. The Section 4.8 covers the major assumptions, calculations, and databases associated with the electricity generation and associated environmental life-cycle interventions.

Table 4.6: GreenConcrete User Input Page – Quarry/Plant Location and Grid Mix Input

Quarry/Plant Location and Grid Mix Input (Please define the grid mix if you know the fuel mix percentage for the electricity. Go to Section 4 for Operation-Electricity Generation Mix Section). Otherwise use the pre-defined State or U.S. Average values	
Cement Raw Materials Quarry and Plant	
Electricity Mix for Cement Raw Materials Mining (Quarry)	Selection from Dropdown List
Electricity Mix for Cement Plant	Selection from Dropdown List
Aggregates Quarry and Processing Plant	
Electricity Mix for Fine Aggregates Quarrying and Processing	Selection from Dropdown List
Electricity Mix for Coarse Aggregates Quarrying and Processing	Selection from Dropdown List
Gypsum Quarry and Processing Plant	
Electricity Mix for Gypsum Quarrying and Processing	Selection from Dropdown List
Limestone Quarry and Processing Plant	
Electricity Mix for Limestone Quarrying and Processing	Selection from Dropdown List
Natural Pozzolan Quarry and Processing Plant	
Electricity Mix for Natural Pozzolan Quarrying and Processing	Selection from Dropdown List
Concrete Batching Plant	
Electricity Mix for Concrete Batching Plant	Selection from Dropdown List
Fly Ash Processing Plant (Coal-Combustion Power Plant)	
Electricity Mix for Fly Ash Processing	Selection from Dropdown List
Granulated Blast Furnace Slag (GBFS) Processing Plant	
Electricity Mix for GBFS Processing	Selection from Dropdown List

4.5.4 Operation Input

As mentioned in the previous section, GreenConcrete LCA tool further allows users to create three customizable grid mixes by entering the percentages of the fuels that contribute to the mix (by percent energy). The Table 4.7 lists common energy sources used in the United States grid mix and default use percentages are calculated based on the EIA's annual energy reviews [192]. Related calculations take place in "Electricity_Grid_Data" tab and details are explained in Section 4.8.2.

Table 4.7: GreenConcrete User Input Page - Electricity Grid Mix Input (by % energy) for User defined Options (Note that US average % values are demonstrated for comparison purposes)

Energy Source for Electricity Grid Mix	**User-defined grid mix 1 (%)**	**User-defined grid mix 2 (%)**	**User-defined grid mix 3 (%)**	**US average (default) (%)**

Bituminous Coal	User Input	User Input	User Input	***44.4%***
Natural gas	User Input	User Input	User Input	***23.3%***
Residual (Heavy) fuel oil	User Input	User Input	User Input	***0.5%***
Distillate (Light) fuel oil	User Input	User Input	User Input	***0.2%***
Petroleum coke	User Input	User Input	User Input	***0.4%***
Nuclear (Uranium)	User Input	User Input	User Input	***20.2%***
Hydro	User Input	User Input	User Input	***6.9%***
Biomass	User Input	User Input	User Input	***1.4%***
Geothermal	User Input	User Input	User Input	***0.4%***
Solar	User Input	User Input	User Input	***0.0%***
Wind	User Input	User Input	User Input	***1.9%***
Lignite coal	User Input	User Input	User Input	**-**

4.5.5 Transportation Input

User input from this section is fed into the “Transportation” worksheet calculations within the Excel version of the GreenConcrete LCA tool. User is asked to enter the type of transportation mode and one-way distance (in km) traveled during transporting concrete and cement raw materials. The first column in Table 4.8 lists these major materials and products as well as their destinations within the system boundary analyzed. Transportation-related energy use and emissions calculations involve user-selected transportation information, of which the details are demonstrated in Table 4.8 and Table 4.9.

Modes and vehicle types are limited to five categories based on the availability of freight transportation-related life-cycle data from the literature. On the User Input Page of the Excel tool, three transportation options are provided for each type of the material/product delivered. This is especially convenient when the transportation of a material involves segmented routes, meaning that more than one mode or model of vehicle is required to deliver a material from one place to another, e.g. fly ash from China to San Francisco may involve rail, water, and truck modes.

Table 4.8: GreenConcrete User Input Page – Transportation Input

Transportation of:	**Distance Traveled (km)**	**Mode of transportation (Select)**
Cement Raw Materials (limestone, clay, etc.) to Cement Plant	User Input	Selection from Dropdown List
Gypsum to Cement Plant	User Input	Selection from Dropdown List
Fly Ash to Cement Plant (if Blended cement)	User Input	Selection from Dropdown List
Granulated Blast Furnace Slag to Cement Plant (if Blended cement)	User Input	Selection from Dropdown List
Cement to Concrete Plant	User Input	Selection from Dropdown List
Fine Aggregates to Concrete Plant	User Input	Selection from Dropdown List
Coarse Aggregates to Concrete Plant	User Input	Selection from Dropdown List
Admixture to Concrete Plant (assume all types are from one plant)	User Input	Selection from Dropdown List

Fly Ash to Concrete Plant	User Input	Selection from Dropdown List
Granulated Blast Furnace Slag to Concrete Plant	User Input	Selection from Dropdown List
Natural Pozzolan to Concrete Plant	User Input	Selection from Dropdown List
Limestone to Concrete Plant	User Input	Selection from Dropdown List

Note: The table above lists one distance and one mode information for Transportation Option_1. The Excel version of the GreenConcrete LCA tool provides three transportation options for each of the material/product delivered in case there is segmented route.

Table 4.9: GreenConcrete User Input Page – Dropdown list options for mode of transportation

Transportation Mode Options:
Road_Class 8b (Model 2005)
Road_Class 5 (Model 2005)
Road_Class 2b (Model 2005)
Rail_Intermodal□Rail
Water_General Cargo

4.5.6 Technology Options Input

In this section of the User-Input page, discrete technology options are provided for cement production processes (see Table 4.10 for major cement production phases) from raw materials preparation to finish milling/grinding to produce portland cement and/or mixing the portland cement (clinker and gypsum) with SCMs to produce blended cements that are ready to exit the cement plant for further use in concrete. User is asked to select among the production technology options listed in the dropdown menu. Table 4.11 demonstrates these options for each of the phases occurring during cement production. Inputs from the technology column are fed into cement production, gypsum production, and SCM preparation "Process and Calculation" tabs, each of which will be discussed in more details in coming sections (see Sections 4.10 and 4.11).

Table 4.10: GreenConcrete User Input Page - Cement Plant Technology Options by Phase

Cement Production Phases	**Product of Each Phase**	**Technology**
Raw Materials Prehomogenization	Raw Meal	Selection from Dropdown List
Raw Materials Grinding	Ground Meal	Selection from Dropdown List
Raw Meal Blending/Homogenization	Blended Meal	Selection from Dropdown List
Pyroprocessing	Clinker	Selection from Dropdown List
Clinker Cooling	Cooled Clinker	Selection from Dropdown List
Finish Milling, Grinding, Blending w/ PC	Blended Cement or Traditional Portland Cement	Selection from Dropdown List

Table 4.11: GreenConcrete User Input Page - Technology Drop-down Options for Cement Production Phases

Raw Materials Pre-homogenization	**Raw Materials Grinding**	**Raw Meal Blending / Homogenization**	**Pyro-processing**	**Clinker Cooling**	**Finish Milling, Grinding, and Blending with Portland Cement**
Dry process_Raw storing, non-preblending	Dry raw grinding_ball mill	Raw meal homogenization, blending, and storage	Wet kiln	Rotary (Tube) Cooler	Tube Mill
Dry process_Raw storing, preblending	Dry raw grinding_tube mill	Slurry blending homogenization and storage	Long dry kiln	Planetary (Satellite) Cooler	Vertical Roller Mill
Wet process_Raw storing	Dry raw grinding_ vertical roller mill		Preheater kiln	Reciprocating Grate Cooler (Conventional)	Ball Mill
	Wet raw grinding_tube mill		Preheater/ Precalciner kiln	Reciprocating Grate Cooler (Modern)	Roller Press
	Wet raw grinding_ wash mill		United States Average kiln	Vertical Gravity Cooler with Planetary Cooler	Horizontal Roller Mill (Horomill)
				Grate Cooler (Recirculating Excess Air)	
				PM Control Options:	
				Fabric Filter (FF)	
				Electrostatic Precipitators (ESP)	

In addition to the production process technology inputs, pyroprocessing phase requires user input for major kiln fuels (by percent kiln energy requirement). In case the user does not know the kiln fuel percentages, he/she can still perform the calculations by selecting the default U.S. average values provided by Portland Cement Association [26]. Data from this section feeds into "Pyroprocessing" tab to estimate energy use and emissions associated with the preparation of six types of traditional fuels and nine types of waste fuels for kiln use. Additionally, input from this section is used to calculate pyroprocessing-related pre-combustion and combustion impacts for four different kiln technology options and one U.S. average kiln option. Table 4.12 tabulates kiln fuel options and default energy percentages (corresponding to the fuel options) for U.S. average case.

Table 4.12: GreenConcrete User Input Page - Cement Pyroprocessing Fuel Use Options

Fuel Options	**Energy, %**	**US Average Fuel, % [26]**
Bituminous coal	User Input	64.1%
Lignite coal	User Input	0.0%
Distillate (diesel or light) fuel oil	User Input	0.8%
Petroleum coke (pet coke)	User Input	21.2%
Residual (heavy) fuel oil	User Input	0.2%
Natural gas	User Input	3.7%
Waste oil	User Input	0.3%
Waste solvent	User Input	4.0%
Waste tire (whole)	User Input	1.8%
Waste tire (shredded)	User Input	1.8%
Waste (other) (non-hazardous)	User Input	2.3%
Waste paper, cardboard	User Input	-
Waste plastics	User Input	-
Waste sewage sludge (dry)	User Input	-
Waste (other) (hazardous)	User Input	-

During cement production, process input and output materials (e.g. raw meal, ground meal, clinker, etc.) are transferred from one process station (e.g. pyroprocessing) to the next one (e.g. finish milling) and this can be accomplished by various conveying technologies (Table 4.13). In addition to the conveyance distance input, the user is asked to select among four different conveying technology options that are commonly used in cement plants (see Table 4.14) for conveyor options). Conveyance distance and technology inputs are used in calculations that take place in "Transportation" worksheet to estimate the associated electricity use impacts.

Table 4.13: GreenConcrete User Input Page – Conveying (within Cement Plant) Technology Options

Product of Cement Production Phase	**Distance Conveyed (m)**	**Conveyance Technology**	**Amount of Material Conveyed (kg)**
Raw meal	User Input	Selection from Dropdown List	Calculated
Ground meal	User Input	Selection from Dropdown List	Calculated
Blended meal	User Input	Selection from Dropdown List	Calculated
Clinker	User Input	Selection from Dropdown List	Calculated
Cooled clinker	User Input	Selection from Dropdown List	Calculated
Blended/ traditional Portland cement	User Input	Selection from Dropdown List	Calculated

Table 4.14: GreenConcrete User Input Page – Dropdown List Options for Conveyance Technology within Cement Production Plant

Cement Conveying Technology Options
Screw pump
Airlift
Dense phase pump
Bucket elevator

Major technological variations in concrete batching plants are captured by two technology variables, namely, PM control technology options (same as cement plant dust control options which are fabric filter and ESP) and loading/mixing technology options (either mixer loading or truck loading). User can select the concrete batching technology option from the drop-down lists provided.

4.5.7 LCA Data Lists and Descriptions

Although "Data Lists and Descriptions" worksheet is not a part of the "User Input" page, it is a complementary page that contains lookup tables for unit conversions, major materials and products, concrete and its materials production stages, fuels, transportation modes and destinations.

In the Excel tool, User Input page provides input to all "Process and Calculation" worksheets which are in turn obtain the emission factors from the "Reference Data Pool" worksheets. These emissions factors are multiplied with the phase inventories (in "Process and Calculation" worksheets) to calculate the total phase impacts. Before describing each of the production processes and related calculations, reference data pool worksheets with the associated LCI data will be the next topic.

4.6 **Reference Data Pool: Fuel Pre-Combustion**

Fuel is consumed during various stages of production of concrete and its ingredients, including quarrying of raw materials (limestone, gypsum, aggregates, etc.), cement pyroprocessing, preparation of SCMs, and concrete mixing and batching. For the assessment of full life-cycle impacts, one has to consider not only direct combustion-related emissions but also the pre-combustion emissions resulting from extracting, processing, and delivering a fuel to the point of use in a quarry, plant or a building prior to combustion [193]. This "Reference Data Pool" calculates pre-combustion related energy use, water consumption, solid waste, and air emissions (listed below in Table 4.15) for traditional fuels including bituminous coal, lignite, distillate (diesel or light) fuel oil, residual (heavy) fuel oil, gasoline, natural gas, and nuclear (uranium).

Unfortunately, no such pre-combustion data exists for waste fuels that are used mostly during clinker pyroprocessing. However, GreenConcrete LCA tool reserves placeholder for future waste fuel pre-combustion LCI data calculations.

Pre-combustion life-cycle energy data excludes the feedstock/embodied energy of the fuels themselves and is estimated based on the NREL (2006) data which consists of quantities of fuel inputs obtained from technosphere used in extracting, processing, and delivering the fuel in GreenConcrete tool. The pre-combustion primary energy for each of the major ten fuels used throughout the tool is calculated as follows in Equation 4.18. Results are tabulated in MJ per unit mass or volume of process fuel "i" (see Table 4.15):

$$ENERGY_{PRECCOMBUSTi} = \sum_{i}^{n=10} \left(HHV_j \times FUEL_{i,j}\right) + ENERGY_{i,RENEW}$$

Equation 4.18: Calculation of pre-combustion energy use factor for fuel "i"

Where:

$ENERGY_{PRECOMBUSTi}$ = Pre-combustion primary energy use for process fuel "i", in MJ per unit mass (kg) or unit volume (l or m^3) of fuel "i";

HHV_j = Average higher heating value (heat content) of fuel "j", in units of MJ per unit mass (kg) or unit volume (l or m^3) of fuel "j";

$FUEL_{i,j}$ = Fuel input "j" from technosphere used for the purpose of extracting, processing, and delivering process fuel "i", in mass (kg) or volume (l or m^3) of fuel "j" per unit mass or volume of fuel "i". Here "j" represents fossil fuels;

$ENERGY_{i,RENEW}$ = Renewable energy input for the purpose of extracting, processing, and delivering process fuel "i", in units of energy (MJ) associated with the renewable source per unit mass (kg) or unit volume (l or m^3) of fuel "i". Here "RENEW" represents renewable energy sources such as; wood, geothermal, hydro, solar, and wind.

Note that subscript "i" corresponds to one of the ten fossil fuels (bituminous coal, lignite, distillate (diesel or light) fuel oil, residual (heavy) fuel oil, gasoline, natural gas, and nuclear) and "j" corresponds to fossil fuel inputs from technosphere (given in the first column of the table) used in extracting, processing, and delivering the fuel "i". In other words, "j" refers to the fuel used to produce the process fuel (used in cement and concrete production) that has an upstream chain associated with it.

Higher heating values for fossil fuels are provided in Table 4.15. Data reflects average conditions for the United States. According to EIA's report, bituminous coal is the most abundant coal in the US with moisture content generally less than 20 percent. The heat content of bituminous coal ranges from 21 to 30 million Btu per short ton on a moist, mineral-matter-free basis. The average HHV corresponds to 24 million Btu per short ton (27.91 MJ/kg of fuel), on the as-received basis (i.e., containing both inherent moisture and mineral matter). On the other hand, lignite is not that common in the US and has high inherent moisture content, sometimes as high as 45 percent. The heat content of lignite ranges from 9 to 17 million Btu per short ton on a moist, mineral-matter-free basis. The average is 13 million Btu per short ton (15.12 MJ/kg of fuel) [194].

Heating values for natural gas, distillate (diesel or light) oil, and residual (heavy) fuels are taken from EIA's 2011 Annual Energy Outlook and are reported as 1,026 Btu per cubic foot (38.23 MJ/m^3), 5.775 million Btu per barrel (38.32 MJ/l), and 6.287 million Btu per barrel (41.72 MJ/l), respectively [195]. Distillate fuel oil is used primarily for space heating, on- and off-highway diesel engines (including railroad engine fuel and fuel for agriculture machinery), and electric power generation. Fuel oils and diesel fuel oils are very similar, but they do have different specifications. Included are fuel oils No. 1, No. 2, and No. 4; and diesel fuels No. 1, No. 2, and No. 4. Residual fuel oil (No. 5 and No. 6) is used in electricity generation, space heating, vessel bunkering, and various industrial purposes including cement kilns [193].

Average HHV for US gasoline is listed as 27.87 MJ per liter of fuel [193]. For petroleum coke, HHV corresponds to 6.024 million Btu per barrel (that is 35.70 MJ per kg) with a bulk density of 0.80 kg per liter [35]. HHV for nuclear is based on NREL LCI data for uranium and calculated as 451,405.30 MJ per kg of uranium [196].

Pre-combustion related water consumption factors are calculated on the basis of the methodology suggested by McMahon et al. [197]. Results are tabulated in liters of water consumed per gigajoules of HHV of energy source. Water is an inseparable component throughout the mining process and consumed for the purpose of extracting and processing fuels, cooling equipment, and suppressing dust. Mining represents about one percent of fresh water withdrawal (total removal of water from a source, including what is consumed and what is returned to its original watershed) and consumption in the United States [198]. Coal mining and washing alone uses between 265 and 984 million liters of water daily depending upon the location of coal source in the US [199]. About 5-70 liters of water per GJ of HHV of coal is needed for coal mining [197]. Oil and natural gas production also requires water for mining, treatment, refining and so on. For natural gas, about 7 liters of water per GJ is estimated as almost no water is used to mine natural gas and this is only for processing [197]. However, there is one exceptional process of hydraulic fracturing whereas between 50,000 to 350,000 gallons of water is required to create one well. It is estimated that roughly 7.5% of U.S. natural gas production requires hydraulic fracturing and the remaining 92.5% production is achieved traditionally [200].

In case of oil production, on average, 5.7 liters (1.5 gallons) of water is consumed for every gallon of oil refined in the U.S. Refining about 800 million gallons (3 billion liters) of petroleum each day, about 3.8 to 7.6 billion liters of water is consumed in the U.S. refining sector. About 90% of U.S. onshore oil production uses between 8 and 20 liters of a combination of produced water, saline-based groundwater, and freshwater for the process of recovering each gallon (3.79 liters) of crude oil. When combined with the water needed to refine each gallon of crude oil, between 13 and 27 liters of water are used to produce and process 1 gallon of crude oil [201]. For the U.S., traditional oil production requires between 28 to 72 liters of water per gigajoule of

HHV. These numbers cover up raw materials and refining processes. In the tool, it is assumed that all conventional liquid oils require the same amount of water per their heating values for ease of calculations.

The water consumption for mining and processing the uranium fuel for nuclear power generation is between 170 and 568 liters of water for each megawatt-hour generated which corresponds to about 29 to 51 liters of water per gigajoule of heating value for uranium.

Within the GreenConcrete LCA tool, amount of water consumed during pre-combustion processes of fossil fuels (in kg per mass or volume of fuel "i") is calculated as follows:

$$\boxed{WATER_{PRECOMBUSTi} = WATER_i * HHV_i * 1/1{,}000 * d_{H2O}}$$

Equation 4.19: Calculation of water consumption amount for fuel pre-combustion LCI

Where:

$WATER_{PRECOMBUSTi}$ = Water consumption for fuel pre-combustion LCI, in kg per unit mass or volume of fuel "i" used in process;

$WATER_i$ = Average water consumption factor associated with fossil fuel production given in liters of water per gigajoule (l/GJ) of higher heating value ($HHV_{i)}$ for fuel "i";

HHV_i = Higher heating value for fuel "i", in units of MJ per unit mass (kg) or unit volume (l or m^3) of fuel "i" (See Table 4.15 for the list of these factors);

d_{H2O} = Density of water, 1 kg per liter;

1/1,000 = Unit conversion factor (1 gigajoule = 1,000 mega joule)

Solid waste generation and air emission factors related to fuel pre-combustion are adapted from NREL's fuel LCI database and various reports [193, 202, 203] and listed in Table 4.15 below.

Table 4.15: GreenConcrete “Reference Data Pool” Worksheet_ Pre-Combustion Life-Cycle Inventory Data for Fuels Used

		Bituminous coal	Lignite coal	Distillate (diesel) fuel oil	Gasoline	Kerosene	LPG	Petroleum coke	Residual (heavy) fuel oil	Natural gas	Nuclear
Unit		kg	kg	l	l	l	l	kg	l	m^3	kg
HHV (MJ/unit)		27.9	15.1	38.3	27.9	27.9	25.4	35.7	41.7	38.2	451,405
Source		[194]	[194]	[195]	[193]	[193]	[193]	[35]	[195]	[195]	[196]
Inputs	**Units**										
Bituminous Coal	kg	1.16E-02	1.40E-02	4.21E-02	3.58E-02	3.92E-02	2.63E-02	-	4.58E-02	1.21E-02	1.03E+03
Lignite Coal	kg	2.40E-05	1.66E-03	3.91E-03	3.33E-03	3.65E-03	2.44E-03	-	4.26E-03	1.12E-03	9.33E+01
Distillate oil	l	1.62E-02	2.10E-03	6.11E-03	5.21E-03	5.70E-03	3.82E-03	-	6.66E-03	1.77E-03	3.97E+01
Gasoline	l	8.63E-04	1.45E-03	7.35E-04	6.26E-04	6.85E-04	4.59E-04	-	8.00E-04	6.13E-04	1.36E+00
Kerosene	l	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	-	0.00E+00	0.00E+00	0.00E+00
LPG	l	2.19E-05	2.30E-05	1.06E-03	9.06E-04	9.91E-04	6.64E-04	-	1.16E-03	4.65E-06	1.21E-01
Residual oil	l	3.09E-03	1.65E-02	4.92E-02	4.19E-02	4.59E-02	3.07E-02	-	5.35E-02	1.35E-03	4.35E+01
Natural Gas	m^3	3.66E-03	7.35E-02	5.56E-02	4.74E-02	5.19E-02	3.47E-02	-	6.05E-02	7.43E-02	4.36E+02
Nuclear	kg	2.90E-08	3.83E-08	1.24E-07	1.05E-07	1.15E-07	7.73E-08	-	1.35E-07	3.30E-08	2.74E-03
Wood (or other biomass)	MJ	1.31E-02	1.73E-02	5.59E-02	4.77E-02	5.22E-02	3.50E-02	-	6.09E-02	1.49E-02	1.24E+03
Hydro	MJ	1.25E-02	1.64E-02	5.31E-02	4.53E-02	4.95E-02	3.32E-02	-	5.78E-02	1.42E-02	1.18E+03
Pre-combustion energy use unit		MJ/kg	MJ/kg	MJ/l	MJ/l	MJ/l	MJ/l	MJ/kg	MJ/l	MJ/m^3	MJ/kg
Pre-combustion energy (See Equation 4.18)		1.28E+00	4.09E+00	5.86E+00	4.99E+00	5.46E+00	3.66E+00	-	6.38E+00	3.38E+00	5.38E+03

Water consumption range **[197]**	l/GJ	5-70	5-70	28-72	28-72	28-72	28-72	28-72	28-72	7	29-51
Water consumption	kg	1.05E+00	5.67E-01	1.92E+00	1.39E+00	1.39E+00	1.27E+00	2.23E+00	2.09E+00	2.68E-01	1.81E+04
Outputs	**Units**										
Solid waste	kg	2.21E-01	5.77E-03	4.64E-02	3.95E-02	4.32E-02	2.90E-02	-	5.05E-02	2.57E-02	5.26E+03
Air emissions											
CO_2-eq	kg	1.85E-01	1.37E-01	4.92E-01	4.19E-01	4.59E-01	3.07E-01	-	5.35E-01	4.46E-01	3.86E+03
Sb	kg	1.43E-10	-	5.25E-10	4.47E-10	4.89E-10	3.28E-10	-	5.71E-10	1.49E-10	1.25E-05
As	kg	3.72E-09	-	1.44E-08	1.23E-08	1.34E-08	9.00E-09	-	1.57E-08	3.25E-09	2.45E-04
Be	kg	5.63E-10	-	6.84E-10	5.83E-10	6.38E-10	4.28E-10	-	7.45E-10	2.19E-10	1.38E-05
Cd	kg	9.69E-10	-	3.59E-09	3.06E-09	3.35E-09	2.25E-09	-	3.91E-09	1.48E-09	4.13E-05
CO_2	kg	9.43E-02	1.07E-01	3.93E-01	3.35E-01	3.67E-01	2.46E-01	-	4.28E-01	1.86E-01	3.63E+03
CO	kg	4.34E-04	4.73E-04	1.27E-02	1.08E-02	1.18E-02	7.91E-03	-	1.38E-02	2.18E-04	2.90E+00
Cr	kg	2.53E-09	-	1.04E-08	8.84E-09	9.68E-09	6.49E-09	-	1.13E-08	3.27E-09	1.67E-04
Co	kg	2.77E-09	-	2.24E-08	1.91E-08	2.09E-08	1.40E-08	-	2.44E-08	1.66E-09	8.73E-05
Cu	kg	8.30E-10	-	1.67E-10	1.43E-10	1.56E-10	1.05E-10	-	1.82E-10	1.22E-10	3.06E-06
CH_2O	kg	5.08E-08	-	2.67E-07	2.28E-07	2.49E-07	1.67E-07	-	2.91E-07	3.01E-07	2.36E-03
Pb	kg	7.30E-09	3.13E-08	1.62E-08	1.38E-08	1.51E-08	1.01E-08	-	1.76E-08	3.86E-09	3.04E-04
Mn	kg	1.04E-08	-	4.42E-08	3.76E-08	4.12E-08	2.76E-08	-	4.81E-08	1.02E-08	7.90E-04
Hg	kg	1.28E-09	1.20E-09	2.66E-09	2.26E-09	2.48E-09	1.66E-09	-	2.89E-09	8.82E-10	6.57E-05
CH_4	kg	3.92E-03	1.30E-03	4.19E-03	3.57E-03	3.91E-03	2.62E-03	-	4.56E-03	1.13E-02	9.09E+00
Ni	kg	3.19E-08	-	2.89E-07	2.46E-07	2.69E-07	1.80E-07	-	3.14E-07	1.66E-08	5.87E-04
NO_x	kg	7.34E-04	3.33E-04	3.00E-03	2.56E-03	2.80E-03	1.88E-03	-	3.27E-03	2.62E-04	2.19E+01
N_2O	kg	1.78E-06	1.45E-06	7.23E-06	6.16E-06	6.74E-06	4.52E-06	-	7.87E-06	3.77E-06	8.84E-02
NMVOC	kg	7.45E-07	8.55E-07	2.54E-06	2.17E-06	2.37E-06	1.59E-06	-	2.77E-06	7.30E-07	6.38E-02
PM_{10}	kg	2.01E-05	1.01E-05	7.70E-05	6.56E-05	7.18E-05	4.81E-05	-	8.38E-05	1.31E-05	3.84E-01

PMtotal	kg	1.53E-03	1.31E-04	2.98E-04	2.54E-04	2.78E-04	1.86E-04	-	3.25E-04	2.27E-05	1.88E+01
SO_2	kg	2.58E-04	4.52E-04	1.67E-03	1.43E-03	1.56E-03	1.05E-03	-	1.82E-03	1.94E-02	7.41E+01
VOC (unspecified)	kg	5.05E-05	-	1.19E-04	1.01E-04	1.11E-04	7.43E-05	-	1.29E-04	6.17E-04	3.52E-01
Zn	kg	5.53E-10	-	1.12E-10	9.50E-11	1.04E-10	6.97E-11	-	1.21E-10	8.13E-11	2.04E-06

4.7 Reference Data Pool: Fuel Combustion

This worksheet estimates the combustion-related emissions for various fossil fuels and waste fuels (only for kiln use) used during quarrying raw materials, clinker pyroprocessing, processing of SCMs, and concrete batching. Cement manufacturing accounts for approximately 86 percent of fuel consumption per unit volume of concrete. About 88 percent of the total fuel and 91 percent of the total energy is used during cement pyroprocessing stage [18, 58]. Therefore, the fuel use during pyroprocessing requires further investigation. Cement production requires fuels with high heat content due to elevated combustion temperatures in the kiln. Furthermore, fuels that are available in large quantities at reasonable cost are required to meet the demand by the industry. For these reasons, U.S. cement kilns depend heavily on fossil fuels; that is, about 92 percent of all plants use coal, coke, or some combination of the two as primary kiln fuel [27].

Most cement plants firing coal as primary fuel obtain coal from a local source or from the nearest State. In the U.S., bituminous coal is the most common type. In general, coal mainly consists of carbon, hydrogen, oxygen, nitrogen and sulfur (see Table 4.16). It can contain significant quantities of sulfur, trace metals, and halogens, and their concentrations are dependent on the area in which the coal was mined.

Other fossil fuels utilized in cement kilns include coke, natural gas, and residual (heavy) and distillate (light) oils. Coke is a solid material remaining after the carbonization of coal, pitch petroleum residues, and other similar carbonaceous materials. Coke used in cement kilns is typically petroleum coke. Natural gas is a naturally occurring mixture of hydrocarbon and non-hydrocarbon gases found beneath the earth's surface. Processed natural gas is principally methane, with small amounts of ethane, propane, butane, pentane, carbon dioxide, and nitrogen. Because of its high heat transfer rate, natural gas is used to perform initial firing of kilns at many cement plants. When the kiln reaches operating temperature, the primary fuel is then brought on-line. Natural gas, and oils are considered "cleaner" than coal because they contain less sulfur per amount of energy provided [204]. Regarding the fuel oil use in kilns, the heavier the fuel oil, the lower is the price of a unit of energy. Therefore, #6 (residual or heavy) fuel oil is the commonly used type in cement kilns despite the secondary costs of handling and preheating processes, their higher sulfur and ash content [35].

A cement kiln can also efficiently recover energy from waste without considerable amount of pollution. Because the “high temperatures and long residence time in the kiln destroy virtually all organic compounds, while efficient dust filters may reduce some other potential emissions to safe levels”[205]. As a result, in recent years, the cement industry has been actively investing in alternative (both hazardous and non-hazardous wastes) fuel sources to reduce fuel costs and air pollutants. In 2006, 65 out of 97 U.S. cement plants reported using waste fuels: 48 of them utilize waste tires, 16 waste oil, 10 solvents, 25 other solid waste, and 15 of them reported using other types of waste [26]. Major non-hazardous wastes include used motor oil collected from commercial automobile service establishments, and used oils generated by industrial manufacturing facilities and other types of facilities. Other waste streams that are burned in cement kilns include plastic and carpet wastes, paint residue, waste water treatment sludge (biosolids), and automobile shredder residue. In general, utilization of alternative fuels other than solvents (including hazardous waste solvents) and scrap tires in cement kilns is relatively low. Alternative fuels other than scrap tires and solvents collectively represented 2.5 percent of the total energy (MJ) while scrap tires constituted 3.6 percent of the total energy input to cement kilns in 2006 [205-207]. Despite their benefits, there are some concerns regarding waste fuel use in cement kilns. Cost is an important factor in selection of alternative fuels in cement production. Additionally, cement plants should also consider various technical issues, including materials processing and handling and air emissions control. Materials handling systems designed for one alternative fuel may not be suitable for another type. Finally, regulatory issues can influence waste fuels utilization. Cement plants using alternative fuels may need to obtain special state permits, including solid waste facility permits. Cement kilns using sludge or scrap tires, for example, may be subject to State regulatory requirements to obtain a “solid waste facility” operating permit. Other States, e.g., South Carolina, exempt “recycling” facilities (including facilities burning alternative fuels for energy recovery) from State solid waste facility permit requirements. Cement kilns are also required to conduct air emissions performance test to demonstrate that the use of alternative fuel would not result in an increase in air emissions [206].

Table 4.16 and 4.17 below summarize LCI emission factors and major characteristics of kiln fuels (including both fossil fuels and waste fuels). Some of the combustion-related air emission factors are calculated as follows:

$$\boxed{EF_{COMBUSTIONi\_}CO_2 = C_{FUELi} \times O_{FUELi} \times \left(\frac{44}{12}\right) \times (d_{FUELi})}$$

Equation 4.20: Calculation of CO_2 emission factor for fuel combustion if C, carbon content of fuel, is known (Option 1)

$$\boxed{EF_{COMBUSTIONi\_}CO_2 = HHV_{FUELi} \times CO_{2\_FUELi}}$$

Equation 4.21: Calculation of CO_2 emission factor for fuel combustion if average CO2 emission (kg) per MJ of heating value of fueli is known (Option 2)

$$\boxed{EF_{COMBUSTIONi\_}SO_2 = S_{FUELi} \times \left(\frac{64}{32}\right) \times (d_{FUELi})}$$

Equation 4.22: Calculation of SO2 emission factor for fuel combustion if S, sulfur content of fuel, is known

$$\boxed{EF_{COMBUSTIONi\_}NO_x = N_{FUELi} \times \left[95\%\left(\frac{30}{14}\right) + 5\%\left(\frac{46}{14}\right)\right] \times (d_{FUELi})}$$

Equation 4.23: Calculation of NO_x emission factor for fuel combustion if N, nitrogen content of fuel, is known

$$\boxed{EF_{COMBUSTIONi\_}CH_4 = HHV_{FUELi} \times CH_{4\_FUELi}}$$

Equation 4.24: Calculation of CH4 emission factor for fuel combustion if average CH_4 emission (kg) per MJ of heating value of fuel “i” is known

Where:

$EF_{COMBUSTIONi\_}CO_2$ = CO_2 emission factor for combustion of fuel “i”, in kg of CO_2 per unit mass (kg) or unit volume (l or m^3) of fuel “i” depending on the type of fuel;

$EF_{COMBUSTIONi\_}SO_2$ = SO_2 emission factor for combustion of fuel “i”, in kg of SO_2 per unit mass (kg) or unit volume (l or m^3) of fuel “i” depending on the type of fuel;

$EF_{COMBUSTIONi\_}NO_x$ = NO_x emission factor for combustion of fuel “i”, in kg of NO_x per unit mass (kg) or unit volume (l or m^3) of fuel "i" depending on the type of fuel;

$EF_{i}\_CH_4$ = CH_4 emission factor for combustion of fuel "i", in kg of CH_4 per unit mass (kg) or unit volume (l or m^3) of fuel "i" depending on the type of fuel;

C_{FUELi} = Total carbon content of fuel "i" by percentage of its mass and listed below in Tables 4.16 and 4.17, in %;

O_{FUELi} = Percent oxidation of fuel "i' when combusted, in % and assumed to be 100% based on IPCC report [34];

(44/12) = Ratio of molecular weight of CO_2 to that of C, unitless;

(64/32) = Ratio of molecular weight of SO_2 to that of S, unitless;

(30/14) = Ratio of molecular weight of NO to that of N, unitless;

(46/14) = Ratio of molecular weight of NO_2 to that of N, unitless;

d_{FUELi} = Density of liquid fuel "i", in kg/l;

HHV_{FUELi} = Higher heating value of fossil fuel or waste fuel "i", in MJ per unit mass (kg) or unit volume (l or m^3) of fuel "i" depending on the type of fuel (see Tables 4.16 and 4.17);

CO_{2_FUELi} factor = Average CO_2 emission factor with respect to HHV of fuel "i", in kg of CO_2 per MJ of fuel. This factor is used when C (%) data is unavailable;

CH_{4_FUELi} factor = Average CH_4 emission factor with respect to HHV of fuel "i", in kg of CH_4 per MJ of fuel. This factor is used when fuel combustion CH_4 emission in kg per mass or volume of fuel is unavailable.

According to EPA data [208-210], generally, 95 percent or more of NO_x present in combustion exhaust will be in the form of NO and the rest is NO_2. Therefore, in the calculations, NO_x is assumed to be composed of 95 percent NO_x and 5 percent NO_2. Regarding SO_2 calculations, SO_2 emissions are assumed to be proportional to the sulfur content of fuel (by percent weight) and not to be affected by boiler size, burner design, or fuel type based on EPA AP-42's statement. It is also assumed that 100 percent of S in fuel is converted to SO_2 after combustion [209, 210].

Numerous other data assumptions are made in calculating combustion LCI data. Trace elements data and associated emissions of As, Be, Cd, Cr, Co, Pb, Mn, Hg, Ni, and Se are assumed to be same for bituminous and lignite coal types based on IPPC report [23]. In the US, energy calculations associated with fuel use involve higher (gross) heating values. As mentioned in the previous Section 4.6, HHV data for fossil fuels are obtained mostly from US sources including [193-195]. On the other hand, due to lack of US database for waste fuels, associated heating values and elemental analysis of fuels are based on European sources [23, 25, 211]. However, EU sources provide lower (net) heating values. According to OECD/EIA report [212], the difference between net and gross heating values are typically about 5 to 6 percent of the gross value for solid and liquid fuels, and about 10 percent for natural gas.

Table 4.16: GreenConcrete "Reference Data Pool" Worksheet _Combustion Characteristics and Life-Cycle Inventory Data for Conventional Fossil Fuels Used throughout the Tool

		Bituminous coal	Lignite coal	Petroleum coke	Natural gas	Residual (heavy) fuel oil	Distillate (diesel or light) fuel oil	Gasoline
Source		[34, 208, 211, 213-215]	[34, 208, 216]	[35, 217]	[34, 35, 209, 216]	[35, 210]	[35, 210, 216]	[34, 215, 217-219]
Unit		kg	kg	kg	m^3	l	l	l
HHV (MJ per unit)		27.91	15.12	35.70	38.23	41.72	38.32	27.87
Density, liquid fuels	kg/l	-	-	0.80	-	0.95	0.84	-
Oxidation, O	%	100	100	100	100	100	100	100
Elemental Analysis of Fuels								
C (total)	%	72.25	66.90	86.57	-	85.70	86.50	-
H	%	4.90	4.70	3.25	-	11.20	13.60	-
O	%	9.30	19.04	-	-	-	-	-
N	%	1.40	1.30	1.67	-	0.37	0.005	-
S	%	1.00	0.80	5.50	-	2.10	0.095	-
Chlorine (Cl)	%	-	-	-	-	-	-	-
Fluorine (F)	%	-	-	-	-	-	-	-
Ash (solid waste)	%	9.00	7.30	0.40	-	-	0.01	-
H_2O	%	8.00	33.70	6.28	-	2.00	0.05	-
Volatiles	%	32.10	29.20	11.18	-	-	-	-
CO_2 per HHV of fuel	kg/MJ	9.49E+01	1.96E+02	8.89E+01	5.10E+01	7.14E+01	6.87E+01	6.93E+01
CH_4 per HHV of fuel	kg/MJ	9.48E-06	9.48E-06	-	8.53E-07	-	2.84E-06	3.00E-06
Solid waste	kg	9.00E-02	7.30E-02	4.00E-03	-	-	1.00E-04	-
Air Emissions								
CO_2-eq	kg	2.66E+00	2.47E+00	3.68E+00	1.94E+00	3.00E+00	2.66E+00	2.42E+00
Sb	kg	8.16E-09	8.16E-09	-	-	6.17E-07	-	-
As	kg	1.86E-07	1.86E-07	-	3.20E-09	1.55E-07	1.72E-09	-
Be	kg	9.53E-09	9.53E-09	-	1.92E-10	3.27E-09	1.29E-09	-
Cd	kg	2.31E-08	2.31E-08	-	1.76E-08	4.68E-08	1.29E-09	-
CO_2	kg	2.65E+00	2.45E+00	3.59E+00	1.94E+00	2.99E+00	2.65E+00	2.32E+00
CO	kg	2.27E-04	2.27E-04	1.43E-03	1.35E-03	5.99E-04	5.99E-04	1.35E-01

Cr	kg	1.18E-07	1.18E-07	-	2.24E-08	9.94E-08	1.29E-09	-
Co	kg	4.54E-08	4.54E-08	-	1.35E-09	7.08E-07	-	-
Cu	kg	-	-	-	1.36E-08	2.07E-07	2.58E-09	-
CH_2O	kg	1.09E-07	1.09E-07	-	1.20E-06	3.95E-06	5.75E-06	1.77E-05
Pb	kg	1.91E-07	1.91E-07	-	8.01E-09	1.78E-07	3.87E-09	-
Mn	kg	2.22E-07	2.22E-07	-	6.09E-09	3.53E-07	2.58E-09	-
Hg	kg	3.76E-08	3.76E-08	-	4.16E-09	1.33E-08	1.29E-09	-
CH_4	kg	9.48E-06	9.48E-06	5.36E-05	8.53E-07	-	2.84E-06	3.00E-06
Ni	kg	1.27E-07	1.27E-07	-	3.36E-08	9.94E-06	1.29E-09	-
NO_X	kg	2.60E-02	2.41E-02	1.55E-02	1.92E-03	7.23E-03	1.11E-04	3.35E-02
N_2O	kg	4.08E-05	4.08E-05	3.03E-04	1.03E-05	6.35E-05	3.12E-05	3.34E-04
NMVOC	kg	4.99E-05	2.34E-05	5.36E-05	9.20E-05	3.36E-05	2.40E-05	6.97E-05
PM_{10}	kg	-	-	-	-	-	-	
PMtotal	kg	-	-	-	-	-	-	2.65E-04
SO_2	kg	2.00E-02	1.60E-02	1.55E-02	-	4.42E-02	2.28E-03	5.01E-04
VOC (unspecified)	kg	7.14E-05	6.43E-05	-	8.81E-05	1.20E-04	6.23E-06	2.84E-03
Zn	kg	-	-	-	4.65E-07	3.42E-06	1.72E-09	-

Table 4.17: GreenConcrete “Reference Data Pool” Worksheet - Combustion Life-Cycle Inventory Data for Waste Fuels Used for Pyroprocessing

		Waste_ oil	Waste_ solvent	Waste_ tire (whole)	Waste_ tire (shredded)	Waste_ paper, cardboard	Waste_ plastics	Waste_ sewage sludge	Waste_ other hazardous	Waste_ other non-hazardous
Source		[21, 23]	[21, 23]	[21, 211, 216]	[21, 211, 216]	[21, 23]	[21, 23, 211]	[20, 23]	[21]	[25]
Unit		kg	kg	kg	kg	kg	kg	kg	kg	kg
HHV (MJ per unit)		32.03	29.40	31.40	37.26	9.98	29.93	11.03	31.31	18.76
Oxidation, O	%	100	100	100	100	100	100	100	100	100
Elemental analysis										
C (total)	%	65.50	45.35	71.50	71.50	44.38	57.20	27.03	61.00	40.50
H	%	10.05	8.15	7.17	7.17	5.02	5.25	4.00	5.50	5.00
O	%	1.70	19.34	7.90	7.90	34.49	8.30	12.64	14.50	17.67
N	%	0.00	1.04	0.50	0.50	0.10	1.44	3.54	0.59	0.20
S	%	0.60	0.00	1.44	1.44	0.23	0.27	0.41	1.00	0.68

Chlorine (Cl)	%	0.26	0.00	0.08	0.08	0.18	0.15	0.04	0.51	0.10
Fluorine (F)	%	-	-	-	-	-	-	-	-	-
Ash (solid waste)	%	5.22	8.50	9.08	9.08	0.60	10.23	38	4.79	16.70
H_2O	%	15.10	17.50	1.00	1.00	15.00	16.82	8.00	11.60	16.30
Volatiles	%	-	-	-	-	-	-	-	-	-
CO_2 per HHV of fuel	kg/MJ	7.61E+01	5.66E+01	8.35E+01	7.04E+01	1.63E+02	7.01E+01	8.99E+01	7.14E+01	7.91E+01
CH_4 per HHV of fuel	kg/MJ	-	-	2.84E-06	2.84E-06	-	-	-	-	-
Solid waste	kg	5.22E-02	8.50E-02	9.08E-02	9.08E-02	6.00E-03	1.02E-01	3.80E-01	4.79E-02	1.67E-01
Air Emissions										
CO_2-eq	kg	2.44E+00	1.66E+00	2.62E+00	2.62E+00	1.63E+00	2.10E+00	9.91E-01	2.24E+00	1.49E+00
Sb	kg	5.51E-09	-	-	-	-	-	-	-	-
As	kg	2.56E-09	3.63E-09	6.91E-09	6.91E-09	3.70E-08	8.30E-10	5.30E-09	5.60E-09	6.20E-09
Be	kg	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Cd	kg	3.32E-09	3.12E-09	1.24E-08	1.24E-08	2.50E-10	9.50E-10	1.57E-09	1.83E-09	1.54E-09
CO_2	kg	2.44E+00	1.66E+00	2.62E+00	2.62E+00	1.63E+00	2.10E+00	9.91E-01	2.24E+00	1.49E+00
CO	kg	-	-	-	-	-	-	-	-	-
Cr	kg	1.29E-08	8.29E-08	2.89E-08	2.89E-08	4.20E-08	8.30E-09	7.10E-08	8.23E-09	8.00E-08
Co	kg	4.72E-09	9.54E-09	1.77E-08	1.77E-08	1.00E-09	9.38E-09	7.33E-09	5.96E-09	1.95E-08
Cu	kg	7.10E-08	1.97E-07	7.00E-08	7.00E-08	4.40E-08	1.03E-07	3.58E-07	4.76E-08	2.69E-07
CH_2O	kg	-	-	-	-	-	-	-	-	-
Pb	kg	2.53E-08	1.45E-07	2.14E-08	2.14E-08	7.00E-09	3.79E-08	0.00E+00	4.02E-08	1.25E-07
Mn	kg	1.54E-08	1.31E-08	1.66E-07	1.66E-07	4.00E-08	4.32E-08	3.21E-07	9.50E-09	2.68E-07
Hg	kg	4.20E-10	8.20E-10	2.70E-10	2.70E-10	2.00E-11	2.00E-11	8.90E-10	1.83E-08	4.00E-10
CH_4	kg	-	-	2.84E-06	2.84E-06	-	-	-	-	-
Ni	kg	1.69E-08	4.43E-08	5.80E-09	5.80E-09	2.50E-09	3.65E-09	3.37E-08	4.96E-09	3.67E-08
NO_X	kg	0.00E+00	1.93E-02	9.29E-03	9.29E-03	1.86E-03	2.67E-02	6.57E-02	1.10E-02	3.71E-03
N_2O	kg	-	-	-	-	-	-	-	-	-
NMVOC	kg	-	-	-	-	-	-	-	-	-
PM_{10}	kg	-	-	-	-	-	-	-	-	-
PMtotal	kg	-	-	-	-	-	-	-	-	-
SO_2	kg	1.20E-02	0.00E+00	2.88E-02	2.88E-02	4.60E-03	5.40E-03	8.20E-03	2.00E-02	1.36E-02
VOC (unspecified)	kg	-	-	-	-	-	-	-	-	-
Zn	kg	2.90E-07	6.30E-07	1.13E-05	1.13E-05	9.10E-08	2.15E-07	8.68E-07	9.74E-07	5.43E-07

4.8 Reference Data Pool: Electricity Grid Mix

Electricity is used during all stages of concrete, cement and other raw materials production. “Electricity Grid Mix Data Pool” provides data for LCI calculations of electricity generation by fuel type, by state. The grid mix data is modified from the Energy Data System (SEDS) which is developed by the U.S. Energy Information Administration (EIA) [192, 220, 221]. EIA estimates the energy consumption data from existing surveys of energy suppliers that report consumption, sales, or distribution of energy at the State level. Direct NO_x, CO_2, SO_2, CH_4 and N_2O emissions from power plants are based on the e-GRID2012 (with the 2009 data). However, direct LCI of all other emissions and total supply-chain effects of electric power generation for both U.S. states and user-defined electricity mixes are calculated based on numerous studies. Following chapters describe major LCA studies used in these calculations (see Table 4.18). The table below provides fuel-related emission factors used in the tool.

Table 4.18: Electric Power Generation Life-Cycle Assessment Literature Review

Study by Name and Year	Location	Energy Source	Direct Effects	Direct + Indirect Effects
NREL LCI Database (2012) **[222-226]**	US	Coal, Lignite, Distillate, Residual, Biomass	Solid waste, GWP, Sb, As, Be, Cd, CO_2, CO, Cr, Co, Cu, CH_2O, Pb, Mn, Hg, CH_4, Ni, NO_x, PM_{10}, PMtotal, Se, SO_2, VOC	-
US EPA WEBFIRE (2012) **[227]**	US	Petcoke, Natural Gas	GWP, Be, Cd, CO_2, CO, Cr, Co, Ni, NO_x, N_2O, NMVOC, PM_{10}, PMtotal, SO_2, VOC	-
Santoyo-Castelazo et al. (2011) **[228]**	Mexico	Coal, Distillate, Residual, Natural Gas, Geothermal, Hydro, Wind	GWP, CO_2, CH_4, NO_x, N_2O, NMVOC, PMtotal, SO_2	GWP, CO_2, CH_4, NO_x, N_2O, NMVOC, PMtotal, SO_2,
Raadal et al. (2011) **[229]**	Worldwide	Hydro (reservoir and river systems), Wind (on- and off-shore turbines)	-	GWP
Fthenakis and Kim (2010) **[230]**	US (CA)	Coal, Lignite, Distillate, Residual, Natural Gas, Biomass, Geothermal (dry and water systems), Hydro, Solar, Wind	Water consumption	Water consumption
Ribeiro and da Silva (2010) **[231]**	Brazil (Itaipu)	Hydro (reservoir)	Solid waste, CO_2, CO, Hg, Pb, CH_4, NO_x, N_2O, PMtotal, SO_2, VOC	Solid waste, CO_2, CO, Hg, Pb, CH_4, NO_x, N_2O, PMtotal, SO_2, VOC
Evans et al. (2009) **[232]**	World-wide	Coal, Natural Gas, Geothermal, Hydro, Solar, Wind	-	Water consumption, GWP
Ardente et al. (2008) **[233]**	EU (Sicily)	Nuclear, Hydro, Wind	-	Energy use (for wind only), GWP
Odeh and Cockerill (2008) **[234]**	UK	Coal, Natural Gas	-	Energy use, GWP, NO_x, PMtotal, SO_2

Deru and Torcellini (2007) **[193]**	US	Coal, Lignite, Distillate, Petcoke, Residual, Natural Gas, Nuclear	-	Energy use
Kone and Buke (2007) **[235]**	Turkey	Lignite, Natural Gas, Nuclear, Biomass, Geothermal, Hydro, Solar, Wind	-	CO_2, CH_4, NO_x, SO_2
Dinca et al. (2007) **[236]**	Romania	Natural Gas	Energy use, CO_2, CO, CH_4, NO_x, PM_{10}, SO_2	CO_2, CO, CH_4, NO_x, PM_{10}, SO_2
Kagel et al, (2007) **[237]**	US	Geothermal	CO_2, NO_x, PMtotal, SO_2	
Pehnt (2006) **[238]**	EU (Germany)	Geothermal, Hydro (river system), Solar, Wind	-	Energy use (except for geothermal), CO_2, CO, CH_4, NO_x, N_2O, NMVOC, PMtotal, SO_2
Hondo (2005) **[239]**	Japan	Coal, Residual, Geothermal, Hydro, Solar, Wind	GWP	GWP
Kannan et al. (2005) **[240]**	Singapore	Natural Gas	GWP	Energy use, GWP, CO_2, CH_4, N_2O
World Energy Council (2004) **[241]**	US, Worldwide	Coal, Lignite, Residual, Natural Gas, Nuclear, Hydro (reservoir and river systems), Biomass, Solar, Wind	-	GWP, NO_x, PMtotal, SO_2
Spath and Mann (2004) **[242]**	US	Coal, Natural Gas, Biomass	-	GWP
Corti and Lombardi (2004) **[243]**	EU (Italy)	Coal, Biomass	GWP	GWP
Lee et al. (2004) **[244]**	Korea	Coal, Distillate, Natural Gas, Nuclear, Hydro	CO_2, NO_x, PMtotal, SO_2	CO_2, NO_x, PMtotal, SO_2
Kannan et al. (2004) **[245]**	Singapore	Residual	GWP	Energy use, GWP, CO_2, CH_4, N_2O
Gagnon et al. (2002) **[246]**	Northeastern region of North America	Coal, Distillate, Residual, Natural Gas, Nuclear, Hydro (reservoir), Solar, Wind	-	CO_2, Hg, NO_x, NMVOC, PMtotal, SO_2
Meier (2002) **[247]**	US (Colorado)	Natural Gas, Nuclear, Biomass, Solar (PV)	GWP	GWP
Pacca and Horvath (2002) **[248]**	US (arid south-west)	Coal, Natural Gas, Hydro, Solar, Wind	-	GWP
Rashad and Hammad (2000) **[249]**	Worldwide	Coal, Nuclear, Solar, Wind	GWP	GWP, NO_x, PMtotal, SO_2 (vary with the energy source)
Spath and Mann (2000) **[203]**	US	Natural Gas	Energy use, GWP, CO_2, CO, CH_2O, CH_4, NO_x, N_2O, NMVOC, PMtotal, SO_2	Energy use, Solid waste, GWP, CO_2, CO, CH_2O, CH_4, NO_x, N_2O, NMVOC, PMtotal, SO_2
Spath et al. (1999) **[202]**	US	Coal	Energy use, Solid waste, GWP, Sb, As, Be, Cd, CO_2, CO, Cr, Co, Cu, Pb, Mn, Hg, CH_4, Ni, NO_x, N_2O,	Energy use, Solid waste, GWP, Sb, As, Be, Cd, CO_2, CO, Cr, Co, Cu, Pb, Mn, Hg, CH_4, Ni, NO_x, N_2O,

			NMVOC, PMtotal, Se, SO_2	NMVOC, PMtotal, Se, SO_2
Mann and Spath (1997) **[250]**	US	Biomass		
Gagnon and van de Vate (1997) **[251]**	Worldwide	Hydro	-	GWP

Notes: For fuels - Coal: bituminous coal; Distillate: distillate (diesel or light) fuel oil: Petcoke: petroleum coke; Residual: residual (heavy) fuel oil
For life-cycle inventories: CH_2O: formaldehyde and see previous tables for other air emissions abbreviations and complete names.

4.8.1 Electric Power Generation LCA Literature Review

When available, the U.S. electricity grid mix data is used in the tool. However, in case if there is no U.S. data for a specific type of power generation technology or LCI category data, international sources are utilized to fill the data gap. For this reason, in addition to U.S. sources, other non-U.S. sources are explained in following pages.

As a general approach, most of the fossil fuel LCAs involves more or less similar life-cycle stages which consist of extraction of fuels and raw materials, processing and transportation of fuels; manufacture and construction of infrastructure; operation of power plants to generate electricity; construction and decommissioning of power plants; and waste disposal. A common feature of the traditional energy sources is that the GHG and other atmospheric emissions arise mainly from the power generation. On the other hand, when renewables are used in electricity generation, emissions arise from stages other than power generation, e.g. construction of wind turbines is the major source of emissions rather than the power generation phase.

4.8.1.1 Electric Power Generation from Bituminous (Hard) Coal

Major data sources for the U.S. LCI of electric power generation from coal consist of various NREL databases and reports [193, 202, 223, 242], an EIA/DOE report [192], and peer-reviewed journal papers [230, 248].

The NREL LCI database [223] examines direct LCI emission factors as well as solid waste per kWh of electricity generated from bituminous coal. Nonetheless, it is limited to only life-cycle stages of transportation of coal to the power plant and combustion of fuel to generate electricity with no consideration of fuel mining, construction and decommissioning of power plants. Data represent national averages for US electricity generation and are generally outdated from 1990s and beginning of 2000s.

Among major US sources, Spath et al. [202] is the most comprehensive of all in terms of direct and supply-chain LCI factors (energy use, solid waste, and air emissions listed in Table 4.18) covered. In this study, life-cycle stages consist of coal mining (both surface and underground), transportation, and preparation of coal, and operation, construction and decommissioning of a coal power plant. Authors examined three systems: 1) a plant that represents the average emissions and efficiency of currently operating coal-fired power plants in the U.S., 2) a new coal-fired power plant that meets the New Source Performance Standards (NSPS), and 3) a highly advanced coal-fired power plant utilizing a low emission boiler system (LEBS). All three power plants were assumed to use Illinois No. 6 coal, excavated from a mine located in central Illinois. The sizes of the Average, NSPS, and LEBS power plants are 360 MW, 425 MW, and

404 MW, respectively, and each plant was assumed to operate at a 60% capacity. However, data in this source goes back to 1980s and 1990s.

Another NREL report by Spath and Mann [242] is limited to total (direct plus supply-chain) energy use and GWP factors for a 600 MW pulverized-coal power plant. The LCA system consists of coal mining, transportation, and power plant operation. Data is yet outdated.

Deru and Torcellini [193] provides the source energy factor for electricity from U.S. coal power plants. Authors determined this factor by assuming an efficiency of 33% for electricity generation.

As opposed to the NREL sources discussed in previous paragraphs, EIA/DOE data is comparably up-to-date [192]. However, it is limited to direct emission factors of CO_2, CH_4, N_2O, NO_x, and SO_2 of U.S. coal power plants.

In addition to NREL and EIA/DOE sources, one U.S. study provides LCI data for coal power plants in certain regions. Pacca and Horvath [248] focus on Colorado river basin but emissions from variations in technology and design of coal power plants are not site-specific. Authors examined total GHG emissions from constructing (inputs of concrete, steel, and aluminum) and operation (including coal extraction, transportation by railroad, and coal combustion) of a coal power plant with a 1000 MW power, with 5.55 TWh per year capacity over a service life of 20 years.

The Canadian LCA by Gagnon et al.[246] provides total LCI emission factors of CO_2, Hg, NO_x, NMVOC, PMtotal, SO_2 within a “cradle-to-grave” system boundary. The focus is on an existing coal power plant without SO_2 scrubbing in north-eastern region of North America and coal has one percent of sulfur content. Authors also provided data for coal plants with SO_2 scrubbing to show how SO_2 can be reduced by certain technologies.

International studies vary in terms of geography and design of power plants: World Energy Council (WEC) [241] examine coal power plants in Australia, EU, and U.S. and provide total emission factors for each fuel cycle. In the study, WEC expressed the total greenhouse gas emissions as kg of CO_2 equivalent per kWh of electricity produced. The total emissions of NO_x, SO_2 and particulates are also included. Three scenarios for the U.S. coal power plants are: 1) With low-NO_x burner (average case); 2) With copper oxide process P(CuO) that removes both SO_2/ NO_x from flue gases; 3) With CO_2 sequestration, a hypothetical case of 90% of the CO_2 is captured from flue gas by chemical absorption and is transported by a 300 km pipeline into an underground disposal site. Five scenarios exist for Australian coal power plants: 1) With pulverised firing and PM emission control (fabric filters) but no control for SO_2/NO_x; 2) With pressurised fluidised bed combustion (PFBC) and emission control for SO_2/NO_x and PM; 3) With integrated gasification combined cycle (IGCC) and emission control for SO_2/NO_x, PM control; 4) With coal gasification, where the hydrogen (H_2) produced operates a solid oxide fuel cell (SOFC); 5) With IGCC and carbon dioxide recovery, a hypothetical case of 90% of the CO_2 is captured, compressed and disposed of in deep sea aquifers. The EU and UK cases represent coal power plant designs with flue gas desulphurisation (FGD) either with or without low-NO_x burners or selective catalytic reduction (SCR). Other combustion processes assessed include: atmospheric fluidised bed combustion (AFBC), PFBC, and IGCC. For particle control, either electrostatic precipitators or fabric filters are used in these cases. WEC report is the most comprehensive report that applies LCA to different power plant technologies.

Similar to WEC report [241], a recent study by Odeh and Cockerill [234] assess total life-cycle energy use, and emissions of GHG, NO_x, particulates and SO_2 for five different UK coal power plant scenarios. Authors consider two technologies, namely supercritical pulverized coal (super-PC) and coal-based integrated gasification combined cycle (IGCC). Analysis is conducted for each of the two technologies with and without carbon capture and sequestration (CCS), and the results are compared with those from a sub-critical coal power plant. All five types of power plants are equipped with NO_x, particulates and SO_2 removal processes (i.e. selective catalytic reduction, SCR, electrostatic precipitation, ESP and flue gas desulfurization, FGD).

Another European study by Corti and Lombardi [243] focus on GHG emissions from coal power plants. Authors particularly analyzed an integrated gasification combined cycle (IGCC), reflecting the present technology of coal gasification systems, including particulate removal system but not H_2S removal system (due to low sulfur content in the feeding biomass), coupled with a gas turbine combined cycle with a CO_2 chemical absorption process, which is a recent technology. They compared specific CO_2 emission findings (0.167 kg CO_2/kWh) with other coal power technologies including a conventional coal IGCC without CO_2 removal (0.700 – 0.790 kg CO_2/kWh), a coal IGCC with CO_2 removal (0.075 - 0.130 kg CO_2/kWh), pulverised coal (PC) conventional steam cycle (0.800 kg CO_2/kWh), PC with CO_2 chemical absorption (0.100 kg CO_2/kWh), PC with CO_2 membrane separation (0.250 kg CO_2/kWh), and coal IGCC with shift reaction and CO_2 chemical absorption (0.40 kg CO_2/kWh).

In addition to U.S. and EU sources, the literature incorporates studies from other parts of the world. Santoyo-Castelazo et al. [228] assessed direct and total life-cycle emissions of CO_2, CH_4, NO_x, N_2O, NMVOC, particulates, and SO_2 for average coal power plants in Mexico. Authors considered the following life cycle stages in their “cradle-to-grave” LCA: When calculating direct emissions, authors considered fuel composition, power plant capacity and efficiency, and emissions control techniques. Accordingly, major assumptions consist of: 1) The average sulfur content in domestic coal is 1 percent, 0.5 percent in imported coal, 2) Coal-fired steam turbine technology is commonly used; 3) Since emission control is not compulsory in Mexico, power plants are assumed to have no control for NO_x/SO_2, exception is PM control by electrostatic precipitators.

Hondo [239] examines “cradle-to-grave” GHG emissions from an average Japanese coal-fired power plant with a capacity of 1000 MW and lifetime of 30 years. The power plant has selective catalytic reduction (SCR) and flue gas desulphurization (FGD) installations. Life-cycle stages consist of mining, transportation, construction, operation and ash disposal, resulting in 0.975 kg-CO_2-eq per kWh. Similarly, Lee et al. [244] apply LCA to analyze direct and total emissions of CO_2, NO_x, PMtotal, and SO_2 for coal power plants in Korea.

Finally, Rashad and Hammad [249], despite focusing on nuclear power plants, compared full supply-chain LCI of different sources of electric power, including pulverized coal in terms of air emissions of CO_2-eq, NO_x, PMtotal, and SO_2 and radioisotopes. Authors present their results by ranges of emissions for each type of electric power source based on literature. In addition to, LCI results, one can get a sense of cost of electric power plants and range of their net generation efficiencies.

It is essential to note that GreenConcrete LCA tool makes use of average U.S. data for calculating both direct and indirect imapacts of electricity generation from bituminous coal. However, international data sources have substituted the U.S. numbers when the U.S. data has been missing.

4.8.1.2 Electric Power Generation from Lignite

NREL LCI database [225] provides direct LCI data for electric power generation from lignite power plants with an efficiency of 35%. Emission factors represent the U.S. average values. Deru and Torcellini [193] is the only source of primary energy use factor for total life-cycle impact calculations.

Since NREL LCI database lacks total life-cycle emission factors (and limited to only direct ones), international data sources [235, 241] are applied to fill these gaps. World Energy Council [241] examines three cases of electric power generation from lignite and the tool uses the average of these three: 1) A 2000-MW lignite power plant with no SO_2/NO_x control in Australia; 2) A 800-MW lignite power plant with flue gas desulfurization (FGD) in Germany; and 3) A 330-MW lignite power plant in Greece which utilizes lignite ash for FGD. In this case, SO_2 emissions vary considerably due to various uncontrollable parameters of the system. This study provides total (direct and supply-chain) LCI factors for CO_2, NO_x, PMtotal, and SO_2.

Turkish electricity generation LCA study by Kone and Buke [235] examine total LCI factors for emissions of CO_2, CH_4, NO_x, and SO_2 from coal power plants. Coal represents the combination of mostly lignite (about 85%) and hard coal (15%). Therefore, factors from this study are reserved for calculations associated with lignite power plants.

In calculating total (direct+indirect) LCI from lignite power plants, international data sources are used [235, 241] as the U.S. database [225] lacks such LCI data.

4.8.1.3 Electric Power Generation from Distillate Fuel Oil, Residual Fuel Oil, and Petroleum Coke

NREL LCI database is the only U.S. source [224, 226] that examines direct LCI emission factors as well as solid waste per kWh of electricity generated from distillate and residual fuel oils but not for petroleum coke. For both electric power sources, 35% of net generation efficiency is assumed. Although, NREL data is representative of US average conditions, it is based on outdated data from EPA and EIA going back to 1990s. Deru and Torcellini [193] provides primary energy use factors for all petroleum-based sources including petroleum coke, distillate and residual fuel oils.

The WebFIRE database contains EPA’s recommended emissions factors for GHG, criteria and major hazardous air pollutants (HAP) for industrial and non-industrial processes. GreenConcrete LCA tool makes use of only WebFIRE’s direct emission factors for petroleum coke used in electricity generation which belongs to external combustion boilers – electricity generation category in the WebFIRE. The tool lacks total LCI data for petcoke power plants due to lack of literature. However, the Excel tool holds a place for inserting supply-chain LCI data for petcoke as part of the future research.

In addition to the U.S. sources, Gagnon et al. [246] examines total LCI (CO_2-eq, Hg, NO_x, NMVOC, PMtotal, SO_2) for electricity generation from distillate and residual fuel oils with sulfur contents of 0.25 percent and 1.5 percent, respectively. The focus is the northeastern section of North America. For residual fuel oil, the sytem is assumed to have no SO_2 scrubbing. For this reason, SO_2 emissions from residuals are eight times larger compared to distillates while NO_x from residuals is, conversely, six times less. Another striking difference is the emissions of NMVOC and particulates: distillates produce two to three orders of magnitude more emissions compared to the residuals. On the other hand, CO_2-eq emissions from both sources are similar (average 0.8 kg per kWh).

In addition to U.S. data sources, the tool utlizes total emission factors from a number of international studies. Santoyo-Castelazo et al. [228] provide direct and total life-cycle emissions of CO_2, CH_4, NO_x, N_2O, NMVOC, particulates, and SO_2 for both distillate and residual fuel oils. The study assumes that: 1) Sulfur content of residuals and distillates are 3.6 percent and 0.5 percent, respectively.

Lee et al. [244] examine the full electricity generation system of distillates with the fuel cycle and the construction of the plant in calculating major emissions of CO_2, NO_x, PMtotal, SO_2. Emission factors represent national averages for Korea.

Residuals, which are more commonly used in power plants, are covered by a number of non-US LCAs [239, 241, 245]. The Japanese study by Hondo [239] provides direct and total GHG emission factor for a typical 1000 MW residual fuel oil power plant with 36.2% net thermal efficiency and 30 years of life-time. Similar to Japanese coal power plants, oil power plants also use SCR and FGD. The system boundary consists of extracting from wells, transporting of crude oil by pipelines to Japanese refineries from importing countries, processing of crude in refinery plants, transporting the residual fuel oil by oil tankers to power plants, construction and operation of the plant during power generation. Total GHG emission from this LCA results in 0.742 kg CO_2-eq per kWh of electricity.

Kannan et al. [245] conducted a comprehensive cradle-to-grave LCA and LCCA (Life-Cycle Cost Analysis) to calculate direct and total GHG emissions and specific energy use for a typical oil-fired steam turbine plant with 250 MW capacity, 33% net efficiency, and 25 years of operation in Singapore. Life-cycle stages include fuel cycle (which starts with crude oil extraction, transportation to refinery, refining, and transportation to power plant), construction of power plant (including construction materials production, plant equipment production, their transportation to the plant, construction of plant), operation, and decommissioning (waste disposal, metal recycling and so on). Additionally, authors conducted sensitivity analysis to understand the effects of change in plant efficiencies (one percent incremental change from 20 to 40 percent plant efficiencies), change in plant lifetime and load factor (20-25-30 years of lifetime and 10 percent increase in annual load factor), material use for plant equipment (what if 30 % more material is used), energy use for water use (imported water vs. desalinated or recovered from waste water). They also studied two scenarios of importing oil from Middle East countries vs. importing from nearby regions to calculate potential reductions in energy use and GHG emissions.

Finally, World Energy Council [241] provides total emission factors for various residual fuel oil-fired plants. The EU case represents average of existing power plants with low-NO_x burners in different regions of Europe. Results from these plants demonstrate varying SO_2 emissions depending on the sulfur content of fuel while other emissions of GHG, NO_x, and particulates are in close proximity. Additionally, the report provides emission factors for a hypothetical UK plant with combined cycle with flue gas desulphurisation (FGD).

4.8.1.4 Electric Power Generation from Natural Gas

Despite the considerable number of national and international studies, mainly two U.S. sources feed data into the GreenConcrete for natural gas power plants. Direct LCI is mostly from EPA WebFIRE [227] and total (direct and supply-chain effects are given separately) LCI is from Spath and Mann [203]. Emission factors (see Table 4.18 for the list) associated with natural gas used in electric power plants is displayed under the category of “external combustion boilers – electricity generation” in WebFIRE. The database consists of EPA’s AP-42 data which is considerably old.

Spath and Mann [203] performed an LCA for a natural gas combined-cycle (NGCC) power generation system with 505 MW capacity and with 48.8% net thermal efficiency. The plant includes selective catalytic reduction (SCR) and water injection systems. The system boundary covers construction and decommissioning of the power plant, construction of the natural gas pipeline, natural gas production and distribution, ammonia production and distribution for NO_x removal, and power plant operation. Results from this study showed that CO_2 accounts for 99% by weight of total air emissions over the life-cycle of NGCC power generation system. Following the CO_2, the next highest emissions, in order of decreasing amount, include CH_4, non-methane hydrocarbons, NO_x, SO_2, CO, particulates, and benzene. In addition to air emissions, authors examined direct and total energy use factors and total solid waste from NGCC system. About 94% of the solid waste was found to be from natural gas production and distribution. In the study, a sensitivity analysis was conducted to understand the effects of variations from the base case NGCC system assumptions. Variables in the sensitivity analysis include: materials requirement for pipelines, natural gas losses, operating capacity factor, power plant efficiency, and NO_x emissions above or under the base case. A more recent study by Spath and Mann [242] compares total GHG emissions from coal-fired and NGCC power systems. The base NGCC system is identical to the former study’s case [203]. Nevertheless, the newer version considers a NGCC plant with CO_2 sequestration Similarly, WEC [241] examines two hypothetical cases of NGCC power plants. The first case of power plant uses a SCR to control NO_x emissions and the second one is with CO_2 sequestration with 90 % of the CO_2 captured from flue gas by chemical absorption and is transported by a 300 km pipeline into an underground disposal site. Results from both studies show that adding sequestration to the system reduced GHG emissions significantly. However, this addition increased fuel consumption and reduced the plant’s capacity resulting in diminishing returns with additional sequestering of CO_2 [242].

Other U.S. sources are comparably less exhaustive in terms of system boundaries or LCI factors included. Deru and Torcellini [193] provide energy factors for generating electricity from natural gas. Meier [247] and Pacca and Horvath [248] examine the full life-cycle GHG emissions of combined-cycle natural gas plants with capacities of 620 MW and 1,000 MW, respectively. In Meier’s case, the power plant has a net efficiency of 43% over its entire life cycle. In Pacca and Horvath study, authors assumed that the boilers were replaced after 30 years of operation (but not the structure of the plany itself). Gagnon et al. [246] examine total emission factors of CO_2, NO_x, NMVOC, particulates, and SO_2 for a NGCC power plant in northeastern America. Authors assumed that natural gas is delivered from 2,000 km distance.

LCI data from above U.S. studies are within close ranges despite the variations in technologies, locations, fuel properties, distribution distances, and other factors. In addition to the U.S. LCI data, GreenConcrete includes international studies in the Excel database to fill the gaps whenever an LCI factor is missing.

The most recent study by Santoyo-Castelazo et al. [228] examined direct and total life-cycle emissions (CO_2, CH_4, NO_x, N_2O, NMVOC, PM, and SO_2) from combined-cycle power plants with 44.5% net genetration efficiency. In their assessment, authors assumed 92% of natural gas is produced domestically and the remaining 8% is imported from the U.S.; of this, 67% of gas is produced onshore and 33% offshore.

Odeh and Cockerill [234] focused on life-cycle energy use, GWP, NO_x, PMtotal, SO_2 from two types of gas power plants with two type of technologies, namely NGCC and IGCC with and without carbon capture and storage (CCS). Within the system boundary, direct LCI from fuel combustion in the power plant, as well as other effects arising from upstream (e.g. production and transportation of limestone, ammonia, catalyst, etc.) and downstream (e.g. waste transportation and disposal) processes, as well as LCI from power plant construction and decommissioning, were also included. Both systems were equipped with SCR and ESPs for emission control. The power generation capacity for non-CCS cases was kept constant at 500 MW with a 75% load factor. For CCS plants, a capture efficiency of 90% is considered. The lifetime for the power plants was 30 years. Similar to the U.S. study [242], results show that the addition of CCS to the system reduced GHG emissions (or reduced GWP) while increasing fossil fuel consumption and other emissions such as NO_x and NH_3 that leads to higher eutrophication and acidification potentials.

WEC [241] consists of life-cycle emission factor (GWP, NO_x, particulates, SO_2) data for different regions worldwide and various natural gas power plant technologies. GreenConcrete Excel version accommodates international WEC data in four sections: 1) Average of natural gas combined cycle with similar technologies in EU (including France, Germany, Italy, Denmark, Norway, Spain, and Sweden). Net generation efficiencies vary from 47% to 58%; 2) Worldwide average from various sources for natural gas combined cycle power plants; 3) Australian NGCC with 49% net efficiency and similar emission control technologies; 4) UK NGCC with low-NO_x burner and 52% net efficiency.

Other studies provide national LCI databases for electricity generation from natural gas, for countries including Romania [236], Turkey [235], Korea [244], and Singapore [240]. Major total life-cycle emission parameters considered in these studies are given in Table 4.18.

4.8.1.5 Electric Power Generation from Nuclear

The energy use and GHG emissions from a nuclear fuel cycle are dominantly due to the fossil fuel-based energy and electricity needed to extract and process fuel and for the construction and production of materials used in power facilities. Most of the energy is consumed to enrich the content of the isotope U-235 in natural uranium. The gas diffusion method consumes about 40 times more electricity than the gas centrifuge method. According to World Energy Council report [241], the highest life-cycle GHG emission from nuclear power plants is 0.040 kg CO_2-eq per kWh. This figure refers to a nuclear fuel cycle where enrichment is based on the gas diffusion method, and the U.S. electricity generation mix with 65% fossil fuel-based source is assumed.

The U.S. nuclear electricity generation LCA sources are a few [193, 246, 247] and limited to only emissions of GHG, NO_x, particulates, and SO_2 for the full life-cycle stages. In GreenConcrete LCA, data from non-U.S. sources replace the missing or incomplete U.S. LCI data when calculating upstream and direct LCI effects of nuclear power plants. Deru and Torcellini (2007) [193] is the only study that offers the source energy factors for generating electricity from nuclear power plants. Meier [247] provides the average U.S. life-cycle GWP rate for nuclear power plants as 0.018 kg CO_2-eq per kWh for comparison purposes but gives no other LCI details pertaining to this type of electric power as the focus of the study is natural-gas fuel cycle. The Canadian study by Gagnon et al. [246] provides life-cycle emissions data (CO_2, NO_x, particulates, and SO_2) for nuclear power plants. Authors present both typical data for northeastern part of America and ranges of values found in the international literature.

The Mexican study [228] provides direct and full life-cycle emissions of CO_2, CH_4, N_2O, NO_x, NMVOC, particulates, and SO_2 for boiling water reactors, the construction of infrastructure being the major source. LCI data is mainly from EcoInvent and GEMIS databases from Europe.

Other international studies vary in depth and breadth. Ardente et al. [233] present full life-cycle GWP as 0.015-0.050 kg CO_2-eq per kWh based on the literature. Authors used these numbers for comparison purposes since the focus of the study was the LCA of an Italian wind farm. Kone and Buke [235] offer full life-cycle data for emissions of CO_2, CH_4, NO_x, SO_2 from various EU sources although nuclear power generation is not a relevant option in Turkey for now but for near-future scenarios.

The Japanese study [239] calculates full life-cycle GHG emissions from two cases of 1,000 MW boiling water reactor (BWR) type with an enrichment of 3.4%, 32.2 % net efficiency, and 30 years of plant lifetime: 1) Base-case system boundary consists of mining, conversion of uranium, enrichment, fuel fabrication, generation of electricity, spent fuel (SF) storage and low-level radioactive waste disposal; 2) Recycling of spent uranium waste case –four more processes are added to the base case's system boundary, which are reprocessing and fabrication of spent fuel into mix oxide fuel and storage and disposal of high-level radioactive waste underground. Results from the study show that enrichment accounts for 62% of the total emissions from nuclear power generation in the base case, which is aligned with WEC's findings. The GHG from the recycling case is found to be slightly less than the base case since the recycled SF waste substituted the primary uranium fuels as energy source.

The Korean LCA [244] data used for calculating direct and upstream air emissions from nuclear power plants are based on older data (going back to 1978) from EPA and UNEP.

World Energy Council [241] compare full life-cycle emissions (GHG, NO_x, particulates, SO_2) from two technologies: 1) Nuclear power plants with gas diffusion method. The average of LCI factors from three plants in Australia, Germany, and UK is used in the tool; 2) Gas centrifuge technology based on a plant in Sweden. Emissions from the second option were calculated to be much smaller.

Finally, Rashad and Hammad [249] assess and compare full life-cycle effects of a 1,000 MW light-water reactor system to other major electiricity generating systems in terms of land requirements, major air emissions, and fossil fuel consumption rates based on world-wide data sources. Results from the study are compatible with other studies.

4.8.1.5.1 Electric Power Generation from Renewable Energy Sources

The GreenConcrete LCA tool accommodates direct and full life-cycle LCI data for calculating the environmental effects from renewable electricity generation in addition to electric power generation from fossil fuels that is explained in prior sections. The tool covers biomass, geothermal, hydropower, solar, and wind in the renewable category.

The common feature of these energy sources is that the emissions of greenhouse gases and other atmospheric pollutants arise from other stages of the life cycle than power generation.

4.8.1.5.2 Electric Power Generation from Biomass

The U.S. LCI data for biomass power systems are mainly based on databases from various sources [193, 222, 242, 250]. Among these sources, WebFIRE specifically provides direct air emissions from wood and bark waste-fired boilers while NREL's focus is direct air emissions from biomass gasification combined-cycle power system used for the U.S. electricity generation. The NREL's U.S. LCI database for this type of electricity generation is under the category of "Electricity, biomass, at power plant". The NREL's biomass production is "represented by a poplar tree crop with a seven-year growing cycle. Electricity generation is accomplished by gasification of biomass followed by a gas turbine. Biomass is produced within the boundaries of this system and is thus not shown as a fuel input. This is cradle-to-gate data, spanning the extraction of fuels and raw materials through the production of electricity. Infrastructure requirements for biomass production, biomass gasification, and biomass electricity generation are also included. Process and fuel emissions are reported together in the original data source and cannot be separated" [222]. Deru and Torcellini [193] is the only source that provides the average life-cycle energy use associated with biomass power systems. Biomass fuel is categorized under renewable fuels group which consists of agricultural crop by-product, municipal solid waste, other biomass solids, wood solids, other biomass liquids, black liquor, sludge waste, wood waste liquids, landfill gas, and other biomass gas.

The major sources of direct and life-cycle emission factors for the U.S. biomass power systems are two versions of NREL reports by Spath and Mann [242, 250]. In the earlier version [250], authors performed an LCA of a hypothetical 113 MW biomass integrated gasification combined cycle (BIGCC) power plant using dedicated wood chip as feedstock with 30 years of lifetime and located in Midwest United States. The system boundary consists of production of biomass as a feedstock (including harvesting), the transportation to the power plant, generation of electricity as well as upstream processes of raw material extraction and production, construction and decommissioning of power plant. Additionally, authors conducted a sensitivity analysis to be able to identify the parameters with the largest effects on the LCA results in terms of fuel resources, air emissions (CO_2, CO, non-methane hydrocarbons including VOCs, CH_4, NO_x, particulate matter, SO_2), energy consumption, water emissions (dissolved matter and $NH4^+$), and solid waste. They covered 20 versions of sensitivity cases in their study. The latest version [242] compares two biomass technologies with or without CO_2 capture and sequestration (CCS): 1) A biomass-fired integrated gasification combined cycle (IGCC) system using a biomass energy crop, and 2) A direct-fired biomass power plant using biomass. System boundary for each case includes the electricity generation and upstream processes of collecting residue biomass (landfill and mulching), transportation, and construction of related equipment and pipelines. For systems with CCS, the CO_2 is captured via a monoethanolamine (MEA) system, compressed, transported via pipeline, and sequestered in underground storage such as a gas field, oil field, or aquifer. For the biomass power systems, it was assumed that several small plants are needed to achieve 600 MW of electricity capacity – which is kept constant throughout the study for comparison of different types of electric power systems. The reason for inclusion of several small biomass plants is that large transportation distances that make the biomass power uneconomical at large scales. The biomass feedstock is assumed to be from landfilling and mulching operations. For this reason, authors considered the avoided methane and CO_2 emissions in LCA calculations. Because of this, direct-fired biomass systems with or without CCS and biomass-fired IGCC system with CCS resulted in negative GWP. Results from this study vary highly from -1.398 kg $CO_{2\text{-eq}}$/kWh to 0.049 kg $CO_{2\text{-eq}}$/kWh due to variations in technologies used in biomass power plants. Although all data is tabulated in GreenConcrete LCA tool, it makes use of the GWP data from cases without CCS as this technology is not common and representative of the U.S. national practice.

Meier [247]'s GWP for biomass power plants is based on literature and are within the ranges of the U.S. national average data. The author does not provide details on the power plant technology as the focus of the study is PV panels and natural gas power plants. Biomass GWP is tabulated for comparison purposes only.

In the tool, data from major the non-U.S. sources are used for comparison purposes [235, 241, 243, 249]. WEC [241] presents full life-cycle GHG emissions factors for IGCC biomass power plants in three different locations: 1) A hypothetical 600 MW IGCC biomass power plant with CO_2 sequestration in the U.S. Feedstock is obtained from tree plantation. The estimated GHGs from the fuel cycle are negative because trees in the energy plantation absorb CO_2 from the atmosphere, and the CO_2 formed during power generation is captured and sequestered under the ground. Without CCS, results are positive; 2) 110 MW IGCC biomass power plant in Australia; 3) 40 MW IGCC biomass power plant in France; 4) 8 MW IGCC biomass power plant in UK. In addition to GHG emissions, the report presents emission factors of NO_x, particulates, and SO_2 for the non-U.S. biomass plants.

The Italian LCA study [243] examines biomass IGCC with upstream CO_2 chemical absorption resulting in stack CO_2 reduction. The system boundary includes biomass production, plant construction and production of materials used in construction, energy production (plant operation for 15 years) and plant dismantling. The major contributions to GHG are from the operation and biomass production phases, with a value higher from biomass production than from operation, since CO_2 emissions are reduced at the stack. Moreover, the photosynthesis is responsible from a reduction of 0.288 kg CO_2 per MJ which results in negative CO_2 over the full life-cycle of the power plant.

Finally, Rashad and Hammad [249] present direct and full life-cycle GWP of biomass power plants which are based on the U.S. and non-U.S. literature.

4.8.1.5.3 Electric Power Generation from Geothermal

The life-cycle emissions of electricity generation from renewable and nuclear power plants are mainly from the construction of infrastructure; the exception to this is geothermal power, where the majority of CO_2 and SO_2 are from direct emissions [228, 252]. Since the visible plumes from some geothermal power plants are made of steam and these plants do not burn fossil fuels, they release virtually no air emissions. Therefore, direct emissions are only limited to CO_2 and SO_2 emissions and average values for these emissions are tabulated in the GreenConcrete LCA tool.

It is important to note that geothermal plants do not emit SO_2 directly, but they emit hydrogen sulfide (H_2S) into the atmosphere, which eventually changes into SO_2 and sulfuric acid. Therefore, any SO_2 emissions associated with geothermal energy derive from H_2S emissions. However, in recent years H_2S emissions are almost negligible as 99.9 % of the H_2S from geothermal noncondensable gases at the plant is converted into elemental sulfur, which can then be used as a non-hazardous soil amendment and fertilizer feedstock. CO_2 emissions from geothermal plants are very small compared to fossil fuel-fired emissions [237]. According to Kagel et al. [237] "Some geothermal reservoir fluids contain varying amounts of certain noncondensable gases, including CO_2. Geothermal steam is generally condensed after passing through the turbine. However, the CO_2 does not condense, and passes through the turbine to the exhaust system where it is then released into the atmosphere through the cooling towers." The amount of direct CO_2 emissions can vary depending on the plant design and technology. For example, plants with air cooling are in a closed loop system and emit no carbon dioxide because in this system the geothermal fluids are never exposed to the atmosphere.

Although geothermal is the third largest source of renewable electricity after hydropower and biomass, the U.S. LCI data sources are limited to one study by Kagel et al. [237]. This study feeds direct CO_2 and SO_2 emission LCI data into GreenConcrete tool which makes use of the average values from a range of emission factors (e.g. factor of 20 g CO_2/kWh is used in the tool as it is the average of 0 and 40 g of CO_2 per kWh as given in the source) while calculating direct CO_2 LCI of geothermal power plants.

Since the literature lacks full life-cycle LCI for the U.S. geothermal power plants, non-U.S. sources are used to fill this gap in GreenConcrete tool. The most recent study by Santoyo-Castelazo et al. [228] provides "cradle-to-grave" emission factors of CO_2, CH_4, N_2O, NO_x, NMVOC, particulates, and SO_2 for a 960 MW Geothermal steam turbine (GST) with 35.5% net generation efficiency in Mexico. As stated before, the majority of life-cycle emissions of CO_2 and SO_2 are from direct emissions. Other air emissions are almost negligible. Two other non-U.S. studies also examine life-cycle GHG emissions for geothermal and data is tabulated in GreenConcrete.

Finally, Pehnt [238] study is an application of LCA methodology to calculate and compare "cradle-to-grave" LCI and LCIA of renewable energy technologies including hydropower (for two capacities of 3.1 MW and 0.3 MW), wind (for 1.5 MW onshore and 2.5 offshore), solar (PV system), and geothermal (hot dry rock type). Major LCI factors for each of the renewable energy sources include CO_2,CO, CH_4, NO_x, N_2O, particulates and SO_2 emissions and their values are tabulated in GreenConcrete LCA, Excel version.

4.8.1.5.4 Electric Power Generation from Hydropower

In GreenConcrete LCA tool, hydropower electricity calculations are based on non-U.S. data for direct LCI and mix of a few U.S. and mostly non-U.S. sources for full life-cycle emission factors.

It is important to note that LCA results for hydropower is highly site-specific as opposed to the other electricity generation technologies. The U.S. LCA studies analyzed reservoir-type hydroelectric power plants and considered emissions from the reservoir and land use impacts in their assessments. Pacca and Horvath [248] calculate GHG emissions from the construction materials, excavation, construction, and operation (including an upgrade for four periods of 10, 20, 30, and 40 years after construction) of Glen Canyon hydroelectric plant on the Colorado

River as well as emissions associated with the flooded biomass decay in the reservoir, loss of net ecosystem production, and land use during lifetime of the power plant. The other U.S. study by Gagnon et al. [246] compare emissions of GHG, NO_x, particulates, and SO_2 from reservoir and run-of-river systems in north-eastern part of North America.

Of all the non-U.S. sources, the recent LCA study by Raadal et al. [229] compare 39 (28 reservoir type and 11 run-of-river technologies) different hydropower systems base on worldwide data sources. Two types of technologies and three cases of hydro power LCAs are analyzed: 1) 8 studies out of 39 examined GHG emissions from reservoir-type hydropower plants including gross emissions from flooded land, varying between 0.2 to 152 g CO_2-eq/kWh. The average emission factor is read from a graph as about 32 g CO_2-eq/kWh; 2) 20 studies focused on reservoir hydro excluding emissions from flooded land, GHG emissions vary from 0.2 to 11.2 g CO_2-eq/kWh; 3) 11 studies examine GHG emissions from the run-of-river hydro power. Such LCAs show the smallest variation within the investigated technologies. Results from this study show four orders of magnitude variations in GHG emissions, fluctuating from 0.2 to 152 g CO_2-equivalents per kWh based on the differences in type of technology, location, and LCA methodologies. For reservoir hydropower, emissions are found to be site specific and with large variations, depending on climate, area of flooded land and other factors. When inundation of land is included, it is found to be the major GHG contributor, when not included, the construction of the infrastructure (dams and tunnels) is responsible from the major GHG emissions.

Santoyo-Castelazo et al. [228] provide average life-cycle emission factors (CO_2, CH_4, SO_2, NO_x, N_2O and PM) for a 10.6 GW hydroelectric power plant with a net generation efficiency of 35.9% in Mexico. Results from the study are consistent with other studies. However, authors do not provide any details about the hydroelectric power system.

The Brazilian hydropower electric generation LCA is based on real case data from Itaipu dam [231]. Itaipu Hydropower Plant supplies 24% of Brazil’s electricity consumption with 14 GW installed capacity. The life-cycle stages include the construction and operation of the dam, important material production and energy consumption (cement, steel, copper, diesel oil, lubricant oil), as well as power plant operation. Within the system boundary, life-cycle emissions associated with reservoir flooding, transportation of materials and workers, and earthworks are also included. GreenConcrete LCA tool makes use of both direct and total life-cycle emissions of solid waste, CO_2, CO, Hg, Pb, CH_4, NO_x, N_2O, PMtotal, SO_2, and VOC when US data is not available.

Pehnt [238] examines and compares full-life cycle resource use and emission factors (including energy use, CO_2, CO, CH_4, NO_x, N_2O, NMVOC, PMtotal, and SO_2) for renewable energy technologies in Germany. For the hydropower plants, the GreenConcrete makes use of average data for 3.1 MW and 300 KW small run-of-river technologies. Another EU study by Ardente et al. [233] provides a range of life-cycle GWP data (15-40 g CO_2-eq/kWh) based on different data sources.

Other three non-U.S. hydropower studies [235, 239, 244] respresent national average LCI emissions and are consistent with other sources.

WEC [241] examines life-cycle emissions (GHG, NO_x, and SO_2) from both reservoir and river systems. In GreenConcrete tool, the reservoir-type LCI represents the average of three large hydropower plants in Africa, Brazil, and Canada with capacities varying between 1,600 and

12,600 MW. The river-system LCI is based on the data from power plants with capacities of 15,300 MW in Canada, and 1,492 and 704 MW in Sweden. Results from the study indicate that the larger the hydropower system the higher the GWP from this system. Accordingly, large run-of-river schemes have very small reservoir sizes (or none at all) and so do not produce significant emissions of GHGs. The oldest GHG emission data for hydropower systems is based on Gagnon and van de Vate report [251]. Authors used IPCC guidelines for their calculations and compared various hydropower systems in Europe and Canada. Results from this source are in line with recent studies concluding that two major sources of emissions are construction of dams, dikes and power stations and the decomposition of biomass from land flooded by the reservoir, producing CO_2 and CH_4 emissions.

4.8.1.5.5 Electric Power Generation from Solar

The U.S. study by Pacca and Horvath [248] analyze the hypothetical GHG emissions from manufacturing and constructing a PV plant (with 100-W panels) with 5.55 TWh of annual electricity generation and 20 years of operation. Since solar power U.S. data is limited, GreenConcrete LCA employs non-U.S. LCI factors to fill the gap in LCI factors. Pehnt [238] investigates environmental performance of solar power energy (PV) systems for current and estimated future technologies in Germany. The author justifies future technologies based on research about advances in module efficiency, improved materials and production methods, e.g. using more recycled aluminum and calculated LCI by changing parameters such as life-time, efficiency, and capacity of PV systems in the study. LCI factors incorporated from this source cover the total and upstream data for energy use and emissions of CO_2, CO, CH_4, NO_x, N_2O, NMVOC, PMtotal, and SO_2 from a current 80-MW solar power technology. Similarly, Hondo [239] examines direct and life-cycle GHG emissions from average solar power systems in Japan and compares results to emerging and future PV technologies. Future technologies are assumed to have larger electricity generation rates with variations in material types used in PV cells. Within the system boundary, major LCA stages consist of construction, PV panel production, operation, and maintenance of the system for base and future PV cases.

Kone and Buke [235] provide life-cycle emission factors for average Turkish solar power systems with no details about the system. Similarly, Ardente et al. [233] offer a range of life-cycle GHG emissions data (50-100 g CO_2-eq/kWh) for PV systems based on different data sources. However, solar power data is for only comparison purposes since the focus of this study is wind turbines in Italy.

In GreenConcrete tool, total GHG and criteria air emissions data from WEC [241] represent two cases: 1) 400 kW solar farm consisting of 50% amorphous and 50% multi-crystalline silicon solar panels supported by galvanised steel framing on concrete foundations in Australia; and 2) Average of smaller capacity (1-13 kW) PV technologies in Germany and Italy with varying types of PV materials, such as single-crystalline silicon, multi-crystalline silicon, amorphous silicon and copper indium gallium diselenide, etc.

Finally, LCI data from Rashad and Hammad [249] study consists of total emission factors of GWP, NO_x, PMtotal, and SO_2 and direct GWP factors for centralized PV systems based on a wide range of data from literature. In the source, PM data is labeled as dust and is entered as PMtotal in the GreenConcrete LCA tool.

4.8.1.5.6 Electric Power Generation from Wind

Similar to the other renewable energy sources like solar and hydropower, the life-cycle emissions of wind power systems vary with the materials and fuels required to construct the wind turbines. It is important to note that the amount of electricity produced by a wind turbine during its life also depends on the load factor of the turbine. This factor is determined by the local wind statistics and the dimensions and other properties of the wind turbine [241]. There are merely two U.S. and one Canadian studies that provide total GHG emission factors [246-248]. Only one of them provides total emission factors of NO_x, particulates, and SO_2 [246] which is calculated for a intermittent wind power system that needs backup from various energy sources. Therefore, similar to the other renewable energy technologies, GreenConcrete LCA tool employs non-U.S. data to fill the LCI data gap in related wind power calculations.

Pacca and Horvath [248] evaluated a wind farm that is generating 5.55 TWh of electricity per year in southern Utah. The system boundary consists of materials and energy used in construction as well as operation of the system for 20 years. After 20 years of operation, it was assumed that wind turbines had to be replaced. The other U.S. study by Meier [247] also calculated the life-cycle GHG emissions of wind turbines based on e-GRID for the U.S. direct emission factors and other data sources for indirect emission factors, following a similar approach used in GreenConcrete LCA.

As opposed to the U.S. sources, the non-U.S. studies provide more detailed LCA data for electricity generation from wind power. The most comprehensive study by Raadal et al. [229] examined GHG emissions from 63 wind power generation LCA case studies. While some studies present results for a specific wind turbine, others present average data for specific wind power projects (with many turbines), and moreover, others are based on average data from several studies. The GHG emission results from this study are demonstrated based on turbine sizes ranging between 30 kW to 3MW and also capacity factors (within a range of 0-55%) that represent varying wind conditions. The largest capacity factor group (46-55%) represents offshore locations with larger infrastructure in the study. Overall, GHG emissions vary between 4.6 g to 55.4 g CO_2-eq per kWh. Results from this study show that the GHG emissions decrease with increased turbine sizes and also decrease with increased capacity factors. Further, the results show that the infrastructure stage (construction of wind turbines) is the life-cycle stage contributing most to the GHG emissions from wind power generation. It accounts for about 90−99% of the total GHG emissions. This life-cycle stage includes material production and processing, waste disposal, transportation, assembling, and installation. Steel production is the activity contributing most to the GHG emissions, followed by concrete production. The GHG emissions at the operational stage of wind power are almost negligible in relation to the total. The system boundary in this study excludes grid losses and infrastructure relating to the grid from the LCA. The backup power necessary to provide a continuous electricity supply is also excluded from the analyses.

Another non-U.S. study by Santoyo-Castelazo et al. [228] analyzes a 23-MW wind power plant with 35.9% net generation efficiency in Mexico. This study provides total LCI emissions factors of CO_2, CH_4, NO_x, N_2O, NMVOC, PMtotal, and SO_2 as an input to GreenConcrete LCA calculations.

Ardente et al. [233] focus specifically on an Italian wind farm with 11 turbines, 660 kW each and compare their results to other studies developed worldwide in terms of life-cycle energy use and

GHG emissions. The system boundary covers production and delivery of energy and raw materials, manufacturing of major components of wind turbines, transportation, installation, maintenance, disassembly and disposal. In the study, wind turbine data from the literature have varying capacities that range from 0.3 to 3,000 kW and load factors that are in between 7.9% and 50.4%.

The German LCA by Pehnt [238] also provides life-cycle energy use and emission factors of CO_2, CO, CH_4, NO_x, N_2O, NMVOC, PMtotal, and SO_2 for one 1.5 MW onshore and one 2.5 MW offshore wind turbine system cases. The system boundary covers production, operation and maintenance, and system recycling/disposal.

Similarly, Kone and Buke [235] provide average life-cycle emission data of CO_2, CH_4, NO_x, and SO_2 related with wind power systems in Turkey. Similarly, Hondo provides national average LCI data for Japan, but emission factors are limited to direct and total GHG emissions. As a base case, which represents the Japanese average case, the author first examined a 300 kW type wind power plant. In addition, a more sophisticated 400 kW type wind power plant was examined as a future case. It was assumed that both 300 and 400 kW types of wind turbines were installed in a small wind park with only a few wind turbines. The future wind power system resulted in less GHG emissions primarily because the outputs are different although the quantity of materials required per kWh for each power plant is almost the same.

WEC [241] provides LCI data for the wind power systems with varying capacities of 0.23 MW - 2.5 MW and load factors ranging from 20% to 46% on the basis of a wide range of LCA studies. The Excel version of the GreenConcrete LCA tool categorizes data from WEC in two groups: 1) Onshore wind turbines worldwide, and 2) Offshore wind turbines in Denmark and Germany.

Thus far, major data sources used in calculating direct and total life-cycle energy use and emissions associated with the electricity generation module in GreenConcrete LCA are analyzed and reviewed. The following graphs summarize energy use, GHG emissions, and major criteria air pollutants data from the U.S. and non-U.S. electricity LCA studies (see Figure 4.4 through Figure 4.17). It is important to note that, the direct energy use and emissions from renewable energy sources are either negligible or no data exists. Most of the direct LCI data is based on the U.S. national databases such as NREL LCI and EPA WebFIRE, while the life-cycle LCI data is based on both U.S. and non-U.S. data sources.

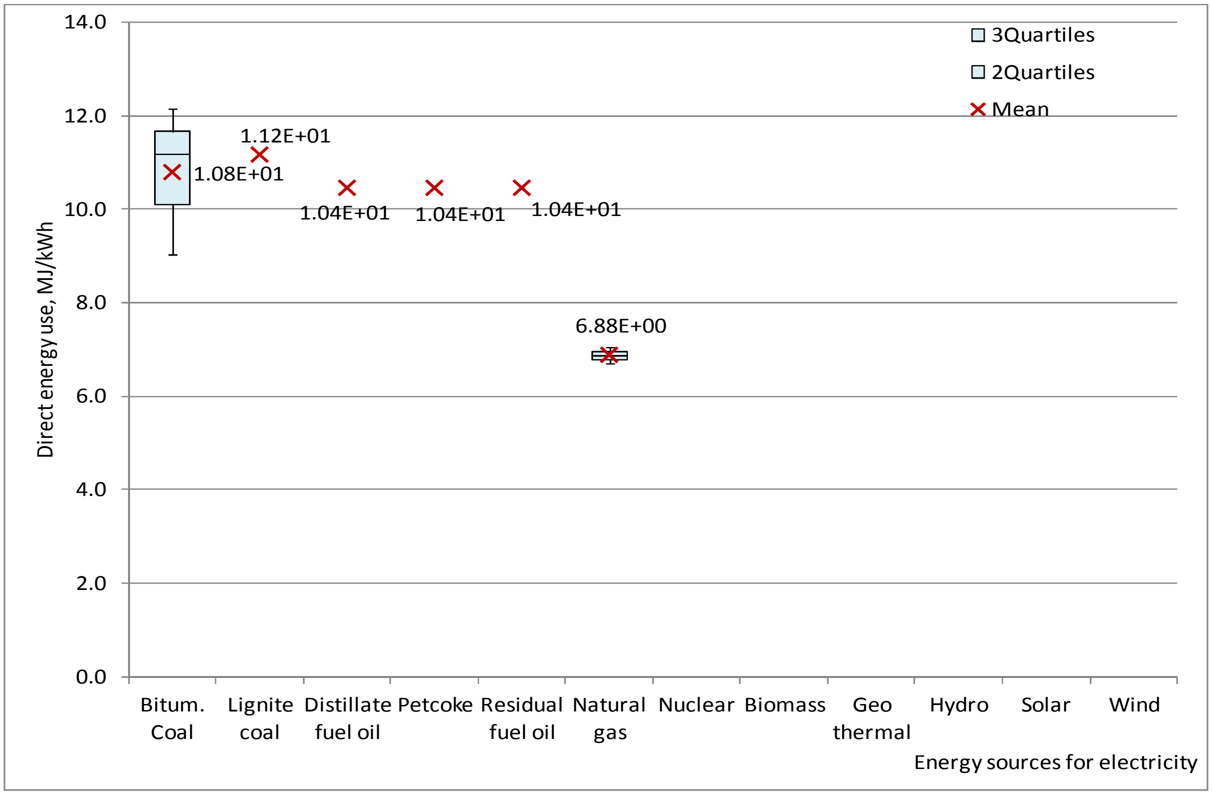


Figure 4.4: Direct energy use associated with various major energy sources used in electricity generation (based on U.S. and non-U.S. data sources)

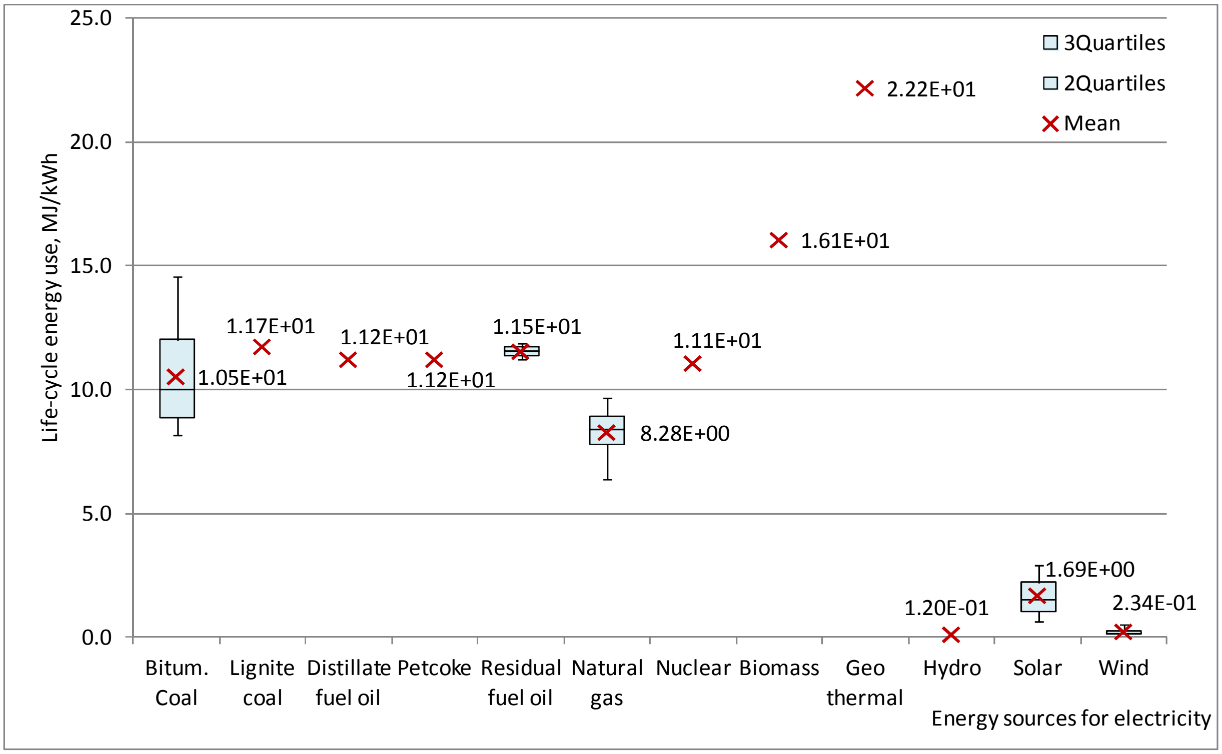


Figure 4.5: Life-cycle primary energy use associated with various major energy sources used in electricity generation (based on U.S. and non-U.S. data sources)

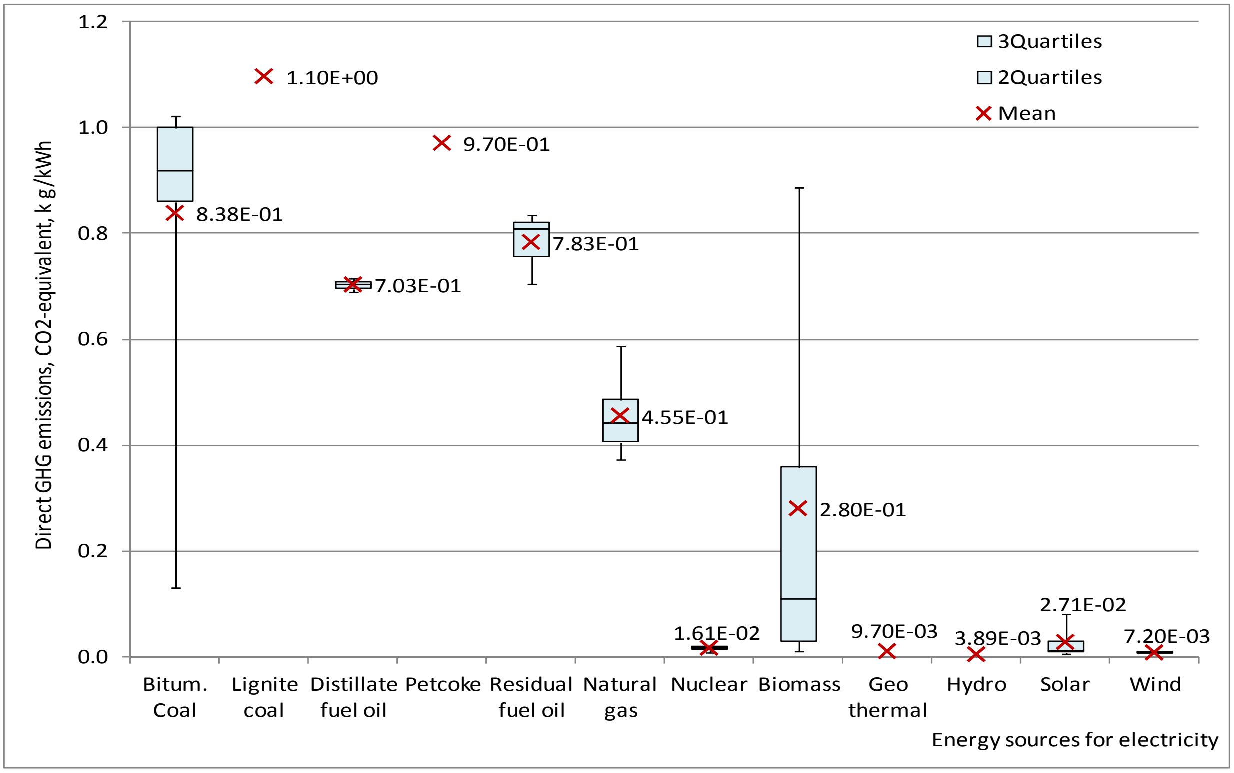


Figure 4.6: Direct GHG emissions data associated with various energy sources used in electricity generation (based on U.S. and non-U.S. data sources)

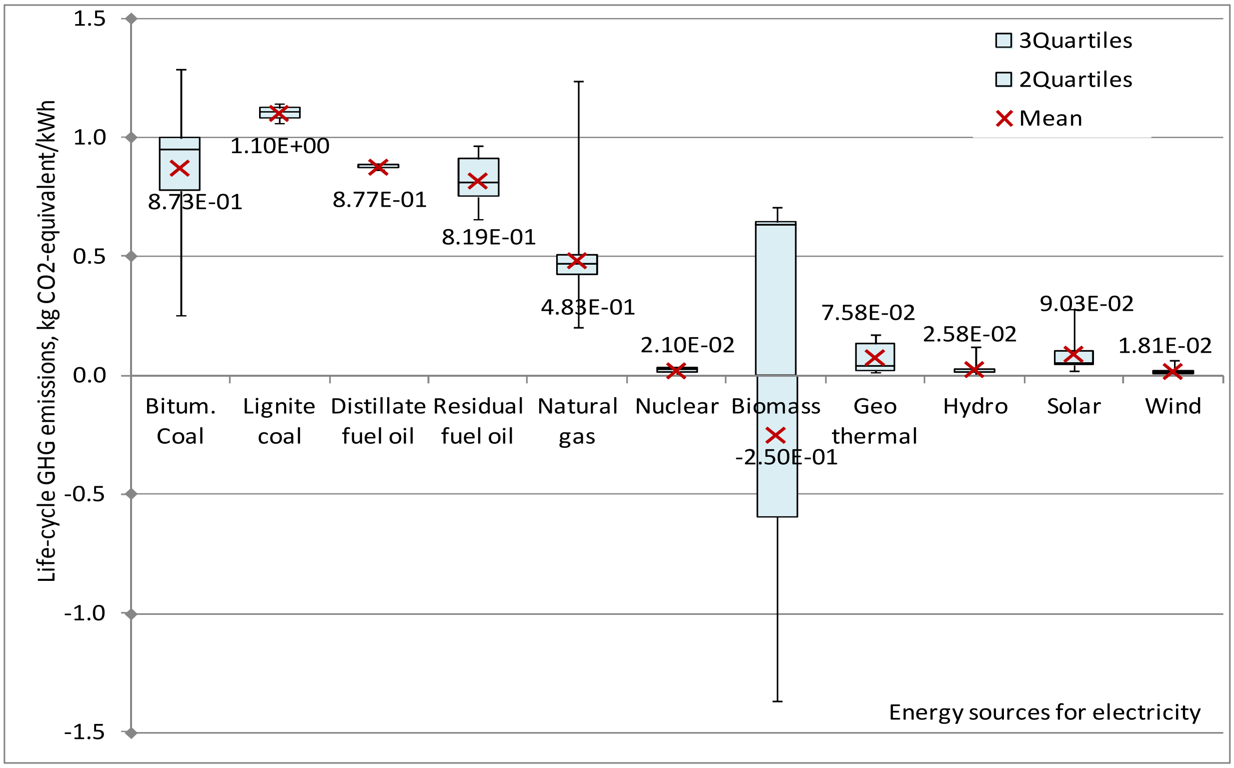


Figure 4.7: Life-cycle GHG emissions data associated with various energy sources used in electricity generation (based on U.S. and non-U.S. data sources)

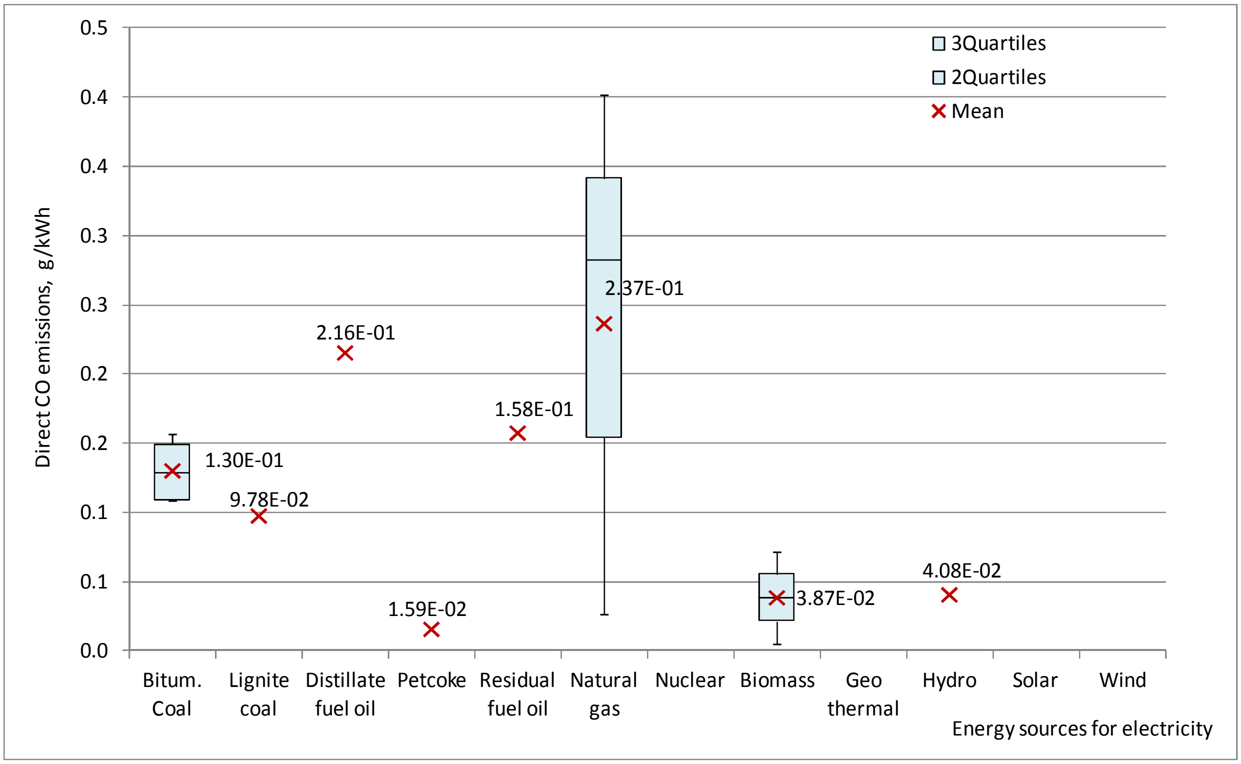


Figure 4.8: Direct CO emissions data associated with various energy sources used in electricity generation (based on U.S. and non-U.S. data sources)

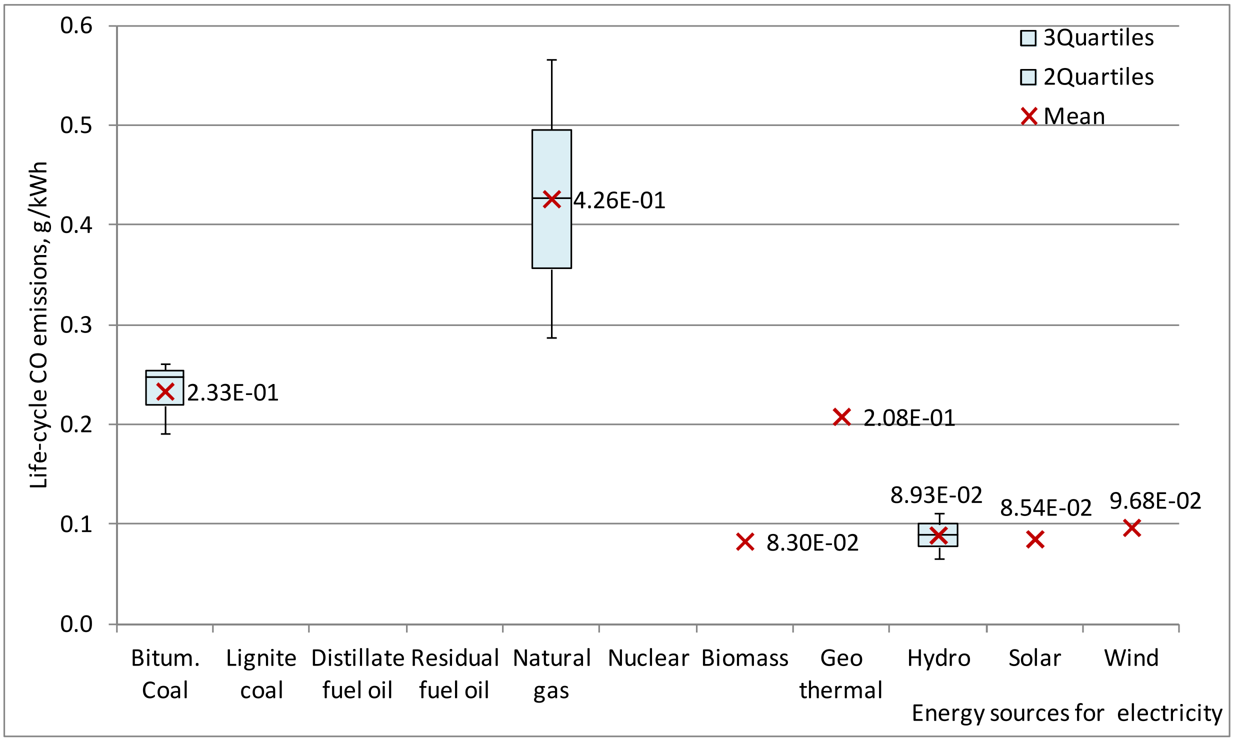


Figure 4.9: Life-cycle CO emissions data associated with various energy sources used in electricity generation (based on U.S. and non-U.S. data sources)

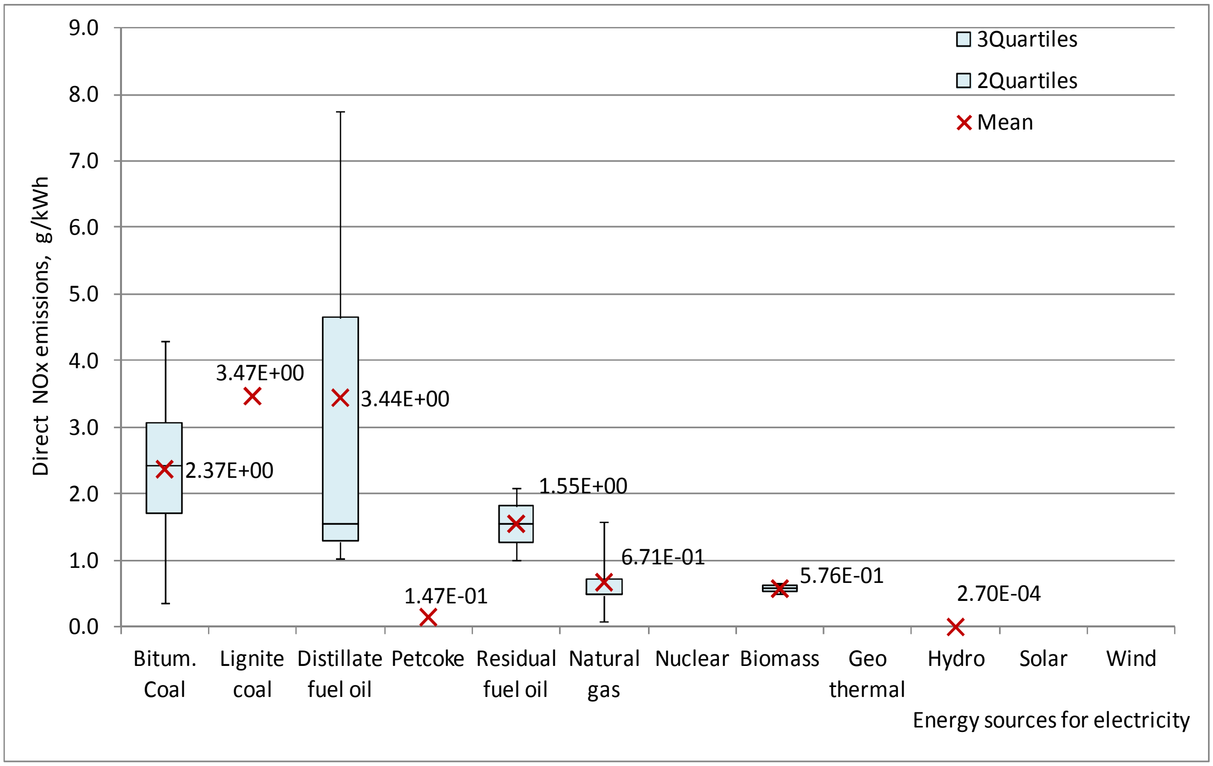


Figure 4.10: Direct NO_x emissions data associated with various energy sources used in electricity generation (based on U.S. and non-U.S. data sources)

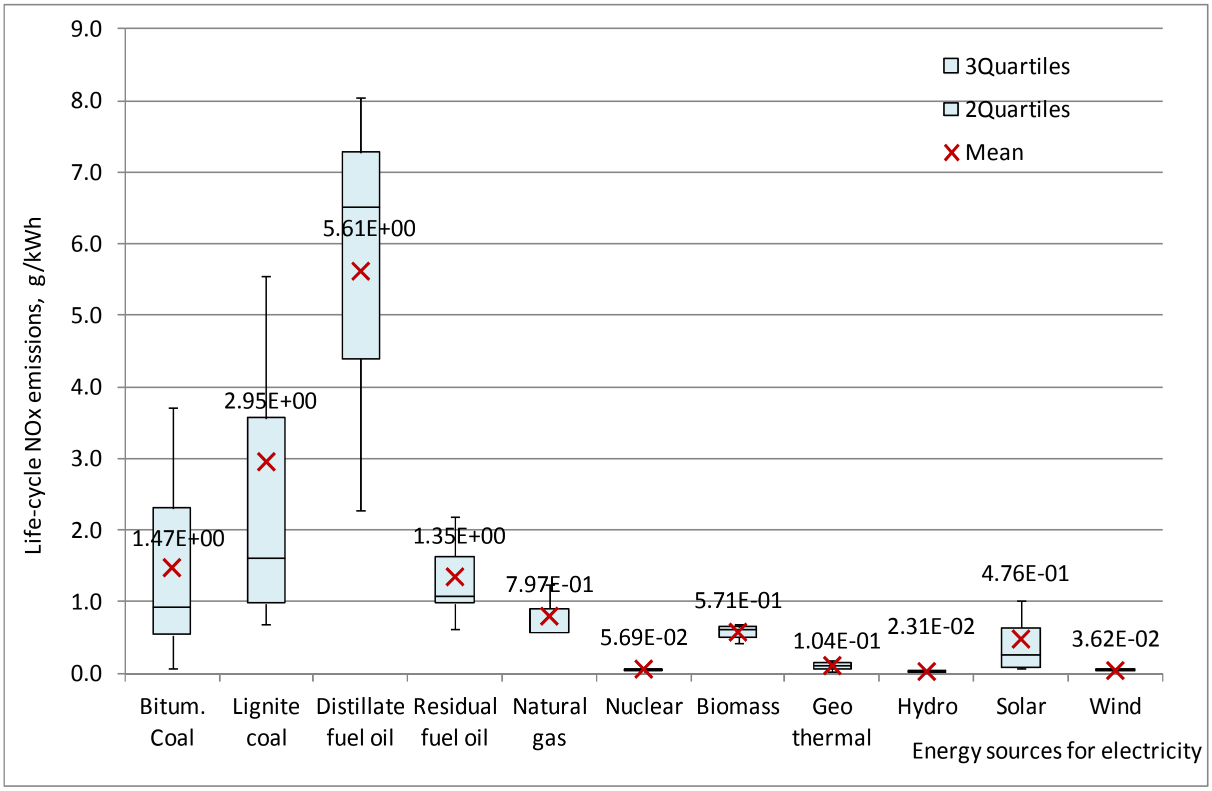


Figure 4.11: Life-cycle NO_x emissions data associated with various energy sources used in electricity generation (based on U.S. and non-U.S. data sources)

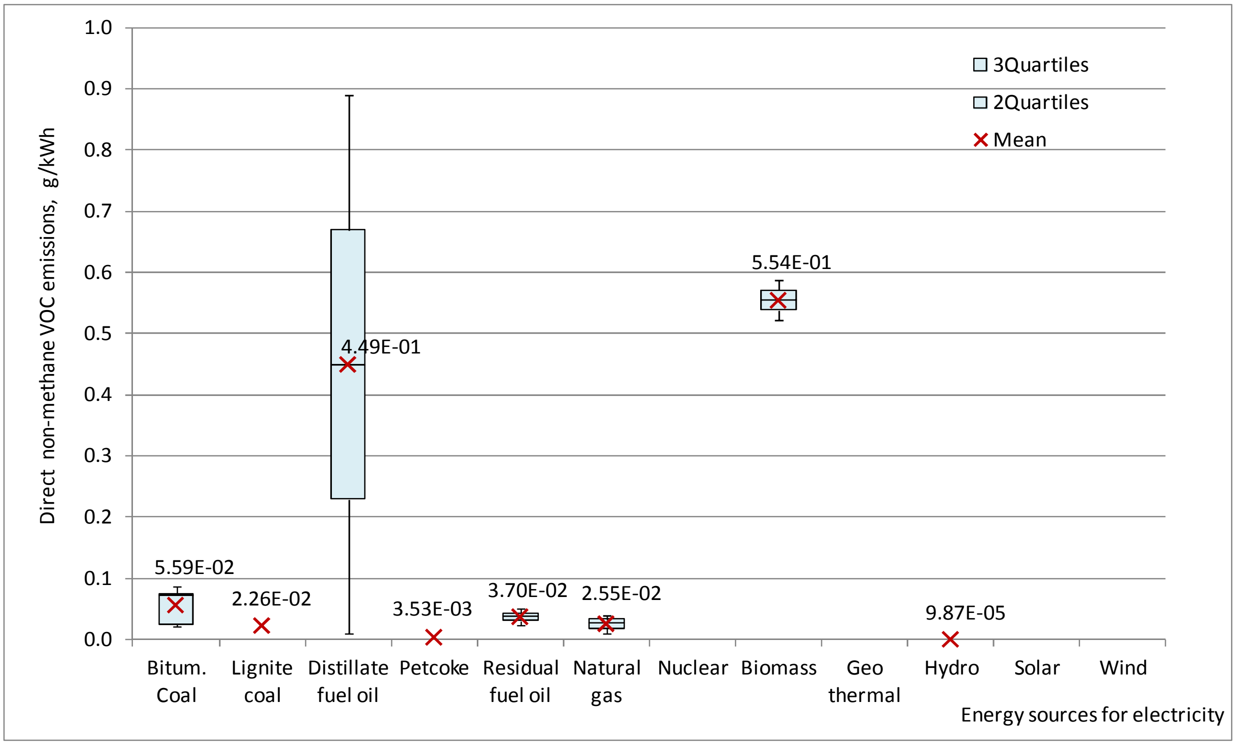


Figure 4.12: Direct non-methane VOC emissions data associated with various energy sources used in electricity generation (based on U.S. and non-U.S. data sources)

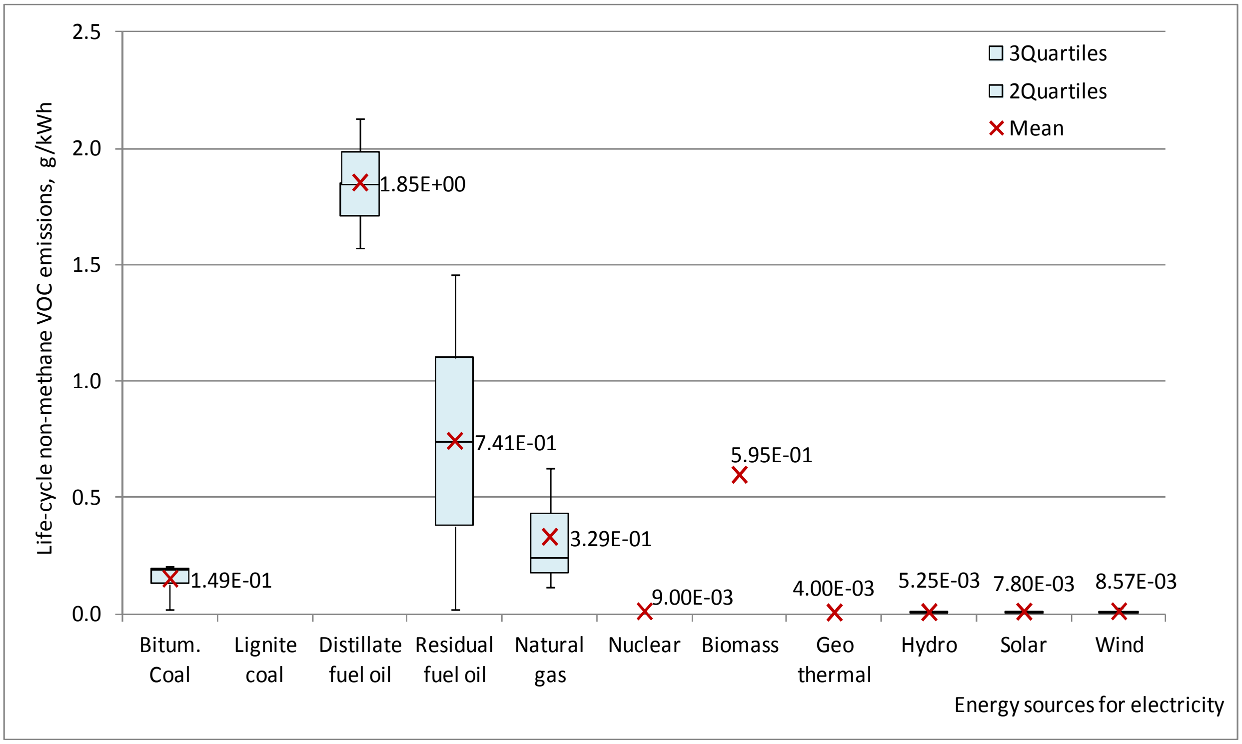


Figure 4.13: Life-cycle non-methane VOC emissions data associated with various energy sources used in electricity generation (based on U.S. and non-U.S. data sources)

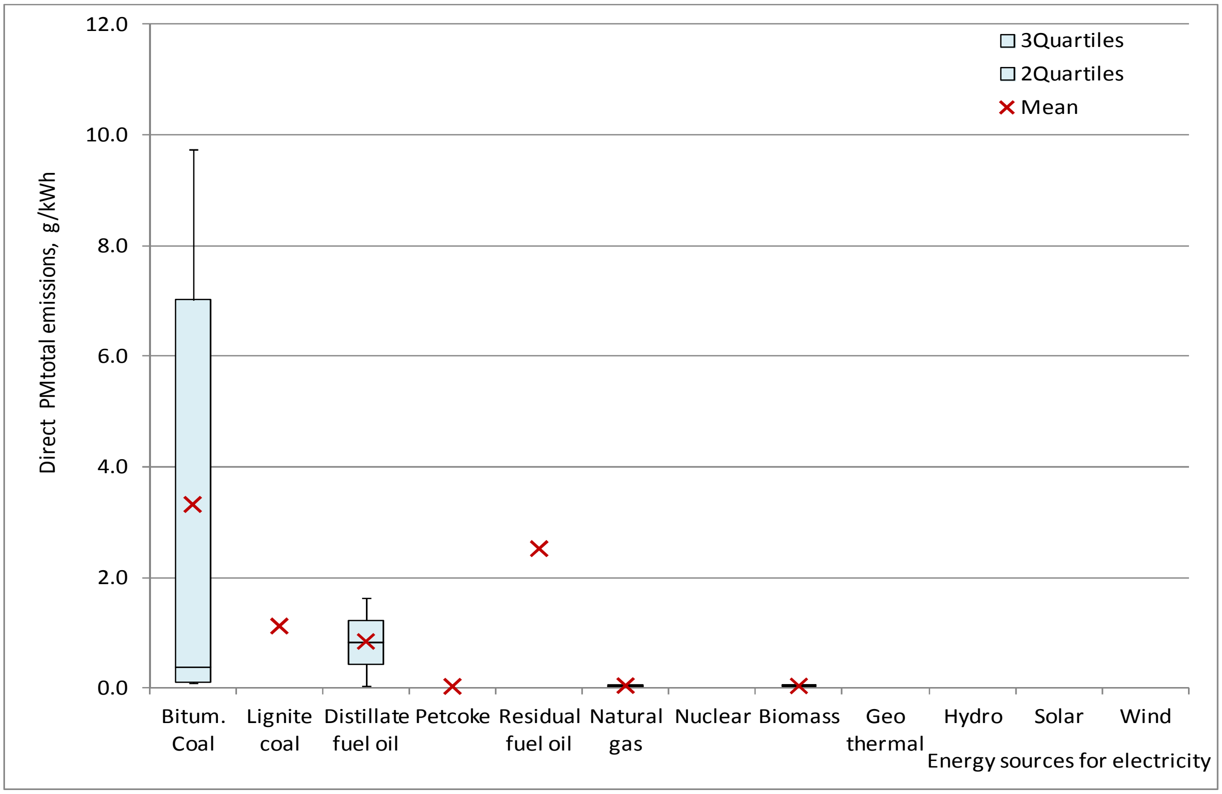


Figure 4.14: Direct PM_{10} emissions data associated with various energy sources used in electricity generation (based on U.S. and non-U.S. data sources)

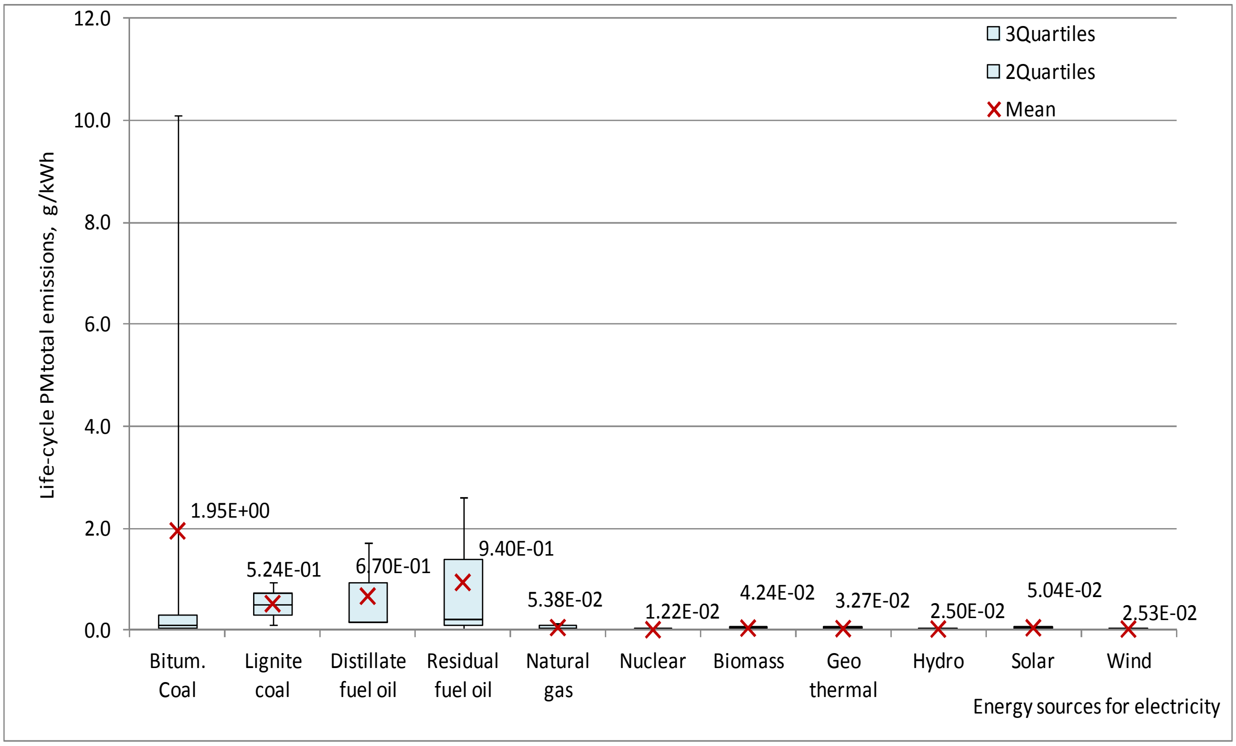


Figure 4.15: Life-cycle PM_{10} emissions data associated with various energy sources used in electricity (based on U.S. and non-U.S. data sources)

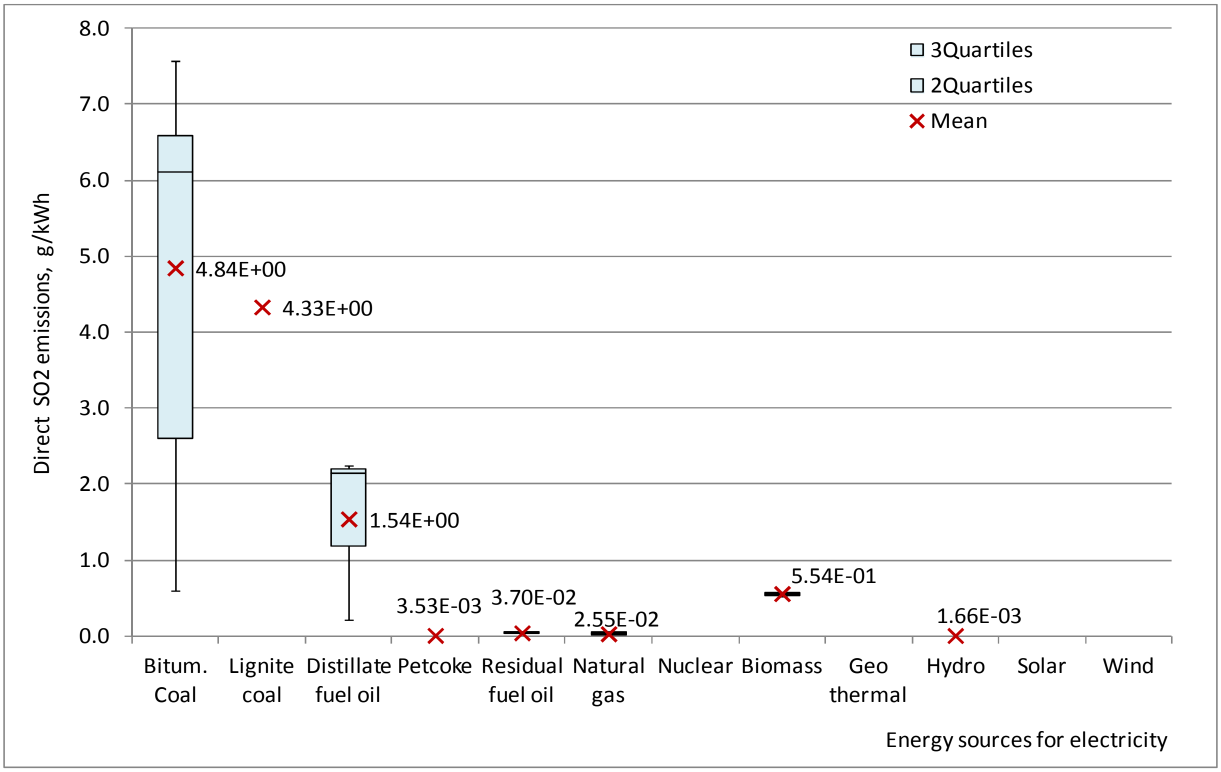


Figure 4.16: Direct SO_2 emissions data associated with various energy sources used in electricity generation (based on U.S. and non-U.S. data sources)

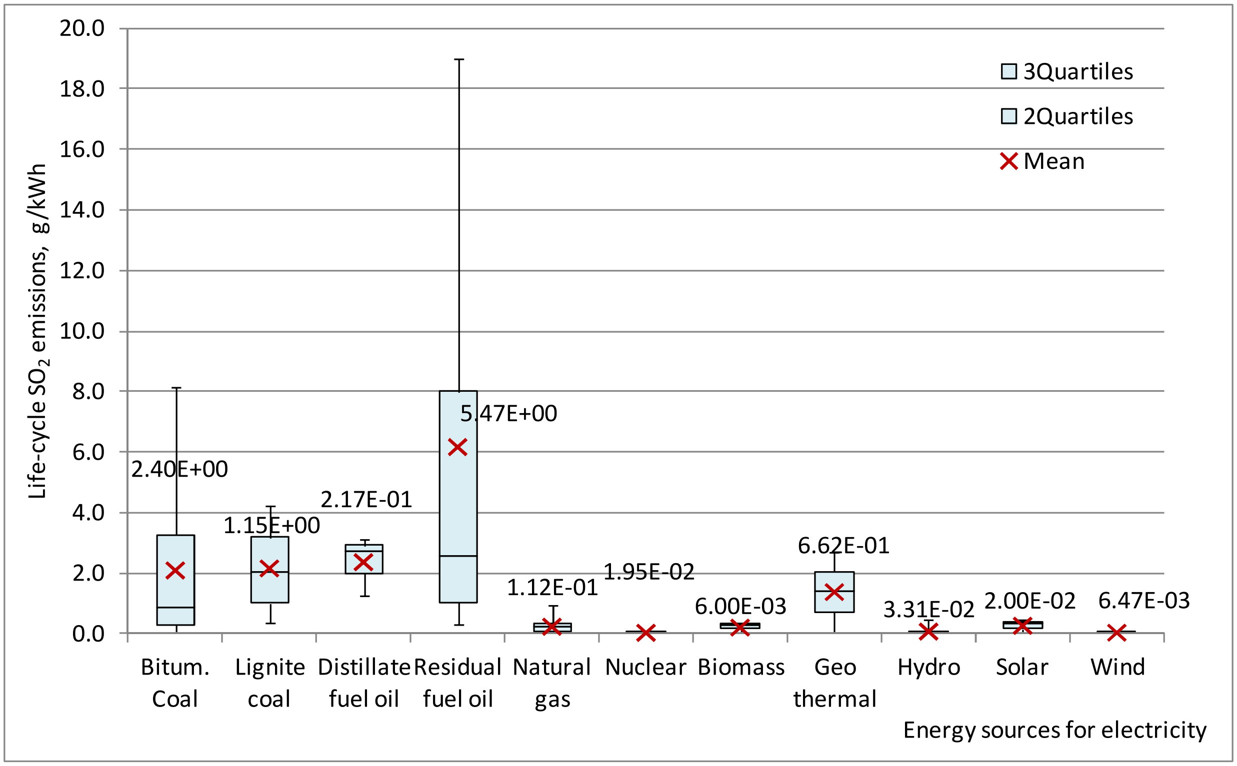


Figure 4.17: Life-cycle SO_2 emissions data associated with various energy sources used in electricity

generation (based on U.S. and non-U.S. data sources)

4.8.1.6 Water consumption associated with Electricity Generation

Water consumption data for electricity generation is described based on two major data sources [230, 232]. GreenConcrete LCA tool makes use of LCI results from the U.S. study by Fthenakis and Kim [230] for calculating direct and supply-chain water consumption impacts (in kg of water consumed per kWh of electricity generated). The study considers both water withdrawal and consumption LCI factors associated with renewable electricity-generation options, i.e., solar, wind, biomass, and hydroelectric, as well as the conventional thermoelectric fuel cycles of coal, natural gas, oil, hydroelectric, and nuclear. Accordingly, "withdrawal" is defined as the amount of water removed from the ground or diverted from a water source for use, while "consumption" refers to the amount of water that is evaporated, transpired, incorporated into products or crops, or otherwise removed from the immediate water environment based on the USGS's definition [253]. Water use for renewable electricity generation is mostly upstream that is related to constructing a power plant or manufacturing an equipment/product such as solar panels, wind turbines, except for the biomass fuel cycle that requires a significant amount of irrigation water. On the other hand, water use for conventional thermoelectric power, i.e., coal, nuclear, natural gas, and oil covers life-cycle stages of extracting fuel from the earth's crust, processing (cleaning, refining, or converting/enriching depending on type of fuel), then transporting to power plants, combusting in the plant to operate the turbine or steam generators, and finally decommissioning the power plant and disposing the spent fuel. Especially, for nuclear fuel cycle, upstream water withdrawal is estimated to be significant for uranium enrichment by gaseous diffusion technology. It is also the most energy-intensive stage which was previously mentioned in the sections related to energy and emission LCI factors for nuclear power plants.

During the operation of conventional thermoelectric power plants, direct water use is mostly for cooling, condensing, and cleaning flue gases purposes. Alternatively, hydroelectric power plants consume large volumes of water due to evaporation from the surface of artificial reservoirs, but wind- and solar-power plants barely need water during their operation [230]. Moreover, wind energy and photovoltaic cells that produce electricity directly from sunlight are considered to have negligible water use according to WBCSD report [254]. Geothermal power plants use more water than conventional steam plants because they run at only 8−15% heat-electricity conversion efficiency.

In addition to Fthenakis and Kim [230], Evans et al.[232] provide life-cycle water consumption data for coal, natural gas, geothermal, hydro, solar, and wind power plants in addition to GWP factors. Based on these two studies [232], following charts summarize direct and life-cycle water consumption data that is used in the GreenConcrete LCA calculations for electricity generation module.

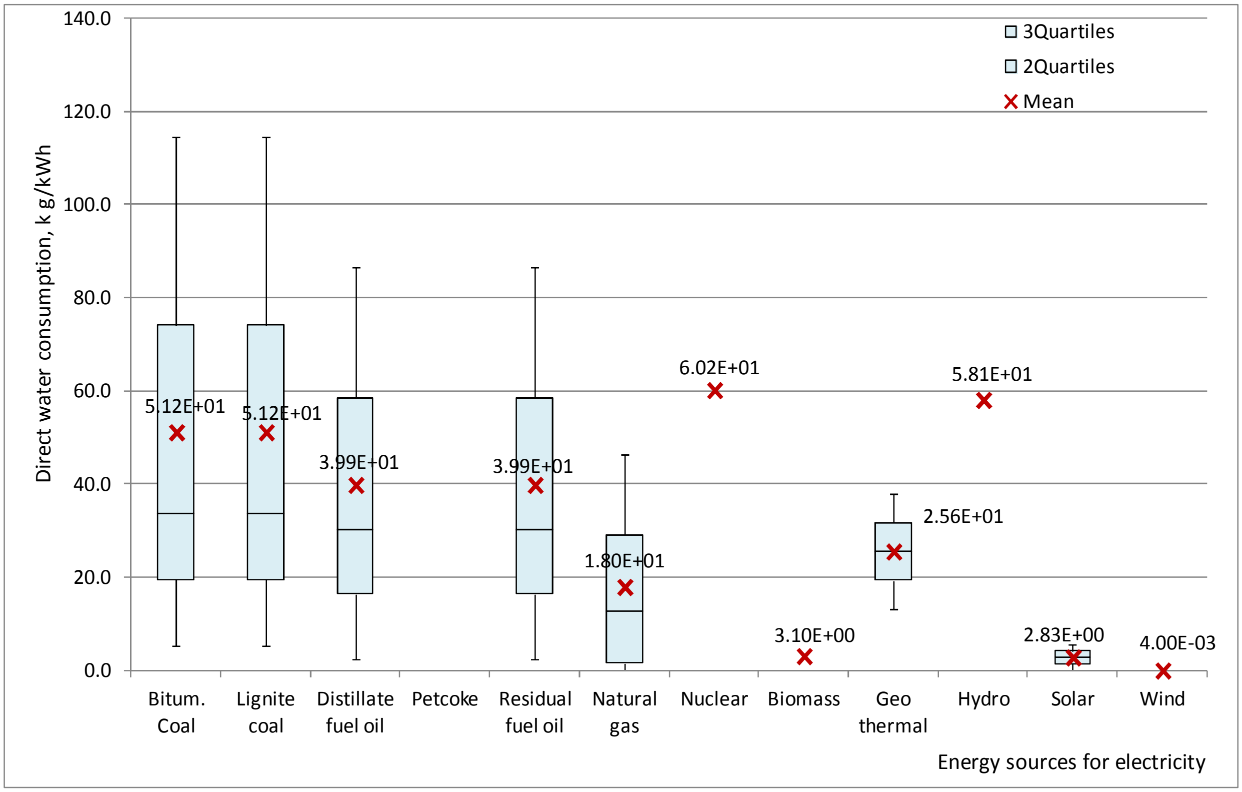


Figure 4.18: Direct water consumption associated with various energy sources used in electricity generation (based on U.S. and non-U.S. data sources)

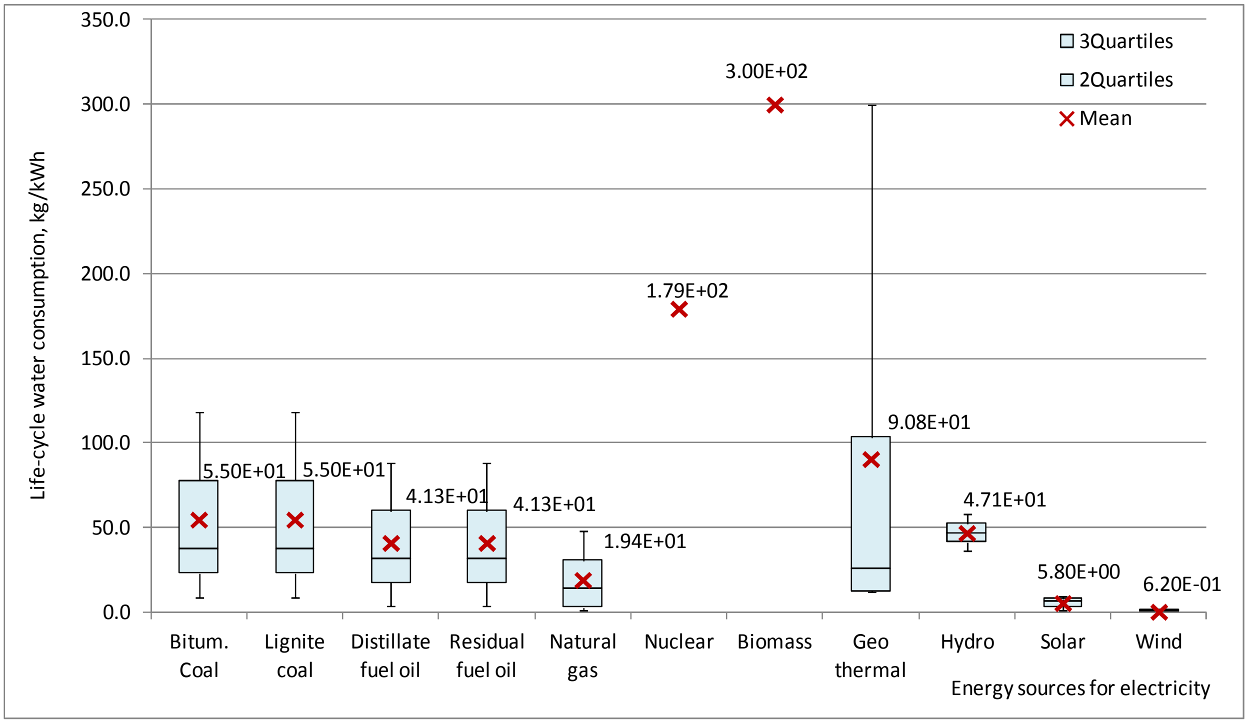


Figure 4.19: Life-cycle water consumption associated with various energy sources used in electricity generation (based on U.S. and non-U.S. data sources)

Average life-cycle emission factors as well as energy use and water consumption factors (from literature) are tabulated and used in GreenConcrete LCA calculations related to electricity generation. For example, when a user selects the nuclear option for electricity generation on the user-input page, the results will be based on the U.S. average data for that type of technology. If U.S. data is limited or not available, non-U.S. data is applied. Variations in electricity generation technologies (e.g. gas diffusion method vs. gas centrifuge method in nuclear power plants) are not considered in calculations since the major focus of this dissertation is cement and concrete production. However, as future work suggestion, the tool will allow users to choose the type of electricity generation technology and he/she will be able to fine-tune the LCA results for that technology option.

The following tables, Table 4.19 through Table 4.22 summarize all direct, total, and up-stream LCI data used in calculating electricity generation impacts for the GreenConcrete LCA tool.

Table 4.19: Direct LCI factors for electricity generation calculations (when State data is missing or it is user defined input, based on literature)

Sources / LCI Factors	Bituminous coal	Natural gas	Residual (heavy) fuel oil	Distillate (diesel fuel oil	Petcoke	Nuclear (uranium)	Hydro	Biomass	Geo-thermal	Solar	Wind	Lignite coal
Energy (MJ/kWh)	1.08E+01	6.70E+00	1.04E+01	1.04E+01	1.04E+01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.12E+01
Water (kg/kWh)	5.12E+01	1.80E+01	3.99E+01	3.99E+01	0.00E+00	6.02E+01	5.81E+01	3.10E+00	2.56E+01	2.83E+00	4.00E-03	5.12E+01
Solid waste (kg/kWh)	7.21E-02	0.00E+00	3.38E-04	0.00E+00	0.00E+00	0.00E+00	2.23E-04	4.11E-04	0.00E+00	0.00E+00	0.00E+00	1.43E-01
Air emissions (kg/kWh)												
$CO_{2\text{-eq}}$	9.44E-01	4.90E-01	7.83E-01	7.03E-01	9.70E-01	1.61E-02	3.89E-03	4.49E-01	9.70E-03	2.71E-02	7.20E-03	1.10E+00
Sb	3.73E-09	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	7.04E-09
As	5.55E-08	9.56E-10	4.17E-08	5.26E-08	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.60E-07
Be	2.22E-09	5.73E-11	8.77E-10	1.11E-09	2.65E-08	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	8.21E-09
Cd	5.52E-09	5.26E-09	1.26E-08	1.59E-08	1.22E-07	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.99E-08
CO_2	9.45E-01	4.78E-01	8.02E-01	8.31E-01	9.70E-01	0.00E+00	1.12E-03	4.48E-01	2.01E-02	0.00E+00	0.00E+00	1.09E+00
CO	1.30E-04	2.14E-04	1.58E-04	2.16E-04	1.59E-05	0.00E+00	4.08E-05	3.87E-05	0.00E+00	0.00E+00	0.00E+00	9.78E-05
Cr	5.80E-08	6.69E-09	2.67E-08	3.37E-08	2.23E-08	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.33E-07
Co	1.01E-08	4.01E-10	1.90E-07	2.40E-07	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	3.91E-08
Cu	2.07E-08	5.04E-10	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
CH_2O	5.30E-08	4.46E-06	1.04E-06	1.32E-06	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	9.38E-08
Pb	4.31E-08	2.39E-09	4.77E-08	6.02E-08	0.00E+00	0.00E+00	6.10E-15	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.64E-07
Mn	5.56E-08	1.82E-09	9.47E-08	1.20E-07	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.92E-07
Hg	2.89E-08	1.24E-09	3.57E-09	4.50E-09	0.00E+00	0.00E+00	3.05E-18	0.00E+00	0.00E+00	0.00E+00	0.00E+00	3.25E-08
CH_4	1.61E-05	2.75E-05	1.94E-05	2.61E-05	0.00E+00	0.00E+00	1.32E-04	2.60E-06	0.00E+00	0.00E+00	0.00E+00	1.56E-05
Ni	5.39E-08	1.00E-08	2.67E-06	3.37E-06	3.50E-07	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.09E-07
NO_x	2.19E-03	2.86E-04	1.55E-03	3.44E-03	1.47E-04	0.00E+00	2.70E-07	5.76E-04	0.00E+00	0.00E+00	0.00E+00	3.47E-03
N_2O	9.92E-06	5.37E-06	1.68E-05	1.24E-05	0.00E+00	0.00E+00	1.21E-11	4.75E-06	0.00E+00	0.00E+00	0.00E+00	2.50E-05
NMVOC	6.49E-05	1.02E-05	5.00E-05	4.45E-04	0.00E+00	0.00E+00	0.00E+00	5.54E-04	0.00E+00	0.00E+00	0.00E+00	2.26E-05
PM_{10}	4.17E-05	3.61E-05	5.99E-05	4.30E-05	9.45E-08	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00

PMtotal	4.77E-03	3.31E-05	2.51E-03	5.53E-04	1.86E-05	0.00E+00	5.32E-06	2.64E-05	0.00E+00	0.00E+00	0.00E+00	1.11E-03
Se	3.41E-07	1.15E-10	2.16E-08	2.72E-08	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	5.08E-07
SO_2	4.75E-03	2.47E-06	9.91E-03	1.54E-03	5.60E-04	0.00E+00	1.66E-06	2.79E-04	7.94E-05	0.00E+00	0.00E+00	4.33E-03
VOC (un-specified)	0.00E+00	2.64E-05	2.39E-05	8.64E-06	3.53E-06	0.00E+00	9.87E-08	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Zn	0.00E+00	1.72E-08	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00

Table 4.20: Total LCI factors for electricity generation calculations (based on literature)

Sources / LCI Factors	Bituminous coal	Natural gas	Residual (heavy) fuel oil	Distillate (diesel fuel oil	Petcoke	Nuclear (uranium)	Hydro	Biomass	Geo-thermal	Solar	Wind	Lignite coal
Energy (MJ/kWh)	1.13E+01	8.75E+00	1.12E+01	1.12E+01	1.12E+01	1.11E+01	1.20E-01	1.61E+01	2.22E+01	1.69E+00	2.34E-01	1.17E+01
Water (kg/kWh)	5.50E+01	1.94E+01	4.13E+01	4.13E+01	0.00E+00	1.79E+02	5.82E+01	3.00E+02	9.08E+01	5.80E+00	6.20E-01	6.07E+01
Solid waste (kg/kWh)	8.15E-02	6.52E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00	3.10E-04	6.30E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Air emissions (kg/kWh)												
CO_2-eq	8.97E-01	4.97E-01	8.19E-01	8.77E-01	0.00E+00	1.70E-02	2.45E-02	-3.84E-01	7.58E-02	9.03E-02	1.81E-02	1.10E+00
Sb	3.64E-09	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
As	4.38E-08	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Be	1.42E-09	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Cd	3.60E-09	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
CO_2	9.39E-01	4.41E-01	7.78E-01	8.11E-01	0.00E+00	1.50E-02	1.49E-02	4.59E-02	6.29E-02	1.66E-01	1.66E-02	1.10E+00
CO	1.75E-04	2.87E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00	8.93E-05	8.30E-05	2.08E-04	8.54E-05	4.84E-05	0.00E+00
Cr	5.24E-08	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Co	6.09E-09	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Cu	2.07E-08	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
CH_2O	0.00E+00	8.57E-06	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Pb	2.66E-08	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.65E-14	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Mn	3.81E-08	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Hg	6.95E-08	0.00E+00	7.50E-09	0.00E+00	0.00E+00	0.00E+00	8.27E-18	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00

CH_4	1.18E-03	2.80E-03	2.27E-03	2.01E-03	0.00E+00	2.00E-05	7.55E-05	5.07E-06	6.08E-05	4.59E-04	6.32E-05	4.72E-03
Ni	5.13E-08	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
NO_x	2.21E-03	7.97E-04	1.63E-03	5.61E-03	0.00E+00	5.00E-05	2.31E-05	6.86E-04	1.04E-04	4.49E-04	3.62E-05	2.95E-03
N_2O	3.34E-06	7.19E-07	1.00E-02	2.00E-05	0.00E+00	5.00E-07	1.67E-07	9.54E-06	1.35E-06	2.00E-07	3.00E-07	0.00E+00
NMVOC	1.54E-04	3.73E-04	2.20E-05	1.85E-03	0.00E+00	9.00E-06	5.25E-06	5.95E-04	4.00E-06	7.80E-06	8.57E-06	0.00E+00
PM_{10}	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
PMtotal	5.61E-03	9.05E-05	9.40E-04	6.70E-04	0.00E+00	2.00E-06	2.50E-05	4.16E-05	3.27E-05	5.04E-05	2.53E-05	5.24E-04
Se	3.59E-07	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
SO_2	3.59E-03	3.21E-04	8.01E-03	2.37E-03	0.00E+00	3.00E-06	8.25E-05	3.02E-04	1.39E-03	2.74E-04	4.99E-05	2.17E-03
VOC (unspecified)	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	3.74E-07	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Zn	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00

Table 4.21: Upstream LCI factors for electricity generation calculations

Sources / LCI Factors	Bituminous coal	Natural gas	Residual (heavy) fuel oil	Distillate (diesel fuel oil	Petcoke	Nuclear (Uranium)	Hydro	Biomass	Geo-thermal	Solar	Wind	Lignite coal
Energy (MJ/kWh)	3.66E-01	3.36E-01	7.72E-01	7.72E-01	7.72E-01	1.11E+01	1.20E-01	0.00E+00	2.22E+01	1.69E+00	2.34E-01	5.81E-01
Water (kg/kWh)	3.81E+00	1.44E+00	1.44E+00	1.44E+00	0.00E+00	1.19E+02	8.00E-02	2.97E+02	6.52E+01	8.68E-01	6.18E-01	3.81E+00
Solid waste (kg/kWh)	0.00E+00	2.61E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00	8.70E-05	4.06E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Air emissions (kg/kWh)												
CO_2-eq	4.10E-02	1.20E-01	8.91E-02	1.32E-01	0.00E+00	1.12E-02	6.22E-03	3.69E-02	6.61E-02	9.03E-02	2.08E-02	0.00E+00
Sb	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
As	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Be	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Cd	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
CO_2	2.30E-02	6.85E-02	9.90E-02	7.08E-02	0.00E+00	1.03E-02	2.22E-03	3.39E-02	4.28E-02	1.15E-01	1.85E-02	0.00E+00
CO	9.60E-05	2.60E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00	7.12E-05	7.79E-05	2.08E-04	8.54E-05	4.84E-05	0.00E+00
Cr	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00

Co	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Cu	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
CH_2O	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Pb	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.04E-14	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Mn	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Hg	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	5.22E-18	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
CH_4	1.16E-03	2.76E-03	2.24E-03	1.96E-03	0.00E+00	2.00E-05	5.00E-06	4.72E-06	6.08E-05	4.59E-04	6.32E-05	0.00E+00
Ni	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
NO_x	2.27E-04	4.75E-04	3.20E-04	5.19E-04	0.00E+00	5.36E-05	6.36E-06	1.93E-04	1.04E-04	4.16E-04	3.81E-05	0.00E+00
N_2O	1.06E-06	7.19E-07	0.00E+00	0.00E+00	0.00E+00	5.00E-07	5.03E-08	9.36E-06	1.35E-06	2.00E-07	3.00E-07	0.00E+00
NMVOC	1.19E-04	6.18E-04	1.41E-03	1.24E-03	0.00E+00	9.00E-06	0.00E+00	7.32E-05	4.00E-06	2.85E-05	8.57E-06	0.00E+00
PM_{10}	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
PMtotal	2.53E-03	7.13E-05	9.00E-05	9.20E-05	0.00E+00	1.74E-05	1.98E-05	2.69E-05	3.27E-05	6.05E-05	2.63E-05	0.00E+00
Se	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
SO_2	1.79E-04	3.22E-04	4.30E-04	7.17E-04	0.00E+00	4.92E-05	6.05E-06	3.90E-05	1.31E-03	2.32E-04	4.67E-05	0.00E+00
VOC (un-specified)	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	2.75E-07	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Zn	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00

4.8.2 Electricity Grid Mix Life-Cycle Inventory Calculations

Direct emission factors for the States and the U.S. average are developed using the EPA's "Emissions and Generation Resource Integrated Database (e-GRID)" in conjunction with the life-cycle emissions developed in the GreenConcrete LCA tool based on peer-reviewed electricity generation LCA studies (see Section 4.8.1). The e-GRID is used to provide direct emission factors for coal, oil, natural gas, nuclear, and renewable power plants, which represent the average rates for all the U.S. power plants. The latest available e-GRID data is obtained from the 2010 version [255]. Calculations of direct and indirect LCI data for the States and the U.S. electricity generation as well as user-defined mixes involve a series of equations and great amount of data. The following sections focus on these calculations regarding the electricity grid mix percentages by energy source and by State. The Figure 4.20 below demonstrates the recent U.S. electricity mix by energy sources. Next, equations for the direct primary energy use per kWh of electricity generated are provided.

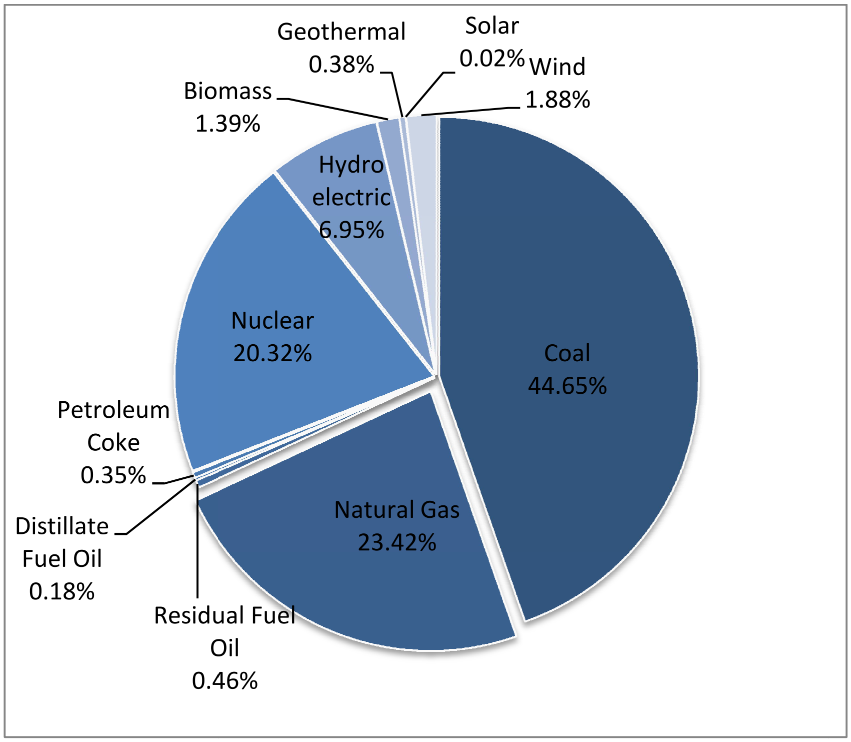


Figure 4.20: 2009 U.S. electricity generation by energy source [220]

Electricity grid mix percentages for the U.S. and each State are calculated based on the EIA's net annual electricity generation data in Appendix A, Table 9.1 as follows:

$$ELECTRIC\_PERCENT_{i,j}\ (\%) = 100\%\ X\ (ELECTRIC\_SOURCE_{i,j}\ /ELECTRIC\_STATE_{j})$$

Equation 4.25: Calculation of State electricity grid mix percentage by energy source

Where:

ELECTRIC_PERCENT$_{i,j}$ (%) = Electricity generation grid mix percentage for State "j" and energy source "i", in %;

ELECTRIC_SOURCE$_{i,j}$ = Net annual electricity generation by energy source “i” by state “j”, in kWh, obtained from the first column of Appendix A, Table 9.1;

ELECTRIC_STATE$_{j}$ = Net annual electricity generation by State “j”, in kWh.

Results from the Equation 4.25 are listed in Table 4.22, demonstrating the significance of geographical variation in electricity generation LCI data. For example, 96% of electricity is generated from coal in West Virginia whereas in Rhode Island, 98% is from natural gas. As a consequence, the associated life-cycle impacts from these two sources will differ considerably.

Table 4.22: Electricity Grid Mix Percentages by US States and by Energy Source

States	Coal (%)	Natural Gas (%)	Residual fuel oil (%)	Distillate fuel oil (%)	Pet coke (%)	Nuclear (%)	Hydro electric (%)	Bio mass (%)	Geo thermal (%)	Solar (%)	Wind (%)
AK	9%	53%	9%	9%	0%	0%	20%	0%	0%	0%	0%
AL	39%	22%	0%	0%	0%	28%	9%	2%	0%	0%	0%
AR	44%	20%	0%	0%	0%	26%	7%	3%	0%	0%	0%
AZ	35%	31%	0%	0%	0%	27%	6%	0%	0%	0%	0%
CA	1%	55%	0%	0%	1%	16%	14%	3%	6%	0%	3%
CO	63%	27%	0%	0%	0%	0%	4%	0%	0%	0%	6%
CT	8%	31%	1%	0%	0%	53%	2%	2%	0%	0%	0%
DC	0%	0%	0%	100%	0%	0%	0%	0%	0%	0%	0%
DE	59%	28%	2%	3%	0%	0%	0%	3%	0%	0%	0%
FL	25%	54%	3%	0%	1%	13%	0%	2%	0%	0%	0%
GA	54%	16%	0%	1%	0%	25%	3%	2%	0%	0%	0%
HI	14%	0%	63%	12%	0%	0%	1%	3%	2%	0%	2%
IA	72%	2%	0%	0%	0%	9%	2%	0%	0%	0%	14%
ID	1%	13%	0%	0%	0%	0%	80%	4%	1%	0%	2%
IL	46%	2%	0%	0%	0%	49%	0%	0%	0%	0%	1%
IN	93%	3%	0%	0%	0%	0%	0%	0%	0%	0%	1%
KS	69%	6%	0%	0%	0%	19%	0%	0%	0%	0%	6%
KY	93%	1%	0%	0%	2%	0%	4%	0%	0%	0%	0%
LA	25%	48%	0%	0%	2%	18%	1%	3%	0%	0%	0%
MA	23%	54%	2%	0%	0%	14%	3%	3%	0%	0%	0%
MD	55%	4%	0%	0%	0%	33%	4%	1%	0%	0%	0%
ME	0%	45%	3%	0%	0%	0%	26%	22%	0%	0%	2%
MI	66%	8%	0%	0%	0%	22%	1%	2%	0%	0%	0%
MN	56%	5%	0%	0%	0%	24%	2%	3%	0%	0%	10%
MO	81%	4%	0%	0%	0%	12%	2%	0%	0%	0%	1%
MS	27%	48%	0%	0%	0%	23%	0%	3%	0%	0%	0%
MT	58%	0%	0%	0%	2%	0%	36%	0%	0%	0%	3%
NC	55%	4%	0%	0%	0%	34%	4%	2%	0%	0%	0%
ND	87%	0%	0%	0%	0%	0%	4%	0%	0%	0%	9%
NE	69%	1%	0%	0%	0%	28%	1%	0%	0%	0%	1%

NH	14%	26%	1%	0%	0%	44%	8%	6%	0%	0%	0%
NJ	8%	33%	0%	0%	0%	56%	0%	2%	0%	0%	0%
NM	73%	22%	0%	0%	0%	0%	1%	0%	0%	0%	4%
NV	20%	69%	0%	0%	0%	0%	7%	0%	4%	0%	0%
NY	10%	31%	2%	0%	0%	33%	21%	2%	0%	0%	2%
OH	84%	3%	0%	0%	1%	11%	0%	0%	0%	0%	0%
OK	45%	46%	0%	0%	0%	0%	5%	0%	0%	0%	4%
OR	6%	28%	0%	0%	0%	0%	58%	1%	0%	0%	6%
PA	48%	13%	0%	0%	0%	35%	1%	1%	0%	0%	0%
RI	0%	98%	0%	0%	0%	0%	0%	2%	0%	0%	0%
SC	34%	10%	0%	0%	0%	52%	2%	2%	0%	0%	0%
SD	39%	1%	0%	0%	0%	0%	54%	0%	0%	0%	5%
TN	52%	1%	0%	0%	0%	34%	13%	1%	0%	0%	0%
TX	35%	48%	0%	0%	0%	10%	0%	0%	0%	0%	5%
UT	82%	15%	0%	0%	0%	0%	2%	0%	1%	0%	0%
VA	37%	17%	1%	1%	0%	40%	2%	3%	0%	0%	0%
VT	0%	0%	0%	0%	0%	74%	20%	6%	0%	0%	0%
WA	7%	11%	0%	0%	0%	6%	70%	1%	0%	0%	3%
WI	62%	9%	0%	0%	1%	21%	2%	2%	0%	0%	2%
WV	96%	0%	0%	0%	0%	0%	2%	0%	0%	0%	1%
WY	91%	1%	0%	0%	0%	0%	2%	0%	0%	0%	5%
U.S. average	**44%**	**23%**	**0%**	**0%**	**0%**	**20%**	**7%**	**1%**	**0%**	**0%**	**2%**
Source	[220]	[220]	[220]	[220]	[220]	[220, 256]	[220, 257]	[220, 257]	[220, 257]	[220, 257]	[220, 257]

The direct energy use factors are calculated in three steps. The first step estimates energy source consumption factor by source by State as follows:

$$ESOURCE\_FACTOR_{i,j} = ELECTRIC\_FUEL_{i,j}/ELECTRIC\_STATE_j$$

Equation 4.26: Calculation of energy source consumption factor

Where:

$ESOURCE\_FACTOR_{i,j}$ = Energy source consumption factor by energy source “i” and State “j”, in units of mass (kg) or volume (l or m^3) of fossil fuel per kWh of electricity or kWh of renewable per kWh of electricity;

$ELECTRIC\_FUEL_{i,j}$ = Amount of fossil fuel “i” consumed to generate the net annual electricity in State “j”, in units of mass (kg) or volume (l or m^3) of fossil fuel (see Appendix A, Table 9.3) or in kWh of renewable source (see Appendix A, Table 9.1);

$ELECTRIC\_STATE_j$ = Net annual electricity generation in State “j” (Second column of Appendix A, Table 9.1), in kWh.

Results from the Equation 4.26 are tabulated in Appendix A, Table 9.4. Before moving to the second step, nuclear power plant LCI calculations involve the physical amount of uranium fuel used and is estimated as follows:

$$ELECTRIC\_FUEL_{URANIUM,j} = ELECTRIC\_SOURCE_{NUCLEAR,j} \times (0.4536\frac{kg}{lb})/(13{,}638\frac{kWh}{lb})$$

Equation 4.27: Calculation of amount of uranium fuel used to generate net annual electricity from nuclear power plants in State “j”

Where:

$\mathrm{ELECTRIC\_FUEL}_{\mathrm{URANIUM,j}}$ = Amount of uranium fuel used to generate net annual electricity from nuclear power plants in State “j”, in kg;

$\mathrm{ELECTRIC\_SOURCE}_{\mathrm{NUCLEAR,j}}$ = Net annual electricity generation by nuclear, by state “j”, in kWh (given in “Nuclear” column of Appendix A, Table 9.1);

$0.4536\frac{kg}{lb}$ = Conversion factor from lb to kg;

$13{,}638\frac{kWh}{lb}$ = kWh of electricity generated per lb of uranium fuel used in the U.S. nuclear power plants.

The second step involves multiplication of factors listed in Appendix A, Table 9.4 with fuel heat contents tabulated in Appendix A, Table 9.5 for calculation of the State fuel heat conversion factors in MJ/kWh (Equation 4.28).

The U.S. fuel heat contents demonstrated in Appendix A, Table 9.5 are provided for all energy sources except for the biomass which are taken directly from EIA sources [258-260]. For ease of calculations, heat content for biomass fuel is assumed to be the average of municipal solid waste (MSW) biogenic, agriculture byproducts and crops, sludge waste, and other biomass solids, black liquor, and wood/wood waste solids and liquids that are commonly used in the U.S. electric power generation (see Table 4.23) and estimated as 12.35 MJ per kg of biomass fuel.

Table 4.23: Average Heat Content of Selected Biomass Fuels [261]

Type of biomass fuel	**Million btu/short ton**	**MJ/kg**
Agricultural byproducts	8.25	9.59
Black liquor	11.76	13.67
Municipal solid waste, biogenic	9.70	11.28
Paper pellets	13.03	15.15
Peat	8.00	9.30
Railroad ties	12.62	14.67
Sludge waste	7.51	8.74
Sludge wood	10.07	11.71
Spent sulfite liquor	12.72	14.79
Utility poles	12.50	14.54
Average heat content:	***10.62***	***12.35***

$$\mathrm{FUEL}_{\mathrm{HCCF}_{\mathrm{i,j}}} = \mathrm{ESOURCE}_{\mathrm{FACTOR}_{\mathrm{i,j}}} \times ESOURCE_{HC_{i,j}}$$

Equation 4.28: Calculation of State fuel heat content conversion factors used in direct energy use associated with electric power generation

Where:

$FUEL\_HCCF_{i,j}$ = State fuel heat content conversion factor for energy source “i” by State “j” (see Appendix A, Table 9.6), in MJ/kWh;

$ESOURCE\_FACTOR_{i,j}$ = described in Equation 4.26;

$ESOURCE\_HC_{i,j}$ = Average heat content for energy source “i” in State “j”, in units of MJ of primary energy consumed per mass (kg) or volume (l or m^3) of fossil fuel or per kWh of renewable energy source (see Appendix A, Table 9.5).

Finally, the third step involves the calculation of direct energy use for each State or the U.S., which is the sum of FUEL_HCCF factors in each row; whereas each row represents a State or the U.S. average (see the last column “Total” in Appendix A, Table 9.6). The equation applied for the direct energy use calculations is as follows:

$$ELECTRIC_{ENERGY_{DIRECTj}} = \sum\nolimits_{i=1}^{n} FUEL_{HCCF_{i,j}}$$

Equation 4.29: Calculation of direct energy use for State and the U.S. electric power generation

Where:

$ELECTRIC\_ENERGY_{DIRECTj}$ = Direct energy consumption factor for State “j” and the U.S. average, in MJ/kWh;

$FUEL\_HCCF_{i,j}$ = State fuel heat content conversion factor for energy source “i” by State “j” (see Appendix A, Table 9.6), in MJ/kWh

The direct emission factors of CO_2, CH_4, N_2O, NO_x, and SO_2 for States and the U.S. electricity generation are taken from e-GRID (see Appendix A, Table 9.7). However, for calculations of other direct emission factors (including solid waste, water consumption, and air emissions except for GHG, NO_x, and SO_2), the following equation is developed:

$$ELECTRIC_{EF_{DIRECTk,j}} = \sum_{i=1}^{n} \left[ELECTRIC_{EF_{DIRECTk,i}} \times ELECTRIC_{SOURCE_{i,j}}\right]$$

Equation 4.30: Calculation of direct emission factors (other than GHG, NO_x, and SO_2) for State and the U.S. electricity generation

Where:

$ELECTRIC\_EF_{DIRECTk,j}$ = Direct emission factor for State “j” or the U.S. average, in kg/kWh, which include direct LCI factors of “k” representing solid waste, water consumption, as well as air emissions of Sb, As, Be, Cd, CO, Cr, Formaldehyde, Pb, Mn, Hg, Ni, non-methane VOC, PM_{10}, PMtotal, Se, VOC, and Zn;

$ELECTRIC\_EF_{DIRECTk,i}$ = Direct LCI emission factor “k” by energy source “i” (based on literature and summarized in Table 4.19), in kg/kWh;

ELECTRIC_SOURCE$_{i,j}$= Electricity generation grid mix percentage for State "j" and energy source "i" calculated by Equation 4.25, in %;

In the equation above the sum of multiplication of factors within the brackets represent a "SUMPRODUCT" function in Excel tool. Results from Equation 4.30 together with e-GRID emission factors in Table 9.7 are summarized in Appendix A, Table 9.8.

When custom electricity grid mix percentages are available, associated direct LCI factors are calculated using a similar approach given in Equation 4.30 with the following modification:

$$ELECTRIC_{LCIF_{DIRECTk,m}} = \sum_{i,k,m}^{n} \left[ELECTRIC_{LCIF_{DIRECTk,i}} \times ELECTRIC_{SOURCE_{i,m}}\right]$$

Equation 4.31: Calculation of direct LCI factors for user-defined custom grid mixes

Where:

ELECTRIC_LCIF$_{DIRECTk,m}$ = Direct emission factor user-defined custom grid mix "m", in MJ/kWh for "k" energy use factor or in kg/kWh for direct LCI factors of "k" representing solid waste, water consumption, as well as air emissions of Sb, As, Be, Cd, CO, CO_2, CH_4, Cr, Formaldehyde, Pb, Mn, Hg, Ni, N_2O, NO_x, non-methane VOC, PM_{10}, PMtotal, Se, SO_2, VOC, and Zn;

ELECTRIC_LCIF$_{DIRECTk,i}$ = Direct LCI factor "k" by energy source "i" (based on literature and summarized in Table 4.19), in MJ/kWh for "k" energy use and in kg/kWh for "k" water consumption, solid waste or air emissions LCI factors;

ELECTRIC_SOURCE$_{i,m}$ = User-defined custom grid mix percentage "m" and energy source "i" obtained from User-Input Page (see Table 4.7 for details), in %.

For a complete and accurate assessment of electricity generation, total (direct + upstream) life-cycle resource use and emission factors should be considered. Life-cycle emission factors of GHG, NO_x, and SO_2 for States and the U.S. average are estimated by adding the direct e-GRID emissions data to the sumproduct of the upstream emission factors of the energy source and the State grid mix percentage by energy source (see Table 4.21 for the results):

$$\begin{aligned} &ELECTRIC_{EF_{TOTALk`,j}} \\ &\quad = ELECTRIC_{EF_{eGRIDk`,j}} + \sum_{i,k`,j}^{n} \left[ELECTRIC_{EF_{UPSTREAMk`,i}} \times ELECTRIC_{SOURCE_{i,j}}\right] \end{aligned}$$

Equation 4.32: Calculation of life-cycle (total) emission factors of GHG, NO_x, and SO_2 for States and the U.S.

Where:

ELECTRIC_EF$_{TOTALk`,j}$ = Total emission factor for State "j" or the U.S. average, whereas "k`" represents one of the air emissions of CO_2, CH_4, and N_2O, NO_x, or SO_2, in kg/kWh;

ELECTRIC_EF$_{eGRIDk,j}$ = Direct emission factor for State "j" or the U.S. average, whereas "k`" represents one of the air emissions of CO_2, CH_4, and N_2O, NO_x, or SO_2 based on e-

GRID, in kg/kWh;

$ELECTRIC\_EF_{UPSTREAMk,i}$ = Upstream (indirect) LCI emission factor “k`” representing one of the air emissions of CO_2, CH_4, and N_2O, NO_x, or SO_2 by energy source “i” (based on literature and summarized in Table 4.21), in kg/kWh;

$ELECTRIC\_SOURCE_{i,j}$ = Electricity generation grid mix percentage for the State “j” and the energy source “i” calculated by Equation 4.25, in %.

Other total LCI factors (other than CO_2, CH_4, and N_2O, NO_x, or SO_2 which are calculated by Equation 4.32) associated with the electricity generation for a given State or for the U.S. average case is calculated differently as follows:

$$\begin{aligned} &ELECTRIC_{LCIF_{TOTALk,j}} \\ &\quad = ELECTRIC_{LCIF_{DIRECTk,j}} + \sum_{i=1}^{n} \left[ELECTRIC_{LCIF_{UPSTREAMk,i}} \times ELECTRIC_{SOURCE_{i,j}}\right] \end{aligned}$$

Equation 4.33: Calculation of direct emission factors (other than GHG, NO_X, and SO_2) for State and US electricity generation

Where:

$ELECTRIC\_LCIF_{TOTALk,j}$ = Total emission factor for State “j” or the U.S. average, in MJ/kWh for “k” energy use factor or in kg/kWh for direct LCI factors of “k” representing any of the factors: solid waste, water consumption, as well as air emissions of Sb, As, Be, Cd, CO, Cr, Formaldehyde, Pb, Mn, Hg, Ni, non-methane VOC, PM_{10}, PMtotal, Se, VOC, and Zn. ;

$ELECTRIC\_LCIF_{DIRECTk,j}$ = Direct emission factor for State “j” or the U.S. average, in MJ/kWh for “k” representing energy use, and is denoted by “$ENERGY_{DIRECTj}$” that is calculated by Equation 4.29 or in kg/kWh, for direct LCI factors of “k” representing any of the factors denoted by “$EMISSIONFACTOR_{DIRECTk,j}$” for solid waste, water consumption, as well as air emissions of Sb, As, Be, Cd, CO, Cr, Formaldehyde, Pb, Mn, Hg, Ni, non-methane VOC, PM_{10}, PMtotal, Se, VOC, and Zn and is calculated by Equation 4.30;

$ELECTRIC\_LCIF_{UPSTREAMi,j}$ = Upstream (indirect) LCI factor by energy source “i” (based on literature and summarized in Table 4.21), in MJ/kWh;

$ELECTRIC\_SOURCE_{i,j}$ = Electricity generation grid mix percentage for State “j” and energy source “i” calculated by Equation 4.25, in %;

Finally, when the user defines the grid mix percentages for electricity generation, GreenConcrete LCA tool calculates associated total LCI factors based on the electricity generation LCA data from literature (see Table 4.20). When the U.S. data is missing, non-U.S. sources are used to fill the gap in the total LCI data calculations:

$$ELECTRIC_{LCIF_{TOTALk,mix}} = \sum_{i=1}^{n}\left[ELECTRIC_{LCIF_{TOTALk,i}} \times ELECTRIC_{SOURCE_{i,mix}}\right]$$

Equation 4.34: Calculation of total LCI factors for user-defined custom grid mix

Where:

ELECTRIC_LCIF$_{TOTALk,mix}$ = Total emission factor for user-defined custom grid mix "mix", in MJ/kWh for "k" energy use factor or in kg/kWh for direct LCI factors of "k" representing solid waste, water consumption, as well as air emissions of Sb, As, Be, Cd, CO, CO_2, CH_4, Cr, Formaldehyde, Pb, Mn, Hg, Ni, N_2O, NO_x, non-methane VOC, PM_{10}, PMtotal, Se, SO_2, VOC, and Zn;

ELECTRIC_LCIF$_{TOTALk,i}$ = Total LCI factor "k" by energy source "i" (based on the literature and summarized in Table 4.20), in MJ/kWh for "k" energy use and in kg/kWh for "k" water consumption, solid waste or air emissions LCI factors;

ELECTRIC_SOURCE$_{i,mix}$ = User-defined custom grid mix percentage "mix" and energy source "i" obtained from the User-Input Page, in %.

4.9 **Transportation**

The shipment of concrete, admixtures, aggregates, natural pozzolans, fly ash, slag, and portland cement and its raw materials (e.g. limestone, gypsum, etc.) is usually done by truck, train, or water means (barges, boat, and vessels). These are the cheapest and easiest forms of transportation. The common land carriers include heavy trucks and diesel locomotives while exported materials (e.g. admixtures, cement, and fly ash) are primarily transported in tank ships [35].

4.9.1 Freight Transportation LCA Literature Review

Most of the freight transportation LCA studies focus on the tail-pipe impacts without the consideration of supply-chain (or indirect) impacts [58, 262-265]. Although it is important to analyze direct implications of transportation, exclusion of indirect impacts which often contribute largely to the total transportation can underestimate the level of energy use or emissions from a specific mode of transportation and comparison among different modes may not be realistic. Currently, three U.S. studies and one EU study cover total life-cycle emissions and energy use associated with common transportation modes used during the life-cycle of concrete and its major ingredients [266-268]. Of these three sources, only Facanha and Horvath [266] provide the associated life-cycle criteria air pollutants in addition to CO_2 emissions for road freight transportation with variations of three types of truck models in this mode, and one type of rail freight mode, except for the water freight transportation. Other two studies are limited to total energy use and GHG emissions associated with generic freight transportation modes of road, rail, and water. Due to the measurement and modeling complexities as well as uncertainties in the description of model/type of road and rail freight vehicles analyzed in these two studies, data is used for just comparison purposes but not in LCA calculations within the GreenConcrete tool. Only Facanha and Horvath [266] data is used for road and rail freight transportation LCA calculations since the data points are more accurately defined. On the other hand, Nealer et al. [267] and Weber and Matthews [268] provide the life-cycle energy use and GHG emission factors associated with water freight transportation in the tool. The EU study by den Boer et al. [269] is an overview of emission factors per tonne-km for different freight modes with different load capacities and models.

Looking into the data details, the most recent study by Nealer et al. [267] use three estimates of low, mean, and high life-cycle energy use and GHG emissions by mode in their LCAs. Life-cycle energy use includes not only the direct energy use but also the supply-chain energy consumed in producing the fuel. This inclusion is valid for all modes studied in the paper. Life-cycle GHG emissions are calculated using EPA's energy conversion factors (in kg of CO_2-equivalent per MJ) for various modes and compared to SimaPro database with insignificant difference. Data sources used in this study include NREL database, GREET model, Bureau of Transportation Statistics' 2002 Commodity Flow Survey using I-O use tables and other freight LCA studies. For road freight mode, 11 truck-related data points are used. Energy consumption varies within the range of low: 0.8; mean: 1.8; and high: 2.7 MJ /ton-km while GHG data varies from low: 0.060; mean: 0.12; to high: 0.19 kg CO_2-equivalent /ton-km. For rail freight transportation, four data points are used. Energy consumption varies within ranges of low: 0.26; mean: 0.28; and high: 0.31 MJ/ ton-km while GHG varies from low: 0.018; mean: 0.019; and high: 0.021 kg CO_2-equivalent /ton-km. For water freight transportation, ten data points are used. Energy consumption varies within the range of low: 0.22; mean: 0.33; and high: 0.45 MJ/ton-km and GHG emissions vary from low: 0.017; mean: 0.025; and high: 0.034 kg CO_2-equivalent /ton-km for water freight LCAs. In the study, “ton” represents “short-ton” and in GreenConcrete LCA, ton is converted to metric ton (tonne) units for consistency.

Weber and Matthews [268] provide total energy intensities and GHG emissions for various modes of freight transportation, including truck, rail, water (inland and international separately), and air. Energy data in the study was taken mostly from U.S. Transportation Energy Data Book [152], GREET model [215], and also literature [266, 270].

Another U.S. study by Facanha and Horvath [266] analyzes life-cycle emission factors for road, rail, and air freight transportation modes with different vehicle models. Inland shipping for the U.S. is not included in the study. Within the system boundary, environmental impacts from vehicles, infrastructure, as well as transportation fuel cycles covering their extraction, refining and distribution are analyzed.

Den Boer et al. [269] study EU emissions within the system boundary of freight transportation. However, emissions from vehicle production, maintenance, wear and tear (from tires, brakes, road surfaces, etc.), end-of-life, and infrastructure are not included. GreenConcrete LCA makes use of only water freight-related emissions data from this source since it provides CO_2, NO_x, and SO_2 emissions data for heavy and bulk cargo shipping since the other sources do not. Additionally, life-cycle energy use and emission factors related to air freight transportation [266-268] and oil- and gas-pipeline transportation [267, 268] modes are provided for comparison purposes. However, these modes of transportation are not valid for concrete and its materials. Therefore, these options are excluded in the GreenConcrete LCA tool calculations. Data from the literature are summarized in Table 4.24 for road and rail modes and in Table 4.25 for water transportation.

Table 4.24: Total LCI factors associated with common freight transportation modes (for on land) based on literature

Mode	**Road_ Class 8b (Model 2005)**	**Road_ Class 5 (Model 2005)**	**Road_ Class 2b (Model 2005)**	**Road_ Generic ****	**Road_ Generic ****	**Rail_ 4,000 hp diesel – electric locomotive**	**Rail_ Generic ****	**Rail_ Generic ****
Payload (tonnes)	11	3	1	na	na	1,899	na	na
Energy use (MJ / tonne-km)				1.98*	2.98		3.09E-01*	3.31E-01
Air emissions (kg / tonne-km)								
CO_2- eq				1.32E-01*	1.98E-01		2.09E-02*	1.98E-02
CO_2	1.28E-01	1.58E-01	1.98E-01			2.74E-02		
CO	4.11E-04	8.22E-04	1.26E-03			2.88E-04		
NO_x	1.76E-03	1.12E-03	1.21E-03	1.76E-03		5.07E-04		
PM_{10}	2.40E-04	3.22E-04	4.04E-04	2.40E-04		3.42E-05		
SO_2	1.03E-04	2.05E-04	3.08E-04	1.03E-04		8.22E-05		
Source	[266]	[266]	[266]	[267]	[268]	[266]	[267]	[268]

*** :** Mean data point
****:** Data not used in GreenConcrete LCA because of the uncertainty in the description of the mode – year – model of the vehicle. Tabulated for comparison purposes.

Table 4.25: Total LCI factors associated with water freight transportation mode based on literature

Mode	**Water_ Inland**	**Water_ Int'l. Container**	**Water_ Int'l. Bulk**	**Water_ Int'l. Tanker**	**Water_ Bulk and Cargo Ship**	**Water_ Generic**	**Average**
Energy use (MJ / tonne-km)	3.31E-01	2.20E-01	2.20E-01	1.10E-01		3.64E-01	2.49E-01
Air emissions (kg / tonne-km)							
CO_2- eq	2.31E-02	1.54E-02	1.21E-02	7.72E-03		2.76E-02	1.72E-02
CO_2					1.65E-02		1.65E-02
CO							
NO_x					3.80E-04		3.80E-04
PM_{10}							
SO_2					7.30E-05		7.30E-05
Source	[268, 270]	[268, 270]	[268, 270]	[268]	[269]	[267]	

4.9.2 Freight Transportation Life-Cycle Inventory Calculations

As previously mentioned in the Section 4.5.5, transportation mode options are limited to only five categories since there are currently three U.S. sources which cover total life-cycle emissions and energy use associated with these five options [266-268]. Despite the limitations in the data, these five modes are believed to be representative in calculating life-cycle emission factors associated with transporting concrete and its materials. The Table 4.26 provides a list of life-cycle energy use and air emission factors used in the GreenConcrete LCA tool calculations. As observed, energy use data is only for water freight transportation due to the lack of data for other modes. Air emissions are limited to GHG emissions, CO, NO_x, PM_{10}, and SO_2.

Table 4.26: Total LCI factors for transportation-related calculations

	Road_ Class 8b (Model 2005)	**Road_ Class 5 (Model 2005)**	**Road_ Class 2b (Model 2005)**	**Rail_Diesel Electric Locomotive**	**Water_ Generic**
Energy Use (MJ/tonne-km)	-	-	-	-	2.49E-04
Air Emissions (kg/tonne-km)					
CO_2-eq	1.28E-04	1.58E-04	1.98E-04	2.74E-05	1.72E-05
CO_2	1.28E-04	1.58E-04	1.98E-04	2.74E-05	1.65E-02
CO	4.11E-07	8.22E-07	1.26E-06	2.88E-07	
NO_x	1.76E-06	1.12E-06	1.21E-06	5.07E-07	3.80E-04
PM_{10}	2.40E-07	3.22E-07	4.04E-07	3.42E-08	
SO_2	1.03E-07	2.05E-07	3.08E-07	8.22E-08	7.30E-05

The following Equation 4.35 is developed to calculate total LCI from transporting materials within the concrete production system boundary.

$$TRANSPORTATION_{TOTAL_{LCI_{i,j,k}}} = DISTANCE_j \times HLOOKUP\left(MODE_i, \left[TRANSPORTATION_{LCIF_{i,k}}\right], LCI_{FACTOR_k}\right)$$

Equation 4.35: Calculation of total LCI for transportation of materials

Where:

$TRANSPORTATION\_TOTAL\_LCI_{i,j,k}$ = Total life-cycle inventory for mode "i" used in transporting material "j" resulting in an LCI factor "k" of which can either be energy use in MJ per tonne of material transported or emission in kg per tonne of material transported;

$DISTANCE_j$ = From "User Input Page_ Transportation Input, Distance Traveled" column which represents the distance traveled for transporting material "j" to a given destination (see Table 4.8 the list of materials and their destinations), in km;

$MODE_i$ = From "User Input Page_Transportation Input, Mode of Transportation" column which represents selected transportation mode "i" used in transporting material "j" (see Table 4.9 for the list of modes), unitless;

$[TRANSPORTATION_{LCIi,j}]$ = Total LCI factors associated with freight transportation based on Table 4.26 with columns representing transportation mode "i" and rows representing corresponding LCI factor "k", which is in MJ/tonne-km for energy use factor or in kg/tonne-km for emission factors.

In the "Results" section, transportation related calculations are finalized by multiplying the results from Equation 4.35 with the total weight of material transported within the concrete production system.

As previously mentioned, "Reference Data Pool" worksheets that have been described thus far provide life-cycle inventories of fuel use during the electricity generation and transportation of materials. Life-cycle inventories of consumption of electricity, fuel, and materials are organized within each materials production phase named "Process and Calculation" worksheets. Emission factors from the "Reference Data Pool" worksheets are multiplied with the phase inventories (in "Process and Calculation" worksheets) to calculate the total phase impacts. Following sections describe the concrete and cement production processes and related calculations in more details.

4.10 **Cement Production Processes**

Among all concrete materials, cement is the most complicated ingredient to analyze because of the varying production stages (each one is described briefly below in Table 4.27), each with different process technologies, and combination of differing raw materials and fuel use options.

Table 4.27: Brief description of the Cement Production "Process and Calculation" Tabs

Process and Calculation Tabs for Cement Production	
Cement_ Raw Meal	Inventories materials (both quarried materials and industrial by-products), fuels, electricity and water inputs as well as associated air and solid waste emissions from quarrying, raw materials prehomogenization, raw materials grinding, and raw meal blending/homogenization processes based on the user input data. Calculations are performed to estimate emissions from electricity use (for all processes), fuel pre-combustion related (only for quarrying), fuel combustion related (only for quarrying) and process related (for all four processes covered in this tab).
Cement_ Pyroprocessing	Organizes and inventories materials, fuels, electricity, and water input and associated output data for four common types of cement kilns in the United States. Calculations are performed to estimate energy use, water consumption, solid waste and air emissions from preparation and combustion of six traditional fuels and nine waste fuels used during pyroprocessing. LCI data is performed for electricity use (for both fuels preparation and pyroprocessing), fuel pre-combustion and fuel combustion related (only for pyroprocessing), and process related (for pyroprocessing and fuels preparation processes).
Cement_ Clinker Cooling	Inventories electricity use and water consumption inputs as well as associated emissions from clinker cooling process. Calculations are performed to estimate emissions from electricity use and process itself based on the user input data for various cooling technology options and two emission control options (ESP and FF).
Cement_ Finish Mill Grind Blend	Inventories materials (gypsum and clinker for portland cement mixes or fly ash/slag in addition to gypsum and clinker mix if blended cement), electricity and water inputs, and associated emissions from cement finish milling, grinding, and blending with additives (gypsum, CKD) and SCMs. Calculations are performed to estimate emissions based on user input data for five different grinding and milling technology options. The "SCM_Preparation" tab below explains the calculations for separate grinding of industrial by-products (only for granulated blast furnace slag, no need for fly ash as it is already fine enough for cement use) for blended cements and related calculations for dry mixing of SCMs with cement that take place in the "Cement_ Finish Mill Grind Blend" tab.
SCM_ Preparation	SCM preparation is assumed take place outside the cement plant and prepared SCMs are transported to the cement plant (or concrete plant if added to concrete directly). This tab organizes and feeds data in "Cement_ Finish Mill Grind Blend" tab for material inputs of industrial by-products (fly ash, granulated blast furnace slag) that are assumed to be added to PC (clinker+ gypsum) by dry mixing. Note that inter-grinding option is not considered as this option involves large quantity of data about materials grindability requirements which is mostly not available.
Calculated Inventory	

	Electricity (in MJ – converted from kWh for ease of comparison to fuel energy consumption values)
	Fuel (in MJ – which is the sum of pre-fuel combustion- and combustion-related impacts)
	Water consumption (in m^3)
	Total solid waste generation (in kg)
	Air emissions (30 air emissions including GHG emissions, criteria air pollutants, major toxic emissions including heavy metals, formaldehyde, etc.)

Each of the five cement production stages involves certain assumptions, calculations and databases that are discussed in coming sections through 4.10.1 to 4.10.6.

4.10.1 Cement_Raw Meal Preparation Worksheet

The "Cement_Raw Meal Preparation" worksheet calculates the LCI for the following cement production stages in the order of:

- Quarrying,
- Raw materials prehomogenization,
- Raw materials grinding, and
- Raw meal blending and homogenization.

Cement raw materials quarrying and raw materials preparation steps are described below (See detailed process flow diagrams for cement production stages in Figure 4.21 and 4.22).

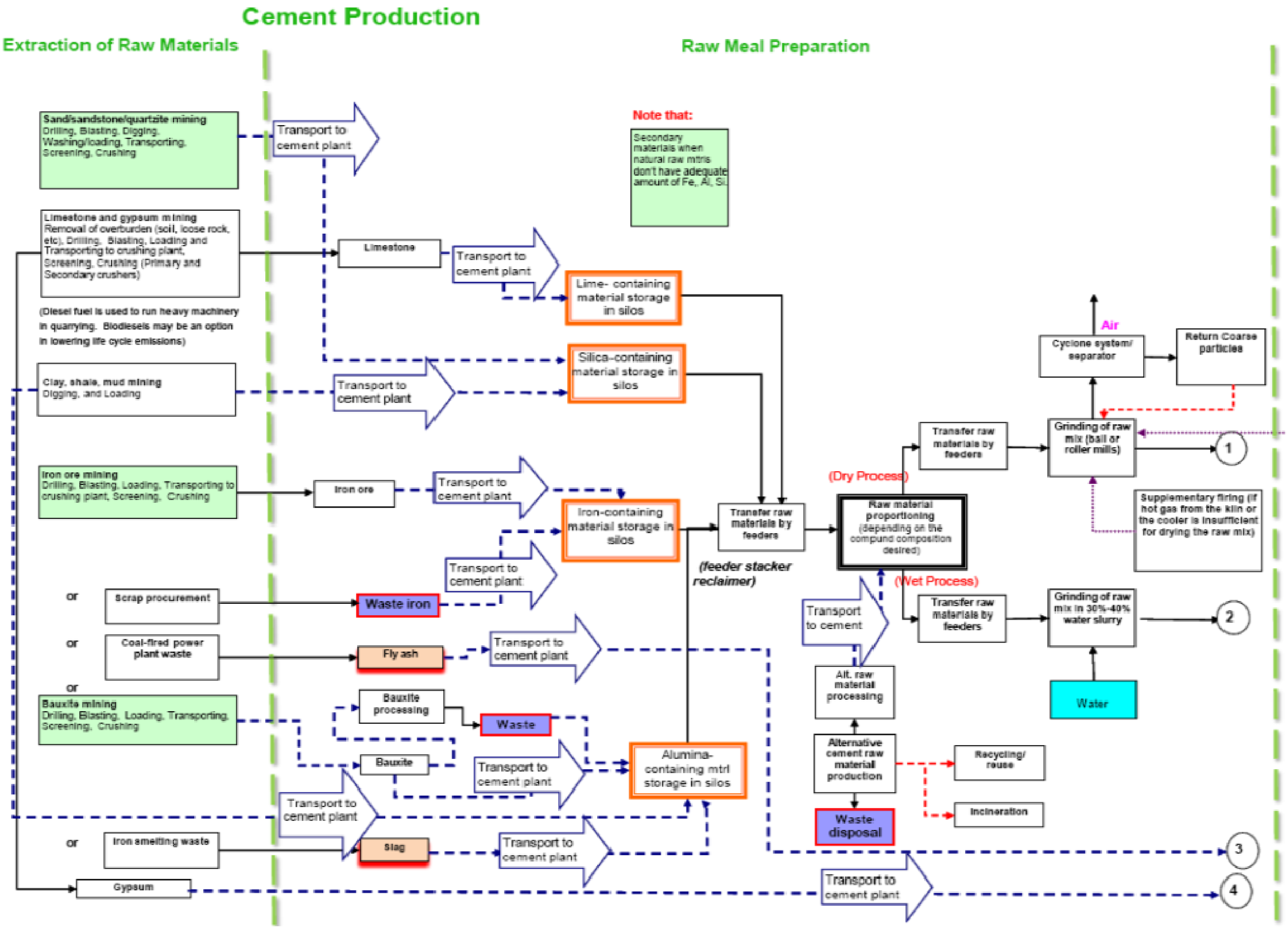
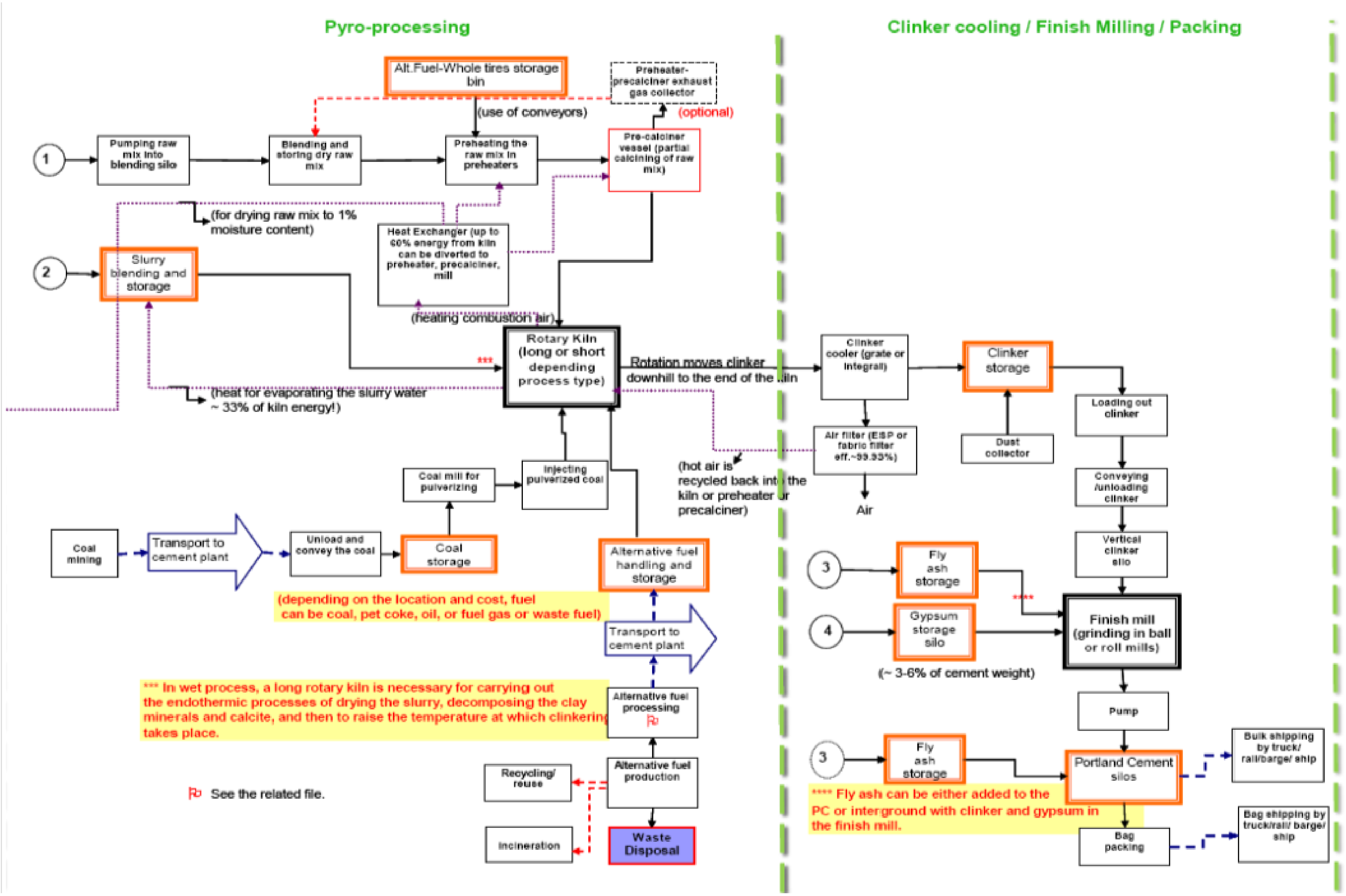


Figure 4.21: Cement production processes for extraction of raw materials and raw meal preparation (continue next page)



(depending on the location and cost, fuel can be coal, pet coke, oil, or fuel gas or waste fuel)

*** In wet process, a long rotary kiln is necessary for carrying out the endothermic processes of drying the slurry, decomposing the clay minerals and calcite, and then to raise the temperature at which clinkering takes place.

🏳 See the related file.

**** Fly ash can be either added to the PC or interground with clinker and gypsum in the finish mill.

Figure 4.22: Cement production processes for pyroprocessing, clinker cooling, finish milling, grinding, and packaging

4.10.1.1 Quarrying

The first step in portland cement production is the extraction of raw materials from the Earth's crust by mining or quarrying. Portland cement clinker consists basically of two natural raw materials: limestone (about 60-70% by mass of cement) and clay (about 15-25%) [35].

Most cement plants are located in close proximity to a source of calcium carbonate (mostly limestone) to minimize transportation distances between the quarry and the plant. Calcareous raw materials (limestone, chalk and cement rock-an impure limestone) are most often extracted from open-face quarries, but sometimes underground mining can be necessary. Other raw materials are obtained from siliceous, argillaceous, and ferriferous ores and minerals, such as clay, iron ore, shale, or sand. These raw materials are usually extracted from open-face quarries but they can also be dredged or excavated from underwater deposits. In order to loosen rocks in the quarry, drilling and blasting are typically required. The loosened rock is then loaded onto heavy diesel trucks by means of power shovels or front-end loaders. Quarrying process requires use of various fuels including; natural gas, diesel fuel, coal, and gasoline (see Table 4.28). Next, quarried materials are transported to the processing plants where primary crushing in a gyratory or raw crusher takes place. At the processing plant, crushing, screening, and conveying of materials require electricity use.

Particulate matter (PM) is the primary process-related air pollutant in this stage. Major sources of PM are: rock drilling, blasting, excavation, loading, hauling, crushing, screening, materials handling, stockpiling, and storing [35, 271].

During quarrying, all cement raw materials are assumed to consume similar quantities of resources and energy inputs as those associated with limestone. This assumption would yield accurate results because limestone constitutes about 60-70% of clinker. Fuel (in mass or volume units) and electricity (in kWh) input data per tonne of quarried material is obtained from NREL [272] database that is developed for limestone extraction from an open-face quarry, which is often the case according to the reference [18]. The amount of quarry water consumed per tonne of raw material quarried is obtained from the Eco-invent database [70].

Table 4.28: GreenConcrete Cement_ Raw Meal Worksheet - Resource and Energy Inputs to Cement Raw Materials Quarrying

Inputs to Quarrying	**(Per tonne of raw material)**	**Unit**	**Source**
Bituminous (hard) coal	0.036	kg	NREL (2012)
Natural gas	0.140	m^3	
Distillate (diesel or light) fuel oil	0.584	l	
Gasoline	0.051	l	
Electricity*	4.230	kWh	
Water	4.351	m^3	Eco-invent (2007)
*Includes crushing, screening, conveying of raw materials after quarrying (Based on limestone mining data)			

Quarrying all together involves use of fossil fuels, water, and electricity. Associated inventories are tabulated in Table 4.28. These values are multiplied with the related emission factors from "Reference Data Pool" worksheets of "Electricity Grid Mix Data", "Pre-Combustion Data for Fuels", and "Fuel Combustion Data" to calculate total quarrying impacts. The calculated numbers are tabulated in the "Results" tab.

Life-cycle inventory calculations for quarrying make use of primary raw material quantities given in Table 4.29.

These input quantities are obtained from the reference [18] based on unpublished data on raw material use from *U.S. Environmental R&D Project Questionnaire – 2000 Plant Data [273]* and are calculated using the standard assumptions of a raw meal to clinker ratio of 1.6 to 1 and a clinker to cement ratio of 0.95 to 1 (gypsum to cement ratio of 0.05 to 1). For the U.S. average kiln conditions, weighted average of the total raw meal is calculated as 1,612 kg per tonne of cement.

Table 4.29: GreenConcrete Cement_ Raw Meal Worksheet – Cement Raw Material Quantities by Cement Kiln Type

	Cement Raw Material Input by Kiln Type						**Source**
1		**Wet kiln**	**Long dry kiln**	**Preheater kiln**	**Preheater/ Precalciner kiln**	**US Average kiln**	[18]
2	**Cement raw materials**	kg/ tonne of cement					
3	*Quarried materials*						
4	Limestone	1,228	1,262	1,137	1,127	1,165	
5	Cement rock, marl	269	131	70	249	207	
6	Shale	65	13	23	68	52	
7	Clay	62	35	100	54	60	
8	Sand	57	36	36	38	40	
9	Slate	7	-	-	-	1	
10	Iron, iron ore	9	15	16	14	14	
11	*Total quarried raw materials*	*1,697*	*1,492*	*1,382*	*1,550*	*1,539*	
12	***Industrial by-products***						
13	Bottom ash	10	19	5	9	10	
14	Fly ash	17	23	7	12	13	
15	Blast furnace slag	25	38	34	9	20	
16	Foundry sand	-	11	5	3	4	
17	Other raw material	3	29	59	23	26	
18	*Total industrial by-products*	*55*	*120*	*110*	*56*	*73*	
19	**Total raw meal**	**1,752**	**1,612**	**1,492**	**1,606**	**1,612**	

Based on the input data above, amount of raw meal (also blended meal) varies with the user-selected kiln technology. This variation is covered in following calculations that involve energy use (in terms of electricity and fuels, separately) and water consumption during quarrying:

$$M_{MEAL} = M_{PORTLANDCEMENT} \times HLOOKUP(KILNTECH_t, [TABLE\ 4.29], ROW\#19_{TOTALRAWMEAL}] \times {}^{1}/_{1,000}$$

Equation 4.36: Calculation of total mass of raw material (raw meal or blended meal) for the selected kiln type

Where:

M_{MEAL} = Total mass of raw material, raw meal, or blended meal, in kg;

$M_{PORTLANDCEMENT}$ = Total mass of portland cement (Clinker + Gypsum), calculated in Equation 4.77, in kg;

KILNTECHt = Kiln technology Lookup from the "User Input Page_Cement Plant Technology Options for Pyroprocessing", "t" refers to one of the five kiln options provided in Row#1 of Table 4.29, unitless;

[TABLE 4.29], ROW#19 = Cement raw material (raw meal or blended meal) quantity by cement kiln type data based on the kiln technologies and corresponding quantities of raw material inputs for the selected type of kiln technology. Row #19 returns the total mass of raw meal for the user-selected kiln option, in kg of raw meal per tonne of portland cement produced;

1/1,000 = Unit conversion factor (1 tonne = 1,000 kg).

$$\boxed{ELECTRICITY_{QUARRYING} = ELECTRIC_{FACTOR,QUARRYING} \times M_{MEAL} \times {}^{1}/_{1,000}}$$

Equation 4.37: Calculation of electricity use for cement raw material quarrying

Where:

$ELECTRICITY_{QUARRYING}$ = Total amount of electricity used during cement raw material quarrying, in kWh;

$ELECTRIC_{FACTOR,\ QUARRYING}$ = Electricity use factor obtained from Row #6, Table 4.28, in kWh/tonne of raw material;

M_{MEAL} = Total mass of raw material, raw meal, or blended meal, in kg (from Equation 4.36);

1/1,000 = Unit conversion factor (1 tonne = 1,000 kg).

$$\boxed{WATER_{QUARRYING} = WATER_{FACTOR,QUARRYING} \times M_{MEAL} \times {}^{1}/_{1,000}}$$

Equation 4.38: Calculation of water consumption for cement raw material quarrying

Where:

$WATER_{QUARRYING}$ = Total amount of water consumed during cement raw material quarrying, in m^3;

$WATER_{FACTOR,\ QUARRYING}$ = Water consumption factor obtained from Row #7, Table 4.28, in m^3/tonne of raw material;

M_{MEAL} = Total mass of raw material, raw meal, or blended meal, in kg (from Equation 4.36);

1/1,000 = Unit conversion factor (1 tonne = 1,000 kg).

$$FUEL_{QUARRYINGi} = FUEL_{FACTOR,QUARRYINGi} \times M_{MEAL} \times {}^{1}/_{1,000}$$

Equation 4.39: Calculation of fuel use for cement raw material quarrying

Where:

$FUEL_{QUARRYINGi}$ = Total amount of fossil fuel “i” used during cement raw material quarrying, in kg, l or m^3 of fuel based on fuel type;

$FUEL_{FACTOR, QUARRYINGi}$ = Fuel use factor obtained from Rows #2 through #5, Table 4.28, in kg, l, or m^3 of fossil fuel “i” per tonne of raw material;

M_{MEAL} = Total mass of raw material, raw meal, or blended meal, in kg (from Equation 4.36);

“i” = Type of fossil fuel used in cement raw material quarrying and can be coal, natural gas, diesel, or gasoline;

1/1,000 = Unit conversion factor (1 tonne = 1,000 kg).

Additionally, process-related PM_{10} emission from quarrying is estimated based on data from Marceau et al. [18]. An emission factor of 0.000785 kg of PM per tonne of raw material is provided. Accordingly, a generalized equation for calculating the process-related emission “k” from quarrying is developed as follows:

$$QUARRYING_{PROCESSk} = PROCESS_{QUARRYING\_EFk} \times M_{MEAL} \times {}^{1}/_{1,000}$$

Equation 4.40: Calculation of quantity of process-related emission “k” for cement raw material quarrying

Where:

$QUARRYING_{PROCESSk}$ = Total quantity of emission “k” associated with quarrying process, in kg;

$PROCESS_{QUARRYING\_EFk}$ = Process-related emission factor “k” associated with quarrying based on literature, kg per tonne of raw material;

M_{MEAL} = Total mass of raw material, raw meal, or blended meal, in kg (from Equation 4.36);

1/1,000 = Unit conversion factor (1 tonne = 1,000 kg).

While Equations 4.37 through 4.40 are self-explanatory, Equation 4.36 requires a more detailed description. In the equation, an *Excel HLOOKUP* function is used to lookup for the kiln type information from the “User Input_Cement Plant Technology Options for Pyroprocessing”. Using the selected kiln information, related data for that kiln type is taken from the “Cement_ Raw Meal Worksheet” in GreenConcrete LCA tool (see Table 4.29). After finding the column corresponding to the kiln type selected in row#1, the function returns the total amount of raw material (raw meal) from the last row (row#19) of the table. Then this lookup value (in kg of raw material or kg of raw meal per tonne of cement) is multiplied by the "Total Mass of Portland Cement" calculated in Equation 4.77 or Equation 4.78 based on the cement type. Finally, the result is multiplied with a unit conversion factor of (1/1000) to convert tonnes of cement to kg of cement to conform to the input units.

In Equation 4.39, fuel consumption results can either be in mass or volume units depending on the type of fuel used. In case of solid fuels (e.g. coal), the result is in mass units (kg). For other fuel types, such as, natural gas (m^3), diesel (l), and gasoline (l) results are in volume units.

Quarrying life-cycle inventory associated with electricity use and fuel use are calculated based on the electricity use and fuel requirements for this stage of cement production and LCI factors developed for Electricity Grid Data, Pre-combustion and Combustion Fuel Data worksheets in GreenConcrete LCA tool. All the production related LCI calculations follow a similar approach. As the last step, the process-related LCI (only PM emissions for the quarrying) is added to the electricity, pre-combustion, and fuel combustion LCI to estimate the total life-cycle impacts of quarrying.

As an example, calculation of a life-cycle inventory "k" from quarrying in a location "j" is described using the following equations, whereas "k" can be energy use, water consumption, solid waste or an air emission:

$$QUARRYING_{LCI_{ELECTRIC\,j,k}} = ELECTRICITY_{QUARRYING} \times HLOOKUP\left(LOCATION_j, TRANSPOSE\ [TABLE\ 9.9], ROW\#_{LCIF\,j,k}\right)$$

Equation 4.41: Calculation of LCI related to electricity use during cement raw material quarrying

Where:

$QUARRYING_{LCI\_ELECTRICj,k}$ = Total life-cycle inventory associated with electricity use during cement raw material quarrying, whereas "j" corresponds to the quarry location; in MJ for "k" energy use factor or in kg for life-cycle inventories corresponding to solid waste, water consumption, and air emissions;

$ELECTRICITY_{QUARRYING}$ = Total amount of electricity used during cement raw material quarrying (calculated in Equation 4.37), in kWh;

$LOCATION_j$ = Location of the cement raw material quarry "j", taken from "User Input Page_Quarry/Plant Location, Grid Mix, and Water Supply Input" and can be State, United States, or user-defined, unitless;

[TABLE 9.9], $ROW\#_{LCIFj,k}$ = Appendix A, Table 9.9 with calculated total LCI data for electricity grid mix (per kWh of electricity) for location "j"; each row representing a life-cycle inventory "k", in MJ/kWh for energy use factor or in kg/kWh for other LCI factors listed in the Table.

In the Equation 4.41 above, Table 9.9 is transposed for accurate representation of data within the Excel tool.

In the tool, a SUMPRODUCT function is used to calculate total LCI for all four types of fuels used during quarrying and this is demonstrated by $\sum_{i,k}^{n}[x_i \times y_k]$ operator symbol. Pre-combustion and combustion LCI related to fossil fuel use during quarrying is calculated as follows:

$$QUARRYING_{LCI\ PRECOMBUSTk} = \sum_{i,k}^{n}[FUEL_{QUARRYINGi} \times PRECOMBUST_{LCIi,k}]$$

Equation 4.42: Calculation of LCI related to pre-combustion fuel use during cement raw material quarrying

$$QUARRYING_{LCI\ COMBUSTk} = \sum_{i,k}^{n}[FUEL_{QUARRYINGi} \times COMBUST_{LCIi,k}]$$

Equation 4.43: Calculation of LCI related to fuel combustion during cement raw material quarrying

Where:

$QUARRYING_{LCI\_PRECOMBUSTk}$ = Total LCI associated with pre-combustion impacts of fossil fuels used in cement raw materials quarrying, in MJ for "k" energy use factor or in kg for life-cycle inventories of solid waste, water consumption, and air emissions;

$QUARRYING_{LCI\_COMBUSTk}$ = Total LCI associated with combustion impacts of fossil fuels used in cement raw materials quarrying, in MJ for "k" energy use factor or in kg for life-cycle inventories of solid waste, water consumption, and air emissions;

$FUEL_{QUARRYINGi}$ = Total amount of fossil fuel "i" used during cement raw material quarrying (calculated in Equation 4.39) , in mass or volume (kg, l or m^3) of fuel based on fuel type;

$PRECOMBUST_{LCIi,k}$ = Pre-combustion fuel LCI factors calculated in Table 4.15 per unit mass or volume of fossil fuel "i" with an associated a life-cycle inventory factor "k", in MJ/mass or volume of fuel for energy use or in kg/ mass or volume of fuel for other LCI factors listed in the Table.

$COMBUST_{LCIi,k}$ = Fuel combustion LCI factors calculated in Table 4.16 per unit mass or volume of fossil fuel "i" with an associated a life-cycle inventory factor "k", in MJ/mass or volume of fuel for energy use or in kg/ mass or volume of fuel for other LCI factors listed in the Table.

"i" = Type of fossil fuel used in cement raw material quarrying and can be coal, natural gas, diesel, or gasoline;

Finally, total LCI is the sum of LCI from electricity use, fuel combustion (including fuel pre-combustion) and process of quarrying:

$$QUARRYING_{TOTALLCIj,k} = QUARRYING_{PROCESSk} + QUARRYING_{LCI\_ELECTRICj,k} + QUARRYING_{LCI\_PRECOMBUSTk} + QUARRYING_{LCI\_COMBUSTk}$$

Equation 4.44: Calculation of total LCI for cement raw material quarrying

4.10.1.2 Raw materials preparation

Quarried and crushed raw materials are subsequently conveyed to silos in a cement plant. The purpose of this step is to achieve required particle size distribution, average particle size, and specific surface within the limits of optimum energy use and cost. Afterward, crushed and stockpiled (could either be pre-blended/pre-homogenized or not) materials are ground into a fine raw mix mostly by dry or less frequently by wet grinding technologies. In recent years, as a result of higher energy consumption, elevated fuel costs, and ongoing obsolescence of wet processing, dry grinding is preferred in most of the cement plants. It is important to note that grinding materials finer than needed causes energy overuse, inefficiency of the raw mill, and excessive dust accumulation in the kiln.

In GreenConcrete LCA tool, raw material input is assumed to be equal to the amount of material output throughout the preparation process as there is little loss in the form of dust or no loss of material at all. Therefore, the quantity of raw materials quarried is equal to the quantity of raw meal which is ultimately equal to the output “blended meal” from the “Cement_ Raw Meal” worksheet and input to the next step “Cement_ Pyroprocessing” worksheet. The following Table 4.30 provides life-cycle inventories of electricity use and water consumption as well as process-related PM_{10} emissions per tonne of cement raw meal prepared by using different technology options. Electricity is used in all processes taking place during raw meal preparation. Water is consumed only for wet grinding option. Subsequently, electricity use factors are multiplied by the related emission factors given in “Reference Data Pool_Electricity Grid Mix Data” worksheet to calculate total environmental interventions from cement raw meal preparation processes. The ultimate results are tabulated in the “Results” tab within the tool.

Table 4.30: GreenConcrete Cement_ Raw Meal Worksheet - Cement Raw Meal Preparation Technology Options and Associated Resource Use Factors and Process PM Emission Rates (that vary with process type, dry vs. wet)

Technology Options	**Electricity (kWh/tonne clinker)**	**Water (m^3/tonne material)**	**PM_{10} (kg/tonne material)**	**Notes**	**Source**
Raw Materials Prehomogenization Technology					
Dry_process_Raw storing, non-preblending	0.250		0.750	PM_{10} from unloading raw materials (dry storage), uncontrolled	**[35, 48, 227, 274]**
Dry Process_Raw storing, preblending	0.500		0.750		
Wet process_Raw storing	0.375		0.750	PM_{10} from unloading raw materials (wet storage), uncontrolled	
Raw Materials Grinding Technology					
Dry raw grinding, ball mill	23.000	-	0.000655	PM_{10} from primary and secondary grinding, controlled (fabric filter) dry process	
Dry raw grinding, tube mill	18.500	-	0.000655	PM_{10} from primary and secondary grinding,	

Dry raw grinding, vertical roller mill	15.500	-	0.000655	controlled (FF) dry process	
Wet raw grinding, tube mill	13.000	0.500	0.000655	PM_{10} from primary and secondary grinding, controlled (FF) wet process	
Wet raw grinding, wash mill	6.500	0.650	0.000655	PM_{10} from primary and secondary grinding, controlled (FF) wet process	
Raw Meal Blending/ Homogenization Technology					
Raw meal homogenization, blending, and storage	1.080				
Slurry blending homogenization and storage	0.400				

Different raw material grinding technology options with varying electricity use and water consumption quantities are listed in Table 4.30. During dry grinding, raw material feeders, stackers, blenders, transfer points on conveyors, and bucket elevators generate fugitive dust emissions in poorly designed raw mills. In wet grinding process, particulate emissions are considered to be negligible, except for during material handling ([35, 48, 271]. The only available data source, that is WebFIRE [227] database by U.S. EPA, does not distinguish PM emissions from wet vs. those from dry grinding process. This indifference in emissions data once again brings about the need for new and detailed LCI data sources.

In the same worksheet where quarrying-related calculations are described, following equations are developed to calculate LCI associated with raw materials prehomogenization, raw materials grinding, and raw meal blending and homogenization processes:

$$ELECTRICITY_{CEMENTRAWPREP} = M_{CLINKER} \times VLOOKUP\left(CEMENT_{RAWPREP_{TECHt}}, [TABLE\ 4.30], COLUMN\#2_{ELECTRIC}\right)/1000$$

Equation 4.45: Calculation of electricity use for cement raw materials preparation processes

Where:

$ELECTRICITY_{CEMENTRAWPREP}$ = Total electricity use associated with cement raw meal preparation processes of prehomogenization, raw material grinding, and raw meal blending and homogenization, in kWh;

MCLINKER = Total mass of clinker, calculated in Equation 4.71, in kg;

$CEMENT_{RAWPREPTECHt}$ = Cement Plant Technology Lookup from User Input Page: Cement raw materials preparation technology “t” selected from column #1 of Table 4.30, unitless;

[TABLE 4.30], $COLUMN\#2_{ELECTRIC}$ = Electricity use factor from column #2 of Table 4.30 related to the cement raw meal preparation technology given in column #1, in kWh per tonne of clinker;

1/1,000 = Unit conversion factor (1 tonne = 1,000 kg).

In Equation 4.45, *Excel VLOOKUP* function is applied to search for the raw materials preparation technology information from “User Input Page_Cement Plant Technology Options” for “Raw Materials Prehomogenization”, “Raw Materials Grinding”, and “Raw Meal Blending /Homogenization” in column #2, Table 4.30. After locating the row corresponding to the selected technology option in column#2, the function returns the electricity use factor for that specific type of raw meal preparation technology per tonne of clinker. Afterwards, this lookup quantity (in kWh of electricity per tonne of clinker) is multiplied with the total mass of clinker calculated in “Cement_ Finish Mill_ Grind_ Blend” tab, Equation 4.71. Finally, the result is multiplied with a unit conversion factor of (1/1,000) to convert tonnes of clinker to kg of clinker to match the user input units entered in kg units.

As mentioned previously, water is consumed only during wet grinding and calculated as follows:

$$WATER_{RAWWETGRIND} = WATER_{FACTOR,WETGRINDING} \times M_{MEAL} \times {}^{1}/_{1,000}$$

Equation 4.46: Calculation of water consumption for wet raw meal grinding

Where:

$WATER_{CEMENTRAWPREP}$ = Total amount of water consumed during cement raw material quarrying, in m^3;

$WATER_{FACTOR,WETGRINDING}$ = Water consumption factor for wet grinding technology from column#3 of Table 4.30, in m^3 of water per tonne of raw material ground;

M_{MEAL} = Total mass of raw meal, in kg (from Equation 4.36);

1/1,000 = Unit conversion factor (1 tonne = 1,000 kg).

As observed in Table 4.30, process-related PM_{10} emissions occur during raw materials-preparation stage. PM data is obtained from EPA’s WebFIRE [227] and is described briefly in the last column of the table. Accordingly, the following equation is developed to calculate process-related PM emissions from cement raw materials preparation:

$$CEMENT\_RAWPREP_{PROCESS\_PM} = \\ M_{MEAL} \times VLOOKUP\left(CEMENT_{RAWPREP_{TECH_t}}, [TABLE\ 4.30], COLUMN\#4_{PM}\right)$$

Equation 4.47: Calculation of quantity of process-related PM emission for cement raw material quarrying

Where:

$CEMENT\_RAWPREP_{PROCESS\_PM}$= Total PM_{10} emissions associated with cement raw meal preparation process, in kg;

M_{MEAL} = Total mass of raw meal (from Equation 4.36), in kg;

$CEMENT_{RAWPREP_{TECHi}}$ = Cement Plant Technology Lookup from User Input Page: Cement raw materials preparation technology “t” selected from column #1 of Table 4.30, unitless;

[TABLE 4.30], COLUMN#4_{PM} = Process-related PM_{10} emission factor from column #4 of Table 4.30 related to the cement raw meal preparation technology described in column #1, in kg per tonne of raw meal;

1/1,000 = Unit conversion factor (1 tonne = 1,000 kg).

Following a similar approach used in quarrying LCI calculations, a life-cycle inventory "k" from cement raw materials preparation in a cement plant located in region "j" is estimated based on an equation involving electricity use-related LCI calculation:

$$CEMENT\_RAWPREP_{LCI_{ELECTRIC}\,j,k} = ELECTRICITY_{RAWPREP} \times HLOOKUP\left(LOCATION_j, TRANSPOSE\ [TABLE\ 9.9], ROW\#_{LCIF\,j,k}\right)$$

Equation 4.48: Calculation of LCI related to electricity use during cement raw meal preparation

Where:

$CEMENT\_RAWPREP_{LCI\_ELECTRICj,k}$ = Total life-cycle inventory associated with electricity use during cement raw meal preparation processes, whereas "j" corresponds to the cement plant location; in MJ for "k" energy use factor or in kg for life-cycle inventories corresponding to solid waste, water consumption, and air emissions;

$ELECTRICITY_{RAWPREP}$= Total amount of electricity used during cement meal preparation (calculated in Equation 4.45), in kWh;

$LOCATION_j$ = Location of the cement plant "j", taken from "User Input Page_Quarry/Plant Location, Grid Mix, and Water Supply Input" and can be State, United States, or user-defined, unitless;

[TABLE 9.9], $ROW\#_{LCIFj,k}$ = Appendix A, Table 9.9 with calculated total LCI data for electricity grid mix (per kWh of electricity) for location "j"; each row representing a life-cycle inventory "k", in MJ/kWh for energy use factor or in kg/kWh for other LCI factors listed in the Table.

As opposed to quarrying, there is no direct fossil fuel use in preparation of cement raw materials. For this reason, total LCI is the sum of LCI of electricity use and process-related LCI (which is only limited to k=PM_{10} and will be zero for all other emission factors):

$$CEMENT\_RAWPREP_{TOTAL_{LCIj},k} = CEMENT\_RAWPREP_{PROCESSk} + CEMENT\_RAWPREP_{j,k}$$

Equation 4.49: Calculation of total LCI for cement raw meal preparation

4.10.1.3 Cement Pyroprocessing

Following blending, grinding, and homogenizing of raw mix into a fine and uniform kiln feed (raw meal), process of exposing the kiln feed to very high temperatures in cement kilns, namely clinkering starts. During pyroprocessing, complicated chemical reactions take place in the kiln system which includes not only the kiln but also coolers, tertiary air ducts, and a calciner. First, raw meal (or the kiln feed) is extracted from the storage area, weighed, and conveyed to the kiln.

Transformation of the kiln feed into clinker in a rotary kiln involves a set of operations - as obtained from the reference [35]:

1. Drying and dehydration of the raw material components;
2. Heating the kiln feed;
3. Decomposition of limestone ($CaCO_3$):
4. Agglomeration of clinker minerals;
5. Synthesis of clinker minerals; and
6. Cooling (associated LCI impacts are calculated in a separate tab named as "Cement_ Clinker Cooling" in the tool).

The end product is clinker. After cooling, clinker is sent to the storage area for finish milling and grinding.

Pyroprocessing is considered as the most energy intensive phase during cement production: responsible for about 91% of the total process energy use [18]. Associated Excel worksheet in the tool consists of LCI factors defined for four types of commonly used cement kilns and an average kiln representing the U.S. practice. These four cement kiln types are briefly described based on literature [18, 23, 35, 48]:

Wet Process Kilns: At present, long wet kilns are rarely used in the U.S. due to some major disadvantages such as poor fuel efficiency and mechanical limitations. The output for a large wet kiln is around 1,500 tonnes per day. The upper economic limit without causing high maintenance cost is about 2,000 tonnes per day. Thermal energy consumption can be as high as 5.4-6.9 MJ per kg of clinker (Table 4.31). The process-related water consumption is about 0.49 m^3 per tonne of cement (Table 4.32).

Long Dry Kilns: Dimensionally, they are similar to long wet kilns. Fuel consumption is comparably improved in long dry kilns as the feed is dry and it is about 4.6-5.4 MJ per kg of clinker (Table 4.31). In this kiln system, water spray cooling is required at the exit (due to high kiln exit temperatures of 700°C) and as a result, the advantage over wet kilns could be small because of higher volumes of non-process water consumption. To solve this problem, kiln chains, kiln metallic crosses, and ceramic heat exchangers are used to split the feed and gas flow. In addition to the fuel consumption improvement, output of long dry kilns is increased by 35-40% percent compared to long wet kilns.

Preheater Kilns: In this system, cyclone separators are used for a better heat exchange between the hot kiln exit gas and the dry raw meal feed. Rotary kiln is relatively short. Material entering the rotary kiln is already at a temperature of 800°C and is partly (20-30%) calcined as some of the clinkering reactions have already started. Kiln capacities can be up to 3,500 tonnes per day with a specific fuel consumption of 3.5-3.8 MJ/kg of clinker (Table 4.31). Compared to a wet kiln, much less amount of process-water is consumed in a dry kiln, which is about 0.007 m^3 per tonne of cement (Table 4.32).

Precalciner Kilns: As described in reference [35] "…In precalciner kilns, the combustion air used for burning fuel in the preheater no longer passes through the kiln, but is taken from the cooler region by a special tertiary air duct to a specially designed combustion vessel in the preheater tower." About 60% of the fuel is burned in the calciner, and about 90% of the raw meal is calcined before entering the rotary kiln section. Precalciner kilns can have outputs as large as 10,000 tonnes per day with specific fuel consumption rates at 3.3-3.6 MJ/kg of clinker. Pyroprocessing water consumption is at a rate of 0.014 m^3 per tonne of cement *(*Table 4.32).

Table 4.31: GreenConcrete Cement_ Pyroprocessing – Thermal Energy Consumption

Cement Pyroprocessing	**Thermal Energy Consumption (MJ/kg Clinker)**			**Source**
Technology Options	**Avg**	**Max**	**Min**	
Wet kiln	6.2	6.9	5.4	[18, 23, 35, 48]
Long dry kiln	5.0	5.4	4.6	
Preheater kiln	3.5	3.8	3.1	
Preheater/precalciner kiln	3.3	3.6	3.0	
Average kiln, United States	3.5	3.8	3.1	

Table 4.32: GreenConcrete Cement_ Pyroprocessing - Electricity Use, Water Consumption, and Process-related PM Emission Factors for the Given Kiln Technology Options

Cement Pyroprocessing	**Electricity Use (kWh/tonne Clinker)**			**Water - process**	**PM - process**	**Source, Electricity and Water**	**Source, PM emission**
Technology Options	**Avg**	**Max**	**Min**	**(kg/ tonne Cement)**	**(kg/ tonne Cement)**		
Wet kiln	21	25	17	485	0.280	[18, 23, 35, 48]	[18]
Long dry kiln	25	30	20	-	0.347		
Preheater kiln	25	25	25	7	0.148		
Preheater/ precalciner kiln	25	25	25	14	0.152		
Average kiln, United States	25	25	25	88	0.232		

Pyroprocessing-related LCI calculations involve estimation of energy use and emission factors associated with the kiln electricity use, fuel pre-combustion and combustion activities (see Pre-Combustion and Combustion Fuel data in Table 4.15, 4.16, and 4.17, respectively) based on thermal energy consumption capacity of the selected kiln option (See Table 4.31 and Table 4.32).

Additional LCI calculations are performed to estimate electricity use impacts resulting from the preparation of fossil fuels and waste fuels burned in the kiln. The Table 4.33 provides electricity use factors utilized in estimating the impacts from the preparation of user-selected kiln fuels.

Solid pulverized fuels are frequently used in the cement industry. Coal is the most widely used one, both in the U.S. and globally. Bituminous coal ranks the first with 64% use in preference followed by petcoke with 21%. Table 4.12 provides average U.S. kiln fuel use percentages. Prior to using in the kiln, solid fuels must be milled and dried. This translates into additional consumption of electricity, that is, 35-45 kWh per tonne of cement depending on the hardness of the fuel (Table 4.33). Although it is not shown in the Table, waste heat from kiln (assumed to have zero impact being waste) is utilized for drying solid fuels.

Other than coal and petcoke, waste tires, waste wood, waste cardboard, and paper are also considered as solid fuels. Solid wastes are usually fed into the kiln without drying as they are assumed to be typically dewatered and dried at the waste treatment plant before delivered to the cement kiln. Again based on the hardness and chemical composition of solid waste fuels, total amount of electricity required for their preparation varies considerably (see Table 4.33 below). A particular emphasis should be given to the use of whole versus shredded tires. Cement plants can observe various technical issues that prevent the firing of whole tires in the kilns. Process-wise, it would be better to use shredded tires in the kiln. However, the practice of shredding has inherent complexities that consist of: cost and capacity of tire shredding equipment and the consumption of additional electricity. For example, shredding requires about 45 kWh of electricity per tonne of cement produced (see Table 4.33). Because of the complexities of shredding process, the usual practice is to utilize a device that introduces whole tires into the cement kiln. For this arrangement, the electricity requirement can be as low as 3 kWh per tonne of cement [20, 35].

Distillate (diesel or light) and residual (heavy) fuel oils are among the liquid fuels commonly used in cement plants. Collectively, they cover only one percent of the total heat required in cement kilns. In recent years, the share of liquid waste fuels including solvents and waste oils has grown considerably, making up about four percent of the kiln energy source matrix. Both fuel oils (heavy fuel oil specifically) and liquid waste fuels require additional electric power and/or steam for heating, pumping, and nebulization (conversion of liquid into a cloud of droplets) prior to kiln use [27, 35]. Liquid fuel preparation requires about 3 kWh of electricity. For liquefying heavy oil, heat is necessary. In the tool, it is assumed that waste heat from kiln is used for heating and liquefying purposes. Presumably, there is no prior heating requirement for waste oils [25].

Table 4.33: GreenConcrete Cement_ Pyroprocessing – Electricity Use Factors for Kiln Fuel Preparation

Kiln Fuels	kWh/tonne Cement	Source
Bituminous coal	40	[20]
Lignite coal	35	[20]
Distillate (diesel or light) fuel oil	-	[20, 35]
Petroleum coke (petcoke)	45	[20]
Residual (heavy) fuel oil	3	[20, 35]
Natural gas	-	[25]
Waste oil	3	[20]
Waste solvent	3	[20]
Waste tire (whole)	3	[25]
Waste tire (shredded)	45	[25]
Waste (other) (non-hazardous)	25	[25]
Waste paper, cardboard, wood	25	[25]
Waste plastics	43	[25]
Waste sewage sludge (dry)	8	[20, 25]
Waste (other) (hazardous)	45	[25]

In addition to the calculated emissions from fuels preparation and combustion, pyroprocessing worksheet of the tool provides data for process-related PM (Table 4.32) as well as cement kiln dust (CKD) and process-related CO_2 emissions data. During pyroprocessing, cement kiln dust (CKD) is collected from the kiln exhaust gases before combustion products are vented into atmosphere. Handling, storage, and deposition of CKD can cause fugitive dust emissions. An industry average of 38.6 kg of CKD per tonne of cement is estimated based on PCA [18]. See notes in Table 4.34 for more details about the end-of-life fate of CKD.

Major gas emissions (in the main kiln stack) from the pyroprocessing system in descending order are: N (nitrogen), CO_2, water, O_2 (oxygen), NO_x, SO_2, CO, and hydrocarbons. CO_2 is the major concern followed by the last four listed gases. In general, one tonne of CO_2 is generated per each tonne of portland cement produced. There are two major sources of CO_2 emitted from cement production: fuel related and calcination related (chemical) CO_2. As its name implies, fuel CO_2 is caused by burning fuels and is estimated from the combustion and precombustion related emission factors for the selected type of kiln fuel. On the other hand, a series of chemical reactions converts calcium and silicon oxides into calcium silicates, that is the cement's main constituent. When the limestone ($CaCO_3$) reaches about 900°C, it undergoes a chemical reaction called "calcination" whereby CO_2 is released and calcium oxide formed, which converts into clinker during pyroprocessing (the reaction is as follows: $CaCO_3 \rightarrow CaO + CO_2$) [275]. About 522 kg of CO_2 per tonne of clinker (Table 4.34) is generated as a result of calcination [30, 47]. CO_2 from combustion are calculated from the carbon contents of the kiln fuels whereas CO_2 from calcination are calculated from the proportion of calcium carbonate ($CaCO_3$) in the raw meal.

Table 4.34: GreenConcrete Cement_ Pyroprocessing – Data for Cement Kiln Dust (CKD) Generation and Calcination-Related CO_2 Emission during Pyroprocessing Stage

Outputs	Avg	Max	Min	Units	Source	Notes
Cement kiln dust (CKD)	38.6	38.6	38.6	kg/tonne cement	[18]	An industry average of 38.6 kg of CKD is generated per tonne of cement. Of this, 30.7 kg (~ 80%) are landfilled and 7.9 kg (~ 20%) are recycled in other applications.
CO_2 from calcination	522	522	522	kg/tonne clinker	[30]	Average calcination-related CO_2 for the United States is 522 kg/tonne of clinker.

Pyroprocessing LCI calculations utilize a number of variables selected by the user including (see Table 4.35 for details):

- Technology lookup for the kiln type,
- User-selected kiln fuel percentages,
- Type of cement produced.

Table 4.35 summarizes major input and output variables used in calculating pyroprocessing LCI factors based on user-selected kiln technology and kiln fuel percentage information. Equations 4.50 through 4.58 describe the calculations associated with these variables.

Table 4.35: GreenConcrete Cement_ Pyroprocessing– Inputs and Outputs for Pyroprocessing LCI Calculations

Technology Lookup from User Input Page	***Kiln Type – User Input Page (Selected from drop-down list)***			**Units**
Inputs	**Average**	**Max**	**Min**	
Fuels Preparation Electricity Use	Calculated	Calculated	Calculated	kWh
Kiln Electricity Use	Calculated	Calculated	Calculated	kWh
Total Electricity Use	*Calculated*	*Calculated*	*Calculated*	*kWh*
Thermal Energy Consumption	Calculated	Calculated	Calculated	MJ
Blended Meal	Calculated	Calculated	Calculated	kg
Water	Calculated	Calculated	Calculated	m^3
Fuel Inputs	**Average**	**Max**	**Min**	
Bituminous coal	Calculated	Calculated	Calculated	kg
Lignite coal	Calculated	Calculated	Calculated	kg
Petroleum coke	Calculated	Calculated	Calculated	kg
Natural gas	Calculated	Calculated	Calculated	m^3
Residual (heavy) fuel oil	Calculated	Calculated	Calculated	l
Distillate (diesel or light) fuel oil	Calculated	Calculated	Calculated	l
Waste oil	Calculated	Calculated	Calculated	l
Waste solvent	Calculated	Calculated	Calculated	l
Waste tire (whole)	Calculated	Calculated	Calculated	kg
Waste tire (shredded)	Calculated	Calculated	Calculated	kg
Waste (other) (non-hazardous)	Calculated	Calculated	Calculated	kg
Waste paper, cardboard	Calculated	Calculated	Calculated	kg
Waste plastics	Calculated	Calculated	Calculated	kg
Waste sewage sludge (dry)	Calculated	Calculated	Calculated	kg
Waste (other) (hazardous)	Calculated	Calculated	Calculated	kg
Outputs	**Average**	**Max**	**Min**	
Clinker (kg)	Calculated	Calculated	Calculated	kg
Cement kiln dust (CKD)	Calculated	Calculated	Calculated	kg
PM	Calculated	Calculated	Calculated	kg
CO_2 emissions from calcination	Calculated	Calculated	Calculated	kg

$$ELECTRICITY_{FUEL\_PREPARATION} = \sum_{i=1}^{n}\left[FUEL_{PERCENT_i} \times ELECTRIC_{FACTOR_{FUEL\_PREPi}}\right] \times M_{PORTLANDCEMENT} \times {}^{1}/_{1,000}$$

Equation 4.50: Calculation of electricity use for (kiln) fuels preparation

$ELECTRICITY_{FUEL\_PREPARATION}$ = Total amount of electricity used for kiln fuel preparation, in kWh;

$FUEL_{PERCENTi}$ = Kiln fuel “i” percentage selected by the user on input page -“User Input Page_Technology Options Input: Fuel Use Options for Cement Pyroprocessing” (see Table 4.12, Column #2_Fuel Use Percentage), in % by kiln energy requirement;

$ELECTRIC_{FACTORFUEL\_PREPf}$ = Electricity use factor in preparation of kiln fuel “i” (see Table 4.33, Column #2_Electricity); in kWh/tonne portland cement;

$M_{PORTLANDCEMENT}$ = Total mass of portland cement (clinker + gypsum), calculated in Equation 4.77, in kg;

1/1,000 = Unit conversion factor (1 tonne = 1,000 kg).

Total amount of electricity used for preparation of kiln fuels is calculated by the sumproduct of kiln fuel use percentages obtained from the second column of Table 4.12 “User Input Page_Technology Options Input: Fuel Use Options for Cement Pyroprocessing” with the electricity use factors listed in the second column of Table 4.33 (in kWh per tonne of portland cement produced). This sumproduct is subsequently multiplied with the total mass of portland cement (clinker + gypsum) calculated in Equation 4.77. Since electricity use factors are listed as per tonne of portland cement and results from the tool are demonstrated in kg, a unit conversion factor (1 tonne per 1,000 kg) is used in the equation above.

In addition to the electricity used for kiln fuel preparation, a substantial amount of power is required for “Kiln Electricity Use” purposes including rotation of the kiln by kiln drive or kiln fans [38]. Based on the electricity use factors tabulated in Table 4.32 and the user-selected kiln-type information, one can calculate the “Kiln Electricity Use” as follows:

$$ELECTRICITY_{KILN\_USEt} = M_{CLINKER} \times VLOOKUP(KILN_{TYPEt}, [TABLE\ 4.32], COLUMN\#2_{ELECTRICt}) \times {}^{1}\!/_{1,000}$$

Equation 4.51: Calculation of kiln electricity use (for powering kiln drive, kiln fan, etc.)

Where:

$ELECTRICITY_{KILN\_USEt}$ = Total amount of electricity used in powering kiln equipment and kiln itself, in kWh;

$KILN_{TYPEt}$ = Lookup from the tool input page “User Input Page_Cement Plant Technology Options by Phase_Pyroprocessing” for user-selected kiln technology “i”, unitless;

[TABLE 4.32], $COLUMN\#2_{ELECTRICt}$ = Electricity use factor from column#2 of Table 4.32, in kWh/tonne of clinker;

“t” = Type of kiln technology - wet kiln, long dry kiln, preheater kiln, preheater/ precalciner kiln, or United States average kiln;

$M_{CLINKER}$ = Total mass of clinker, calculated in Equation 4.71, in kg;

1/1,000 = Unit conversion factor (1 tonne = 1,000 kg).

In Equation 4.51, *Excel VLOOKUP* function is applied to search for the kiln technology information “User Input Page_Cement Plant Technology Options by Phase_Pyroprocessing” (see Table 4.10 and Table 4.11). After locating the row corresponding to the selected technology option in column#2, the function returns the electricity use factor for that specific type of kiln technology per tonne of clinker. Afterwards, this lookup quantity (in kWh of electricity per tonne of clinker) is multiplied with the total mass of clinker calculated in “Cement_ Finish Mill_ Grind_ Blend” tab, Equation 4.71. Finally, the result is multiplied with a unit conversion factor of (1/1,000) to convert tonnes of clinker to kg of clinker to match the user input units entered in kg units.

Lastly, total pyroprocessing electricity use, in kWh, is the sum of the electricity use results from Equation 4.50 and Equation 4.51:

$$ELECTRICITY_{PYROPROCESSt} = ELECTRICITY_{FUEL_{PREPARATION}} + ELECTRICITY_{KILN_{USEt}}$$

Equation 4.52: Calculation of total electricity use during pyroprocessing

As mentioned in previous paragraphs, thermal energy consumption for the production of clinker in a kiln is another important source of CO_2 emissions in addition to those from calcination [25, 275]. To be able to estimate CO_2 (and all other air) emissions from fuel combustion, one needs to know the amount of fuel utilized in the kiln. This requires the following two-step calculations described in Equation 4.53 and Equation 4.54. In the first step, thermal energy consumption for the selected kiln type is calculated as follows:

$$ENERGY_{KILN\_THERMALt} = M_{CLINKER} \times VLOOKUP(KILN_{TYPEt}, [TABLE\ 31], COLUMN\#2_{\mathrm{THERMAL}t}) \times {}^{1}/_{1,000}$$

Equation 4.53: Calculation of kiln thermal energy consumption

Where:

$ENERGY_{KILN\_THERMALt}$ = Thermal energy consumption by kiln “t”, in MJ;

$KILN_{TYPEt}$ = Lookup from the tool input page “User Input Page_Cement Plant Technology Options by Phase_Pyroprocessing” for user-selected kiln technology “t”, unitless;

[TABLE 4.31], $COLUMN\#2_{THERMALt}$ = Thermal energy consumption factor for kiln “t”, from column#2 of Table 4.31, in MJ/tonne of clinker;

“t” = Type of kiln technology - wet kiln, long dry kiln, preheater kiln, preheater/ precalciner kiln, or United States average kiln;

$M_{CLINKER}$ = Total mass of clinker, calculated in Equation 4.71, in kg;

1/1,000 = Unit conversion factor (1 tonne = 1,000 kg).

In the second step, results from Equation 4.53 are applied to estimate fuel quantities based on the user-selected kiln fuel composition. Units are in kilogram (kg) for solid fuels (coal, petcoke, solid waste fuels); liter (l) for liquid fuels (heavy oil, diesel, liquid waste fuels); and cubic meter (m^3) for natural gas:

$$FUEL_{PYROPROCESSi,t} = \frac{FUEL_{PERCENT_{PYROPROCESSi}} \times ENERGY_{KILN_{THERMALt}}}{HLOOKUP\left(FUEL_j, [TABLE\ 4.16, TABLE\ 4.17], ROW\#4_{HHVi}\right)}$$

Equation 4.54: Calculation of quantities of kiln fuels

Where:

$\text{FUEL}_{\text{PYROPROCESSi,t}}$ = Total mass or volume of kiln fuel “i” used in a kiln type “t”, depending on the fuel type in kg, liters, or m^3;

$\text{FUEL\_PERCENT}_{\text{PYROPROCESSi}}$ = User-defined kiln fuel “i” by thermal energy requirement percentage of kiln “t”. Obtained from the input page “User Input Page_Technology Options Input_Fuel Use Options for Cement Pyroprocessing”, in %;

$\text{ENERGY}_{\text{KILN\_THERMALt}}$ = Thermal energy consumption by kiln “t” (from Equation 4.53), in MJ;

FUEL_{i} = Type of kiln fuel (see the first column of Table 4.12 for the list of fossil and waste fuels);

[TABLE 4.16, TABLE 4.17], $\text{ROW\#4}_{\text{HHVi}}$ = Higher heating value of the kiln fuel “i” listed in row#4 of Table 4.16 and Table 4.17 for fossil fuels and waste fuels, respectively, in MJ per mass (kg) or volume (l or m^3) of fuel.

After calculating the amount of fuels used in the cement kiln, one can estimate the pre-combustion (only for fossil fuels) and combustion LCI (both for fossil and waste fuels) by applying the inventory factors tabulated in Table 4.15, Table 4.16, and Table 4.17. However, before pyroprocessing LCI calculations, other process related inputs and emissions worth mentioning at this point.

Other inputs to pyroprocessing stage include: blended meal as the material input to pyroprocessing, which is the output from Cement_ Raw Meal worksheet. The total mass is already calculated in Equation 4.36. In Table 4.35, additionally, kiln water consumption is estimated based on PCA’s cement LCI study [18]. According to the study, out of 133 U.S. cement plants only 4 of them reported their process water use data while details were unpublished. Therefore, water data may involve uncertainties. Keeping this in mind, kiln process-water consumption is estimated based on the water consumption factors provided in Table 4.32:

$$\begin{aligned} &WATER_{PYROPROCESSt} \\ &\quad = VLOOKUP(KILN_{TYPEt}, [TABLE\ 4.32], COLUMN\#5_{\text{WATERt}}) \times M_{PORTLANDCEMENT} \\ &\qquad \times {}^{1}/_{1,000} \times d_{H2O} \end{aligned}$$

Equation 4.55: Calculation of water consumption factor for pyroprocessing

Where:

$WATER_{PYROPROCESSt}$ = Total mass of water consumed during pyroprocessing for kiln type "t", in kg;

$KILN_{TYPEt}$ = Lookup from the tool input page "User Input Page_Cement Plant Technology Options by Phase_Pyroprocessing" for user-selected kiln technology "t", unitless;

[TABLE 4.32], $COLUMN\#5_{WATERt}$ = Pyroprocessing water consumption factor for kiln type "t", from column#5 of Table 4.32, in kg/tonne of portland cement;

$M_{PORTLANDCEMENT}$ = Total mass of portland cement, calculated in Equation 4.77, in kg;

d_{H2O} = Density of water, in m^3/1,000 kg;

1/1,000 = Unit conversion factor (1 tonne = 1,000 kg);

The VLOOKUP Excel function returns the water consumption factor that is corresponding to the user-selected kiln type in the column#5 of Table 4.32 which consists of data obtained from various sources [18, 23, 35, 48].

In addition to calculations of pyroprocessing energy, electricity, water, and raw material inputs, Table 4.35 provides the information related to mass of clinker, solid waste in the form of "cement kiln dust (CKD)", process-related PM emissions from pyroprocessing, and CO_2 emissions from calcination during clinkering in the kiln. The major product of pyroprocessing stage is clinker and its mass is estimated in the "Cement_Finish Mill_Grind_Blend" worksheet since its quantity depends on other cement ingredients (e.g. gypsum, fly ash, slag, etc.) that are blended with clinker to produce the final product "cement".

CKD from pyroprocessing is considered as part of the solid waste emissions and its mass is calculated as follows:

$$M_{CKD} = EF_{CKD} \times M_{PORTLAND\ CEMENT} \times {}^{1}/_{1,000}$$

Equation 4.56: Calculation of total mass of cement kiln dust from pyroprocessing

Where:

M_{CKD} = Total mass of cement kiln dust (CKD), in kg;

EF_{CKD} = United Stated cement industry average emission factor for CKD, from Table 4.34, in kg/tonne of portland cement;

$M_{PORTLANDCEMENT}$ = Total mass of portland cement, calculated in Equation 4.77, in kg;

1/1,000 = Unit conversion factor (1 tonne = 1,000 kg);

CO_2 emissions from calcination during pyroprocessing (or clinkering process in the kiln) are calculated by the multiplication of CO_2 emission factor of 522 kg/tonne of clinker with the total mass of clinker produced:

$$CALCINATION_{CO2} = EF_{CALCINATION_{CO2}} \times M_{CLINKER} \times {}^{1}/_{1,000}$$

Equation 4.57: Calculation of CO_2 emissions from calcination process during pyroprocessing

Where:

$CALCINATION_{CO2}$ = Total mass of CO_2 emissions from calcination during pyroprocessing stage of cement production, in kg;

$EF_{CALCINATION\_CO2}$ = United Stated cement industry average emission factor for calcination-related CO_2, from Table 4.34, in kg/tonne of portland cement;

$M_{CLINKER}$ = Total mass of clinker, calculated in Equation 4.71, in kg;

1/1,000 = Unit conversion factor (1 tonne = 1,000 kg);

The major source of process-related particulate matter is the stored clinker and it can be airborne during handling. The emission factor for such PM varies with the type of cement kiln technology (see Table 4.32) and the total amount is calculated as follows:

$$PM_{PYROPROCESSt} = VLOOKUP\left(KILN_{TYPEt}, [TABLE\ 4.32], COLUMN\#6_{\mathrm{PROCESS\_PMt}}\right) \times M_{PORTLANDCEMENT} \times {}^{1}/_{1{,}000}$$

Equation 4.58: Calculation of process-related PM emissions during pyroprocessing

Where:

$PM_{PYROPROCESSt}$ = Total mass of process-related PM emission for user-selected kiln “t”, in kg;

$KILN_{TYPEt}$ = Lookup from the tool input page “User Input Page_Cement Plant Technology Options by Phase_Pyroprocessing” for user-selected kiln technology “t”, unitless;

[TABLE 4.32], $COLUMN\#6_{PROCESS\_PMt}$ = Pyroprocessing PM emission factor for kiln type “t”, from column#6 of Table 4.32, in kg/tonne of portland cement;

$M_{PORTLANDCEMENT}$ = Total mass of portland cement, calculated in Equation 4.77, in kg;

1/1,000 = Unit conversion factor (1 tonne = 1,000 kg);

Process-related emissions estimated above are added to other life-cycle inventories from electricity use and fuel combustion (including pre-combustion impacts). Total emission factors from the “Reference Data Pool” worksheets (refer to Table 4.15 for pre-combustion-, Table 4.16 for fossil fuel combustion-, Table 4.17 for waste fuel combustion-, and Table 4.20 for electricity generation-related total life-cycle inventory data) are multiplied by the phase interventions (e.g., calculated fuel inputs in Table 4.35) to calculate total impacts from pyroprocessing. For an LCI factor “k” from pyroprocessing stage in a cement kiln type “t” located in location “j” is described as follows, whereas “k” can be energy use, water consumption, solid waste or an air emission:

$$PYROPROCESSING_{LCI\ ELECTRIC\,j,k} = ELECTRICITY_{PYROPROCESSt} \times HLOOKUP\left(LOCATION_j, TRANSPOSE\ [TABLE\ 9.9], ROW\#_{LCIF\,j,k}\right)$$

Equation 4.59: Calculation of LCI related to total electricity use during pyroprocessing

Where:

$PYROPROCESSING_{LCI\_ELECTRICj,k}$ = Total life-cycle inventory associated with electricity use during pyroprocessing, which is the sum of electricity used in kiln fuel preparation and in operation of the kiln system including fans, kiln drive for rotation, etc. The "j" corresponds to the cement plant location; in MJ for "k" energy use factor or in kg for life-cycle inventory factors corresponding to solid waste, water consumption, and air emissions;

$ELECTRICITY_{PYROPROCESSt}$ = Total amount of electricity used during pyroprocessing (calculated in Equation 4.52) and "t" refers to the user-selected kiln type, in kWh;

$LOCATION_j$ = Location of the cement plant "j", taken from "User Input Page_Quarry/Plant Location, Grid Mix, and Water Supply Input" and can be a State, United States, or user-defined location, unitless;

[TABLE 9.9], $ROW\#_{LCIFj,k}$ = Appendix A, Table 9.9 with calculated total LCI data for electricity grid mix (per kWh of electricity) for location "j"; each row representing a life-cycle inventory "k", in MJ/kWh for energy use factor or in kg/kWh for other LCI factors listed in the Table.

Following the electricity use impact calculations, pre-combustion and combustion-related LCI which cover impacts from the use of kiln fuels during pyroprocessing is calculated as follows:

$$PYROPROCESSING_{LCI\ PRECOMBUSTk} = \sum_{i=1}^{n=6} \left[FUEL_{PYROPROCESSi,t} \times PRECOMBUST_{LCIi,k}\right]$$

Equation 4.60: Calculation of LCI related to pre-combustion fuel use during pyroprocessing

$$PYROPROCESSING_{LCI\ COMBUSTk} = \sum_{i=1}^{n=15} \left[FUEL_{PYROPROCESSi,t} \times COMBUST_{LCIi,k}\right]$$

Equation 4.61: Calculation of LCI related to fuel combustion in cement kilns during pyroprocessing

Where:

$PYROPROCESSING_{LCI\_PRECOMBUSTk}$ = Total LCI associated with pre-combustion impacts of fossil fuels used in pyroprocessing, in MJ for "k" energy use factor or in kg for life-cycle inventories of solid waste, water consumption, and air emissions;

$PYROPROCESSING_{LCI\_COMBUSTi,k}$ = Total LCI associated with combustion impacts of kiln fuels used in cement raw materials quarrying, in MJ for "k" energy use factor or in kg for life-cycle inventories of solid waste, water consumption, and air emissions;

$FUEL_{PYROPROCESSi,t}$ = Total mass or volume of kiln fuel "i" used in a kiln "t", calculated in Equation 4.54, units change depending on the fuel type, in kg, liters, or m^3;

$PRECOMBUST_{LCIi,k}$ = Pre-combustion fuel LCI factors calculated in Table 4.15 per unit mass or volume of fossil fuel “i” with an associated a life-cycle inventory factor “k”, in MJ/mass or volume of fuel for energy use or in kg/ mass or volume of fuel for other LCI factors listed in the Table;

$COMBUST_{LCIi,k}$ = Fuel combustion LCI factors calculated in Table 4.16 (for fossil fuels) and Table 4.17 (for waste fuels) per unit mass or volume of kiln fuel “i” with an associated a life-cycle inventory factor “k”, in MJ/mass or volume of fuel for energy use or in kg/ mass or volume of fuel for other LCI factors listed in the Table.

“i” = Type of kiln fuel (see the first column of Table 4.12 for the list of fossil and waste fuels);

Pre-combustion data is limited to fossil fuels since data is not available for waste fuels. Combustion LCI data consist of both fossil and waste fuels.

Finally, total LCI is the sum of LCI from electricity use, fuel combustion (including fuel pre-combustion) and process of pyroprocessing itself:

$$\begin{aligned} PYROPROCESSING_{TOTALLCIj,k} &= PYROPROCESSING_{PROCESSk} + PYROPROCESSING_{LCI\_ELECTRICj,k} \\ &+ PYROPROCESSING_{LCI\_PRECOMBUSTk} + PYROPROCESSING_{LCI\_COMBUSTk} \end{aligned}$$

Equation 4.62: Calculation of total LCI for cement pyroprocessing

As an example of estimation of total CO_2 emissions (here “k” in Equation 4.62 is CO_2) from pyroprocessing: First, CO_2 emission from each of the sources is calculated separately by Equations 4.57, 4.59, 4.60, and 4.61. Then, the results from each of the equations are added to estimate the total pyroprocessing emission. Different from other emissions calculations, calcination CO_2 is added to the total below:

$$\begin{aligned} PYROPROCESSING_{TOTAL\_CO2} &= PYROPROCESSING_{CALCINATION\_CO2} + PYROPROCESSING_{ELECTRIC\_CO2} \\ &+ PYROPROCESSING_{PRECOMBUST\_CO2} + PYROPROCESSING_{COMBUST\_CO2} \end{aligned}$$

Equation 4.63: Example calculation of total CO_2 emissions associated with cement pyroprocessing stage

Following the pyroprocessing stage, comes the clinker cooling.

4.10.2 Clinker Cooling Worksheet

Clinker leaves the rotary kiln at a temperature around 1200-1250°C. Therefore, it has to be cooled down rapidly to allow further handling and conveying within the plant. In addition to clinker cooling, this process has a couple of other benefits including heat recovery from the clinker back to the kiln by preheating the air used for combustion. Moreover, rapid cooling prevents continuation of undesired chemical reactions in the clinker which may negatively affect its quality and grindability. Three major types of clinker coolers with different versions of commonly used grate coolers are included in the tool [35, 48]:

Rotary (tube) coolers: This type of cooler uses the same principle as the rotary kiln, but for reversed heat exchange. Currently, none of the cement plants use this type in the United States. Electricity use for cooling (only) is around 3.5 - 4 kWh/tonne of clinker (which translates to 3.3 -

3.8 kWh/tonne of cement for 1 to 0.95 cement to clinker ratio).

Planetary (satellite) coolers: Due to their design, planetary coolers are comparably susceptible to high wear and thermal shock effects. For this reason, they can be costly to maintain. Additionally, clinker exit temperatures may still be high without additional cooling by water injection (similar to tube coolers). Therefore, this type is not suitable for precalciner kilns as exhaust air cannot be extracted for preheating purposes. These coolers were popular back in 1960s and 1970s in preheater, long dry, and wet kilns. Today, as most kiln systems have calciners, planetary coolers are being obsolete. Electricity use can be as low as 0.5-1.5 kWh per tonne of clinker (0.5-1.4 kWh/tonne of cement) since no fans or motors are required as these coolers are self-adjusting.

Grate coolers: There are two types of grate cooler designs: traveling grate and reciprocating grate (steps with pushing edges). Due to mechanical complexity and poor clinker recuperation, travelling grate design was abandoned in 1980’s. Reciprocating grate coolers are preferred in modern kiln systems due to a number of advantages. First, preheated air is recovered for the combustion. Hot air can also be used for drying raw materials or solid kiln fuels. Grate coolers thus provide the most efficient and most flexible heat recovery system for modern dry process kilns.

The Table 4.37 provides electricity use factors for modern (4-8 kWh/tonne of clinker, that is 3.8-7.6 kWh/tonne of cement) and conventional reciprocating grate coolers (average 5 kWh/tonne of clinker, that is 4.75 kWh/tonne of cement) as well as for two other grate cooling configurations. These two additional configurations are developed to avoid dedusting the excess air from grate coolers and are known as vertical gravity cooler with grate (also called g-cooler) and grate cooler with re-circulating excess air. Electricity use is the highest for grate coolers with re-circulating excess air, average of 9.5 kWh/tonne of clinker (9.03 kWh/tonne of cement), followed by g-coolers with average rate of 8.5 kWh/tonne of clinker (8.08 kWh/tonne of cement).

PM emission from clinker cooler system is the major process-related type of emission. It is mostly coarse (only about 0-15% of PM is smaller than 10 microns) and consists of cement particles. Therefore, it is preferably returned to the process. But dust in the stored clinker can be airborne during handling. PM emissions for the user-selected dust control technology, which are fabric filter (FF) and electrostatic precipitator (ESP) are tabulated in the last column of Table 4.36 below.

On the User-Input page of the tool, two cooling technology drop-down list selections are provided: 1) Clinker cooling technology with six options, and 2) PM control technology with two options (FF or ESP). Cooling-related electricity use is the sum of cooling technology-related and PM-emission control-related. Results are in kWh per tonne of portland cement produced (see Table 4.36 and Table 4.37).

Table 4.36: GreenConcrete Cement_ Clinker Cooling – Electricity Use for PM Control Technology Options and Associated PM Emissions

Cement Clinker Cooling	**Electricity Use (kWh/tonne Cement)**			**PM (kg/tonne Cement)**
Technology Options	**Avg**	**Max**	**Min**	**Avg**
Fabric Filter (FF)	1.902	2.092	1.712	0.00006

Electrostatic Precipitators (ESP)	1.664	1.902	1.427	0.00005

Table 4.37: GreenConcrete Cement_ Clinker Cooling – Electricity Use for Common Cooling Technology Options

Clinker Coolers	**Electricity Use (kWh/tonne Cement)**			**Source**
Technology Options	**Avg**	**Max**	**Min**	
Rotary (Tube) Cooler	= 3.563 + (FF or ESP)	= 3.800 + (FF or ESP)	= 3.325 + (FF or ESP)	[18, 29, 48]
Planetary (Satellite) Cooler	= 0.950 + (FF or ESP)	= 1.425 + (FF or ESP)	= 0.475 + (FF or ESP)	
Reciprocating Grate Cooler (Conventional)	= 4.750 + (FF or ESP)	= 4.750 + (FF or ESP)	= 4.750 + (FF or ESP)	
Reciprocating Grate Cooler (Modern)	= 5.700 + (FF or ESP)	= 7.600 + (FF or ESP)	= 3.800 + (FF or ESP)	
Vertical Gravity Cooler w/ Grate Cooler (G-Cooler)	= 8.075 + (FF or ESP)	= 8.075 + (FF or ESP)	= 8.075 + (FF or ESP)	
Grate Cooler (Recirculating Excess Air)	= 9.025 + (FF or ESP)	= 9.025 + (FF or ESP)	= 9.025 + (FF or ESP)	

In Table 4.36, it must be noted that FF (fabric filter) or ESP (electrostatic precipitator) corresponds to an Excel VLOOKUP calculation that checks the user input selection for the type of PM-emission control and returns the electricity factor for that type of emission control, then adds this value to the cooling-only electricity use factors provided for six different types of cooling options given in the first column of Table 4.37. Thus, electricity use factors calculated in Table 4.39 are the sum of electricity power used for cooling and dust control.

Based on the data provided in Table 4.36 and Table 4.37, following calculations take place in Table 4.37 to estimate average electricity use LCI factors in kWh per tonne of clinker. Depending on the type of technology option for dust (PM) control (either FF or ESP) and cooler technology, the cooling electricity use factor in Table 4.37 is calculated as follows:

$$\begin{aligned} AVG\_ELECTRICITY_{COOLERc,PM\_CONTROLd} \\ = [VLOOKUP(COOLER_c, [TABLE\ 4.37], COLUMN\#2) \\ + VLOOKUP(PM\_CONTROL_d, [TABLE\ 4.36], COLUMN\#2)] \end{aligned}$$

Equation 4.64: Calculation of average electricity use factor for clinker cooling based on user-selected technology cooling and PM emission control technology

Where:

AVG_$_{\text{ELECTRICITYCOOLERc,PMCONTROLd}}$ = Average amount electricity required in a clinker cooling system with cooler technology "d" and PM control technology "c", in kWh per tonne of portland cement;

COOLERc = Cement Plant Technology Lookup from User Input Page_Clinker Cooling, whereas "c" refers to one of the six clinker cooling technology options listed in the first column of Table 4.37;

PM_CONTROLd = Clinker Cooling PM Control Technology Options Lookup from User Input Page_Technology Options Input, whereas “d” refers to one of the two PM control technology options (either FF or ESP) listed in the first column of Table 4.36;

[TABLE 4.36], COLUMN#2 = Average electricity use factor for the user-selected PM control technology, in kWh/tonne of portland cement;

[TABLE 4.37], COLUMN#2 = Average electricity use factor for the user-selected cooler technology “c’, in kWh/tonne of portland cement;

Total cooling electricity consumption is calculated by the multiplication of the average electricity factor from Equation 4.64 with total mass of portland cement:

$$ELECTRICITY_{COOLING} = AVG\_ELECTRICITY_{COOLERc,PM\_CONTROLd} \times M_{PORTLAND\ CEMENT} \times {}^{1}/_{1,000}$$

Equation 4.65: Calculation of total clinker cooling electricity use

Where:

$ELECTRICITY_{COOLING}$ = Total clinker cooling electricity use, in kWh;

$AVG\__{ELECTRICITYCOOLERc,PMCONTROLd}$ = Average amount electricity required in a clinker cooling system with cooler technology “d” and PM control technology “c”, kWh per tonne of portland cement;

$M_{PORTLANDCEMENT}$ = Total mass of portland cement, calculated in Equation 4.77, in kg;

1/1,000 = Unit conversion factor (1 tonne = 1,000 kg);

Additionally, Table 4.38 summarizes the water consumed per tonne of clinker by various cooling technology options.

Table 4.38: GreenConcrete Cement_ Clinker Cooling – Water Consumption data for LCI calculations

Cement Clinker Cooling	**Water Consumption (m^3/tonne Clinker)**			**Source**
Technology Options	Average	Max	Min	
Rotary (Tube) Cooler	0.030	0.060	0.000	[48]
Planetary (Satellite) Cooler	0.020	0.040	0.000	
Reciprocating Grate Cooler (Conventional)	0.000	0.000	0.000	
Reciprocating Grate Cooler (Modern)	0.000	0.000	0.000	
Vertical Gravity Cooler w/ Planetary Cooler	0.000	0.000	0.000	
Grate Cooler (Recirculating Excess Air)	0.000	0.000	0.000	

As observed in Table 4.38, only tube and planetary coolers consume water. Therefore, water consumption factors calculated in will yield zero results for technology options other than tube and planetary coolers:

$$WATER_{COOLINGc} = VLOOKUP(COOLER_c, [TABLE\ 4.38], COLUMN\#2) \times M_{CLINKER} \times {}^{1}/_{1{,}000}$$

Equation 4.66: Calculation of average water consumption factor for clinker cooling

Where:

$WATER_{COOLINGc}$ = Total mass of water consumed during clinker cooling for the user-selected cooler technology “c”, in m^3;

COOLERc = Cement Plant Technology Lookup from User Input Page_Clinker Cooling, whereas “c” refers to one of the six clinker cooling technology options listed in the first column of Table 4.37;

[TABLE 4.38], COLUMN#2 = Average cooling water consumption factor, from column#2 in Table 4.38, in m^3/tonne of clinker;

$M_{CLINKER}$ = Total mass of clinker, calculated in Equation 4.71, in kg;

1/1,000 = Unit conversion factor (1 tonne = 1,000 kg);

The VLOOKUP Excel function returns the water consumption factor that is corresponding to the user-selected cooler technology in the column#2 of Table 4.38.

Additionally, process-related PM during cooling is estimated based on the PM emission control technology factors listed in column# 5 of Table 4.36:

$$PM_{COOLINGd} = VLOOKUP(PM\_CONTROL_d, [TABLE\ 4.36], COLUMN\#5) \times M_{PORTLANDCEMENT} \times {}^{1}/_{1{,}000}$$

Equation 4.67: Calculation of process-related PM emissions during clinker cooling

Where:

$PM_{COOLINGd}$ = Total mass of process-related PM emission for the user-selected PM emission control technology “d”, in kg;

PM_CONTROLd = Clinker Cooling PM Control Technology Options Lookup from User Input Page_Technology Options Input, whereas “d” refers to one of the two PM control technology options (either FF or ESP) listed in the first column of Table 4.36;

[TABLE 4.36], COLUMN#5 = Mass of average PM emissions for the user-selected PM control technology, in kg per tonne of portland cement;

MPORTLANDCEMENT = Total mass of portland cement, calculated in Equation 4.77, in kg;

1/1,000 = Unit conversion factor (1 tonne = 1,000 kg).

Table 4.39 summarizes the clinker cooling LCI calculation inputs and outputs calculated through

Equation 4.64 through Equation 4.67:

Table 4.39: GreenConcrete Cement_ Clinker Cooling – LCI Calculations

Technology Lookup from User Input Page	**Clinker Cooler Type – User Input (Selected from drop-down list)**			**Units**
Inputs	**Average**	**Max**	**Min**	
Electricity	Calculated	Calculated	Calculated	kWh
Clinker	Calculated	Calculated	Calculated	kg
Water	Calculated	Calculated	Calculated	m^3
Outputs	**Average**	**Max**	**Min**	
Clinker, Cooled	Calculated	Calculated	Calculated	kg
PM	Calculated	Calculated	Calculated	kg

Finally, LCI factors are calculated by multiplying the electricity use factors in "Reference Data Pool" worksheet with the cooling electricity use inventories to estimate total impacts from clinker cooling. Again, the LCI results from this cement production stage are summarized in "Results" tab of the tool. For an LCI factor "k" from the clinker cooling stage in a location "j", which is the location of the cement plant, is described as follows, whereas "k" can be energy use, water consumption, solid waste or an air emission:

$$COOLING_{LCI\ ELECTRIC\,j,k} = \\ ELECTRICITY_{COOLING} \times HLOOKUP\left(LOCATION_j, TRANSPOSE\ [TABLE\ 9.9], ROW\#_{LCIF\ j,k}\right)$$

Equation 4.68: Calculation of LCI related to total electricity use during clinker cooling

Where:

$\text{COOLING}_{\text{LCI\_ELECTRICj,k}}$ = Total life-cycle inventory associated with electricity use during clinker cooling, in MJ for "k" energy use factor or in kg for life-cycle inventory factors corresponding to solid waste, water consumption, and air emissions;

$\text{ELECTRICITY}_{\text{COOLING}}$ = Total amount of electricity used during clinker cooling (calculated in Equation 4.65), in kWh;

$\text{LOCATION}_{\text{j}}$ = Location of the cement plant "j", taken from "User Input Page_Quarry/Plant Location, Grid Mix, and Water Supply Input" and can be a State, United States, or user-defined location, unitless;

[TABLE 9.9], $\text{ROW\#}_{\text{LCIFj,k}}$ = Appendix A, Table 9.9 with calculated total LCI data for electricity grid mix (per kWh of electricity) for location "j"; each row representing a life-cycle inventory "k", in MJ/kWh for energy use factor or in kg/kWh for other LCI factors listed in the Table.

Finally, total LCI for factor of "k" is estimated as the sum of LCI from electricity use and process-related (only for when "k" is PM emission) during clinker cooling:

$$COOLING_{TOTALLCI\,j,k} = COOLING_{LCI\_ELECTRIC\,j,k} + COOLING_{LCI\_PROCESSk}$$

Equation 4.69: Calculation of total LCI for clinker cooling

It is necessary to note that the major product of cooling is the clinker cooled, and its mass is equal to the mass of clinker input from pyroprocessing. Similar to all other GreenConcrete tool material quantity calculations, mass of input material is assumed to be equal to the mass of output material as long as the process converting an input to an output does not involve chemical reactions (e.g., combustion, calcination, and so on). Cooled clinker is one of the major inputs to next cement production process, namely finish milling, grinding, and blending stage.

4.10.3 Cement Finish Milling, Grinding, and Blending Worksheet

Portland cement is produced by intergrinding cement clinker with about five percent of gypsum (or anhydrite) in a cement mill. Blended cements, also known as "composite" cements, contain other constituents such as granulated blast-furnace slag (GBFS), natural or industrial pozzolans (e.g., fly ash from coal power plants or volcanic tuff), or inert fillers such as limestone in addition to clinker and gypsum. Mineral additions in blended cements are either interground with clinker or ground separately and then mixed with portland cement. In the tool, second approach (separate grinding of each material and mixing with PC later on) is selected for ease of calculations and less data requirement since intergrinding different combinations of materials (e.g., fly ash with clinker vs. slag with clinker) may require different electricity use factors depending on the grindability of each material and combination of these materials. On the other hand, if ground separately, grinding-related energy data is readily available for each of the material (e.g., clinker, gypsum, fly ash, and slag) mixed in the blended cement. Associated electricity use results from grinding of each material are added to estimate LCI factors for this cement production stage.

Before describing the "C_FinishMillGrindBlend" tab in GreenConcrete LCA tool and related calculations, following paragraphs briefly explain processes taking place in this stage.

There are mainly four major steps: 1) Finish milling and grinding; 2) Classifying and separating; 3) Conveying; and 4) Cement storage, packaging, and shipping. In the tool, electricity use associated with first and third steps are calculated while for second and last steps, it is assumed to be negligible. LCI calculations associated with electricity use for powering conveyors are built-in in "Transportation" worksheet.

In the first step, clinker size is reduced by means of grinding (milling) with the use of ball mills, roller mills, roll presses, or combination of them (see Table 4.41 for technology options).

Conventional *tube (ball) mills* with open circuit (without separator) are mainly used when producing only one type of cement. Closed circuit tube mills with a separator are more flexible, but – as with open circuit mills – are limited with regard to the moisture content of the mill feed. The consumption of electrical energy in tube mills is generally high compared to the other mill types [48].

Vertical roller mills can handle higher moisture contents in the mill feed and are therefore well suited for blended cements with higher rates of (moist) mineral additions or for separate grinding of mineral additions. Vertical mills can also be used in combination with a tube mill [48].

High pressure *roller presses* so far consume the lowest amount of energy for grinding process. However, they require a high degree of maintenance, and the particle size distribution of the finished product has to be optimised. Roller presses are mainly used in combination with tube mills [48].

A more recent development in cement grinding is the *horizontal roller mill*. The mill feed passes several times between the roller and the shell along the mill due to centrifugal forces and fixed material transfer devices [48].

The largest share of electricity is consumed in this step which corresponds to about 30-40% of total power consumption during cement production [35]. Any improvement in increasing the efficiency of the grinding system can reduce energy consumption and costs considerably. Finish milling system mainly consists of feeders, mills, elevators, and separators.

In the second step, materials are classified based on the size of each particle with the purpose of removing finer particles from coarser ones so that coarse particles are further ground without over-grinding the smaller ones. Originally, most grinding was done wet in open circuit without a separator as it was much easier and kilns were mostly wet process type. However, in today's modern installations, almost all grinding is performed in a dry environment with a separator or in closed circuit to reduce quantity of energy and water use. After the separation step comes removal of the product. A settling chamber, a cyclone, or a bag filter can be used for the product collection.

In the third step, materials are transferred between different operation units and workstations on a given cement plant site.

Table 4.40, Table 4.41, Table 4.42, Table 4.43, and Table 4.44 demonstrate process calculations as well as data and related sources used in these LCI calculations. In "Cement Finish Milling and Grinding" worksheet, quantities of materials mixed in with clinker and gypsum are estimated to reach the total mass of portland cement which is used in all other cement production process calculations throughout the tool. A number of assumptions are made prior to material quantity calculations. For all U.S. cements, it is presumed that average gypsum to (clinker+gypsum) ratio is 5% by weight (clinker to cement ratio corresponds to an average of 95% by mass for Type I, II, II, and V) and this ratio varies between 3% and 7% of gypsum for max clinker quantity of 97% and min clinker quantity of 93%, respectively [18, 28]. Since the minimal content of mineral components in the U.S. cement types 'I (SM)' and 'I (PM)' are not specified in the ASTM C595 standard, it is assumed to be 5% in the GreenConcrete LCA tool based on Boesch et al. [25]. Average, maximum, and minimum mass quantities refer to the mass of clinker, e.g. for maximum amount of clinker the amount of additive has to be minimum or vice versa in related equations (e.g. Equation 4.70) and Table 4.40.

Calculations associated with mass of cement and its ingredients are described in following equations (Equation 4.70 and Equation 4.72):

$$
\begin{aligned}
CLINKER\_AVG_{TYPEn} &= 0.95 \times (1 - CKD_{AVG\,TYPEn} - FA_{AVG\,TYPEn} - GBFS_{AVG\,TYPEn}) \\
CLINKER\_MAX_{TYPEn} &= 0.97 \times (1 - CKD_{MAX\,TYPEn} - FA_{MAX\,TYPEn} - GBFS_{MAX\,TYPEn}) \\
CLINKER\_MIN_{TYPEn} &= 0.93 \times (1 - CKD_{MIN\,TYPEn} - FA_{MIN\,TYPEn} - GBFS_{MIN\,TYPEn})
\end{aligned}
$$

Equation 4.70: Calculation of average/max/min unit mass of clinker per kg of cement

Where:

$CLINKER\_AVG(MAX/MIN)_{TYPEn}$ = Average (max or min) unit mass of clinker in portland cement type "n", calculated in Table 4.40, in kg/kg of cement;

$CKD_{AVG\ (MAX/MIN)\ TYPEn}$ = Average (Max or Min) mass of cement kiln dust (CKD) in portland cement type “n”, which returns zero for all cement types except for “n = portland cement_with recycled CKD” as given in Table 4.40, in kg/kg of cement;

$FA_{AVG\ (MAX/MIN)\ TYPEn}$ = Average (Max or Min) mass of fly ash (FA) in portland cement type “n”, which returns zero for all cement types except for “n = Blended cement_Portland pozzolan cement,Type IP/P and “n = Blended cement_Pozzolan-modified portland cement,Type I[PM]” as given in Table 4.40, in kg/kg of cement;

$GBFS_{AVG\ (MAX/MIN)\ TYPEn}$ = Average (Max or Min) mass of granulated blast furnace slag (GBFS) in portland cement type “n”, which returns zero for all cement types except for “n = Blended cement_Portland blast furnace slag cement, Type IS, “n = Blended cement_Slag modified portland cement, Type I[SM]”, and “n = Blended cements_Slag cement, Type S” as given in Table 4.40, in kg/kg of cement.

Total mass of clinker, which is the average “$M_{CLINKER}$”, is used in cement production-related equations throughout the GreenConcrete LCA tool. Based on the calculated CLINKER_AVG (MAX/MIN) $_{TYPEn}$ value from Equation 4.70, average $M_{CLINKER}$ (also max and min $M_{CLINKER}$) is calculated as follows:

$$M_{CLINKER}(avg) = VLOOKUP(CEMENT_{TYPEn}, [TABLE\ 4.40], COLUMN\#2_{CLINKER\_AVGn}) \times Total\ Mass\ of\ Cement$$

$$M_{CLINKER}(max) = VLOOKUP(CEMENT_{TYPEn}, [TABLE\ 4.40], COLUMN\#3_{CLINKER\_MAXn}) \times Total\ Mass\ of\ Cement$$

$$M_{CLINKER}(min) = VLOOKUP(CEMENT_{TYPEn}, [TABLE\ 4.40], COLUMN\#4_{CLINKER\_MINn}) \times Total\ Mass\ of\ Cement$$

Equation 4.71: Calculation of total mass of clinker based on the type and amount of cement input in concrete mix

Where:

$M_{CLINKER}$ = Total mass of clinker, average/max/min, in kg;

$CEMENT_{TYPEn}$ = User selected cement type “n”, given in the first column of Table 4.40;

[TABLE 4.40], $COLUMN\#2_{CLINKER\_AVGn}$ = Average unit mass of clinker in portland cement type “n” calculated in Equation 4.70 and tabulated in column #2 of Table 4.40, in kg/kg of cement;

[TABLE 4.40], $COLUMN\#3_{CLINKER\_MAXn}$ = Maximum unit mass of clinker in portland cement type “n” calculated in Equation 4.70 and tabulated in column #3 of Table 4.40, in kg/kg of cement;

[TABLE 4.40], $COLUMN\#4_{CLINKER\_MINn}$ = Minimum unit mass of clinker in portland cement type “n” calculated in Equation 4.70 and tabulated in column #4 of Table 4.40, in kg/kg of cement;

Total Mass of Cement = Calculated in Equation 4.4 and taken from “User Input Page_Concrete Mix Proportions: Material Quantities” section of GreenConcrete LCA tool, kg.

For all cement types, gypsum is added to the clinker and its unit mass per kg of cement is estimated based on the calculated quantity of clinker from Equation 4.70:

$$GYPSUM\_AVG_{TYPEn} = \frac{5}{95} \times CLINKER\_AVG_{TYPEn}$$

$$GYPSUM\_MAX_{TYPEn} = \frac{7}{93} \times CLINKER\_MIN_{TYPEn}$$

$$GYPSUM\_MIN_{TYPEn} = \frac{3}{97} \times CLINKER\_MAX_{TYPEn}$$

Equation 4.72: Calculation of average/max/min mass of gypsum per kg of cement, based on unit mass of clinker from Equation 4.70

Where:

GYPSUM_AVG(MAX/MIN)$_{\text{TYPEn}}$ = Average (max or min) mass of gypsum for portland cement type "n", calculated in Table 4.40, in kg/kg of cement;

CLINKER_AVG (MAX/MIN) $_{\text{TYPEn}}$ = Average (Max or Min) mass of clinker per unit mass of cement, calculated in Equation 4.70, in kg/kg of cement;

Ratios of 5/95, 7/93, 3/97 each corresponds to "gypsum to clinker mass ratio" for average, max, and min gypsum contents vs. average, min, and max clinker contents, respectively.

Within the GreenConcrete LCA tool, total mass of gypsum "M$_{\text{GYPSUM}}$" is calculated using the VLOOKUP function:

$$M_{GYPSUM}(avg) = VLOOKUP(CEMENT_{TYPEn}, [TABLE\ 4.40], COLUMN\#5_{GYPSUM\_AVGn}) \times Total\ Mass\ of\ Cement$$

$$M_{GYPSUM}(max) = VLOOKUP(CEMENT_{TYPEn}, [TABLE\ 4.40], COLUMN\#6_{GYPSUM\_MAXn}) \times Total\ Mass\ of\ Cement$$

$$M_{GYPSUM}(min) = VLOOKUP(CEMENT_{TYPEn}, [TABLE\ 4.40], COLUMN\#7_{GYPSUM\_MINn}) \times Total\ Mass\ of\ Cement$$

Equation 4.73: Calculation of total mass of gypsum based on the total mass of cement input used in concrete mix

Where:

M$_{\text{GYPSUM}}$ = Total mass of gypsum, average/max/min, in kg;

CEMENT$_{\text{TYPEn}}$ = User selected cement type "n", given in the first column of Table 4.40;

[TABLE 4.40], COLUMN#5$_{\text{GYPSUM\_AVGn}}$ = Average unit mass of gypsum in portland cement type "n" calculated in Equation 4.72 and tabulated in column #5 of Table 4.40, in kg/kg of cement;

[TABLE 4.40], COLUMN#6$_{GYPSUM\_MAXn}$ = Maximum unit mass of gypsum in portland cement type "n" calculated in Equation 4.72 and tabulated in column #6 of Table 4.40, in kg/kg of cement;

[TABLE 4.40], COLUMN#7$_{GYPSUM\_MINn}$ = Minimum unit mass of gypsum in portland cement type "n" calculated in Equation 4.72 and tabulated in column #7 of Table 4.40, in kg/kg of cement;

Total Mass of Cement = Calculated in Equation 4.4 and taken from "User Input Page_ Concrete Mix Proportions: Material Quantities" section of GreenConcrete LCA tool, in kg.

For portland cement types I, II, III, and V, mass of cement kiln dust (CKD), fly ash (FA), granulated blast furnace slag (GBFS) are zero (see Table 4.40). Unit mass of slag for blended cements of Type IS, I[SM] and Type S, and mass of fly ash for Type IP/P and Type I[PM] are tabulated in Table 4.40, respectively. These typical quantities of fly ash and slag in blended cements are taken from ASTM C595 standard [276] while CKD quantities are based on Huntzinger et al. [19].

Within the GreenConcrete LCA tool, total mass of major cement additives (cement kiln dust, fly ash, and granulated blast furnace slag) "M$_{CKD}$", "M$_{FA}$", and "MA$_{GBFS}$" are calculated by the VLOOKUP function in a similar way, respectively:

$$M_{CKD}(avg) = VLOOKUP(CEMENT_{TYPEn}, [TABLE\ 4.40], COLUMN\#8_{CKD\_AVGn}) \times Total\ Mass\ of\ Cement$$

$$M_{CKD}(max) = VLOOKUP(CEMENT_{TYPEn}, [TABLE\ 4.40], COLUMN\#9_{CKD\_MAXn}) \times Total\ Mass\ of\ Cement$$

$$M_{CKD}(min) = VLOOKUP(CEMENT_{TYPEn}, [TABLE\ 4.40], COLUMN\#10_{CKD\_MINn}) \times Total\ Mass\ of\ Cement$$

Equation 4.74: Calculation of total mass of cement kiln dust (CKD) based on the total mass of cement input used in concrete mix

Where:

M$_{CKD}$ = Total mass of CKD average/max/min, in kg;

CEMENT$_{TYPEn}$ = User selected cement type "n", given in the first column of Table 4.40;

[TABLE 4.40], COLUMN#8$_{CKD\_AVGn}$ = Average unit mass of CKD in portland cement type "n", tabulated in column #8 of Table 4.40 based on literature, in kg/kg of cement;

[TABLE 4.40], COLUMN#9$_{CKD\_MAXn}$ = Maximum unit mass of CKD in portland cement type "n", tabulated in column #9 of Table 4.40 based on literature , in kg/kg of cement;

[TABLE 4.40], COLUMN#10$_{CKD\_MINn}$ = Minimum unit mass of CKD in portland cement type "n", tabulated in column #10 of Table 4.40 based on literature, in kg/kg of cement;

Total Mass of Cement = Calculated in Equation 4.4 and taken from "User Input Page_ Concrete Mix Proportions: Material Quantities" section of GreenConcrete LCA tool, in kg.

$$M_{FA\_CEMENT}(avg) = VLOOKUP(CEMENT_{TYPEn}, [TABLE\ 4.40], COLUMN\#11_{FA\_AVGn}) \times Total\ Mass\ of\ Cement$$

$$M_{FA\_CEMENT}(max) = VLOOKUP(CEMENT_{TYPEn}, [TABLE\ 4.40], COLUMN\#12_{FA\_MAXn}) \times Total\ Mass\ of\ Cement$$

$$M_{FA\_CEMENT}(min) = VLOOKUP(CEMENT_{TYPEn}, [TABLE\ 4.40], COLUMN\#13_{FA\_MINn}) \times Total\ Mass\ of\ Cement$$

Equation 4.75: Calculation of total mass of fly ash (FA) based on the total mass of cement input used in concrete mix

Where:

M_{FA_CEMENT} = Total mass of fly ash (FA) average/max/min, in kg;

$CEMENT_{TYPEn}$ = User selected cement type “n”, given in the first column of Table 4.40;

[TABLE 4.40], $COLUMN\#11_{FA\_AVGn}$ = Average unit mass of FA in portland cement type “n”, tabulated in column #11 of Table 4.40 based on literature, in kg/kg of cement;

[TABLE 4.40], $COLUMN\#12_{FA\_MAXn}$ = Maximum unit mass of FA in portland cement type “n”, tabulated in column #12 of Table 4.40 based on literature , in kg/kg of cement;

[TABLE 4.40], $COLUMN\#13_{FA\_MINn}$ = Minimum unit mass of FA in portland cement type “n”, tabulated in column #13 of Table 4.40 based on literature, in kg/kg of cement;

Total Mass of Cement = Calculated in Equation 4.4 and taken from “User Input Page_ Concrete Mix Proportions: Material Quantities” section of GreenConcrete LCA tool, in kg.

$$M_{GBFS}(avg) = VLOOKUP(CEMENT_{TYPEn}, [TABLE\ 4.40], COLUMN\#14_{GBFS\_AVGn}) \times Total\ Mass\ of\ Cement$$

$$M_{GBFS}(max) = VLOOKUP(CEMENT_{TYPEn}, [TABLE\ 4.40], COLUMN\#15_{GBFS\_MAXn}) \times Total\ Mass\ of\ Cement$$

$$M_{GBFS}(min) = VLOOKUP(CEMENT_{TYPEn}, [TABLE\ 4.40], COLUMN\#16_{GBFS\_MINn}) \times Total\ Mass\ of\ Cement$$

Equation 4.76: Calculation of total mass of granulated blast furnace slag (GBFS) based on the total mass of cement input used in concrete mix

Where:

M_{GBFS} = Total mass of granulated blast furnace slag (GBFS) average/max/min, in kg;

$CEMENT_{TYPEn}$ = User selected cement type “n”, given in the first column of Table 4.40;

[TABLE 4.40], $COLUMN\#14_{GBFS\_AVGn}$ = Average unit mass of GBFS in portland cement type “n”, tabulated in column #14 of Table 4.40 based on literature, in kg/kg of cement;

[TABLE 4.40], $COLUMN\#15_{GBFS\_MAXn}$ = Maximum unit mass of GBFS in portland cement type "n", tabulated in column #15 of Table 4.40 based on literature , in kg/kg of cement;

[TABLE 4.40], $COLUMN\#16_{GBFS\_MINn}$ = Minimum unit mass of GBFS in portland cement type "n", tabulated in column #16 of Table 4.40 based on literature, in kg/kg of cement;

Total Mass of Cement = Calculated in Equation 4.4 and taken from "User Input Page_ Concrete Mix Proportions: Material Quantities" section of GreenConcrete LCA tool, in kg.

In GreenConcrete LCA tool, total mass of cement for Type I, II, III, and V portland cement is essentially the sum of mass of clinker and gypsum. In case of blended cements, additives of fly ash or GBFS are blended with clinker and gypsum mix after cement finish milling and grinding process occurs. Therefore, preceding equations that have incorporated mass of portland cement "$M_{PORTLAND\_CEMENT}$" in processes of cement production refer to the mass of clinker and gypsum mix. Therefore, "$M_{PORTLAND\_CEMENT}$" for conventional Type I, II, III, and V cements are calculated as:

$$M_{PORTLANDCEMENT} = M_{CLINKER} + M_{GYPSUM}$$

Equation 4.77: Calculation of total mass of portland cement – for Type I, II, III, and V

Where:

$M_{PORTLANDCEMENT}$ = Total mass of portland cement for Type I, II, III, and V, in kg;

$M_{CLINKER}$ = Total mass of clinker, calculated in Equation 4.71, in kg;

M_{GYPSUM} = Total mass of gypsum, calculated in Equation 4.73, in kg.

In case the user selects a blended cement type, total mass of blended cement, "$M_{BLENDEDCEMENT}$" is calculated as:

$$M_{BLENDEDCEMENT} = M_{CLINKER} + M_{GYPSUM} + M_{CKD} + M_{FA} + M_{GBFS}$$

Equation 4.78: Calculation of total mass of blended cement – for Type IS, I[SM], S, IP/P, I[PM] and with recycled CKD

Where:

$M_{BLENDEDCEMENT}$ = Total mass of blended cement, in kg;

$M_{CLINKER}$ = Total mass of clinker, calculated in Equation 4.71, in kg;

M_{GYPSUM} = Total mass of gypsum, calculated in Equation 4.73, in kg;

M_{CKD} = Total mass of cement kiln dust (CKD), calculated in Equation 4.74, in kg;

M_{FA} = Total mass of fly ash (FA), calculated in Equation 4.75, in kg;

M_{GBFS} = Total mass of granulated blast furnace slag (GBFS), calculated in Equation 4.76, in kg.

Calculated mass of ingredients of cement as well as the mass of portland cement (or blended cement based on user’s preference) are tabulated in Table 4.44 together with electricity use and water consumption inputs to “Cement Finish Milling and Grinding” stage.

Table 4.40: GreenConcrete _ Cement Finish Milling and Grinding – Major Cement Types and Mass of Its Ingredients per Unit Weight of Selected Cement Type

Cement Types	**Clinker (kg)**			**Gypsum (kg)**			**Cement Kiln Dust (CKD) (kg)**			**Fly Ash (kg)**			**Granulated Blast Furnace Slag (kg)**		
	Avg.	Max	Min	Avg.	Max	Min	Avg.	Max	Min	Avg.	Max	Min	Avg.	Max	Min
Portland cement_Normal, Type I	0.950	0.970	0.930	0.050	0.030	0.070	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Portland cement_Moderate sulfate resistance, Type II	0.950	0.970	0.930	0.050	0.030	0.070	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Portland cement_High early strength, Type III	0.950	0.970	0.930	0.050	0.030	0.070	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Portland cement_High sulfate resistance, Type V	0.950	0.970	0.930	0.050	0.030	0.070	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Blended cement_Portland blast furnace slag cement, Type IS	0.499	0.728	0.279	0.026	0.023	0.021	0.000	0.000	0.000	0.000	0.000	0.000	0.475	0.250	0.700
Blended cement_Slag modified portland cement, Type I[SM]	0.808	0.922	0.698	0.043	0.029	0.053	0.000	0.000	0.000	0.000	0.000	0.000	0.150	0.050	0.250
Blended cements_Slag cement, Type S	0.143	0.291	0.000	0.008	0.009	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.850	0.700	1.000
Blended cement_Portland pozzolan cement,Type IP/P	0.689	0.825	0.558	0.036	0.026	0.042	0.000	0.000	0.000	0.275	0.150	0.400	0.000	0.000	0.000
Blended cement_Pozzolan-modified portland cement, Type I[PM]	0.855	0.922	0.791	0.045	0.029	0.060	0.000	0.000	0.000	0.100	0.050	0.150	0.000	0.000	0.000
Portland cement_with recycled CKD	0.784	0.825	0.744	0.041	0.026	0.056	0.175	0.150	0.200	0.000	0.000	0.000	0.000	0.000	0.000
Portland cement_User-defined 1								calculated							
Portland cement_User-defined 2								calculated							
Portland cement_User-defined 3								calculated							

Electricity use factors associated with cement finish milling and grinding process are estimated based on CEMBUREAU's assumption of 350 m^2/kg “Blaine” cement fineness [48, 205, 211]. These factors are illustrated in Table 4.41.

Table 4.41: GreenConcrete _ Cement Finish Milling and Grinding – Electricity Use Factors for Milling and Grinding Technology Options

Cement Finish Milling and Grinding	**Electricity Use (kWh/tonne Cement)**			
Technology Options	**Average**	**Max**	**Min**	**Source**
Tube Mill	34.675	34.675	34.675	[38, 40, 48, 205, 211, 277]
Vertical Roller Mill	27.100	29.200	25.000	
Ball Mill	36.000	42.000	30.000	
Roller Press	27.500	33.000	22.000	
Horizontal Roller Mill (Horomill)	25.500	28.000	23.000	

Power consumption during cement finish milling and grinding depends heavily on the fineness of the final product and its additives [48, 205, 211, 277]. The fineness of cement influences major cement properties such as setting time. Below, Table 4.42 demonstrates Blaine fineness factors for major cement types and their related grindability factors which are included in electricity use LCI calculations in Equation 4.79.

Table 4.42: GreenConcrete _ Cement Finish Milling and Grinding – Blaine Fineness and Grindability Factors with respect to 350 (m^2/kg) Blaine Fineness for Major Portland Cement Types

	Blaine fineness (m^2/kg)			**Grindability factor with respect to Blaine fineness of 350 (m^2/kg)**		
Cement Types	**Ave**	**Max**	**Min**	**Ave**	**Max**	**Min**
Portland cement_Normal, Type I	381	497	310	1.09	1.42	0.89
Portland cement_Moderate sulfate resistance, Type II	378	514	318	1.08	1.47	0.91
Portland cement_High early strength, Type III	547	672	319	1.56	1.92	0.91
Portland cement_High sulfate resistance, Type V	385	681	287	1.10	1.95	0.82
Blended cements_Portland blast furnace slag cement,Type IS	381	497	310	1.09	1.42	0.89
Blended cements_Slag modified portland cement,Type I[SM]	381	497	310	1.09	1.42	0.89
Blended cements_Slag cement , Type S	381	497	310	1.09	1.42	0.89
Blended cements_Portland pozzolan cement,Type IP/P	381	497	310	1.09	1.42	0.89
Blended cements_Pozzolan-modified portland cement,Type I[PM]	381	497	310	1.09	1.42	0.89
Portland cement_With recycled CKD	381	497	310	1.09	1.42	0.89
Portland cement_User-defined 1	381	497	310	1.09	1.42	0.89
Portland cement_User-defined 2	381	497	310	1.09	1.42	0.89
Portland cement_User-defined 3	381	497	310	1.09	1.42	0.89

Using the average grindability factors estimated with respect to 350 m^2/kg Blaine fineness in

Table 4.42, one can adjust the finish milling and grinding electricity use factors in Table 4.41. By this adjustment, the property of cement fineness is factored in *average* electricity use calculations, in units of kWh per tonne of cement via cement type and user-selected finish milling and grinding technology option:

$$ELECTRICITY_{FINISHGRINDx,CEMENT\_TYPEn} = VLOOKUP(FINISHGRIND_x, [TABLE\ 4.41], COLUMN\#2) \times VLOOKUP(CEMENT_{TYPE_n}, [TABLE\ 4.42], COLUMN\#6) \times M_{PORTLANDCEMENT} \times {}^{1}/_{1{,}000}$$

Equation 4.79: Calculation of average electricity use factor for cement finish milling and grinding based on user-selected technology options

Where:

$ELECTRICITY_{FINISHGRINDx,CEMENT\_TYPEn}$ = Average amount of electricity required for finish milling and grinding of portland cement of type “n” using technology “x”, in kWh;

$FINISHGRIND_x$ = Cement Plant Technology Lookup from User Input Page_ Cement Finish Milling/Grinding/Blending w/Portland Cement, whereas “x” refers to one of the five technology options listed in the first column of Table 4.41;

$CEMENT\_TYPE_n$ = Type of portland cement produced in the plant and is listed in the second column of Table 4.42 under the heading of “Cement Types” and each type is represented by “n”;

[TABLE 4.41], COLUMN#2 = Average electricity use factor for the user-selected cement finish milling and grinding technology “x”, in kWh/tonne of portland cement;

[TABLE 4.42], COLUMN#6 = Average grindability factor estimated for portland cement type “n” with respect to a Blaine fineness of 350 kg/m^2, unitless;

$M_{PORTLANDCEMENT}$ = Total mass of portland cement, in kg.

A small amount of water can be consumed when tube mill or vertical roller mill is used in the finish milling and grinding process. Table 4.43 summarizes water consumption factors associated with these two technology options.

Table 4.43: GreenConcrete Cement_ Finish Milling and Grinding – Water Consumption Factors for Milling and Grinding Technology Options

Cement Finish Milling and Grinding	**Water Consumption (m^3/tonne Clinker)**			
Technology Options	**Average**	**Max**	**Min**	**Source**
Tube Mill	0.02	0.04	0.00	[38, 40, 48, 205, 211, 277]
Vertical Roller Mill	0.01	0.02	0.00	
Ball Mill	0.00	0.00	0.00	
Roller Press	0.00	0.00	0.00	
Horizontal Roller Mill (Horomill)	0.00	0.00	0.00	

Based on Table 4.43, the following equation is developed:

$$WATER_{FINISHGRINDx} = VLOOKUP(FINISHGRIND_X, [TABLE\ 4.43], COLUMN\#2) \times M_{CLINKER} \times {}^{1}/_{1,000}$$

Equation 4.80: Calculation of average water consumption factor for finish milling and grinding processes at cement plant

Where:

$WATER_{FINISHGRINDx}$ = Total mass of water consumed during cement finish milling and grinding for the user-selected technology "x", in m^3;

$FINISHGRIND_x$ = Cement Plant Technology Lookup from User Input Page_ Cement Finish Milling/Grinding/Blending w/Portland Cement, whereas "x" refers to one of the five technology options listed in the first column of Table 4.41;

[TABLE 4.43], COLUMN#2 = Average water consumption factor, from column#2 in Table 4.43, in m^3/tonne of clinker;

$M_{CLINKER}$ = Total mass of clinker, calculated in Equation 4.71, in kg;

1/1,000 = Unit conversion factor (1 tonne = 1,000 kg);

The VLOOKUP Excel function returns the water consumption factor that is corresponding to the user-selected technology option in column#2 of Table 4.43.

Associated LCI input and output results calculated in equations provided in parentheses below are summarized in Table 4.44:

Table 4.44: GreenConcrete Cement_ Finish Milling and Grinding – LCI Calculations

Technology Lookup from User Input Page	***Cement Type – User Input (Selected from drop-down list)***			**Units**
Inputs	**Average**	**Max/Min**	**Min/Max**	
Electricity (see Equation 4.79)	Calculated	Calculated	Calculated	kWh
Clinker (see Equation 4.71)	Calculated	Calculated	Calculated	kg
Gypsum (see Equation 4.73)	Calculated	Calculated	Calculated	kg
Cement Kiln Dust (CKD) (see Equation 4.74)	Calculated	Calculated	Calculated	kg
Fly ash (FA) (see Equation 4.75)	Calculated	Calculated	Calculated	kg
Granulated Blast Furnace Slag (GBFS) (see Equation 4.76)	Calculated	Calculated	Calculated	kg
Water	Calculated	Calculated	Calculated	m^3
Portland Cement (Type I, II, III, V) (see Equation 4.77)	Calculated	Calculated	Calculated	kg
Outputs	**Average**	**Max/Min**	**Min/Max**	
Cement (Blended or PC)	Calculated	Calculated	Calculated	kg

As a final point, LCI factors are calculated by the multiplication of electricity use factors in "Reference Data Pool" worksheet with the finish milling and grinding electricity use inventories to estimate total impacts from this process Similar to other cement production processes, associated LCI are summarized in "Results" tab. For an LCI factor "k" in a location "j", which is the location of the cement plant, is prescribed as follows, whereas "k" can be energy use, water consumption, solid waste or an air emission:

$$FINISHGRIND_{LCI\ ELECTRIC j,k} = ELECTRICITY_{FINISHGRIND} \times HLOOKUP\left(LOCATION_j, TRANSPOSE\ [TABLE\ 9.9], ROW\#_{LCIF\ j,k}\right)$$

Equation 4.81: Calculation of LCI related to total electricity use during cement finish milling and grinding

Where:

$FINISHGRIND_{LCI\_ELECTRICj,k}$ = Total life-cycle inventory associated with electricity use during cement finish milling and grinding, in MJ for "k" energy use factor or in kg for life-cycle inventory factors corresponding to solid waste, water consumption, and air emissions;

$ELECTRICITY_{FINISHGRIND}$ = Total amount of electricity used during cement finish milling and grinding (calculated in Equation 4.79), in kWh;

$LOCATION_j$ = Location of the cement plant "j", taken from "User Input Page_Quarry/Plant Location, Grid Mix, and Water Supply Input" and can be a State, United States, or user-defined location, unitless;

[TABLE 9.9], $ROW\#_{LCIFj,k}$ = Appendix, Table 9.9 with calculated total LCI data for electricity grid mix (per kWh of electricity) for location "j"; each row representing a life-cycle inventory "k", in MJ/kWh for energy use factor or in kg/kWh for other LCI factors listed in the Table.

Since electricity use is the only source of emissions, the total LCI for this stage is the result from Equation 4.81.

While cement production processes take place, raw materials and products are conveyed within the plant from one point to another. Conveying involves: 1) Raw materials to mill processing and blending silos; 2) Raw feed to the kiln; 3) Clinker from clinker cooling to the finish milling (or to the storage area); and 4) Cement product from finish mill to the silos. During the last stage, cement is stored in bulk or in packages ready-to-be shipped to concrete plants for future use [35]. The following section focuses on the process of conveying within a cement plant.

4.10.4 Cement Plant Conveying Worksheet

There are two types of conveying equipment used in cement plants: mechanical conveyors and pneumatic conveyors. Mechanical conveyors include: belt conveyors, screw conveyors, and belt bucket elevators. Pneumatic ones are: air gravity conveying, pipeline conveying, rotary feeder systems, screw pump systems, pressure tank systems, and airlift systems. While conveying, particulate emissions can be of major concern in addition to emissions associated with electricity power consumption [271].

Table 4.45: GreenConcrete _ Cement Conveying – Electricity Use Factors for User-Selected Technology Options

Conveyor technology	**Screw pump**	**Airlift**	**Dense phase pump**	**Bucket elevator**
Conveying electricity use factor (kWh/kg.m)	1.20E-06	1.10E-05	5.90E-06	4.10E-06

Conveying LCI calculations involve the estimation of electricity use which requires data for type of conveyance technology; distance and mass of material/product conveyed within the system (see Table 4.13). The technology is user-selected from a drop-down list of four options listed in Table 4.45, while distance is entered as user input on the User Input page under section "Conveying (within Cement Plant) Technology Options". Mass of material/product conveyed is calculated in various cement production process tabs and involve raw meal, ground meal, blended meal (Equation 4.36), clinker, cooled clinker (Equation 4.71), and blended/traditional Portland cement (Equation 4.77, Equation 4.78). The sumproduct of electricity use factors from Table 4.45 with the total mass of materials and conveyance distances (m) summarized in Table 4.13 provide the associated electricity use for conveying:

$$\begin{aligned}&ELECTRICITY_{CONVEYING}\\&=\sum_{i,Y}^{n} ELECTRIC_{CONVEY\_Y}\times[VLOOKUP(CONVEYING_{Y},[TABLE\ 4.13],COLUMN\#2_{DISTANCEi})\\&\qquad\qquad\times VLOOKUP(CONVEYING_{Y},[TABLE\ 4.13],COLUMN\#4_{MASSi})]\end{aligned}$$

Equation 4.82: Calculation of average electricity use factor for cement plant conveying based on user-selected conveying technology options

Where:

$ELECTRICITY_{CONVEYING}$ = Total electricity required for conveying cement material "i", in kWh;

$ELECTRIC_{CONVEY\_Y}$ = Conveying electricity use factor for user-selected technology option "$_{Y}$" from Table 4.45, in kWh/kg.m;

$CONVEYING_{Y}$ = Cement Plant Technology Lookup from User Input Page_ Conveying Technology Options, whereas "$_{Y}$" refers to one of the four technology options listed in Table 4.45;

[TABLE 4.13], $COLUMN\#2_{DISTANCEi}$ = Distance for conveying material/product "i" within the cement plant, in m;

[TABLE 4.13], $COLUMN\#4_{MASSi}$ = Mass of cement material/product "i" conveyed within the cement plant, in kg;

MATERIAL "i"= "i" refers to any of the six materials/products conveyed with the cement plant from one process point to other.

Since electricity use is the only source of emissions, total LCI associated with the electricity use to power the conveying system is calculated using an Excel HLOOKUP function considering the location of the cement plant for electricity grid mix selection, as follows:

$$\begin{aligned}&CONVEYING_{LCI\ ELECTRIC\,j,k} =\\&ELECTRICITY_{CONVEYING}\times HLOOKUP\left(LOCATION_{j},TRANSPOSE\ [TABLE\ 9.9],ROW\#_{LCIF\,j,k}\right)\end{aligned}$$

Equation 4.83: Calculation of LCI related to total electricity use during conveying within the cement plant

Where:

$CONVEYING_{LCI\_ELECTRICj,k}$ = Total life-cycle inventory associated with electricity use during conveying within the cement plant, in MJ for "k" energy use factor or in kg for life-cycle inventory factors corresponding to solid waste, water consumption, and air emissions;

$ELECTRICITY_{CONVEYING}$ = Total amount of electricity used during conveying (calculated in Equation 4.82), in kWh;

$LOCATION_j$ = Location of the cement plant "j", taken from "User Input Page_Quarry/Plant Location, Grid Mix, and Water Supply Input" and can be a State, United States, or user-defined location, unitless;

[TABLE 9.9], $ROW\#_{LCIFj,k}$ = Appendix, Table 9.9 with calculated total LCI data for electricity grid mix (per kWh of electricity) for location "j"; each row representing a life-cycle inventory "k", in MJ/kWh for energy use factor or in kg/kWh for other LCI factors listed in the Table.

The cement production ends when the final product is conveyed from finish mill to the silos. During the last stage of cement production, cement is stored in bulk or in packages ready-to-be shipped to the concrete plants for future use. LCI factors associated with gypsum production and SCM processing (limited to fly ash and slag) are calculated in separate worksheets and results are added to cement production afterwards. It is important to note that gypsum is added to clinker during finish grinding and milling while SCMs are assumed to be blended with portland cement after finish milling and grinding stage. In addition to their use in blended cements, SCMs are mixed with other concrete materials at concrete batch plants. In either option, SCMs are assumed to be processed or prepared prior to mixing with other materials.

The following sections describe gypsum and SCMs used in cement and concrete.

4.10.5 Gypsum Production Worksheet

Calcium sulphate in the form of gypsum ($CaSO_4*2H_2O$) or anhydrite ($CaSO_4$) is an auxiliary component of portland cements and used to control setting. As previously mentioned, it constitutes about 5 percent by mass of cement.

Following its extraction from quarries or underground mines, gypsum is crushed and stockpiled near a plant. As needed, the stockpiled ore is further crushed and screened to about 50 millimeters in diameter. If the moisture content of the mined ore is greater than about 0.5% by mass, the ore must be dried in a rotary dryer or a heated roller mill. Gypsum dried in a rotary dryer is conveyed to a roller mill, where it is ground to the extent that 90% of it is less than 149 micrometers. The ground gypsum exits the mill in a gas stream and is collected in a product cyclone. While electricity is used in crushing and milling dominantly, other processes that involve dryers, heated roller mills, impact mills, calciners as well as equipment for extraction of gypsum ore use mostly distillate fuel oil [278]. Based on NREL and EcoInvent databases [70], Table 4.46 is prepared:

Table 4.46: GreenConcrete_Gypsum Production - input and output data for LCI calculations

Input	**Unit**	**per kg of gypsum**	**Source**
Diesel (distillate) fuel oil	l	4.67E-04	[219]
Electricity	kWh	9.16E-04	[70]
Process-related PM_{10}	kg	1.12E-04	[70]
Output	**Average**	**Min**	**Max**
Total amount of gypsum (kg) (see Equation 4.73)	Calculated	Calculated	Calculated

Gypsum production LCI calculations involve electricity use as well as fuel combustion and pre-combustion impacts in a similar approach carried out in cement raw material quarrying equations:

$$\boxed{ELECTRICITY_{GYPSUM} = ELECTRIC_{FACTOR\_GYPSUM} \times M_{GYPSUM}}$$

Equation 4.84: Calculation of electricity use for gypsum production

Where:

$ELECTRICITY_{GYPSUM}$ = Total amount of electricity used for gypsum production, in kWh;

$ELECTRIC_{FACTOR\_GYPSUM}$ = Electricity use factor obtained from row #3 of Table 4.46, in kWh/kg of gypsum;

M_{GYPSUM} = Total mass of gypsum, calculated in Equation 4.73, in kg.

$$\boxed{FUEL_{GYPSUM} = FUEL_{FACTOR\_GYPSUM} \times M_{GYPSUM}}$$

Equation 4.85: Calculation of fuel use (diesel) for gypsum production

Where:

$FUEL_{GYPSUM}$ = Total volume of diesel used in gypsum production, in l;

$FUEL_{FACTOR\_GYPSUM}$ = Fuel use factor obtained from row #2 of Table 4.46, in liter per kg of gypsum;

M_{GYPSUM} = Total mass of gypsum, calculated in Equation 4.73, in kg.

Additionally, process-related PM_{10} emission is estimated based on EcoInvent database [70]. An emission factor of 0.000112 kg of PM per kg of gypsum is provided. Accordingly, a generalized equation for calculating the process-related emission "k" is developed as follows:

$$\boxed{GYPSUM_{PROCESSk} = PROCESS_{GYPSUM\_EFk} \times M_{GYPSUM}}$$

Equation 4.86: Calculation of mass of process-related emission "k" for gypsum production

Where:

$GYPSUM_{PROCESSk}$ = Total mass of emission "k", that is PM_{10}, associated with gypsum production, in kg;

$\text{PROCESS}_{\text{GYPSUM\_EFk}}$ = Process-related emission factor “k” based on literature, kg per kg of gypsum;

M_{GYPSUM} = Total mass of gypsum, calculated in Equation 4.73, in kg.

Gypsum production LCI associated with electricity use and fuel use are calculated based on the electricity use and fuel requirements estimated in Equations 4.84 and 4.85 simultaneously with LCI factors developed for Electricity Grid Data, Pre-combustion and Combustion Fuel Data worksheets in GreenConcrete LCA tool. Similar to cement production process LCIs, a life-cycle inventory “k” from gypsum production in a location “j” is calculated below, whereas “k” can be energy use, water consumption, solid waste or an air emission from electricity use, fuel use, and production process:

$$GYPSUM_{LCI_{ELECTRIC\,j,k}} = ELECTRICITY_{GYPSUM} \times HLOOKUP\left(LOCATION_j, TRANSPOSE\ [TABLE\ 9.9], ROW\#_{LCIF\,j,k}\right)$$

Equation 4.87: Calculation of LCI related to electricity use during gypsum production

Where:

$\text{GYPSUM}_{\text{LCI\_ELECTRICj,k}}$ = Total life-cycle inventory associated with electricity use during gypsum production, whereas “j” corresponds to the gypsum quarry/plant location; in MJ for “k” energy use factor or in kg for life-cycle inventories corresponding to solid waste, water consumption, and air emissions;

$\text{ELECTRICITY}_{\text{GYPSUM}}$ = Total amount of electricity used in gypsum production (calculated in Equation 4.84), in kWh;

$\text{LOCATION}_{\text{j}}$ = Location of the gypsum quarry and processing plant “j”, taken from “User Input Page_Quarry/Plant Location, Grid Mix, and Water Supply Input” section and can be State, United States, or user-defined, unitless;

[TABLE 9.9], $\text{ROW\#}_{\text{LCIFj,k}}$ = Appendix A, Table 9.9 with calculated total LCI for electricity grid mix (per kWh of electricity) for location “j”; each row representing a life-cycle inventory “k”, in MJ/kWh for energy use factor or in kg/kWh for other LCI factors listed in the Table.

Following electricity use impacts, pre-combustion and combustion-related LCI factor “k” associated with the use of diesel (distillate) fuel oil during gypsum production is estimated as follows:

$$GYPSUM_{LCI\_PRECOMBUSTk} = FUEL_{GYPSUM} \times PRECOMBUST_{LCI\_DIESEL,k}$$

Equation 4.88: Calculation of LCI related to pre-combustion fuel during gypsum production

$$GYPSUM_{LCI\_COMBUSTk} = FUEL_{GYPSUM} \times COMBUST_{LCI\_DIESEL,k}$$

Equation 4.89: Calculation of LCI related to fuel combustion during gypsum production

Where:

$GYPSUM_{LCI\_PRECOMBUSTk}$ = Total LCI associated with pre-combustion impacts of diesel (distillate fuel oil) use in gypsum production, in MJ for “k” energy use factor or in kg for life-cycle inventories of solid waste, water consumption, and air emissions;

$GYPSUM_{LCI\_COMBUSTk}$ = Total LCI associated with combustion impacts of diesel (distillate fuel oil) use in gypsum production in MJ for “k” energy use factor or in kg for life-cycle inventories of solid waste, water consumption, and air emissions;

$FUEL_{GYPSUM}$ = Total volume of diesel used in gypsum production, in l;

$PRECOMBUST_{LCI\_DIESEL,k}$ = Pre-combustion fuel LCI factors calculated in Table 4.15 per unit volume of diesel (distillate fuel oil) with an associated life-cycle inventory factor “k”, in MJ/l for energy use or in kg/ l for other LCI factors listed in the Table.

$COMBUST_{LCI\_DIESEL,k}$ = Fuel combustion LCI factors calculated in Table 4.16 per unit volume of diesel (distillate fuel oil) with an associated life-cycle inventory factor “k”, in MJ/l for energy use or in kg/ l for other LCI factors listed in the Table.

Finally, total LCI is the sum of LCI from electricity use, fuel combustion (including fuel pre-combustion) and process of quarrying/processing of gypsum:

$$\begin{aligned} GYPSUM_{TOTAL\_LCI j,k} \\ = GYPSUM_{PROCESSk} + GYPSUM_{LCI\_ELECTRIC j,k} + GYPSUM_{LCI\_PRECOMBUSTk} \\ + GYPSUM_{LCI\_COMBUSTk} \end{aligned}$$

Equation 4.90: Calculation of total LCI for gypsum production

4.10.6 Supplementary Cementitious Materials (SCM) Preparation Worksheet

Various industrial wastes and byproducts can be utilized as supplementary cementitious materials (known as SCMs) in cement production. Cements with SCMs (also known as blended cements) are frequently used in Europe, but not in North America, where generally, SCMs are directly added to concrete. The use of fly ash, natural pozzolans, and slag are common in blended cements. They offer economical, environmental, and durability advantages to the manufacturers including: reduced fuel consumption and CO_2 emissions per tonne of cement; reduced landfill costs; and improvement in durability due to control of silica-alkali reaction, improved workability, and replacement of $Ca(OH)_2$ with additional C-S-H and so on [279].

The “SCM Preparation” worksheet provides data for the estimation of the LCI factors for blended cements and concrete mixes with SCM selections.

4.10.6.1Fly Ash Processing

Fly ash is made of unburnt particulates (mainly siliceous components) that are released in exhaust gas when coal is burnt in power plants to produce electricity.

ASTM [276] classifies fly ash in two categories: Class F and Class C. The combustion of bituminous and anthracite coals (except in fluidized bed combustion) usually produces Class F, a pozzolanic ash containing silica, aluminum, and high levels of iron. Pozzolanic materials produce cement when mixed with water. The combustion of sub-bituminous and lignite coals generally produces Class C, a pozzolanic and cementitious ash high in calcium or lime. The most common and economical use for Class C fly ash is as partial replacement for portland cement in concrete manufacturing (normally up to 30%, but can be as high as 50% in some applications). Environmental benefits of using fly ash in portland cement are remarkable. It is estimated that using one metric ton of fly ash can result in one metric ton of reduction in CO_2 emissions from cement production [280]. However, there are some challenges in using fly ash as SCM, which is mostly because of regulations. The Clean Air Act of 1990 requires power plants to reduce nitrogen oxide (NO_x) emissions, which complicates fly ash use in ready-mix concrete plants, the largest market for fly ash. Restriction of oxygen for NO_x reduction in power plants results in fly ash with unburned carbon in it. This type of fly ash is unsuitable for use in concrete unless it is reprocessed or counteracted. Using catalytic process, which is another method to reduce NO_x emissions, can leave residual ammonia on fly ash. Though ammonia does not have a detrimental effect on the performance of fly ash in concrete, ammonia fumes from concrete mix can be intolerable under certain working conditions.

Heavy metals (mostly mercury) found in fly ash is another concern. In their studies, Babbitt and Lindner [281-283] demonstrate that beneficial use of coal combustion products (CCPs, including fly ash) result in small reductions in metal emissions to land and water but these reductions are not significant compared to total emissions produced by CCPs. This concern exists primarily in CCP applications where they are applied directly to land without any modification, as in the case of soil amendment and road construction. However, *when used in concrete, heavy metals in fly ash are bound in a cementitious matrix and are very stable. Therefore, leaching of these constituents in concrete applications is negligible* [284].

In the tool, related LCI are calculated for fly ash in blended cements and fly ash mixed in concrete separately using the data summarized in Table 4.47. According to EPA, process energy requirements and non-energy emissions associated with fly ash are zero based on the assumption that fly ash has low-carbon content (less than 3-4%) with little or no requirement for processing. But currently, fly ash from power plants with new NO_x emission control technology has high carbon content (5-9%) and requires processing before used as SCM.

Following equations calculate the LCI required for drying and treatment processes taking place during fly ash preparation prior to its use.

Table 4.47: GreenConcrete_SCM Preparation - Fly ash processing input and output data for LCI calculations, adapted from [44]

Input	**unit**	**per tonne of fly ash**
Natural gas	m^3	7.59E+00
Distillate (Diesel or Light) fuel oil	l	1.03E+00
Electricity	kWh	6.82E+00
Output		
PM, total	kg	3.23E-02
Solid waste	kg	8.48E-02
Fly ash in concrete or in cement	tonnes	Calculated based on the user input

Total mass of fly ash in blended cements is calculated in Equation 4.75 as "M_{FA_CEMENT}". Fly ash in concrete mix is obtained from the total amount cell under "User Input Page_Material

Quantities_Fly Ash" and demonstrated as "$M_{FA\_CONCRETE}$". In the calculations, "M_{FA} represents either of "M_{FA_CEMENT}" or "$M_{FA\_CONCRETE}$" as a similar approach is applied.

Associated electricity use, pre-combustion and combustion LCI for fly ash preparation are calculated as follows:

$$ELECTRICITY_{FA} = ELECTRIC_{FACTOR\_FA} \times M_{FA} \times 1/1{,}000$$

Equation 4.91: Calculation of electricity use for fly ash preparation

Where:

$ELECTRICITY_{FA}$ = Total amount of electricity used in fly ash preparation, in kWh;

$ELECTRIC_{FACTOR\_FA}$ = Electricity use factor obtained from row #4 of Table 4.47, in kWh/tonne of fly ash;

M_{FA}= Total mass of fly ash, as "M_{FA_CEMENT}" calculated in Equation 4.75 or "$M_{FA\_CONCRETE}$" from User Input page, in kg;

1/1,000 = Unit conversion factor (1 tonne = 1,000 kg).

$$FUEL_{FAi} = FUEL_{FACTOR\_FAi} \times M_{FA}$$

Equation 4.92: Calculation of amount fuel use in fly ash preparation

Where:

$FUEL_{FAi}$ = Total amount of fossil fuel "i" used in fly ash preparation, in l or m^3 of fuel based on fuel type;

$FUEL_{FACTOR\_FAi}$ = Fuel use factor obtained from column#3, rows #2 through #3, Table 4.47, in l or m^3 of fossil fuel "i" per tonne of fly ash;

M_{FA}= Total mass of fly ash, as "M_{FA_CEMENT}" calculated in Equation 4.75 or "$M_{FA\_CONCRETE}$" from User Input page, in kg;

"i" = Type of fossil fuel used in fly ash preparation, mostly for drying process and can be natural gas or distillate (diesel) fuel oil;

1/1,000 = Unit conversion factor (1 tonne = 1,000 kg).

Process PM_{10} emission and solid waste factors from drying and treatment are 0.0323 kg and 0.0848 kg per tonne of fly ash, respectively. A generalized equation for process-related emission "k" can be developed as follows:

$$FLYASH_{PROCESSk} = PROCESS_{FA\_EFk} \times M_{FA}$$

Equation 4.93: Calculation of mass of process-related emission "k" for fly ash preparation

Where:

$FLYASH_{PROCESSk}$ = Total mass of process-related emission "k", either PM_{10} or solid waste, associated with fly ash preparation, in kg;

$PROCESS_{FA\_EFk}$ = Process-related emission factor “k” based on literature, kg per kg of fly ash;

M_{FA}= Total mass of fly ash, as “M_{FA_CEMENT}” calculated in Equation 4.75 or “$M_{FA\_CONCRETE}$” from User Input page, in kg;

Fly ash preparation LCI associated with electricity use and fuel use are calculated using the results from Equations 4.92 and 4.93, simultaneously, with the LCI factors developed for Electricity Grid Data, Pre-combustion and Combustion Fuel Data worksheets in GreenConcrete LCA tool. Similar to prior total LCI estimations, a life-cycle inventory “k” from fly ash preparation in a location “j” is calculated below, whereas “k” can be energy use, water consumption, solid waste or an air emission:

$$FLYASH_{LCI_{ELECTRIC\,j,k}} = ELECTRICITY_{FA} \times HLOOKUP\left(LOCATION_j, TRANSPOSE\ [TABLE\ 9.9], ROW\#_{LCIF\,j,k}\right)$$

Equation 4.94: Calculation of LCI related to electricity use during fly ash preparation

Where:

$FLYASH_{LCI\_ELECTRICj,k}$ = Total life-cycle inventory associated with electricity use during fly ash preparation, whereas “j” corresponds to the location where the process takes place; in MJ for “k” energy use factor or in kg for life-cycle inventories corresponding to solid waste, water consumption, and air emissions;

$ELECTRICITY_{FA}$ = Total amount of electricity used in fly ash preparation (calculated in Equation 4.91), in kWh;

$LOCATION_j$ = Location of the fly ash processing plant “j”, taken from “User Input Page_Quarry/Plant Location, Grid Mix, and Water Supply Input” section and can be State, United States, or user-defined, unitless;

[TABLE 9.9], $ROW\#_{LCIFj,k}$ = Appendix A, Table 9.9 with calculated total LCI for electricity grid mix (per kWh of electricity) for location “j”; each row representing a life-cycle inventory “k”, in MJ/kWh for energy use factor or in kg/kWh for other LCI factors listed in the Table.

Subsequently, pre-combustion and combustion-related LCI factor “k” for the amount of fossil fuel used in fly ash preparation is estimated by means of SUMPRODUCT function in the designated Excel worksheet as follows:

$$FLYASH_{LCI\_PRECOMBUSTk} = \sum_{i,k}^{n}\left[FUEL_{FAi} \times PRECOMBUST_{LCIi,k}\right]$$

Equation 4.95: Calculation of LCI related to pre-combustion fuel use during fly ash preparation

$$FLYASH_{LCI\ COMBUSTk} = \sum_{i,k}^{n} \left[FUEL_{FAi} \times COMBUST_{LCI\_i,k}\right]$$

Equation 4.96: Calculation of LCI related to fuel combustion during fly ash preparation

Where:

$FLYASH_{LCI\_PRECOMBUSTk}$ = Total LCI associated with pre-combustion impacts of fuel “i” e.g., diesel (distillate) fuel oil or natural gas, used in fly ash preparation, in MJ for “k” energy use factor or in kg for life-cycle inventories of solid waste, water consumption, and air emissions;

$FLYASH_{LCI\_COMBUSTi,k}$ = Total LCI associated with combustion impacts of fuel “i” e.g., diesel (distillate) fuel oil or natural gas, used in fly ash preparation in MJ for “k” energy use factor or in kg for life-cycle inventories of solid waste, water consumption, and air emissions;

$FUEL_{FAi}$ = Total volume of fuel used in fly ash preparation, calculated in Equation 4.92, in l or m^3 of fossil fuel “i;

$PRECOMBUST_{LCIi,k}$ = Pre-combustion fuel LCI factors calculated in Table 4.15 per unit volume of fossil fuel with an associated life-cycle inventory factor “k”, in MJ/l, MJ/m^3 for energy use or in kg/ l, kg/m^3 for other LCI factors listed in the Table.

$COMBUST_{LCIi,k}$ = Fuel combustion LCI factors calculated in Table 4.16 per unit volume of diesel (distillate) fuel oil or natural gas with an associated life-cycle inventory factor “k”, in MJ/l, MJ/m^3 for energy use or in kg/ l, kg/m^3 for other LCI factors listed in the Table.

To end with the fly ash preparation process, total LCI is estimated as the sum of calculated LCIs related to electricity use, fuel combustion (including fuel pre-combustion) and process of itself:

$$\begin{aligned} FLYASH_{TOTAL\_LCIj,k} &\\ = FLYASH_{PROCESSk} + FLYASH_{LCI\_ELECTRICj,k} + FLYASH_{LCI\_PRECOMBUSTk} &\\ + FLYASH_{LCI\_COMBUSTk} & \end{aligned}$$

Equation 4.97: Calculation of total LCI for fly ash preparation

Difference between C and F type not reflected in calculations: however can be considered in allocation scenarios.

4.10.6.2 Granulated Blast Furnace Slag (GBFS) Processing

GBFS is a by-product of blast furnace iron production and its properties vary with the cooling method (water or air) applied. Granulated slag is rapidly cooled by large quantities of water to produce a sand-like granule that is primarily ground into cement commonly known as ground granulated blast furnace slag cement, Type S. Air-cooled blast furnace slag that is processed through a screening and crushing plant is generally used as non-cementitious light-weight aggregate. However, energy use and CO_2 benefits of air-cooled slag are limited compared to GBFS type. Air-cooled slag is more common in the United States [279, 285].

There are various differences in fly ash and GBFS use as SCM. The rate of utilization of slag is usually much higher than that of fly ash due to the uniformity of slag from a specified source and can be used without excessive grinding [279]. Slag cement can also substitute 25 to 80 percent (by mass) of portland cement. Especially, mass concrete structures, such as dams, are allowed to utilize 65 to 80 percent slag cement to decrease heat generation. This limit is up to 50 percent for paving and structural concrete [59].

LCA for GBFS preparation consist of processes of quenching and granulation, dewatering and/or drying, grinding, and storage in addition to transportation of slag from iron and steel plant to the cement plant and/or to concrete plant. During preparation stage, major LCI inputs include consumption of pressurized water, electricity, and fuel. Table 4.48 illustrates raw data adapted from Chen et al. [43] and data from Table 4.49 is used in LCI calculations within the tool.

Table 4.48: GreenConcrete_SCM Preparation - GBFS processing raw input and output data [43]

Processes and inputs/ outputs	**unit**	**per tonne of slag**
Quenching		
Water for quenching	m^3	7.68E-01
Electricity for water pumps	kWh	1.16E+01
PM from process	kg	7.40E-02
Dewatering and/or drying		
Natural gas	m^3	8.24E+00
Distillate (Diesel or Light) oil	l	1.14E+00
Electricity	kWh	6.34E+00
PM from process	kg	9.30E-03
Crushing		
Electricity	kWh	5.58E-02
Grinding		
Water	m^3	5.80E-02
Distillate (Diesel or Light) oil	l	1.21E-01
Natural gas	m^3	7.24E-01
Electricity	kWh	7.32E+01
Solid waste	kg	3.09E-02
PM from process	kg	1.08E-01
Storage piles		
PM from process	kg	4.46E-03
Storage silos		
Water	m^3	9.35E-02
Electricity	kWh	3.49E+00
PM from process	kg	2.40E-02

Table 4.49: GreenConcrete_SCM Preparation – Total GBFS processing input and output data used in LCI calculations

Input	**unit**	**per tonne of slag**

Natural gas, total	m^3	8.96E+00
Distillate (Diesel or Light) oil, total	l	1.26E+00
Electricity, total	kWh	9.47E+01
Water, total	m^3	9.19E-01
Output		
PM, process	kg	2.19E-01
Solid waste, total	kg	3.09E-02
GBFS in concrete or in cement	kg	Calculated

Total mass of GBFS in blended cements is calculated with Equation 4.76 as “M_{GBFS_CEMENT}”. If mixed in concrete, GBFS’s mass is obtained from the “User Input Page_Material Quantities_ Granulated Blast Furnace Slag” and demonstrated as “$M_{GBFS\_CONCRETE}$”. In the calculations, “M_{GBFS} represents either of “M_{GBFS_CEMENT}” or “$M_{GBFS\_CONCRETE}$” as a similar approach is applied.

Electricity use, pre-combustion and combustion LCI associated with GBFS preparation is calculated with following Equations (Equation 4.98 – Equation 4.104):

$$ELECTRICITY_{GBFS} = ELECTRIC_{FACTOR\_GBFS} \times M_{GBFS} \times 1/1{,}000$$

Equation 4.98: Calculation of electricity use for GBFS preparation and treatment

Where:

$ELECTRICITY_{GBFS}$ = Total amount of electricity used in GBFS preparation, in kWh;

$ELECTRIC_{FACTOR\_GBFS}$ = Electricity use factor obtained from column#3, row #4 of Table 4.49, in kWh/tonne of slag;

M_{GBFS}= Total mass of GBFS, as “M_{GBFS_CEMENT}” calculated in Equation 4.76 or “$M_{GBFS\_CONCRETE}$” from User Input page, in kg;

1/1,000 = Unit conversion factor (1 tonne = 1,000 kg).

$$FUEL_{GBFSi} = FUEL_{FACTOR\_GBFSi} \times M_{GBFS}$$

Equation 4.99: Calculation of amount fuel use in GBFS preparation

Where:

$FUEL_{GBFSi}$ = Total amount of fossil fuel “i” used in GBFS preparation, in l or m^3 of fuel depending on the fuel type selected;

$FUEL_{FACTOR\_GBFSi}$ = Fuel use factor obtained from column#3, rows #2 through #3, Table 4.49, in l or m^3 of fossil fuel “i” per tonne of GBFS;

M_{GBFS}= Total mass of GBFS, as “M_{GBFS_CEMENT}” calculated in Equation 4.76 or “$M_{GBFS\_CONCRETE}$” from User Input page, in kg;

“i” = Type of fossil fuel used in GBFS preparation (for dewatering, drying, and grinding processes) and can be natural gas or distillate (diesel) fuel oil based on the process type;

1/1,000 = Unit conversion factor (1 tonne = 1,000 kg).

Total process-related PM_{10} emission and solid waste factors are given as 0.219 kg and 0.0309 kg per tonne of GBFS, respectively. A generalized equation for process-related emission "k" can be developed as follows:

$$\boxed{GBFS_{PROCESSk} = PROCESS_{GBFS\_EFk} \times M_{GBFS}}$$

Equation 4.100: Calculation of mass of process-related emission "k" for GBFS preparation

Where:

$GBFS_{PROCESSk}$ = Total mass of process-related emission "k", either PM_{10} or solid waste, associated with GBFS preparation, in kg;

$PROCESS_{GBFS\_EFk}$ = Process-related emission factor "k" based on literature, kg per kg of GBFS;

M_{GBFS}= Total mass of GBFS, as "M_{GBFS_CEMENT}" calculated in Equation 4.76 or "$M_{GBFS\_CONCRETE}$" from User Input page, in kg;

GBFS preparation LCI associated with electricity use and fuel use are calculated using the results from Equations 4.98 and 4.99 simultaneously with LCI factors developed for Electricity Grid Data, Pre-combustion and Combustion Fuel Data worksheets in GreenConcrete LCA tool. Similarly, a life-cycle inventory "k" from GBFS preparation in a location "j" is calculated as following:

$$\boxed{\begin{aligned} &GBFS_{LCI_{ELECTRIC\,j,k}} = \\ &\quad ELECTRICITY_{GBFS} \times HLOOKUP\left(LOCATION_j, TRANSPOSE\ [TABLE\ 9.9], ROW\#_{LCIF\,j,k}\right) \end{aligned}}$$

Equation 4.101: Calculation of LCI related to electricity use during GBFS preparation

Where:

$GBFS_{LCI\_ELECTRICj,k}$ = Total life-cycle inventory associated with electricity use during GBFS preparation, whereas "j" corresponds to the location where the process takes place; in MJ for "k" energy use factor or in kg for life-cycle inventories corresponding to solid waste, water consumption, and air emissions;

$ELECTRICITY_{GBFS}$ = Total amount of electricity used in GBFS preparation (calculated in Equation 4.98), in kWh;

$LOCATION_j$ = Location of the GBFS processing and treatment plant "j", taken from "User Input Page_Quarry/Plant Location, Grid Mix, and Water Supply Input" section and can be State, United States, or user-defined, unitless;

[TABLE 9.9], $ROW\#_{LCIFj,k}$ = Appendix A, Table 9.9 with calculated total LCI for electricity grid mix (per kWh of electricity) for location "j"; each row representing a life-cycle inventory "k", in MJ/kWh for energy use factor or in kg/kWh for other LCI factors listed in the Table.

Subsequently, pre-combustion and combustion-related LCI factor “k” for the amount of fossil fuel used in GBFS preparation processes is estimated by means of SUMPRODUCT function in the designated Excel worksheet as follows:

$$GBFS_{LCI\_PRECOMBUSTk} = \sum_{i,k}^{n} [FUEL_{GBFSi} \times PRECOMBUST_{LCIi,k}]$$

Equation 4.102: Calculation of LCI related to pre-combustion fuel use during GBFS preparation

$$GBFS_{LCI\ COMBUSTk} = \sum_{i,k}^{n} [FUEL_{GBFSi} \times COMBUST_{LCI\_i,k}]$$

Equation 4.103: Calculation of LCI related to fuel combustion during GBFS preparation

Where:

$GBFS_{LCI\_PRECOMBUSTk}$ = Total LCI associated with pre-combustion impacts of fuel “i” e.g., diesel (distillate) fuel oil or natural gas, used in GBFS preparation, in MJ for “k” energy use factor or in kg for life-cycle inventories of solid waste, water consumption, and air emissions;

$GBFS_{LCI\_COMBUSTi,k}$ = Total LCI associated with combustion impacts of fuel “i” e.g., diesel (distillate) fuel oil or natural gas, used in GBFS preparation in MJ for “k” energy use factor or in kg for life-cycle inventories of solid waste, water consumption, and air emissions;

$FUEL_{GBFSi}$ = Total volume of fuel used in GBFS preparation, calculated in Equation 4.99 in l or m^3 of fossil fuel “i;

$PRECOMBUST_{LCIi,k}$ = Pre-combustion fuel LCI factors calculated in Table 4.15 per unit volume of fossil fuel with an associated life-cycle inventory factor “k”, in MJ/l, MJ/m^3 for energy use or in kg/ l, kg/m^3 for other LCI factors listed in the Table.

$COMBUST_{LCIi,k}$ = Fuel combustion LCI factors calculated in Table 4.16 per unit volume of diesel (distillate) fuel oil or natural gas with an associated life-cycle inventory factor “k”, in MJ/l, MJ/m^3 for energy use or in kg/ l, kg/m^3 for other LCI factors listed in the Table.

To end with the GBFS preparation process, total LCI is estimated as the sum of calculated LCIs related to electricity use, fuel combustion (including fuel pre-combustion) and process of itself:

$$GBFS_{TOTAL\_LCIj,k} = GBFS_{PROCESSk} + GBFS_{LCI\_ELECTRICj,k} + GBFS_{LCI\_PRECOMBUSTk} + GBFS_{LCI\_COMBUSTk}$$

Equation 4.104: Calculation of total LCI for GBFS preparation prior to use in blended cements or concrete

4.11 Concrete Production Processes

The Table 4.50 below briefly describes the processes and materials inventoried during the concrete production process.

Table 4.50: Brief description of the Concrete and other than Cement Materials Production "Process and Calculation" Tabs

Process and Calculation Tabs for the Concrete Production (see Table 4.27 for cement production process descriptions)	
Aggregates Production	LCI of quarried raw materials (sand, gravel, stone, etc.), fuels, electricity and water inputs as well as associated air and solid waste emissions from quarrying, crushing, conveying, crushing, and screening processes based on the user input data. Calculations are performed to estimate emissions associated with electricity use, fuel pre-combustion, fuel combustion, and processes taking place in fine and coarse aggregates production.
Admixtures Production	Organizes and inventories materials, fuels, electricity, and water input and associated output data for admixtures. LCI data is performed on the basis of the European Federation of Concrete Admixture Association's Eco-profiles.
Concrete Mixing and Batching	Inventories electricity use and water consumption inputs as well as associated emissions from concrete batching processes. Calculations are performed to estimate emissions from electricity use and process itself based on the user input data for various technology options and two emission control options (ESP and FF).
Calculated Inventory	
	Electricity (in MJ, converted from kWh for ease of comparison to fuel energy consumption values)
	Fuel (in MJ, which is the sum of pre-fuel combustion- and combustion-related impacts)
	Water consumption (in m^3)
	Total solid waste generation (in kg)
	Air emissions (30 air emissions including GHG emissions, criteria air pollutants, major toxic emissions including heavy metals, formaldehyde, etc.)

4.11.1 Coarse and Fine Aggregates Production

Fine aggregates mixed in concrete are mainly sand and gravel which are extracted either by open pit excavation or by dredging. Open pit excavation requires power shovels, draglines, front end loaders, and bucket wheel excavators during the process. Diesel is the major type of fuel used on-site. In rare situations, blasting may be needed to loosen the deposit. Mining by dredging involves removal of sand and gravel from the bottom of water by suction or bucket-type dredges, however this is rare. After mining, materials are transported to the crushing and processing plant by trucks, belt conveyors, or other means.

Most of the sand and gravel used as fine aggregates in concrete are processed prior to use. The processing of sand and gravel involves use of different combinations of washers, screens, and classifiers to segregate particle sizes; crushers to reduce oversized material; as well as storage and loading facilities. After processing, the sand is transported to storage bins or stockpiles by belt conveyors, bucket elevators, or screw conveyors to be further transported to the concrete plant by heavy diesel trucks [286] .

Generally, coarse aggregates are crushed stones which are described in EPA's AP-42 report [287] as: "Major rock types processed by the crushed stone industry include limestone, granite, dolomite, sandstone, quartz, and quartzite." Rock and crushed stone products are mostly loosened by drilling and blasting and are loaded by power shovels or front-end loaders into large hauling trucks that carry the material to the aggregate processing plants. Processing commonly includes crushing, screening, size classification, material handling and storage operations. First, feeders or screens separate large boulders from finer rocks that do not require primary crushing. Jaw, impactor, or gyratory crushers are usually used for initial size reduction. Crushed stones normally which are 7.5 to 30 centimeters in diameter, are discharged onto a belt conveyor and conveyed to a surge pile for temporary storage or are sold as coarse aggregates. Stones from the surge pile are conveyed to a vibrating screen where oversized rocks are separated from smaller stones. The undersized material from the screen is considered to be a part of the product stream and is transported to a storage pile and sold as base material. Stones that are too large to pass through the top deck of the scalping screen are processed in the secondary crusher. Cone crushers are commonly used for secondary crushing (although impact crushers are sometimes used), which typically reduces material to about 2.5 to 10 centimeters in diameter. The material from the second level of the screen bypasses the secondary crusher because it is sufficiently small for the last crushing step. The output from the secondary crusher and the secondary screen are transported by conveyor to the tertiary circuit, which includes a sizing screen and a tertiary crusher. Tertiary crushing is usually performed using cone crushers or other types of impactor crushers. Oversized material from the top deck of the sizing screen is fed to the tertiary crusher. The tertiary crusher output, which is typically about 0.50 to 2.5 centimeters, is returned to the sizing screen. Various product streams with different size gradations are separated in the screening operation. Products are later conveyed or trucked directly to finished product bins, to open area stock piles, or to other processing systems such as washing, air separators, and screens and classifiers (for the production of manufactured sand). Some stone crushing plants produce manufactured sand. This is a small-sized rock product with a maximum size of 0.50. Crushed stone from the tertiary sizing screen is sized in fines screen with relatively small mesh sizes. Oversized material is processed in a cone crusher or a hammermill (fines crusher) adjusted to produce small diameter material. The output is returned to the fines screen for resizing. In certain cases, washing of stone is required to meet the end product specifications.

In a synopsis; fossil fuel use, mostly in the form of diesel fuel, during on-site excavation, hauling, in addition to off-site transportation is responsible from about 30 percent of the total energy use, which corresponds to 14 MJ/tonne of fine aggregates and 22 MJ/tonne of coarse aggregates based on the type and quantity of fossil fuels used (See GreenConcrete_Aggregates worksheet for calculations). Mechanical crushing is the main process that consumes electricity during coarse aggregates production. On the other hand, fine aggregates are assumed to begin as raw sand, which is quarried by excavators and loaded into haulers. The haulers dump the sand where it is washed and conveyed to the grading plant. Electricity is used for vibrating screens to filter the sand into standard grades, which are then stockpiled. There is no crushing involved in fine aggregates (sand) processing. Based on the calculations in GreenConcrete LCA Excel tool, electricity use constitutes about 70 percent of total energy use, which corresponds to about 35 MJ/tonne of fine aggregates and 45 MJ/tonne of coarse aggregates, respectively. These calculated values coincide with the data from various sources [57, 58].

Figure 4.23 and Table 4.51 summarize major processes and associated inputs in the form of electricity use, fossil fuels, and water consumption for coarse and fine aggregates production.

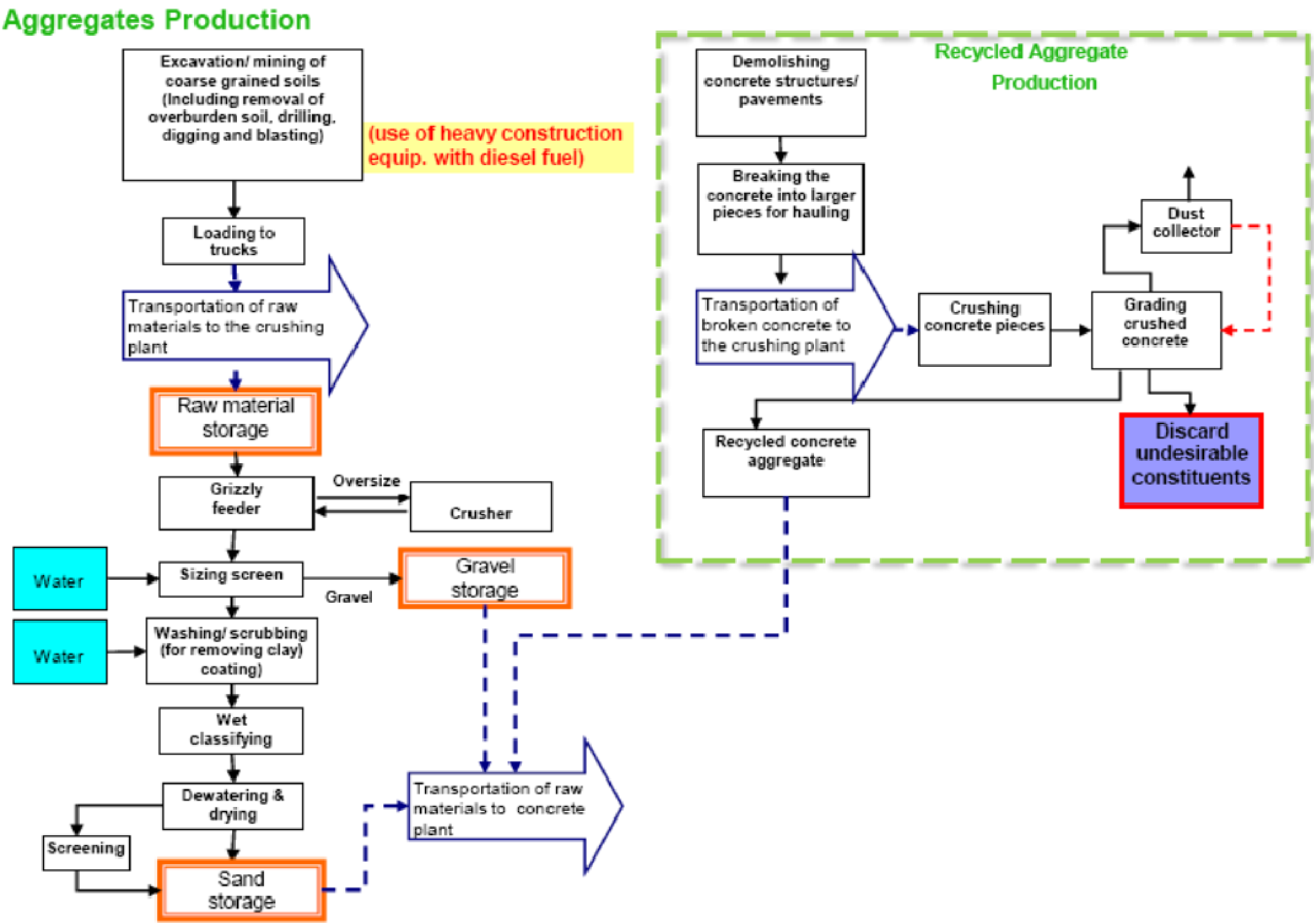


Figure 4.23: Aggregates (including recycled aggregates) production processes

Table 4.51: GreenConcrete_Aggregates Production –Input and output data used in LCI calculations

		Sand and gravel (Fine aggregate)	**Crushed stone (Coarse aggregate)**	**Source**
Input	**Unit**	**per kg of fine aggregate**	**per kg of coarse aggregate**	[58, 288]
Electricity	kWh	2.65E-03	3.42E-03	
Natural gas	m^3	4.15E-11	4.53E-10	
Residual (Heavy) fuel oil	l	5.26E-05	6.05E-05	
Distillate (Diesel or Light) fuel oil	l	2.35E-04	3.89E-04	
Gasoline	l	2.27E-05	3.92E-05	
Water	m^3	1.47E-02	2.23E-03	
Output				
Aggregates	kg	User-input page	User-input page	

Total mass of fine and coarse aggregates in concrete mix is obtained from Equation 4.6 (as "Total Mass of Fine Aggregates", $M_{FINE\_AGGREGATE}$) and Equation 4.7 (as "Total Mass of Coarse Aggregates", $M_{COARSE\_AGGREGATE}$), respectively.

The LCI for electricity use, pre-combustion and combustion of fuels used for the aggregates production is calculated as follows (see from Equation 4.105 to Equation 4.118):

$$\boxed{ELECTRICITY_{FINE\_AGGREGATE} = ELECTRIC_{FACTOR\_FINE} \times M_{FINE\_AGGREGATE}}$$

Equation 4.105: Calculation of electricity use for fine aggregates production

Where:

$ELECTRICITY_{FINE\_AGGREGATE}$ = Total amount of electricity used in fine aggregates production, in kWh;

$ELECTRIC_{FACTOR\_FINE}$ = Electricity use factor obtained from column #3, row #3 of Table 4.51, in kWh/kg of fine aggregate;

$M_{FINE\_AGGREGATE}$= Total mass of fine aggregates, calculated in Equation 4.6 based on user input, in kg.

$$\boxed{\begin{aligned}&ELECTRICITY_{COARSE\_AGGREGATE}\\&\qquad = ELECTRIC_{FACTOR\_COARSE} \times M_{COARSE\_AGGREGATE}\end{aligned}}$$

Equation 4.106: Calculation of electricity use for coarse aggregates production

Where:

$ELECTRICITY_{COARSE\_AGGREGATE}$ = Total amount of electricity used in coarse aggregates production, in kWh;

$ELECTRIC_{FACTOR\_COARSE}$= Electricity use factor obtained from column #4, row #3 of Table 4.51, in kWh/kg of coarse aggregate;

$M_{COARSE\_AGGREGATE}$= Total mass of coarse aggregates, calculated in Equation 4.7 based on user input, in kg.

Quantities of major fossil fuels used on- and off-site activities are calculated by the multiplication of total mass of aggregate and the fossil fuel use factors from Table 4.51:

$$\boxed{FUEL_{FINE\_AGGREGATEi} = FUEL_{FACTOR\_FINEi} \times M_{FINE\_AGGREGATE}}$$

Equation 4.107: Calculation of amount fossil fuel use in fine aggregates production

Where:

$FUEL_{FINE\_AGGREGATEi}$ = Total amount of fossil fuel "i" used in fine aggregate production (including quarrying), in l or m^3 of fuel depending on the fuel type selected;

$FUEL_{FACTOR\_FINEi}$ = Fuel use factor obtained from column#3, rows #4 through #7, Table 4.51, in l or m^3 of fossil fuel "i" per kg of fine aggregate;

$M_{FINE\_AGGREGATE}$= Total mass of fine aggregates, calculated in Equation 4.6 based on user input, in kg;

"i" = Type of fossil fuel used in fine aggregate production and can be natural gas, distillate (diesel) fuel oil, residual (heavy) fuel oil, or gasoline based on the process type.

$$\boxed{FUEL_{COARSE\_AGGREGATEi} = FUEL_{FACTOR\_COARSEi} \times M_{COARSE\_AGGREGATE}}$$

Equation 4.108: Calculation of amount of fossil fuel use in coarse aggregates production

$FUEL_{COARSE\_AGGREGATEi}$ = Total amount of fossil fuel "i" used in coarse aggregate production (including quarrying), in l or m^3 of fuel depending on the fuel type selected;

$FUEL_{FACTOR\_COARSEi}$ = Fuel use factor obtained from column#4, rows #4 through #7, Table 4.51, in l or m^3 of fossil fuel "i" per kg of coarse aggregate;

$M_{COARSE\_AGGREGATE}$= Total mass of coarse aggregates, calculated in Equation 4.7 based on user input, in kg;

"i" = Type of fossil fuel used in fine aggregate production and can be natural gas, distillate (diesel) fuel oil, residual (heavy) fuel oil, or gasoline based on the process type.

Water consumption associated with coarse and fine aggregates quarrying and production is calculated in Equation 4.109 and Equation 4.110:

$$\boxed{WATER_{FINE\_AGGREGATEi} = WATER_{FACTOR\_FINEi} \times M_{FINE\_AGGREGATE}}$$

Equation 4.109: Calculation of water consumption in fine aggregates production

Where:

$WATER_{FINE\_AGGREGATEi}$ = Total volume of water consumption during fine aggregate production (including quarrying), in m^3;

WATER$_{\text{FACTOR\_FINEi}}$ = Water consumption factor obtained from column#3, row #8, Table 4.51, in m^3 of water per kg of fine aggregate;

M$_{\text{FINE\_AGGREGATE}}$= Total mass of fine aggregates, calculated in Equation 4.6 based on user input, in kg.

$$WATER_{COARSE\_AGGREGATEi} = WATER_{FACTOR\_COARSEi} \times M_{COARSE\_AGGREGATE}$$

Equation 4.110: Calculation of water consumption in coarse aggregates production

WATER$_{\text{COARSE\_AGGREGATEi}}$ = Total volume of water consumption during coarse aggregate production (including quarrying), in m^3;

WATER$_{\text{FACTOR\_COARSEi}}$ = Water consumption factor obtained from column#4, row#8, Table 4.51, in l or m^3 of fossil fuel "i" per kg of coarse aggregate;

M$_{\text{COARSE\_AGGREGATE}}$= Total mass of coarse aggregates, calculated in Equation 4.7 based on user input, in kg.

LCI associated with electricity and fuel use during production of fine and coarse aggregates are calculated using the results from Equations through 4.105 to 4.110, simultaneously with LCI factors developed for Electricity Grid Data, Pre-combustion and Combustion Fuel Data worksheets in GreenConcrete LCA tool. Similarly, a life-cycle inventory "k" related to production of fine and coarse aggregates in a location "j" is calculated as following:

$$FINE\_AGGREGATE_{LCI_{ELECTRIC\,j,k}} = \\ ELECTRICITY_{FINE} \times HLOOKUP\left(LOCATION_j, TRANSPOSE\ [TABLE\ 9.9], ROW\#_{LCIF\,j,k}\right)$$

Equation 4.111: Calculation of LCI related to electricity use during fine aggregates production

$$COARSE\_AGGREGATE_{LCI_{ELECTRIC\,j,k}} = \\ ELECTRICITY_{COARSE} \times HLOOKUP\left(LOCATION_j, TRANSPOSE\ [TABLE\ 9.9], ROW\#_{LCIF\,j,k}\right)$$

Equation 4.112: Calculation of LCI related to electricity use during coarse aggregates production

Where:

FINE_AGGREGATE$_{\text{LCI\_ELECTRICj,k}}$ = Total life-cycle inventory associated with electricity use during fine aggregates production, whereas "j" corresponds to the location where the process takes place; in MJ for "k" energy use factor or in kg for life-cycle inventories corresponding to solid waste, water consumption, and air emissions;

COARSE_AGGREGATE$_{\text{LCI\_ELECTRICj,k}}$ = Total life-cycle inventory associated with electricity use during coarse aggregates production, whereas "j" corresponds to the location where the process takes place; in MJ for "k" energy use factor or in kg for life-cycle inventories corresponding to solid waste, water consumption, and air emissions;

ELECTRICITY$_{\text{FINE}}$ = Total amount of electricity used in fine aggregates production (calculated in Equation 4.105), in kWh;

$ELECTRICITY_{COARSE}$ = Total amount of electricity used in coarse aggregates production (calculated in Equation 4.106), in kWh;

$LOCATION_j$ = Location of the fine or coarse aggregates production plant "j", taken from "User Input Page_Quarry/Plant Location, Grid Mix, and Water Supply Input" section and can be State, United States, or user-defined, unitless;

[TABLE 9.9], $ROW\#_{LCIFj,k}$ = Appendix A, Table 9.9 with calculated total LCI for electricity grid mix (per kWh of electricity) for location "j"; each row representing a life-cycle inventory "k", in MJ/kWh for energy use factor or in kg/kWh for other LCI factors listed in the Table.

Subsequently, pre-combustion and combustion-related LCI factor "k" for the amount of fossil fuel used during fine and coarse aggregates production processes is estimated by means of SUMPRODUCT function in the designated Excel worksheet as follows:

$$FINE\_AGGREGATE_{LCI\_PRECOMBUSTk} = \sum_{i,k}^{n} \left[FUEL_{FINE\_AGGREGATEi} \times PRECOMBUST_{LCIi,k}\right]$$

Equation 4.113: Calculation of LCI for pre-combustion fuel use during fine aggregates production

$$FINE\_AGGREGATE_{LCI\ COMBUSTk} = \sum_{i,k}^{n} \left[FUEL_{FINE\_AGGREGATEi} \times COMBUST_{LCI\_i,k}\right]$$

Equation 4.114: Calculation of LCI for fuel combustion during fine aggregates production

$$COARSE\_AGGREGATE_{LCI\ PRECOMBUSTk} = \sum_{i,k}^{n} \left[FUEL_{COARSE\_AGGREGATEi} \times PRECOMBUST_{LCI\_i,k}\right]$$

Equation 4.115: Calculation of LCI for pre-combustion fuel use during coarse aggregates production

$$COARSE\_AGGREGATE_{LCI\ COMBUSTk} = \sum_{i,k}^{n} \left[FUEL_{COARSE\_AGGREGATEi} \times COMBUST_{LCI\_i,k}\right]$$

Equation 4.116: Calculation of LCI for fuel combustion during coarse aggregates production

Where:

$FINE\_AGGREGATE_{LCI\_PRECOMBUSTk}$ = Total LCI associated with pre-combustion impacts of fuel "i", e.g., natural gas, distillate (diesel) fuel oil, residual (heavy) fuel oil, or gasoline, used in fine aggregates production, in *MJ* for "k" energy use factor or in kg for life-cycle inventories of solid waste, water consumption, and air emissions;

$COARSE\_AGGREGATE_{LCI\_PRECOMBUSTk}$ = Total LCI associated with pre-combustion impacts of fuel "i", e.g., natural gas, distillate (diesel) fuel oil, residual (heavy) fuel oil, or gasoline, used in coarse aggregates production, in *MJ* for "k" energy use factor or in *kg* for life-cycle inventories of solid waste, water consumption, and air emissions;

FINE_AGGREGATE$_{LCI\_COMBUSTi,k}$ = Total LCI associated with combustion impacts of fuel “i”, e.g., natural gas, distillate (diesel) fuel oil, residual (heavy) fuel oil, or gasoline, used in fine aggregates production in *MJ* for “k” energy use factor or in *kg* for life-cycle inventories of solid waste, water consumption, and air emissions;

COARSE_AGGREGATE$_{LCI\_COMBUSTi,k}$ = Total LCI associated with combustion impacts of fuel “i”, e.g., natural gas, distillate (diesel) fuel oil, residual (heavy) fuel oil, or gasoline, used in coarse aggregates production in *MJ* for “k” energy use factor or in *kg* for life-cycle inventories of solid waste, water consumption, and air emissions;

FUEL$_{FINE\_AGGREGATEi}$ = Total volume of fossil fuel used in fine aggregates production, calculated in Equation 4.107, in *l* or m^3 of fuel “i;

FUEL$_{COARSE\_AGGREGATEi}$ = Total volume of fossil fuel used in coarse aggregates production, calculated in Equation 4.108, *l* or m^3 of fuel “i;

PRECOMBUST$_{LCIi,k}$ = Pre-combustion fuel LCI factors calculated in Table 4.15 per unit volume of fossil fuel with an associated life-cycle inventory factor “k”, in *MJ/l*, MJ/m^3 for energy use or in *kg/ l*, kg/m^3 for other LCI factors listed in the Table.

COMBUST$_{LCIi,k}$ = Fuel combustion LCI factors calculated in Table 4.16 per unit volume of fossil fuel with an associated life-cycle inventory factor “k”, in *MJ/l*, MJ/m^3 for energy use or in *kg/ l*, kg/m^3 for other LCI factors listed in the Table.

To end with the fine and coarse aggregates production, total LCI is estimated as the sum of calculated LCIs related to electricity use, fuel combustion (including fuel pre-combustion) and process of itself:

$$\begin{aligned} FINE\_AGGREGATE_{TOTAL\_LCI j,k} &= FINE\_AGGREGATE_{PROCESSk} + FINE\_AGGREGATE_{LCI\_ELECTRIC j,k} \\ &+ FINE\_AGGREGATE_{LCI\_PRECOMBUSTk} + FINE\_AGGREGATE_{LCI\_COMBUSTk} \end{aligned}$$

Equation 4.117: Calculation of total LCI for fine aggregates production

$$\begin{aligned} COARSE\_AGGREGATE_{TOTAL\_LCI j,k} &= COARSE\_AGGREGATE_{PROCESSk} + COARSE\_AGGREGATE_{LCI\_ELECTRIC j,k} \\ &+ COARSE\_AGGREGATE_{LCI\_PRECOMBUSTk} + COARSE\_AGGREGATE_{LCI\_COMBUSTk} \end{aligned}$$

Equation 4.118: Calculation of total LCI for coarse aggregates production

4.11.2 Admixtures Production

Producers use admixtures to modify the properties of the concrete, to reduce the cost of concrete construction, to improve the quality of concrete during mixing, transporting, placing, and curing, and to overcome difficult situations, such as hot or cold weather concrete pouring, early strength requirements, very low water cement ratio requirements, pumping requirements, etc. [289]. Five major types of chemical admixtures which are included in the tool are described briefly as follows:

Water-reducing agents (Plasticisers): Various water reducing admixtures under different names, such as, water-proofers, densifiers, and workability aids are commercially available. Water-reducing admixtures are added to concrete to achieve certain workability (slump) at a lower water/cement ratio [290]. They are used to improve the quality of concrete and to obtain specified strength at lower cement content. They also improve the properties of concrete containing marginal- or low-quality aggregates and facilitate in pouring concrete under difficult conditions. Water reducers have been used primarily in bridge decks, low-slump concrete overlays, and patching concrete.

Water-reducing admixtures can be categorized according to their active ingredients, which are: Salts and modifications of hydroxylized carboxylic acids (HC type); salts and modifications of lignosulfonic acids (lignins); and polymeric materials (PS type) [291]. They are dissolved in water and typically contain 30-45% active matter [190].

Superplasticisers: They are a special category of water-reducing agents with complicated chemical structures. Their use allows further water reduction (compared to normal water reducing admixtures) or alternatively much higher workability without undesirable side effects like excessive air entrainment or set retardation. The major purpose of using superplasticizers is to produce flowing concrete with very high slump in the range of 175-225 mm to be used in heavily reinforced structures and in placements where adequate consolidation by vibration cannot be readily achieved. The other major application is the production of high-strength concrete at water to cement ratios ranging from 0.3 to 0.4.

Three major types of raw materials used in superplasticizers are sulfonated naphthalene formaldehyde (SNF), sulfonated melamine formaldehyde (SMF), and polyacrylates. Very small amounts of other materials are often added such as triethanolamine (to counteract retardation), tributyl phosphate (to reduce excessive air entrainment), and hydroxycarboxylic acid salts or lignosulfonates (to increase retardation). Additionally, proprietary superplasticizers can be blends of main ingredients [290, 291]. The superplasticisers are dissolved in water and typically contain 30-45% active matter [190].

Set-retarding agents (Retarders): are known to delay hydration of cement without affecting the long-term mechanical properties. They are used in concrete to offset the effect of high temperatures, which decrease setting times, or to avoid complications when unavoidable delays between mixing and placing occur. One of the most important applications of retarding admixtures is hot-weather concrete placements, when delays between mixing and placing operation, may result in early hardening. Another important application is in prestressed concrete, where retarders prevent the concrete from setting before vibrating operations are completed. Set retarders also allow use of high-temperature curing in prestressed concrete production without affecting the ultimate strength of the concrete.

Since most of the water reducers have a retarding tendency, some of the ingredients in water reducers, such as lignosulfonic acids and hydroxycarboxylic acids, are also a basis for set-retarding admixtures. Other important materials used in producing set retarders are sugars and their derivatives [291]. Retarders are dissolved in water and typically contain 17-46% active matter [190].

Accelerating admixtures (Accelerators): Accelerating admixtures are used either to increase the rate of early strength development or to shorten the time of setting, or both in concrete mixes. Major raw materials used in accelerators include calcium chloride, calcium nitrate, calcium formate, and calcium thiocyanate, with very small amounts of other materials occasionally being included in the formulations, such as calcium thiosulfate and triethanolamine (TEA). TEA is not normally used alone but it is sometimes used in other categories of admixtures to compensate for retarding influences. Among all these raw materials, calcium chloride is the most common accelerator used in concrete. However, there is growing interest in using "chloride-free" accelerators as replacement for calcium chloride because calcium chloride in reinforced concrete can promote corrosion of steel reinforcement, especially in moist environments. But corrosion-related problems can be reduced or eliminated with proper proportioning, proper consolidation, and adequate cover thickness [290, 291]. The accelerators are normally dissolved in water and typically contain 35-50% active matter [190].

Air entraining agents: Air-entraining admixtures are organic materials, usually in the solution form. When added to water in a concrete mix, these admixtures entrain a controlled quantity of air in uniformly dispersed microscopic bubbles. There are three major reasons for intentionally entraining air into concrete: increase in freeze-thaw and scaling resistances, increased workability, and reduction in bleeding and segregation of fresh concrete. In literature, various chemical surfactants are described as suitable for the formulation of air-entraining agents for concrete. However, in practice, a relatively small number of raw materials are used and these are: salts of wood resins, synthetic detergents, salts of petroleum acids, and fatty and resinous acids and their salts [290, 291]. The air entrainers are dissolved in water and typically contain 3-12% active matter [190].

Waterproofing (water resisting) admixtures: Based on EFCA’s definition: “Waterproofing admixtures are used to decrease the amount of water which is absorbed by the hardened concrete due to capillary suction. Because of the lower water permeability, concrete which is directly in contact with water or a wet environment will have an increased durability.” Waterproofing admixtures are based on salts of oleic acid, stearic acid, caprylic acid, and fatty acid soaps. They may also contain water reducing admixtures to make the concrete denser and less porous. Waterproofing admixtures are usually dissolved in water and typically contain 10-43% active matter [190].

The quantity of an admixture used in concrete is small, well below 1 percent by mass of concrete, relative to other constituents of the mix. However its effect, depending on the amount used and the time it is added during the concrete mixing cycle, may be quite strong. They are generally excluded in concrete LCAs because their impacts are assumed to be negligible because of their small quantities. Essentially, SETAC guidelines [31] confirm this reasoning by stating that inputs to an LCA can be excluded if:

1. *They are less than 1 percent of the total mass of the materials/products;*
2. *They do not have a significant impact associated with energy consumption; and*
3. *They do not contribute significantly to a toxic emission.*

However without a comprehensive LCA, it is hard to decide about their real impacts. As a first step to admixtures LCA, an inventory of inputs (materials, energy, and water) and outputs as wastes and emissions is essential which requires data for:

- Chemical/toxicological (in terms of heavy metals, dioxins, carcinogens, etc.) composition and quantities of active ingredients used commonly in admixtures;

- Major production steps and process flows of admixtures and related environmental inputs of materials, energy use in terms of electricity and fuels, and water consumption as well as outputs, e.g., emissions, wastes to/from these processes including process-related air emissions of GHG emissions, criteria air pollutants, heavy metals, dioxins/furans and other toxic air emissions;

- Additionally, waste disposal during concrete mixing and placing and leaching behavior of admixtures in concrete during use and end-of-life phases;

Different from other concrete ingredients, chemical substances used in concrete admixtures could be a major concern in terms of their toxicological properties. Among different concrete admixtures, plasticizers and superplasticizers are the most commonly used, representing approximately 80% of European and 70% of US admixture consumption [190, 291]. A simple back-of-an envelope calculation shows that about 3.24 kg of superplasticiser is required for one cubic meter of a 35 MPa (with a unit weight of 2,370 kg/m^3) ready-mixed concrete, which adds up to roughly 0.33 million tonnes of plasticizers use annually in Europe. Associated environmental impacts can be considerable.

It is important to note that there exists little or no environmental data regarding the production of admixtures, their handling and mixing with other concrete ingredients and after concrete is hardened. Manufacturers can be a good source of information but their data is generally confidential. As part of a future research work, comprehensive LCA of chemical admixtures production for the United States is essential for a complete GreenConcrete LCA tool, which currently holds the place for the associated LCI calculations for admixtures.

For the existing GreenConcrete LCA calculations, LCI inputs and outputs related to admixtures are adapted from European Federation of Concrete Admixture Association’s Eco-profile which covers cradle-to-gate production of admixtures in Europe [190]. Data is summarized in Table 4.52 as follows:

Table 4.52: GreenConcrete_Admixtures Production - Input and output data for LCI calculations, adapted from EFCA Eco-Profiles [190]

per kg of admixture		**Water-reducing (Plasticiser)**	**Superplasticiser**	**Set-retarding (Retarder)**	**Accelerating (Accelerator)**	**Air entraining**	**Waterproofing (Water resisting)**
Typical dosage (% by weight of cement)	%	0.45%	1.35%	0.50%	1.25%	0.35%	0.78%
Energy use (total)	MJ	4.60E+00	1.83E+01	1.77E+01	2.28E+01	2.10E+00	5.60E+00
Non-hazardous solid waste	kg	3.40E-03	2.10E-02	9.10E-02	3.20E-03	2.90E-04	2.40E-05
Hazardous solid waste	kg	1.70E-04	4.50E-04	7.40E-04	1.20E-04	5.90E-05	7.40E-05
Air Emissions	kg						
GWP (CO_2-eq)		2.29E-01	7.67E-01	1.42E+00	1.26E+00	1.03E-01	3.74E-01
As		4.70E-08	5.80E-08	1.60E-08	1.80E-07	8.60E-09	4.40E-08
CO_2		2.20E-01	7.20E-01	7.60E-02	1.20E+00	8.60E-02	2.50E-01
CO		1.10E-04	5.50E-04	8.10E-04	1.00E-03	1.10E-04	5.70E-04
Cr		6.80E-10	1.60E-08	5.60E-09	6.70E-08	3.30E-09	1.70E-08
Hg		2.80E-09	9.40E-08	2.90E-08	3.40E-08	1.90E-08	9.20E-09
CH_4		3.80E-04	1.20E-03	5.80E-02	2.50E-03	6.20E-04	2.80E-03
Ni		9.30E-07	4.60E-07	1.50E-07	1.70E-06	4.60E-08	4.20E-07
NO_x		5.20E-04	1.80E-03	1.70E-03	2.30E-03	3.50E-04	1.60E-03
N_2O			6.70E-05	3.50E-05	-	8.60E-06	2.00E-04
SO_2		8.50E-04	3.60E-03	1.40E-03	2.80E-03	3.20E-04	8.80E-04
VOC (unspecified)		1.70E-04	2.90E-04	-	-	-	-

Calculations within the corresponding Excel worksheet are straightforward and basically involve the multiplication of total of weight (active matter only) of admixture "i" with the quantity of LCI factor (energy use, solid waste, or air emission) "k" from Table 4.52 as follows:

$$ADMIXTURE_{TOTAL\_LCIi,k} = M_{ADMIXTUREi} \times LCI_{FACTORi,k}$$

Equation 4.119: Calculation of total LCI for admixture production

Where:

$\mathrm{ADMIXTURE}_{\mathrm{TOTAL\_LCIi,j,k}}$ = Total life-cycle inventory associated with admixture type "i" resulting in an LCI factor "k" of which can either be energy use in MJ or emission (solid waste or air emission) in kg;

$\mathrm{M}_{\mathrm{ADMIXTUREi}}$ = Total mass of admixture "i" from User Input page, in kg;

$\mathrm{LCI}_{\mathrm{FACTORi,k}}$ = LCI factor from Table 4.52 with columns representing admixture type "i" and rows representing corresponding LCI factor "k", which is in MJ/kg for energy use factor or in kg/kg of admixture for emission factors.

"Results" worksheet within the tool tabulates total life-cycle inventory that is taken directly from Equation 4.119 for the type of admixture selected by the user on "User Input Page".

4.11.3 Water Consumption

Water is used for various purposes during concrete production and its raw materials extraction, processing, and production. Water consumption calculations are presented under related headings of cement, aggregates, SCMs production processes as well as electricity generation and fuel LCI estimations in previous sections.

At the concrete batching plant, water is consumed extensively as batch water in concrete (about 15-20 percent by volume of the mix is water) and for equipment clean-up. Potable water is generally utilized as batch water. Recycled water can also be used but with care because contaminants may adversely influence strength, appearance, and quality of concrete. Additionally, water is sprayed on paved roadways, at aggregate transfer points and storage piles as dust suppressant to prevent particulates from becoming airborne. It is also used for rinsing charge hopper at the truck mixer load point. Truck wash-off and wash-out consume large amounts of water in the ready mixed concrete manufacturing. Unused concrete in the mixing drums needs to be washed out thus recycled water is a good option for this purpose of cleaning. A single washout may require 100 to 1,000 liters of water. This amount varies with the number of operating trucks, number of central mixers at plants, the frequency of washout, the volume of returned concrete, and the amount of water used per wash. The wash-off is performed for truck exteriors to prevent cement build-up on truck drum exteriors and to give truck a clean look during its transit. Potable water is usually preferred for wash-off. The average water volume has been estimated as 40 liters per truck per wash-off [47, 271].

Figure 4.24 illustrates two major types of concrete batching processes, namely dry batching (also known as truck mixing) and wet batching (central mixing). For dry batching, all materials are individually weighed and discharged to ready-mix concrete truck drum and the concrete is mixed on the way to the construction site. In case of wet batching, all concrete ingredients are mixed in a central mixer before pumped into the truck drum.

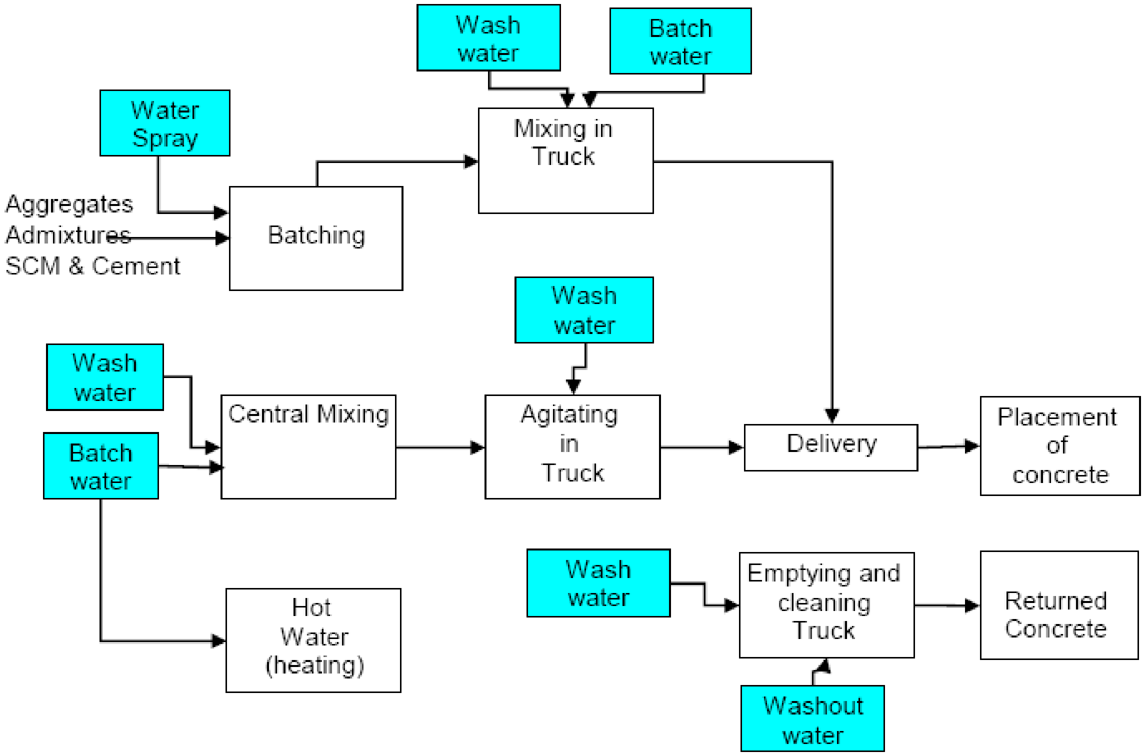


Figure 4.24: Water consumption during concrete batching, adapted from [47]

Water consumption factors are calculated for each of the processes described in the GreenConcrete LCA tool and demonstrated in "Results" page.

In the Excel version of GreenConcrete LCA tool, water consumption LCI factor calculations are based on USGS's 2005 water use data [87]. The report provides water withdrawal estimates by State, source of water, and use category. The term "water withdrawal" for each category represents "the total amount of water removed from the water source, regardless of how much of that total is consumptively used. In most cases, some fraction of the total withdrawal will be returned to the same or a different water source after use and is available for other withdrawals." Because of the uncertainty of estimating consumptive use and return flows on a category and State basis, estimates of consumptive use are not provided in the USGS report, therefore, the tool does not involve related calculations. In the report, water sources include surface water and groundwater, both fresh and saline. Categories include public supply, domestic, irrigation, livestock, aqua-culture, industrial, mining, and thermoelectric power. GreenConcrete LCA tool considers only industrial water use data. Water for industrial use may be delivered from a public supplier or be self-supplied; for this reason two options are available in the water use drop-down lists on the User Input Page. Appendix A, Table 9.10 summarizes average surface-water and groundwater withdrawals data by State and by "Industrial Self-Supplied Water Withdrawal" and "Public-Supply Water Withdrawals for Industrial Use" as well as "Mining Water Withdrawals". However, since mining water related energy use and emission factors are not available, water use selection options are limited to industrial and public-supply uses on the User Input Page as mentioned before. Following calculations and data presented below are used to reach Table 4.55, which is the summary of water LCI factors.

Table 4.53: Data for GHG emission calculations associated with chemicals used as part surface water and groundwater treatment (for public supply sources)

Chemical (i=1, 2,…7)	**Mass (g/m^3 of water)**	**GWP (g $CO_{2\text{-eq}}$ /g chemical) - GaBi**	**Energy (MJ/g chemical) - GaBi**	**Notes**	**Source**
Surface water					
Alum	0.35	0.314012130	0.011383253	Assumed %100 aluminum sulfate, imported surface water	[163, 292, 293]
Aqueous ammonia	0.84	2.888469000	0.036863181	Imported surface water	
Caustic soda	3.3	4.256609000	0.016637836	Imported surface water	
Chlorine	5.3	1.390869147	1.390869147	Imported surface water	
Ferric chloride	4	0.195488363	0.003023699	Imported surface water	
Sodium hypochlorite	1.9			Imported surface water	
Other	2.8	1.507574607	0.017594435	Imported surface water	
Groundwater					
Chlorine	5.3	1.390869147	1.390869147	Imported surface water	[293]

GHG emissions associated with the use of the chemicals during water treatment are calculated in Equation 4.120 by applying a sumproduct function which involves mass of chemical in g per m^3 of water (from column #2 of Table 4.53) "$M_{CHEMICALi}$" and corresponding GWP factor in g CO_2-eq. per m^3 of water "$GWP_{CHEMICALi}$" (from column #3 of Table 4.53). The breakdown between CO_2, CH_4, and N_2O was taken from EIO-LCA, Sector #325188: All other basic inorganic chemical manufacturing sector. However, there were no direct CH_4 and N_2O emissions data related to inorganic chemical manufacturing in the EIO-LCA 2002.

$$WATER\_CO_{2_{PUBLIC,SURFACE\_CHEMICALi}} = (1) \times (\frac{1}{1{,}000}) \sum_{i}^{n} [M_{CHEMICALi} \times GWP_{CHEMICALi}]$$

$$CH_{4_{SURFACE\_WATER\_CHEMICALi}} = (0) \times (\frac{1}{1{,}000}) \times \sum_{i}^{n} [M_{CHEMICALi} \times GWP_{CHEMICALi}]$$

$$N_2O_{SURFACE\_WATER\_CHEMICALi} = (0) \times (\frac{1}{1{,}000}) \times \sum_{i}^{n} [M_{CHEMICALi} \times GWP_{CHEMICALi}]$$

Equation 4.120: Calculation of GHG emissions from chemicals used in water treatment for public supply, surface water sources

Where:

$CO_{2WATER\_CHEMICALi}$ = CO_2 from chemical "i" used in water treatment process for public supply, surface water, in kg/m^3 of water;

$CH_{4WATER\_CHEMICALi}$ = CH_4 from chemical "i" used in water treatment process for public supply, surface water, in kg/m^3 of water;

$N_2O_{WATER\_CHEMICALi}$ = N_2O from chemical "i" used in water treatment process for public supply, surface water, in kg/m^3 of water;

1 = Corresponds to 100% of GHG emissions is CO_2, unitless;

0 = Corresponds to 0% of GHG emissions is CH_4 or N_2O, unitless;

$M_{CHEMICALi}$ = Mass of chemical "i" taken from column #2 of Table 4.53, in g/m^3 of water;

$GWP_{CHEMICALi}$ = GWP factor from the corresponding chemical "i" and obtained from column #3 of Table 4.53, in g of CO_2-equivalent/g of chemical;

1/1,000 = Unit conversion factor for 1 kg = 1,000 g.

Water is assumed to be pumped by electricity for all water use options. Table 4.54 provides the electricity use factors for both self-supplied industrial water and public water supplies for sources of surface water and groundwater options. Electricity requirement for these options cover supply, treatment (with chemicals), and distribution processes. Major data sources include a journal article which analyzes life-cycle air emissions from supplying water by Stokes and Horvath [292], EIO-LCA (eiolca.net) and GaBi software [163] which calculate GWP data for chemicals used in water treatment and a dissertation assessing life-cycle water impacts of U.S. transportation fuels by Scown [293].

Table 4.54: Electricity use data for surface water and groundwater supply phases (supply, treatment, distribution)

per m^3 of water	Electricity (kWh)	Notes	Sources
Self-Supplied Industrial Water			
Surface water	0.079	Based on the electricity use factor for municipal surface water pumping of 0.073 kWh/m^3, with an upward adjustment based on the reduced scale of pumping, the need for distribution pumping within the facility, and the energy requirements for the treatment purposes, e.g., softening, chlorination.	[293, 294]
Groundwater	0.198	Based on the unit electricity requirement for municipal groundwater system well pumping (0.161 kWh/m^3) with the additional energy requirements for system pressurization and/or distribution pumping.	[294]
Public Water Supply			
Surface water	0.482	Total	
Raw water pumping	0.073	Based on the electricity consumption factor for municipal surface water pumping of 0.073 kWh/m^3	[293, 294]
In-plant pumping	0.170	For imported surface water	[292, 293]
Distribution	0.220	For imported surface water	[292, 293]
Chemicals	0.0188	Total electricity use for chemicals	
alum	0.0026	Operations for surface water treatment are as follows: Raw water is first screened to remove gross debris and contaminants. Then water is pre-oxidized using chlorine or ozone treatment to kill any disease carrying organisms and to remove taste or odor causing	[293, 294]
lime	0.0124		
polymer	0.0032		
chlorine	0.0005		

		substances. Alum and /or polymeric materials are added to the water to aid in the flocculation and coagulation of finer particles. A second disinfection step kills any remaining organisms. Then the treated water is distributed by high pressure pumping.	
Groundwater	0.66053		
Supply	0.220	Calculated based on [293], adjusted for scale using 14% factor from EPRI (2002) [294]	
Distribution	0.440		
Chemical-chlorine	0.00053	Based on EPRI (2002) [294], assume chlorine requirement for groundwater is same as for surface water	

Finally, Table 4.55 summarizes the electricity use and GHG emission factors associated with water consumption LCI calculations based on the data from Table 4.53, Table 4.54, and Equation 4.120.

Table 4.55: GreenConcrete_Water Consumption – Summary of electricity use and GHG emissions data

User Choices	**Electricity (kWh/m^3 Water**	**CO$_2$ in chemicals (kg/m^3 Water)**	**CH$_4$ in chemicals (kg/m^3 Water)**	**N$_2$O in chemicals (kg/m^3 Water)**
Surface water option				
Self-Supplied Industrial Water	7.90E-02			
Public Water Supply	4.82E-01	2.90E-02	0.00E+00	0.00E+00
Groundwater option				
Self-Supplied Industrial Water	1.85E-01			
Public Water Supply	6.61E-01	7.37E-03	0.00E+00	0.00E+00

Although the Excel version of the tool provides the data and calculations described in Section 4.11.3, the results from the tool excludes the water consumption LCI associated with the production of concrete and its ingredients. That is because of the uncertainty embedded in the withdrawal and consumption LCI data for the concrete production processes. Therefore, this section serves as a guideline for future research purposes.

The last concrete production stage covers the concrete mixing and batching processes, with the end product being the ready-mixed concrete.

4.11.4 Concrete Mixing and Batching Processes

Concrete batching is the “process of measuring and introducing into the mixer the ingredients for a batch of concrete” [9]. The process description of “concrete batching” is based on U.S. EPA’s Compilation of Air Pollution Emission Factors [295]:

Approximately 75 percent of the U.S. concrete is produced at ready-mix concrete plants. At most of these plants, cement, fine and coarse aggregates, SCMs, and water are all gravity fed from the weight hopper into the mixer trucks. The concrete is mixed on the way to the site where the concrete is to be poured. At some of these plants, the concrete may also be manufactured in a central mix drum and transferred to a transport truck. Rarely, concrete is dry-batched or prepared at a building construction site.

The raw materials can be delivered to a plant by rail, truck or barge – all these three options and their associated LCI are considered in the GreenConcrete LCA. Within the batching plant, cement is transferred to elevated storage silos pneumatically or by bucket elevator. Fine and coarse aggregates are transferred to elevated bins by front end loader, clam shell crane, belt conveyor, or bucket elevator. From these elevated bins, the constituents are fed by gravity or screw conveyor to weigh hoppers, which combine the proper amounts of each material. In addition to transferring ingredients, plant operations also include mixing, heating, lighting, and cooling of the plant.

Types and amounts of fuel and energy use during concrete batching vary from one concrete plant to another. Batching process is primarily powered by electricity that is used for operating mixing equipment [57]. Various types of fuel, mostly diesel, is used in forklifts and loaders for moving raw materials and concrete in the plant, boilers for heating water and building, and power washers. Most of the fuel (diesel fuel) is used in transporting batched concrete. Natural gas is used in boilers for hot water and building heating purposes [58]. Table 4.56 demonstrates the list of fuels and electricity consumption in a typical U.S. concrete plant.

Table 4.56: GreenConcrete_Concrete Mixing and Batching –Input and output data used in LCI calculations

Input	**unit**	**per m^3 of concrete**	**Notes**	**Source**
Natural gas	m^3	3.28E-09	In boilers (for hot water and building heating)	[58]
Distillate (Diesel or Light) fuel oil	l	4.38E-07	In plant-only vehicles, e.g., loaders, boilers forklifts, generators	
Electricity	kWh	4.11E+00	Plant-use, e.g., for mixing, conveying	
Water, excluding batch water	m^3	6.50E-01	-	
Solid waste	kg	2.40E+01	Mostly in the form of concrete and small amounts of paste	

PM which consists mostly of cement and other cementitious materials dust but also some aggregate and sand dust is the major concern during concrete batching. Additionally, this PM can be the source of emissions of certain metals. Such PM emissions and associated metal emission factors with or without emission control technologies for cement silo filling, SCM silo filling, transfer of coarse and fine aggregates to elevated bins and weight hoppers as well as two different concrete batching and loading options (truck mix vs. central mix) are covered in following tables (Table 4.57, Table 4.58, and Table 4.59).

Table 4.57: Concrete Batching Process-related Average PM Emission Factors (adapted from U.S. EPA's AP-42 Concrete Batching Data [295])

		kg of PM per tonne of material			
Material, input	**Unit**	**PM Emission Control with Fabric Filter**		**Uncontrolled**	
		Particulates (PM_{10})	Particulates (total)	Particulates (PM_{10})	Particulates (total)
Cement (silo filling)	kg	1.70E-04	5.00E-04	2.40E-01	3.60E-01
Fly Ash F (silo filling)*	kg	2.40E-03	4.50E-03	6.50E-01	1.57E+00

GBFS (silo filling)*	kg	2.40E-03	4.50E-03	6.50E-01	1.57E+00
Condensed Silica Fume (silo filling)*	kg	2.40E-03	4.50E-03	6.50E-01	1.57E+00
Natural Pozzolan (silo filling)*	kg	2.40E-03	4.50E-03	6.50E-01	1.57E+00
Limestone (sili filling)*	kg	2.40E-03	4.50E-03	6.50E-01	1.57E+00
Water	kg				
Fine Aggregates**	kg			5.10E-04	1.10E-03
Coarse Aggregates**	kg			1.70E-03	3.50E-03
Plasticiser	kg				
Superplasticiser	kg				
Retarder	kg				
Accelerating admixture	kg				
Air entraining admixture	kg				
Waterproofing	kg				
Mixer loading (central mix)***	kg	2.80E-03	9.20E-03	7.80E-02	2.86E-01
Truck loading (truck mix)***	kg	1.31E-02	4.90E-02	1.55E-01	5.59E-01
Fine Aggregates - loading weight hopper	kg			1.30E-03	2.60E-03
Coarse Aggregates - loading weight hopper	kg			1.30E-03	2.60E-03

* Assume all SCMs have same PM factors since no data by type of SCM exists

** PM emissions that occur while transferring aggregates to elevated bins, at average 4.48 m/s (10 mph) wind speed, coarse and fine aggregates with moisture contents of 1.77% and 4.17%, respectively.

*** PM emission factors are from cement and SCMs during loading operation (central mix loading vs. truck mix loading). Therefore, mass of cement and SCMs are considered for the related PM emission calculations in the tool.

Table 4.58: Concrete Batching Process-related Average Metal Emission Factors, with emission control option (adapted from EPA's U.S. AP-42 Concrete Batching Data [295]

Material, input	**Unit**	**Emission Control with Fabric Filter (in kg of metal emissions per tonne of material)**							
		Arsenic (As) and Arsenic Compounds	Beryllium (Be)	Cadmium (Cd) and Cadmium Compounds	Chromium (Cr) and Chromium Compounds	Lead (Pb) and Lead Compounds	Manganese (Mn)	Nickel (Ni) and Nickel Compounds	Selenium (Se) and Selenium Compounds
Cement (silo filling)	kg	2.12E-09	2.43E-10		1.45E-08	5.46E-09	5.87E-08	2.09E-08	
Fly Ash F (silo filling)*	kg	5.00E-07	4.52E-08	9.92E-09	6.10E-07	2.60E-07	1.28E-07	1.14E-06	3.62E-08
GBFS*(silo filling)	kg	5.00E-07	4.52E-08	9.92E-09	6.10E-07	2.60E-07	1.28E-07	1.14E-06	3.62E-08
Condensed Silica Fume (silo filling)*	kg	5.00E-07	4.52E-08	9.92E-09	6.10E-07	2.60E-07	1.28E-07	1.14E-06	3.62E-08
Natural Pozzolan(silo filling)*	kg	5.00E-07	4.52E-08	9.92E-09	6.10E-07	2.60E-07	1.28E-07	1.14E-06	3.62E-08
Limestone (silo filling)*	kg	5.00E-07	4.52E-08	9.92E-09	6.10E-07	2.60E-07	1.28E-07	1.14E-06	3.62E-08
Water	kg								
Fine Aggregates	kg								
Coarse Aggregates	kg								
Plasticiser	kg								
Superplasticiser	kg								
Retarder	kg								
Accelerating admixture	kg								
Air entraining admixture	kg								
Waterproofing	kg								
Mixer loading (central mix)**	kg	1.48E-07		3.55E-10	6.34E-08	1.83E-08	1.89E-06	1.24E-07	
Truck loading (truck mix)**	kg	3.01E-07	5.18E-08	4.53E-09	2.05E-06	7.67E-07	1.04E-05	2.39E-06	5.64E-08
Fine Aggregates -loading weigh hopper	kg								
Coarse Aggregates - loading weigh hopper	kg								

* Assume all SCMs have same heavy metal emission factors since no data by type of SCM exists

** Emission factors are for cement and SCMs during loading operation (central mix loading vs. truck mix loading) with emission control with fabric filter. Therefore, total mass of cement and SCMs are considered in the related calculations in the tool.

Table 4.59: Concrete Batching Process-related Average Metal Emission Factors, with uncontrolled emissions option (adapted from EPA's AP-42 Concrete Batching Data [295]

Material, input	**Unit**	**Emissions, Uncontrolled (in kg of metal emissions per tonne of material)**							
		Arsenic (As) and Arsenic Compounds	Beryllium (Be)	Cadmium (Cd) and Cadmium Compounds	Chromium (Cr) and Chromium Compounds	Lead (Pb) and Lead Compounds	Manganese (Mn)	Nickel (Ni) and Nickel Compounds	Selenium (Se) and Selenium Compounds
Cement (silo filling)	kg	8.38E-07	8.97E-09	1.17E-07	1.26E-07	3.68E-07	1.01E-06	8.83E-06	3.62E-08
Fly Ash F (silo filling)*	kg	8.38E-07	8.97E-09	1.17E-07	1.26E-07	3.68E-07	1.01E-06	8.83E-06	3.62E-08
GBFS*(silo filling)	kg	8.38E-07	8.97E-09	1.17E-07	1.26E-07	3.68E-07	1.01E-06	8.83E-06	3.62E-08
Condensed Silica Fume (silo filling)*	kg	8.38E-07	8.97E-09	1.17E-07	1.26E-07	3.68E-07	1.01E-06	8.83E-06	3.62E-08
Natural Pozzolan(silo filling)*	kg	8.38E-07	8.97E-09	1.17E-07	1.26E-07	3.68E-07	1.01E-06	8.83E-06	3.62E-08
Limestone (silo filling)*	kg	8.38E-07	8.97E-09	1.17E-07	1.26E-07	3.68E-07	1.01E-06	8.83E-06	3.62E-08
Water	kg								
Fine Aggregates	kg								
Coarse Aggregates	kg								
Plasticiser	kg								
Superplasticiser	kg								
Retarder	kg								
Accelerating admixture	kg								
Air entraining admixture	kg								
Waterproofing	kg								
Mixer loading (central mix)****	kg	4.19E-06		5.92E-09	7.11E-07	1.91E-07	3.06E-05	0.00000164	
Truck loading (truck mix)****	kg	6.09E-06	1.22E-07	1.71E-08	5.71E-06	1.81E-06	3.06E-05	5.99E-06	1.31E-06
Fine Aggregates -loading weigh hopper	kg								
Coarse Aggregates - loading weigh hopper	kg								

* Assume all SCMs have same heavy metal emission factors since no data by type of SCM exists

** Emission factors are for cement and SCMs during loading operation (central mix loading vs. truck mix loading) with no emission control. Therefore, total mass of cement and SCMs are considered in the related calculations in the tool.

For concrete batching, LCI calculations involve estimation of impacts from electricity use, pre-combustion and combustion of fuel use, and process of transferring, loading, and mixing of ingredients.

Electricity use, pre-combustion, and combustion LCI associated with concrete batching are calculated as follows similar to prior LCI calculations conducted for cement and other concrete materials (see from Equation 4.121 to Equation 9.1):

$$\boxed{ELECTRICITY_{CONCRETE} = ELECTRIC_{FACTOR\_CONCRETE} \times V_{CONCRETE}}$$

Equation 4.121: Calculation of electricity use during concrete batching

Where:

$ELECTRICITY_{CONCRETE}$ = Total amount of electricity used during concrete batching, in kWh;

$ELECTRIC_{FACTOR\_CONCRETE}$ = Electricity use factor obtained from column #3, row #4 of Table 4.56, in kWh/m^3 of concrete;

$V_{CONCRETE}$ = Total volume of concrete produced, from User Input Page (see last row in Table 4.2), in m^3.

Mass or volume of fossil fuels used during concrete batching processes are calculated by the multiplication of total volume of concrete and the fossil fuel use factors from Table 4.56:

$$\boxed{FUEL_{CONCRETEi} = FUEL_{FACTOR\_CONCRETEi} \times V_{CONCRETE}}$$

Equation 4.122: Calculation of amount fossil fuel use during concrete batching

Where:

$FUEL_{CONCRETEi}$= Total amount of fossil fuel “i” used during concrete batching, in l or m^3 of fuel depending on the fuel type selected;

$FUEL_{FACTOR\_CONCRETEi}$ = Fuel use factor obtained from column#3, rows #2 through #3, Table 4.56, in l or m^3 of fossil fuel “i” per m^3 of concrete;

$V_{CONCRETE}$ = Total volume of concrete produced, from User Input Page (see last row in Table 4.2), in m^3;

“i” = Type of fossil fuel used during concrete batching and can be natural gas or distillate (diesel) fuel oil on the process type.

Process water consumption (other than batching) associated with concrete batching (mostly for cleaning purposes) is calculated below:

$$\boxed{WATER_{CONCRETEi} = WATER_{FACTOR\_CONCRETEi} \times V_{CONCRETE}}$$

Equation 4.123: Calculation of water consumption during concrete batching

Where:

$WATER_{CONCRETEi}$ = Total volume of water consumption during concrete batching, in m^3;

$WATER_{FACTOR\_CONCRETEi}$ = Water consumption factor obtained from column#3, row #5, Table 4.56, in m^3 of water per m^3 of concrete;

$V_{CONCRETE}$= Total volume of concrete produced, from User Input Page (see last row in Table 4.2), in m^3;

LCI associated with electricity and fuel use during concrete batching are calculated using the results from Equations 4.121 and 4.122, simultaneously with LCI factors developed for Electricity Grid Data, Pre-combustion and Combustion Fuel Data worksheets in GreenConcrete LCA tool. Therefore, similar to other process calculations, a life-cycle inventory "k" related to electricity use during batching process in a concrete plant in location "j" is calculated as follows:

$$CONCRETE_{LCI_{ELECTRIC\,j,k}} = ELECTRICITY_{CONCRETE} \times HLOOKUP\left(LOCATION_j, TRANSPOSE\ [TABLE\ 9.9], ROW\#_{LCIF\,j,k}\right)$$

Equation 4.124: Calculation of LCI related to electricity use during concrete batching

Where:

$CONCRETE_{LCI\_ELECTRICj,k}$ = Total life-cycle inventory associated with electricity use during concrete batching, whereas "j" corresponds to the location where the process takes place; in MJ for "k" energy use factor or in kg for life-cycle inventories corresponding to solid waste, water consumption, and air emissions;

$ELECTRICITY_{CONCRETE}$ = Total amount of electricity used during concrete batching (calculated in Equation 4.121), in kWh;

$LOCATION_j$ = Location of the concrete batching plant "j", taken from "User Input Page_Quarry/Plant Location, Grid Mix, and Water Supply Input" section and can be State, United States, or user-defined, unitless;

[TABLE 9.9], $ROW\#_{LCIFj,k}$ = Appendix A, Table 9.9 with calculated total LCI for electricity grid mix (per kWh of electricity) for location "j"; each row representing a life-cycle inventory "k", in MJ/kWh for energy use factor or in kg/kWh for other LCI factors listed in the Table.

Subsequently, pre-combustion and combustion-related LCI factor "k" for the amount of fossil fuel used during concrete batching processes is estimated by means of SUMPRODUCT function in the designated Excel worksheet as follows:

$$CONCRETE_{LCI\_PRECOMBUSTk} = \sum_{i,k}^{n}\left[FUEL_{CONCRETEi} \times PRECOMBUST_{LCIi,k}\right]$$

Equation 4.125: Calculation of LCI for pre-combustion fuel use during concrete batching

$$CONCRETE_{LCI\ COMBUSTk} = \sum_{i,k}^{n}\left[FUEL_{CONCRETEi} \times COMBUST_{LCI\_i,k}\right]$$

Equation 4.126: Calculation of LCI for fuel combustion during concrete batching

Where:

$\text{CONCRETE}_{\text{LCI\_PRECOMBUSTk}}$ = Total LCI associated with pre-combustion impacts of fuels “i”, e.g., natural gas or distillate (diesel) fuel oil, used during concrete batching, in *MJ* for “k” energy use factor or in kg for life-cycle inventories of solid waste, water consumption, and air emissions;

$\text{CONCRETE}_{\text{LCI\_COMBUSTk}}$ = Total LCI associated with combustion impacts of fuels “i”, e.g., natural gas or distillate (diesel) fuel oil, used during concrete batching in *MJ* for “k” energy use factor or in *kg* for life-cycle inventories of solid waste, water consumption, and air emissions;

$\text{FUEL}_{\text{CONCRETEi}}$ = Total volume of fossil fuel used during concrete batching, calculated Equation 4.122, in *l* or m^3 of fuel “i;

$\text{PRECOMBUST}_{\text{LCIi,k}}$ = Pre-combustion fuel LCI factors calculated in Table 4.15 per unit volume of fossil fuel with an associated life-cycle inventory factor “k”, in *MJ/l*, MJ/m^3 for energy use or in *kg/ l*, kg/m^3 for other LCI factors listed in the Table.

$\text{COMBUST}_{\text{LCIi,k}}$ = Fuel combustion LCI factors calculated in Table 4.16 per unit volume of fossil fuel with an associated life-cycle inventory factor “k”, in *MJ/l*, MJ/m^3 for energy use or in *kg/ l*, kg/m^3 for other LCI factors listed in the Table.

Process-related LCI calculations involve total mass of concrete ingredients (except for the admixtures) in estimating PM and associated metal emission factors. Based on the user’s selection of the “Concrete Batching Plant PM Control Technology Options” and “Batching Plant Loading/Mixing Options” from User Input Page, following equations are developed:

IF “Concrete Batching Plant PM Control Technology Options” = “Controlled with Fabric Filter”, which is the default, THEN:

$$PROCESS_{CONCRETE_{FF\_PM10}} = \sum_{i}^{n} M_i \times (\frac{1}{1{,}000}) \times VLOOKUP(CONCRETE_i, [TABLE\ 4.57], COLUMN\#3, ROWS\#4 \rightarrow \#12)$$

$$PROCESS_{CONCRETE_{FF\_PM_{TOTAL}}} = \sum_{i}^{n} M_i \times (\frac{1}{1{,}000}) \times VLOOKUP(CONCRETE_i, [TABLE\ 4.57], COLUMN\#4, ROWS\#4 \rightarrow \#12)$$

Equation 4.127: Calculation of total PM_{10} and PM_{TOTAL} emission factors resulting from transferring of cement, SCMs, and aggregates during concrete batching, with emission control with fabric filter option

IF “Concrete Batching Plant PM Control Technology Options” = “Uncontrolled”, THEN:

$$PROCESS_{CONCRETE_{UNCONTROLLED\_PM10}} = \sum_{i}^{n} M_i \times (\frac{1}{1{,}000}) \times VLOOKUP(CONCRETE_i, [TABLE\ 4.57], COLUMN\#5, ROWS\#4 \rightarrow \#12)$$

$$PROCESS_{CONCRETE_{UNCONTROLLED\_PMTOTAL}} = \sum_{i}^{n} M_i \times (\frac{1}{1{,}000}) \times VLOOKUP(CONCRETE_i, [TABLE\ 4.57], COLUMN\#6, ROWS\#4 \rightarrow \#12)$$

Equation 4.128: Calculation of total PM_{10} and PM_{TOTAL} emission factors resulting from transferring of cement, SCMs, and aggregates during concrete batching, with emission control with no emission control option

Where:

$PROCESS_{CONCRETE\_FF\_PM10}$ = Total process-related PM_{10} emission, controlled with FF, associated with transferring of concrete materials in concrete plant, in kg;

$PROCESS_{CONCRETE\_FF\_PMTOTAL}$ = Total process-related PM_{TOTAL} emission, controlled with FF, associated with transferring of concrete materials in concrete plant, in kg;

$PROCESS_{CONCRETE\_UNCONTROLLED\_PM10}$ = Total process-related PM_{10} emission, uncontrolled, associated with transferring of concrete materials in concrete plant, in kg;

$PROCESS_{CONCRETE\_UNCONTROLLED\_PMTOTAL}$ = Total process-related PM_{TOTAL} emission, uncontrolled, associated with transferring of concrete materials in concrete plant, in kg;

M_i = Total mass of concrete material “i”, taken from Column#3 of Table 4.4 and listed in the first column of Table 4.57, in tonne;

$CONCRETE_{MATERIALi}$ = “i” represents major materials in the concrete mix, which corresponds to cement, fly ash, GBFS, natural pozzolan, limestone (as SCM), water, fine aggregates, coarse aggregates (Table 4.57), unitless;

[TABLE 4.57], COLUMN#3, ROWS#4 →#12 = PM_{10} emission factor controlled with FF option, listed in Column#3 of Table 4.57 and from transferring concrete material “i” listed in Column #1 (Material Input) from Row#4 (cement) to Row#12 (coarse aggregates), in kg per tonne of material “i”;

[TABLE 4.57], COLUMN#4, ROWS#4 →#12 = PM_{TOTAL} emission factor controlled with FF option, listed in Column#4 of Table 4.57 and from transferring concrete material “i” listed in Column #1 (Material Input) from Row#4 (cement) to Row#12 (coarse aggregates), in kg per tonne of material “i”;

[TABLE 4.57], COLUMN#5, ROWS#4 →#12 = PM_{10} emission factor for uncontrolled emission option, listed in Column#5 of Table 4.57 and from transferring concrete material “i” listed in Column #1 (Material Input) from Row#4 (cement) to Row#12 (coarse aggregates), in kg per tonne of material “i”;

[TABLE 4.57], COLUMN#6, ROWS#4 →#12 = PM_{TOTAL} emission factor for uncontrolled emission option, listed in Column#6 of Table 4.57 and from transferring/loading/unloading concrete material “i” listed in Column #1 (Material Input) from Row#4 (cement) to Row#12 (coarse aggregates), in kg per tonne of material “i”;

1/1,000 = Unit conversion factor for 1 tonne = 1,000 kg.

Based on the type of loading (mixer loading (central mix) vs. truck loading (truck mix)) and emission control technology (FF or uncontrolled), PM emissions and related metal emissions "k" from loading/unloading and mixing cement and cementitious materials vary:

IF "Batching Plant Loading/Mixing Options" = "Mixer Loading (Central Mix)", THEN:

$$PROCESS\_CENTRALMIX_{CONCRETE\_FFk} = EF_{CENTRAL\_FFk} \times \frac{1}{1{,}000} \times \sum_{i}^{n=6} M_{Ci}$$

$$PROCESS\_CENTRALMIX_{CONCRETE\_UNCONTROLk} = EF_{CENTRAL\_UNCONTROLk} \times \frac{1}{1{,}000} \times \sum_{i}^{n=6} M_{Ci}$$

Equation 4.129: Calculation of process-related emission factors (PM and metal emissions) resulting from mixer loading (central mix) during concrete batching

IF "Batching Plant Loading/Mixing Options" = "Truck Loading (Truck Mix)", which is the default, THEN:

$$PROCESS\_TRUCKMIX_{CONCRETE\_FFk} = EF_{TRUCK\_FFk} \times \frac{1}{1{,}000} \times \sum_{i}^{n=6} M_{Ci}$$

$$PROCESS\_TRUCKMIX_{CONCRETE\_UNCONTROLk} = EF_{TRUCK\_UNCONTROLk} \times \frac{1}{1{,}000} \times \sum_{i}^{n=6} M_{Ci}$$

Equation 4.130: Calculation of process-related emission factors (PM and metal emissions) resulting from truck loading (truck mix) during concrete batching

Where:

$PROCESS\_CENTRALMIX_{CONCRETE\_FFk}$ = Process-related emission "k" controlled with FF, associated with mixer loading (central mix) during concrete batching, in kg;

$PROCESS\_CENTRALMIX_{CONCRETE\_UNCONTROLk}$ = Process-related emission "k" uncontrolled, associated with mixer loading (central mix) during concrete batching, in kg;

$PROCESS\_TRUCKMIX_{CONCRETE\_FFk}$ = Process-related emission "k" controlled with FF, associated with truck loading (truck mix) during concrete batching, in kg;

$PROCESS\_TRUCKMIX_{CONCRETE\_UNCONTROLk}$ = Process-related emission "k" uncontrolled, associated with truck loading (truck mix) during concrete batching, in kg;

$EF_{CENTRAL\_FFk}$ = Emission factor "k" for central mixing controlled with FF technology option, from row #19 of Table 4.57 and Table 4.58, in kg per tonne of material "i";

$EF_{CENTRAL\_UNCONTROLk}$ = Emission factor "k" for central mixing uncontrolled technology option, from row #19 of Table 4.57 and Table 4.59, in kg per tonne of material "i";

EF_{TRUCK_FFk} = Emission factor "k" for truck mixing controlled with FF technology option, from row #20 of Table 4.57 and Table 4.58, in kg per tonne of material “i”;

$EF_{TRUCK\_UNCONTROLk}$ = Emission factor “k” for truck mixing uncontrolled technology option, from row #20 of Table 4.57 and Table 4.59, in kg per tonne of material “i”;

M_{Ci} = Total mass of cementitious material “C_i”, taken from Column#3 of Table 4.4 and listed in the first column of Table 4.57 (also in Table 4.58 and Table 4.59), in tonne;

“k” = Corresponds to emissions of PM and related metal emissions (As, Be, Cd, Cr, Pb, Mn, Ni, and Se) from loading/mixing processes during concrete batching;

“Ci” = Corresponds to cement or one of the cementitious materials including fly ash, GBFS, condensed silica fume, natural pozzolan, limestone;

1/1,000 = Unit conversion factor for 1 tonne = 1,000 kg.

Finally, process-related total emission “k” resulting from concrete batching is represented by “$CONCRETE_{LCI\_PROCESSk}$” and calculated by simply adding the results from Equations 4.127, 4.128, 4.129, and 4.130 depending on the type of emission control and process of transferring loading and unloading. To end with the concrete batching process, total LCI is estimated as the sum of calculated LCIs related to electricity use, fuel combustion (including fuel pre-combustion) and process itself:

$$\boxed{\begin{aligned} &CONCRETE_{TOTAL\_LCIj,k} \\ &\quad = CONCRETE_{LCI\_PROCESSk} + CONCRETE_{LCI\_ELECTRICj,k} + CONCRETE_{LCI\_PRECOMBUSTk} \\ &\quad\quad + CONCRETE_{LCI\_COMBUSTk} \end{aligned}}$$

Equation 4.131: Calculation of total LCI for concrete batching processes

4.11.5 Non-Process Related Electricity and Fuel Use for Cement Plants

Based on the latest data tables from the “2006 Manufacturing Energy Consumption Survey” (MECS), average non-process related electricity use in cement facilities is estimated. The electricity use factor per kg of cement is calculated using the total cement production amount, which is about 98.2 million metric tonnes according to the USGS Minerals Yearbook [296].

Table 4.60: Manufacturing Energy Consumption Survey (MECS) 2006 - End Uses of Fuel Consumption, Cements Sector [297]

	Net Demand for Electricity (million kWh)	**Electricity use (kWh per kg of cement)**
NAICS Code: 327310 Cements		
Direct Uses, Total, Non-process	***1,902***	***0.019375***
Facility HVAC	765	0.007793
Facility Lighting	622	0.006336

Other Facility Support	363	0.003698
Onsite Transportation	80	0.000815
Other Non-process Use	72	0.000733

$$\boxed{ELECTRICITY_{CEMENT\_FACILITY} = ELECTRIC_{FACTOR\_CEMENTFACILITY} \times M_{CEMENT}}$$

Equation 4.132: Calculation of non-process related electricity use factor in a cement plant

Where:

ELECTRICITY$_{\text{CEMENT\_FACILITY}}$ = Total amount of non-process electricity used in a cement plant, in kWh;

ELECTRIC$_{\text{FACTOR\_CEMENTFACILITY}}$ = Electricity use factor obtained from Table 4.60, which is 0.019375 kWh per kg of portland cement produced at the facility;

M$_{\text{PORTLANDCEMENT}}$ = Total mass of cement produced, calculated in Equation 4.77, in kg.

Cement plant electricity involves facility HVAC, lighting, other support systems, onsite transportation, and other non-process uses.

The LCI associated with the facility electricity use is calculated below and results from the equation are considered in the total cement production electricity use LCI estimation:

$$\boxed{\begin{aligned} &CEMENT_{FACILITY}{}_{LCI_{ELECTRIC}}{}_{j,k} = \\ &\quad ELECTRICITY_{CEMENT_{FACILITY}} \times \\ &\qquad\qquad HLOOKUP\left(LOCATION_j, TRANSPOSE\;[TABLE\;9.9], ROW\#_{LCIF\;j,k}\right) \end{aligned}}$$

Equation 4.133: Calculation of LCI related to non-process electricity use in a cement plant

Where:

CONCRETE$_{\text{LCI\_ELECTRICj,k}}$ = Total life-cycle inventory associated with electricity use during concrete batching, whereas “j” corresponds to the location where the process takes place; in MJ for “k” energy use factor or in kg for life-cycle inventories corresponding to solid waste, water consumption, and air emissions;

ELECTRICITY$_{\text{CONCRETE}}$ = Total amount of electricity used during concrete batching (calculated in Equation 4.121), in kWh;

LOCATION$_{\text{j}}$ = Location of the concrete batching plant “j”, taken from “User Input Page_Quarry/Plant Location, Grid Mix, and Water Supply Input” section and can be State, United States, or user-defined, unitless;

[TABLE 9.9], ROW#$_{\text{LCIFj,k}}$ = Appendix, Table 9.9 with calculated total LCI for electricity grid mix (per kWh of electricity) for location “j”; each row representing a life-cycle inventory “k”, in MJ/kWh for energy use factor or in kg/kWh for other LCI factors listed in the Table.

Non-process electricity use impacts are added to the total cement production results in the tool. Results section tabulates LCI and LCIA from all the processes occurring in the tool. Following chapters briefly describe the results tab in two major parts: LCI and LCIA.

4.12 Results from the Tool

The results from the Excel version of the GreenConcrete LCA are displayed using both tables and graphs in two separate worksheets. The results are broken down by life-cycle phases from cradle-to-gate and further by sources of environmental effects (pre-combustion and combustion fuel use, electricity use, water consumption, and process itself), and environmental effects (solid waste, antimony (Sb), arsenic (As), beryllium (Be), cadmium (Cd), CO_2, CO, chromium (Cr), cobalt (Co), copper (Cu), formaldehyde (CH_2O), lead (Pb), manganese (Mn), mercury (Hg), CH_4, nickel (Ni), NO_x, N_2O, non-methane volatile organic compounds (NMVOC), particulates (PM_{10} and total), selenium (Se), SO_2, VOCs, zinc), and environmental impacts (acidification-air, ecotoxicity-air and water, eutrophication-air and water, global warming potential (GWP)-air, human health cancer-air and water, human health non-cancer-air and water, human health criteria-air, photochemical smog-air) that are adapted from TRACI.

The Web version is limited to only primary energy use, GWP in CO_{2}-eq., criteria air pollutants (CO, NO_x, Pb, PM_{10}, and SO_2) and VOCs by concrete and cement production phases. While criteria air pollutants and VOC results are represented in tabular form, energy use and GWP are displayed in graphical format.

5 Dormitory Building Case Study

Prerequisite data necessary for the LCA of a building case study were obtained from a design and engineering company (Prokon) located in Ankara, Turkey. The case study is located in Istanbul (with temperate climate) and constitutes an 8-story dormitory building complex that was designed as part of a larger project called "Istanbul Seismic Risk Mitigation and Emergency Preparedness Project". Within the project, there are two main dormitory buildings (A and B), a library, a laundry and boiler building, a security building, a transformer building, in addition to the infrastructure and landscaping. The targeted users of the campus development are college students. The project costs 100-million Turkish Liras (TL), whereas the dormitory buildings (A and B) constitute 57.7 million TL as of 2010. Table 5.1 is a brief description of the dormitory building sections A and B, on the basis of the detailed technical information from Prokon.

Table 5.1: Brief description of dormitory buildings in the project

Properties	**Dormitory building section A (A1, A2, A3)**	**Dormitory building section B (B1, B2)**
Width (m)	20.2	35.4
Length (m)	49.5	36
Height (m)	28	28
One-floor area (m^2)	1,000	1,274
Number of floors	8	8
Total floor area (m^2)	**8,000**	**10,195**

Within the scope of the research, materials quantity takeoffs for both cast-in-place reinforced-concrete frame and structural steel frame versions of building B were used in LCA calculations.

5.1 Concrete Frame vs. Steel Frame Buildings

The case building (the focus is "Dormitory Building B") was initially designed as a concrete frame while a steel option was later developed for cost and seismic risk assessment (for earthquake zone type 1) and comparison purposes. Both building options are the same eight-story building with a total area of 10,195 m^2, the exception being the structural frames (reinforced concrete vs. steel). Both buildings are expected to be used for 50 years on the basis of consensus about average building life-time estimates in literature [1, 99, 111, 112, 121, 122]. The functional unit for the case study is defined as "per building with a service life of 50 years".

The substructure of both building types includes concrete foundation with horizontal and vertical water barriers at foundation level. The water barriers are flexible polyolefin (FPO) membrane. The concrete frame building consists of reinforced concrete retaining and shear walls (C25 type concrete), foundation and slabs (C30 type concrete) and beams and columns (C35 type concrete) (Table 5.2). The steel frame is designed with concrete shear walls (C25), concrete foundation and slabs (C30 type concrete) and moment resisting steel frames in one direction and braced steel frames in other direction to resist earthquake loads (see the configuration of structural steel components for steel frame in Figure 5.1). The types of structural steel used in the building include St37, St44, and St52, which are all in compliance with Turkish Standard Institute (TSI) standards. Galvanized steel decking is installed under reinforced concrete slabs with 12 cm slab thickness.

Table 5.2: Characteristics of structural concrete used in dormitory buildings (based on technical specifications from Prokon, 2010)

Concrete Type	**Characteristic compressive strength, fck (MPa)**	**Characteristic tensile strength, fctk (MPa)**	**28-day elasticity module, Ec (MPa)**
C25 (retaining walls)	25	1.8	30,000
C30 (foundation and slabs)	30	1.9	32,000
C35 (beams, columns, staircases)	35	2.1	33,000

For both building types, the major shell components include flat roof panels insulated with extruded polystyrene foam (XPS), hollow-clay brick walls (exterior and interiors), as well as natural stone (andasite and granite) and compact laminate exterior façade claddings, aluminum curtain wall system and sun breakers (screens) for the exterior surfaces, marble sills and parapets for balconies, as well as silicone-based grained exterior facade paint, glazing (glass) for the aluminum-framed exterior windows. Typical interior finishes include aluminum and gypsum suspended board ceilings insulated with rockwool, stairs (colored marble covering and steel handrails), partition walls (glass, gypsum board panels), cement fibre board sandwiched wall system (only in steel frame building), compact laminate interior wall claddings, and flooring (carpet, ceramic tile, terrazzo tile or marble flooring, depending on the future use of the designated area). Additionally, two elevators, one motorized sliding door, and heating/cooling systems constitute the mechanical parts. The list of all building materials together with their descriptions and sources of data is provided in Appendix B, Table 9.11.

The LCA of the dormitory building is developed and quantified by means of a process-based LCA based on literature, manufacturer's product descriptions and technical specifications, and documents from both engineering and construction companies.

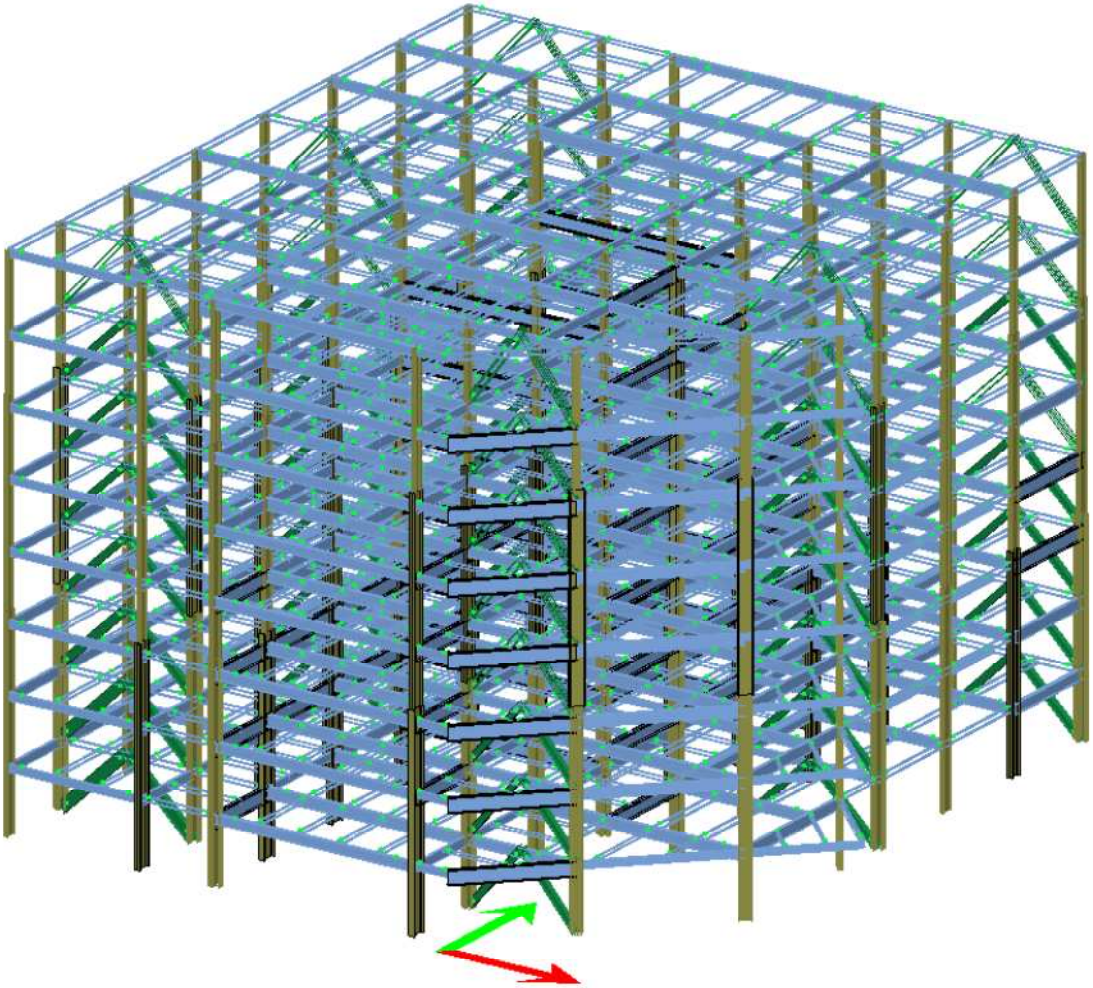


Figure 5.1: Configuration of steel frame elements for the steel dormitory building option (Source: Prokon A.S. 2010)

5.2 Building Materials Extraction and Manufacturing Phase

Table 5.3 lists the quantities of materials used in both types of buildings. Originally, material quantities were documented in units of area, mass, length, or volume. Based on the technical specifications (from Prokon) and product information from manufacturers, all quantities are converted to mass units for ease of calculation and comparison purposes (see Appendix B, Table 9.11).

For the concrete-frame building, reinforced concrete that is used in foundations, beams, slabs, and columns constitutes almost 80% of total weight of the building materials. For the steel-frame, C30 reinforced concrete which is used in foundation contributes to 68% of the total weight, whereas the share of structural steel is only 9%. Differences in quantities and types of various building materials in both structural frame options are shown in Table 5.3. Obviously, the weight percentage of reinforcing steel bars is more (about twice) in concrete- frame building compared to the percentage in steel-frame building. On the other hand, weight percentage of structural steel elements in the steel-frame building (about 9% of total weight) far exceeds the amount used in the concrete frame structure (about 0.04%).

Table 5.3: Input data for building materials and related components used in concrete- and steel-frame buildings

Materials	**Building component (s)**	**Weight of materials (MW_i), concrete frame (kg)**	**% Weight concrete frame**	**Weight of materials (MW_i), steel frame (kg)**	**% Weight steel frame**	**Construction waste factor (%)**	**Typical service life (years) [6, 70, 155, 298-301]**	**Service life-span range (years) [155]**	**No. of replacements**	**Data sources for waste factors**
1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**
Aluminum	Window frames with heat insulation, external	28,217	0.085%	28,217	0.147%	5%	50	25-50	-	[302]
Aluminum	Door frames with no heat insulation, internal	6,550	0.020%	6,550	0.034%	5%	**25**	10-30	1	[302]
Aluminum	Door frames, with heat insulation, external	3,284	0.010%	3,284	0.017%	5%	50	25-50	-	[302]
Aluminum	Suspended ceilings	7,118	0.022%	7,118	0.037%	5%	**25**	15-35	1	[302]
Aluminum	Façade cladding, curtain wall system, standard	3,267	0.010%	3,267	0.017%	5%	50	30-50	-	[302]
Aluminum	Sun breakers (screens)	1,951	0.006%	1,951	0.010%	5%	50	30-50	-	[302]
Brick, hollow, clay	Masonary wall	**1,559,386**	**4.722%**	**530,397**	**2.760%**	10%	50	50-100	-	[303]
Ceramic	Floor covering (tiles)	34,005	0.103%	34,005	0.177%	10%	20	10-30	2	[303]
Ceramic	Wall cladding (tiles)	144,669	0.438%	144,669	0.753%	10%	25	10-30	1	[303]
Concrete, structural	C25, retaining walls	2,220	0.007%	2,220	0.012%	7%	50	47-100	-	[304]
Concrete, structural	C30, foundation	**8,024,487**	**24.299%**	**13,065,191**	**67.982%**	7%	50	60-120	-	[304]
Concrete, structural	C35, beams, columns, slabs	**18,397,224**	**55.710%**	-	-	7%	50	47-100	-	[304]
Concrete, non-structural	150 dose lean concrete, protective surface	581,033	1.759%	581,033	3.023%	7%	50	25-60	-	[304]
Concrete, non-structural	250 dose lean concrete,	611,939	1.853%	611,939	3.184%	7%	50	25-60	-	[304]

Materials	Building component (s)	Weight of materials (MW_i), concrete frame (kg)	% Weight concrete frame	Weight of materials (MW_i), steel frame (kg)	% Weight steel frame	Construction waste factor (%)	Typical service life (years) [6, 70, 155, 298-301]	Service life-span range (years) [155]	No. of replacements	Data sources for waste factors
1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**
	protective surface									
Concrete, non-structural	400 dose leveling concrete, screed, mixed on site	16,314	0.049%	16,314	0.085%	7%	50	25-60	-	[304]
Concrete, non-structural	500 dose leveling concrete, screed, mixed on site	527,056	1.596%	527,056	2.742%	7%	50	25-60	-	[304]
Elevator	Electric human elevator, 2 units per building	1,260	0.004%	1,260	0.007%	0%	25	20-40	1	
Glass, flat	Partition wall, interior, modular	4,683	0.014%	4,683	0.024%	10%	20	10-30	2	[303]
Glass, flat	Window, 4mm heat control coated (low-E) glass + 16mm air space + 4mm flat glass, exterior	63,677	0.193%	63,677	0.331%	10%	50	40-70	-	[303]
Glass, flat	Partition wall, 90 min. fire resistant with automatic glazed door system	3,134	0.009%	3,134	0.016%	10%	15	-	3	[303]
Gypsum board	Partition wall (with rockwool in between two gypsum panels), interior	1,163	**0.004%**	203,011	1.056%	10%	50	30-65	-	[150]
Gypsum board	Suspended ceilings	37,847	**0.115%**	247,502	**0.400%**	10%	25	12-32	1	[150]
Cement fibre board + gypsum board	Wall cladding, external - Only in Steel Building option	-	**0.000%**	76,847	**1.288%**	10%	50	25-50	-	[150]
(XPS) Extruded polystyrene foam	Heat insulation for roofs, basement floor, under floor	22,469	0.068%	22,469	0.117%	10%	50	25-50	0	[150]

Materials	Building component (s)	Weight of materials (MW_i), concrete frame (kg)	% Weight concrete frame	Weight of materials (MW_i), steel frame (kg)	% Weight steel frame	Construction waste factor (%)	Typical service life (years) [6, 70, 155, 298-301]	Service life-span range (years) [155]	No. of replacements	Data sources for waste factors
1	2	3	4	5	6	7	8	9	10	11
	coverings, and exterior façade casing									
Flexible polyolefin (FP) membrane	Horizontal and vertical water insulation at foundation level, basement, and lowered floor	1,473	0.004%	1,473	0.008%	10%	50	25-50	0	[101]
Polypropylene membrane	Vapor barrier, wet cores	2,285	0.007%	2,285	0.012%	10%	50	25-50	0	[101]
Rock wool	Sound insulation for suspended ceilings	4,100	0.012%	4,100	0.021%	10%	25	12-32	1	[150]
Marble	Floor covering tiles, as well as sill, parapet and capping	517,732	1.568%	517,732	2.694%	5%	50	30-65	-	[101]
Lime washing with quick lime	Ceiling cover	540	0.002%	540	0.003%	7%	5	4-10	9	[304]
Paint, water based	Matt paint, interior	2,561	0.008%	2,561	0.013%	7%	5	4-10	9	[304]
Paint, water based	Semi-matt paint, interior	3,685	0.011%	3,685	0.019%	7%	5	4-10	9	[304]
Paint, silicone and water based	Grained paint, exterior facade	1,255	0.004%	1,255	0.007%	7%	10	10-20	4	[304]
Paint, silicone and water based	Decorative paint, interiors	633	0.002%	633	0.003%	7%	5	4-10	9	[304]
Paint, silicone and water based	Fasarit brand spray paint, exterior facade surfaces	9,179	0.028%	1,353	0.007%	7%	10	10-20	4	[304]
Paint_Anti mold	Anti-mold paint	679	0.002%	679	0.004%	7%	5	4-10	9	[304]
Plaster, lime-	Exterior façade	14,829	0.021%	14,829	0.077%	7%	50	30-60	-	[304]

Materials	Building component (s)	Weight of materials (MW_i), concrete frame (kg)	% Weight concrete frame	Weight of materials (MW_i), steel frame (kg)	% Weight steel frame	Construction waste factor (%)	Typical service life (years) [6, 70, 155, 298-301]	Service life-span range (years) [155]	No. of replacements	Data sources for waste factors
1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**
based	surface									
Plaster, gypsum-based	Interior façade surface	589,566	0.744%	42,750	0.222%	7%	50	30-60	-	[304]
Polyamide	Floor covering (carpet)	421	0.001%	421	0.002%	6%	8	5-15	6	[301]
PVC	Floor covering	11,442	0.035%	11,442	0.060%	6%	8	5-15	6	[301]
Steel, structural	Reinforcing bar (ribbed, in any diameter)	**1,926,400**	**5.833%**	463,570	2.412%	0.25%	50	30-70	-	[119]
Steel, structural	Reinforcement mesh	1,730	0.005%	76,730	0.399%	0.25%	50	30-70	-	[119]
Steel, structural	Hot-dip galvanized with zinc alloy, oil-painted (TS 914 EN ISO 1461)	12,054	0.037%	**1,695,052**	**8.820%**	0.25%	50	30-70	-	[119]
Steel, non-structural	Hot-dip galvanized steel; various iron, metal sheet, plate, and sections	14,723	0.045%	14,723	0.077%	0.25%	50	30-70	-	[119]
Steel, non-structural	Steel handrails with 2 layers of oil-paint steel; stairs, balcony	888	0.003%	888	0.005%	0.25%	50	30-70	-	[119]
Steel, stainless	Guardrails, gutters	9,608	0.029%	9,608	0.050%	0.25%	50	30-70	-	[119]
Steel, galvanized	90 min. fire resistant door and subframe made of galvanized steel	416	0.001%	416	0.002%	0%	10 (technical specs.)	-	4	
Stone, natural	Façade cladding	24,671	0.075%	24,671	0.128%	5%	50	40-75	-	[101]
Terrazzo tiles	Floor covering, interior surfaces	40,860	0.124%	40,860	0.213%	1%	50	30-60	-	[6]
Terrazzo tiles	Floor covering, exterior surfaces	6,995	0.021%	6,995	0.036%	1%	50	30-60	-	[6]

Materials	Building component (s)	Weight of materials (MW_i), concrete frame (kg)	% Weight concrete frame	Weight of materials (MW_i), steel frame (kg)	% Weight steel frame	Construction waste factor (%)	Typical service life (years) [6, 70, 155, 298-301]	Service life-span range (years) [155]	No. of replacements	Data sources for waste factors
1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**
Wood, laminated	Door, interior	53,345	0.162%	53,345	0.278%	0%	30	20-50	1	[304]
Wood, laminated	Floor covering (parquet)	6,603	0.020%	6,603	0.034%	4%	20	15-50	2	[300]
Wood, laminated	Facade cladding Compact, high-pressure (HPL)	25,613	0.078%	25,613	0.133%	4%	50	30-65	-	[300]
Wood, hard	American panel door leaf + frame (100x220), interior	7,584	0.023%	7,584	0.039%	0%	25	20-40	1	[305, 306]
Door system	Automatic revolving door, one unit	337	0.001%	337	0.002%	0%	25	25-50	1	[307]
Copper, wire and conductors	Electrical	266	0.001%	266	0.01%	7%	35		1	[308]
Total Weight (kg)		**33,023,515**	**100%**	**19,210,796**	**100%**					

Following the structural components, brick (hollow clay type) walls constitute about 5% of total weight of the concrete frame as opposed to 3% share in the steel frame. While a considerable amount of cement fibre boards are used as façade claddings in steel-frame building, none is used in concrete-frame option. All other materials are more or less similar by weight percentages, as observed in Table 5.3.

5.2.1 LCI Results for Building Materials

As stated before, based on the quantity takeoff and information from manufacturers (from Table 5.3 and Appendix B, Table 9.11) and energy consumption and emission factors (from Appendix B, Table 9.14 and Table 9.15), total primary energy consumption and associated GWP for both concrete- and steel-framed buildings are calculated and listed in Table 5.4. Results are limited to only two environmental measures since energy use and GWP are currently the only available data for all building materials in the case study. Calculations involve multiplication of the quantity of material with the corresponding energy use and/or emission factor (GWP in this case) obtained from many different data sources. LCA results for the building materials are summarized in Figure 5.2 and Figure 5.3 by building material type (e.g., aluminum, concrete, marble, glass, etc.). In Figure 5.4 and Figure 5.5, results are shown by building components (e.g., wall systems, doors, windows, and ceilings, etc.). As clearly observed in both of the cases, structural materials (and components), which are steel and concrete, consume the largest amount of energy during their manufacturing. Consequently, the same structural materials (and components) are the major sources of GWP. Non-structural concrete used in surface protection and screeding, aluminum and clay bricks follow structural concrete and steel components in energy use and GWP ranking.

Table 5.4: Total building materials primary energy consumption and GHG emissions results, calculated

			Concrete Frame		**Steel Frame**	
#	**Material**	**Building component or element (s)**	**Primary Energy (GJ)**	**GHG (metric tons CO_2-eq.)**	**Primary Energy (GJ)**	**GHG (metric tons CO_2-eq.)**
1	Aluminum	Window frames with heat insulation, external	5.39E+03	8.70E+01	5.39E+03	8.70E+01
2	Aluminum	Door frames with no heat insulation, internal	1.43E+03	6.03E+01	1.43E+03	6.03E+01
3	Aluminum	Door frames, with heat insulation, external	6.27E+02	1.01E+01	6.27E+02	1.01E+01
4, 5	Aluminum	Suspended ceilings	2.23E+03	8.41E+01	2.23E+03	8.41E+01
6	Aluminum	Façade cladding, curtain wall system, standard	2.83E+02	1.66E+01	2.83E+02	1.66E+01
7	Aluminum	Sun breakers (screens)	6.10E+02	2.30E+01	6.10E+02	2.30E+01
8, 9, 10, 11	Brick, hollow, clay	Wall	6.79E+03	3.44E+02	2.31E+03	1.17E+02
12	Ceramic	Floor covering (tiles)	3.85E+02	2.23E+01	3.85E+02	2.23E+01
13	Ceramic	Wall cladding (tiles)	1.76E+03	1.01E+02	1.76E+03	1.01E+02
14	Concrete,	C25, retaining walls	6.12E+01	1.20E+01	6.12E+01	1.20E+01

			Concrete Frame		Steel Frame	
#	Material	Building component or element (s)	Primary Energy (GJ)	GHG (metric tons CO_2-eq.)	Primary Energy (GJ)	GHG (metric tons CO_2-eq.)
	structural					
15	Concrete, structural	C30, foundation	7.90E+03	1.57E+03	1.29E+04	2.56E+03
16	Concrete, structural	C35, beams, columns, slabs	1.98E+04	3.99E+03	0.00E+00	0.00E+00
17	Concrete, non-structural	150 dose lean concrete, protective surface	4.09E+02	7.73E+01	4.09E+02	7.73E+01
18	Concrete, non-structural	250 dose lean concrete, protective surface	5.49E+02	1.14E+02	5.49E+02	1.14E+02
19	Concrete, non-structural	400 dose leveling concrete, screed, mixed on site	2.90E+02	2.50E+01	2.90E+02	2.50E+01
20	Concrete, non-structural	500 dose leveling concrete, screed, mixed on site	9.06E+03	7.99E+02	9.06E+03	7.99E+02
21	Elevator (equipment)	Electric human elevator, 2 units per building	2.29E+02	1.41E+01	2.29E+02	1.41E+01
22	Glass, flat	Partition wall, interior, modular	7.26E+01	5.32E+00	7.26E+01	5.32E+00
23	Glass, flat	Window, 4mm heat control coated (low-E) glass + 16mm air space + 4mm flat glass, exterior	2.01E+03	1.47E+02	2.01E+03	1.47E+02
24	Glass, flat	Partition wall, 90 min. fire resistant with automatic glazed door system	1.67E+02	7.30E+00	1.67E+02	7.30E+00
25	Gypsum board	Partition wall (with rockwool in between two gypsum panels), interior	1.62E+00	9.02E-02	2.83E+02	1.57E+01
26	Gypsum board	Suspended ceilings	2.90E+02	1.61E+01	5.89E+02	3.28E+01
27	Cement fibre board + gypsum board	Wall cladding, external - Only in Steel Building option	0.00E+00	0.00E+00	3.09E+03	1.79E+02
28, 29, 30, 31	(XPS) Extruded polystyrene foam	Heat insulation for roofs, basement floor, under floor coverings, and exterior façade casing	2.04E+03	4.30E+01	2.04E+03	4.30E+01
32, 33, 34, 35, 36	Flexible polyolefin (FP) membrane	Horizontal and vertical water insulation at foundation level, basement, and lowered floor	4.71E+00	2.21E-01	4.71E+00	2.21E-01
37, 38	Polypropylene	Vapor barrier, wet cores	7.07E+00	3.82E+00	7.07E+00	3.82E+00

			Concrete Frame		**Steel Frame**	
#	**Material**	**Building component or element (s)**	**Primary Energy (GJ)**	**GHG (metric tons CO_2-eq.)**	**Primary Energy (GJ)**	**GHG (metric tons CO_2-eq.)**
	membrane					
39a, 39b	Rock wool	Sound insulation for suspended ceilings	6.85E+01	3.30E+00	6.85E+01	3.30E+00
40	Wood, laminated	Floor covering (parquet)	9.26E+02	1.28E+01	9.26E+02	1.28E+01
41	Wood, laminated	Door, interior	6.78E+02	-7.40E+00	6.78E+02	-7.40E+00
42	Wood, laminated	Facade cladding, exterior and interior surfaces. Compact, high-pressure (HPL)	1.45E+03	4.36E+01	1.45E+03	4.36E+01
43	Wood, hard	American panel door leaf + frame (100x220), interior	2.15E+02	-5.32E+00	2.15E+02	-5.32E+00
44	Other, equipment	Automatic revolving or sliding door, one unit	2.05E+01	1.29E+00	2.05E+01	1.29E+00
45, 46, 47, 48	Marble	Floor covering tiles, as well as sill, parapet and capping	3.42E+02	6.07E+01	3.42E+02	6.07E+01
49	Lime washing with quick lime	Ceiling cover	3.37E+00	4.15E-01	3.37E+00	4.15E-01
50	Paint, water based	Matt paint, interior	7.53E+01	3.71E+00	7.53E+01	3.71E+00
51	Paint, water based	Semi-matt paint, interior	9.96E+01	4.91E+00	9.96E+01	4.91E+00
52	Paint, silicone and water based	Grained paint, exterior facade	5.71E+00	2.81E-01	5.71E+00	2.81E-01
53	Paint, silicone and water based	Decorative paint, interiors	2.12E+01	1.04E+00	2.12E+01	1.04E+00
54	Paint, silicone and water based	Fasarit brand spray paint, exterior facade surfaces	3.51E+01	1.73E+00	3.51E+01	1.73E+00
55	Paint_Anti mold	Anti-mold paint	1.63E+01	8.04E-01	1.63E+01	8.04E-01
56	Plaster, lime-based	Exterior façade surface	1.45E+01	2.18E+00	1.45E+01	2.18E+00
57	Plaster, gypsum-based	Interior façade surface	8.82E+02	5.95E+01	1.53E+02	1.04E+01
58	Polyamide	Floor covering (carpet)	1.39E+01	5.70E-01	0.00E+00	0.00E+00
59	PVC	Floor covering	8.08E+02	3.77E+01	0.00E+00	0.00E+00
60a	Steel, structural	Reinforcing bar (ribbed, in any diameter)	3.88E+04	3.24E+03	9.33E+03	7.79E+02
60b	Steel, structural	Reinforcement mesh	3.48E+01	2.91E+00	1.54E+03	1.29E+02
61	Steel, structural	Steel, structural, hot-rolled	5.68E+02	3.86E+01	6.54E+04	4.45E+03

			Concrete Frame		Steel Frame	
#	**Material**	**Building component or element (s)**	**Primary Energy (GJ)**	**GHG (metric tons CO_2-eq.)**	**Primary Energy (GJ)**	**GHG (metric tons CO_2-eq.)**
62a	Steel, non-structural	Hot-dip galvanized steel (TS 914 EN ISO 1461) - various iron, metal sheet, plate, and sections	4.65E+02	3.16E+01	5.68E+02	3.86E+01
62b	Steel, non-structural	Steel handrails with 2 layers of oil-paint steel (stairs, balcony)	3.43E+01	2.33E+00	3.43E+01	2.33E+00
63	Steel, stainless	Guardrails, gutters, etc.	7.21E+02	6.53E+01	7.21E+02	6.53E+01
64	Steel, galvanized	90 min. fire resistant door and subframe _galvanized steel (110x220)	2.26E+01	1.47E+00	2.26E+01	1.47E+00
65	Stone, natural (basalt andasite and granite)	Façade cladding	2.41E+02	1.80E+01	2.41E+02	1.80E+01
66a	Terrazzo tiles	Floor covering, interior surfaces	6.53E+01	4.50E+00	6.53E+01	4.50E+00
66b	Terrazzo tiles	Floor covering, exterior surfaces	1.12E+01	7.71E-01	1.12E+01	7.71E-01
69	Copper, wire and conductors	Electrical round shaped conductors	3.65E+01	2.07E+00	3.65E+01	2.07E+00

Note: #67 and #68 items which are steel and wood formwork, respectively, are considered in temporary materials LCA section.

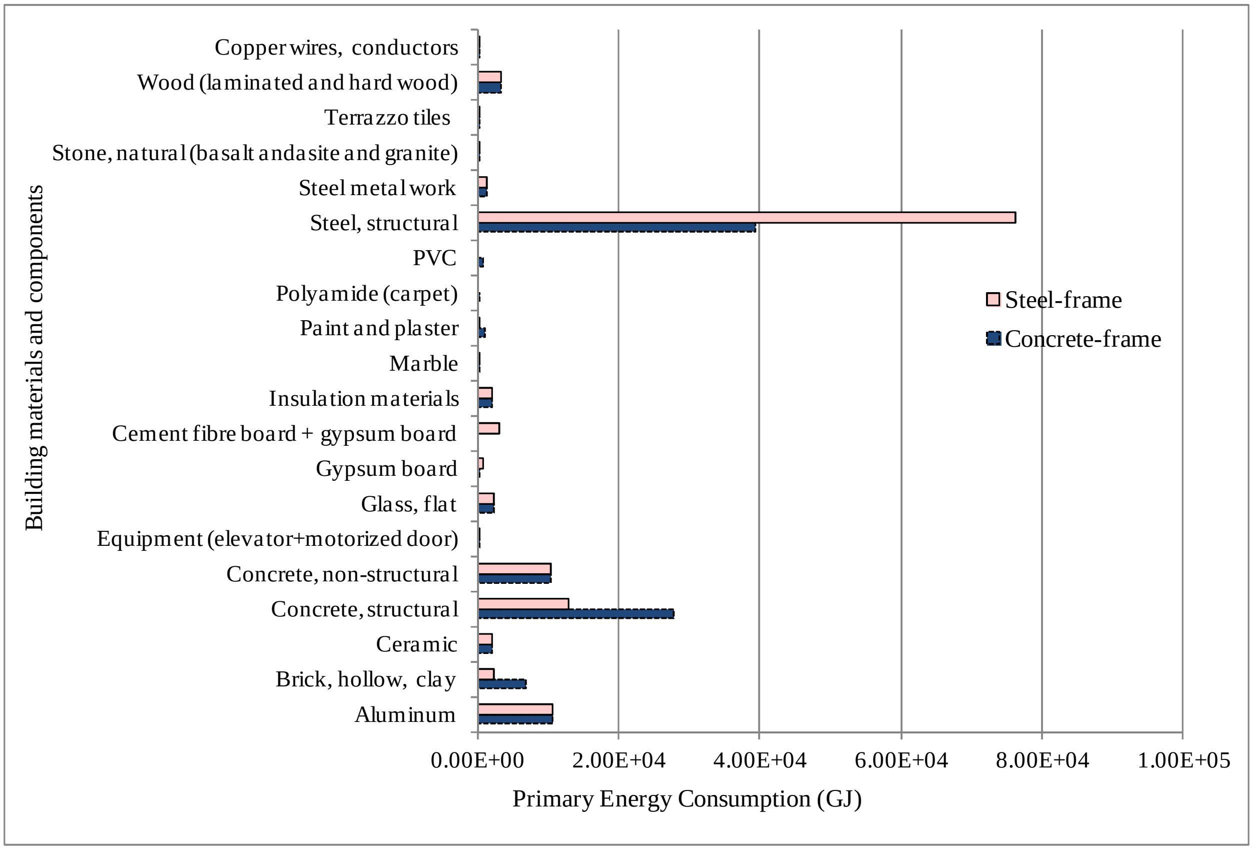


Figure 5.2: Primary energy consumption related with materials manufacturing (concrete vs. steel frame)

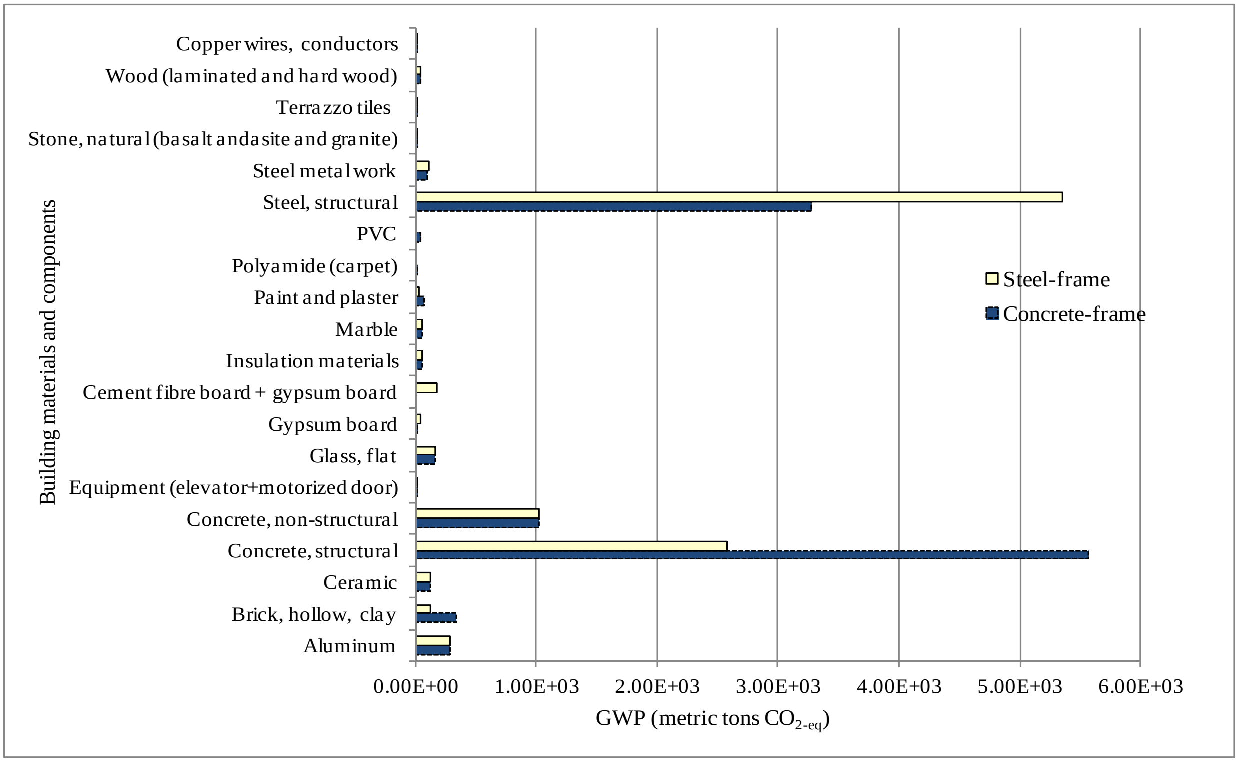


Figure 5.3: GWP related with materials manufacturing

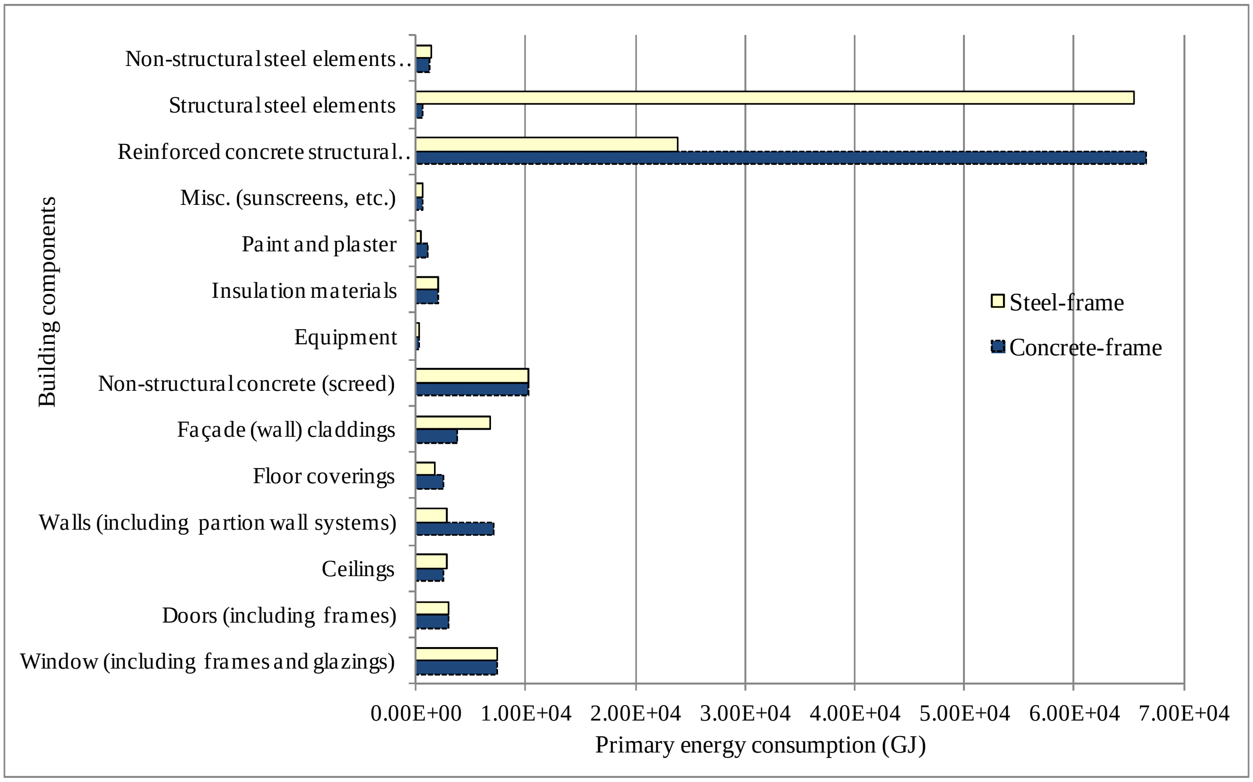


Figure 5.4: Primary energy consumption related with major building components for concrete- and steel-framed buildings

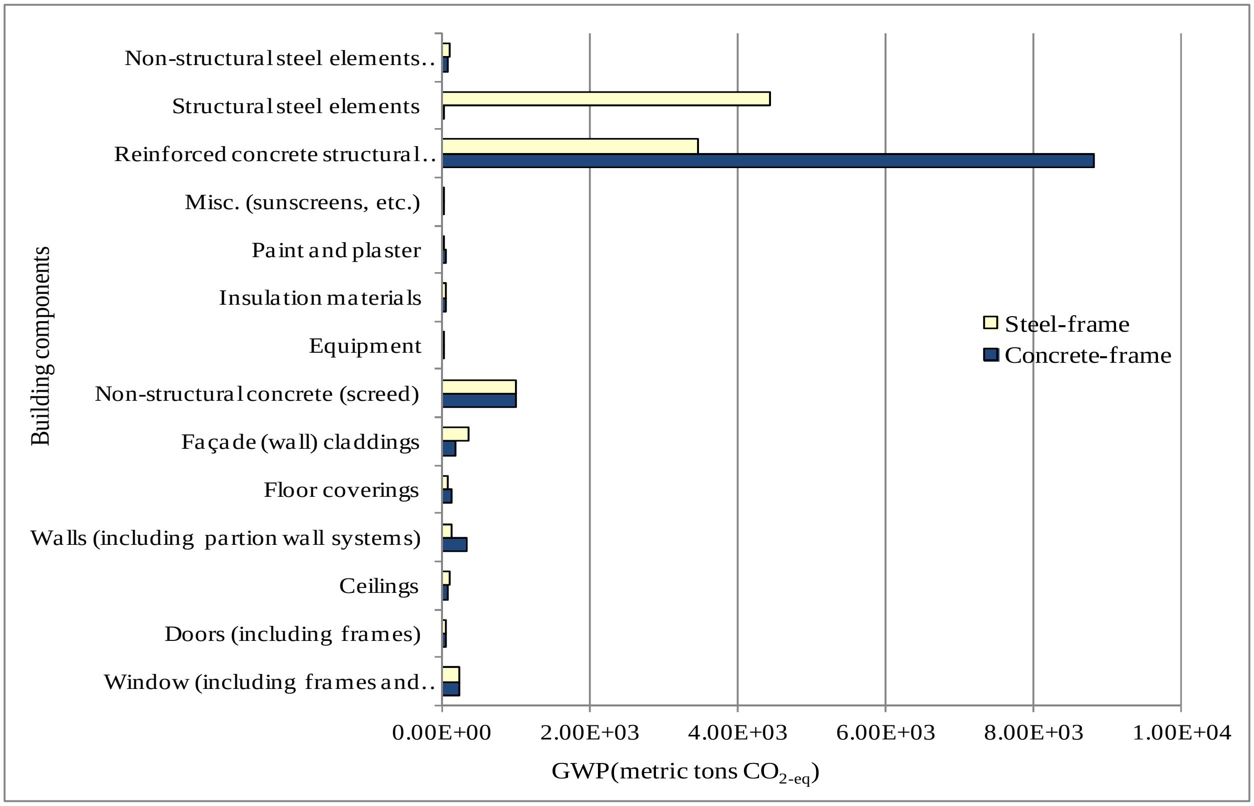


Figure 5.5: GWP related with major building components for concrete- and steel-framed building

5.3 Construction Phase

To estimate energy use and activity-level emissions associated with the transportation of building materials and equipment to/from construction site and on-site equipment use during construction of buildings, various data sources are utilized. The following sections describe these major data sources and approaches applied throughout the construction phase LCA calculations.

5.3.1 Transportation of Building Materials and Equipment to/from Construction Site Input

Prior to calculating the impacts from construction, first transportation of materials (including temporary materials) and equipment to the site are considered. It is assumed that all trucks are "2004+" model with 45,000 cumulative miles with varying truck weight classes. Table 5.5 provides an overview of heavy-duty vehicle classes with their gross vehicle weight ratings (GVW is the weight of the truck when it is fully loaded including cargo, fuel, and passengers) and cargo weight capacities (or truck capacity). Both GVWR and truck capacity values are utilized in estimating truck-related energy consumption and air emissions for concrete- and steel-frame dormitory buildings.

Table 5.5: Heavy-duty vehicle classifications (based on U.S. EPA's MOBILE 6 [309, 310] and SmartWay Truck Tool [311])

Diesel-engine Heavy Duty Truck Classification in MOBILE6	Description	Gross Vehicle Weight Rating (GVWR) (lb)	Cargo Weight or Truck Capacity (metric tons)
2B	Light heavy-duty diesel trucks	8,501-10,000	1.20
3	Light heavy-duty diesel trucks	10,001-14,000	1.90
4	Light heavy-duty diesel trucks	14,001-16,000	2.70
5	Light heavy-duty diesel trucks	16,001-19,500	3.60
6	Medium heavy-duty diesel trucks	19,501-26,000	4.90
7	Medium heavy-duty diesel trucks	26,001-33,000	6.60
8A	Heavy heavy-duty diesel trucks	33,001-60,000	10.90
8B	Heavy heavy-duty diesel trucks	> 60,000	23.00

In addition to the truck classification information, transportation LCI calculations require average one-way distance for transporting the materials and equipment from supplier or manufacturer to the construction site, number of trips to the site, return utilization factor, sulfur content of diesel fuel, and construction waste factors. Table 5.6 and Table 5.7 summarize the quantities of major structural materials and temporary materials together with the weight of construction equipment and their delivery destinations and distances. Table 5.8 provides the transportation-related input data for both concrete- and steel-framed buildings. Within the table, the U.S. EPA's MOBILE 6 data [309, 310, 312] are commonly applied for calculations. The related data are presented in Appendix C (Table 9.16 through Table 9.21). In Table 5.8, model year, cumulative truck mileage, truck weight classes, return utilization factor, and fuel sulfur content data are selected from the drop-down lists in Excel format of construction LCA calculations using the GreenConcrete tool. Average one-way trip distances to and from the construction site are determined based on the location of material (or equipment) suppliers. Construction waste percentages are obtained from literature and provided in Table 5.3. Truck fuel efficiency (mpg) in Column #5 (Table 5.8) is estimated on the basis of two variables: truck model year (Column #2) and corresponding fuel economies obtained from Appendix C, Table

9.17. Based on the truck weight class selected, matching cargo weight or truck capacity (except for the concrete mixer drum capacity that is based on the mixer truck manufacturer's data) is taken from Table 5.5 and this number is used in calculating the "number of trips to the site" for both building types:

$$\begin{aligned} &Number\ of\ Trips\ to\ Site \\ &\qquad = Weight\ (Volume)\ of\ Material\ or\ Equipment/Truck\ (Mixer)\ Capacity \end{aligned}$$

Equation 5.1: Calculation of number of trips by truck to the construction site

Where:

Number of Trips to Site = number of trips made by a truck or concrete truck mixer to deliver building materials or construction equipment to site/ from site, unitless;

Weight (Volume) of Material or Equipment = Represents the weight of building materials (Table 5.3) or construction equipment (Appendix C, Table 9.28, in metric tons or volume of concrete, in m^3;

Truck (Mixer) Capacity = Represents the cargo carrying capacity of a heavy-duty vehicle (Table 5.5), in tonnes or drum capacity of a concrete truck mixer (Appendix C, Table 9.28), in m^3.

A return factor of "1" is assigned in Table 5.8 to represent a truck that is fully allocated to deliver only the specified material or equipment to the construction site and then it returns to the manufacturer or the supplier empty. Only the excavated soil is assigned a factor of "0". When the equipment is rented, it is returned to the supplier and related transportation numbers are given under the "Equipment from Site" row in Table 5.8.

The approach for calculating the weight of the total site waste from concrete frame construction is adapted from CDEST [119] and interpreted as follows:

$$MW_{SW} = MW_{WFORM} \times (1 + WF_{FORM}) + MW_C \times W_C$$

Equation 5.2: Calculation of total site waste related with concrete frame construction

Where:

MW_{SW} = Total site waste (in debris box), in metric tons;

MW_{FORM} = Plywood form weight, from Table 5.6, in metric tons;

WF_{FORM} = Waste factor for the plywood form [101], in %;

MW_C = Concrete weight, from Table 5.3, in metric tons;

WF_C= Waste factor for concrete, Table 5.3, %

In the calculations, it is assumed that the plywood formwork material is used the maximum times possible and then disposed in the debris box. In contrast, steel forms are returned to the supplier (rented) and therefore not included in Equation 5.2. In case of the steel frame construction, waste generation is calculated as follows:

$$MW_{SW} = MW_{FORM} \times (1 + WF_{FORM}) + MW_C \times WF_C + MW_{FP} \times WF_{FP} + MW_S \times WF_S$$

Equation 5.3: Calculation of total site waste for steel frame construction

Where:

MW_{SW} = Total site waste (in debris box), in metric tons;

MW_{FORM} = Plywood form weight, Table 5.7, in metric tons;

WF_{FORM} = Waste factor for the plywood form [101], in %;

MW_{C} = Concrete weight, from Table 5.3, in metric tons;

WF_{C}= Waste factor for concrete, Table 5.3, in %;

MW_{FP} = Fireproofing weight, Table 5.7, in metric tons;

WF_{FP}= Waste factor for fireproofing, CDEST [119], in %;

MW_{S} = Structural steel weight, from Table 5.3, in metric tons;

WF_{S}= Waste factor for structural steel, from Table 5.3, in %;

The amounts of consumable materials, such as form release oil, are calculated on the basis of data from literature [85]. Accordingly, about 180 ml of form oil is used per m^3 of concrete. The unit weight of form release oil is 7.43 lbs/gallon.

In case of the steel-framed building, since the steel elements are already purchased as painted with oil-based paint from the manufacturers, there is no requirement for additional painting in calculations. However, about 0.09 metric tonnes of cementitious fireproofing is applied per square meter of the steel frame based on Prokon's estimations.

During the construction stage, water is used for cleaning the concrete pump, hose, as well as for washing the exterior and interior of trucks on site. Since unused concrete in the mixing drum cannot be used, it needs to be washed out. The washoff is performed for truck exterior to prevent cement build-up on truck drum exteriors and to give truck a clean look during its transit. Potable water is usually preferred for washoff [47, 271].

Table 5.6: Summary of materials, temporary and consumable materials and equipment weight associated with construction and transportation phases for reinforced concrete frame

	Quantity	**Units**	**Destination**	**One-Way Distance (km)**
Concrete, structural	11,827	m^3	Site	20
Reinforcing bar	1,926	tonne	Site	300
Plywood formwork	13	tonne	Site	100
Steel formwork	557	tonne	Site	100
Form release oil	2	tonne	Site	100
Debris box	1,864	tonne	Site	20
Air compressor	2	tonne	Site	50
Forklift	16	tonne	Site	50
Small equipment	14	tonne	Site	50
Forklift	16	tonne	Supplier	50
Small equipment	14	tonne	Supplier	50
Concrete pump	1	piece	Site	50
Crane	1	piece	Site	50
Concrete mixer delivering the concrete, pump, and crane are assumed to travel to the site under its own power				

Table 5.7: Summary of materials, temporary materials and equipment weight associated with construction and transportation phases for steel frame

	Quantity	**Units**	**Destination**	**One-Way Distance (km)**
Concrete, structural (foundation)	13,067	m^3	Site	20
Reinforcing bar	464	tonne	Site	300
Steel, structural	1,695	tonne	Site	300
Fireproofing for steel frame members	12	tonne	Site	300
Plywood formwork	13	tonne	Site	100
Form release oil	2.1	tonne	Site	100
Debris box	934	tonne	Site	20
Air compressor	2	tonne	Site	50
Forklift	16	tonne	Site	50
Small Equipment	14	tonne	Site	50
Forklift	16	tonne	Supplier	50
Small Equipment	2	tonne	Supplier	50
Concrete pump	1	piece	Site	50
Crane	1	piece	Site	50

Table 5.8: Transportation input for concrete-frame and steel-frame buildings

Item (Material, product or equipment)	Model year	Cummulative truck mileage (10K mi)	Truck weight classes*	Truck fuel efficiency (mpg)	Truck capacity (TCd$_i$) (tonnes) (concrete, m^3)	Average one-way distance (OD$_i$) (km)	Return factor (RF$_i$) (0-1)	Number of trips to site (concrete frame)	Number of trips to site (steel frame)	Sulfur content of diesel fuel (ppm)	Waste factor (WF$_i$),%
1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
Excavated soil	2004+	45	8B	6	23	100	0	2,059	2,059	15	-
Backfill (brought from outside area)	2004+	45	8B	6	23	100	1	849	849	15	-
Sandfill	2004+	45	8B	6	23	100	1	4	4	15	-
Aluminum - Window frames with heat insulation, external	2004+	45	7	8	7	150	1	5	5	15	5%
Aluminum - Door frames with no heat insulation, internal	2004+	45	7	8	7	150	1	1	1	15	5%
Aluminum - Door frames, with heat insulation, external	2004+	45	7	8	7	150	1	1	1	15	5%
Aluminum - Suspended ceilings	2004+	45	7	8	7	150	1	2	2	15	5%
Aluminum - Façade cladding -Curtain wall system, standard	2004+	45	7	8	7	150	1	1	1	15	5%
Aluminum - Sun breakers (screens)	2004+	45	4	10	3	150	1	1	1	15	5%
Brick, hollow, clay - Wall	2004+	45	8A	7	11	50	1	**144**	**49**	15	10%
Ceramic - Floor covering (tiles)	2004+	45	7	8	7	50	1	6	6	15	10%
Ceramic - Wall cladding (tiles)	2004+	45	7	8	7	50	1	22	22	15	10%
Concrete, structural - C25, retaining walls	2004+	45	8B	6	8	20	1	**4**	**1**	15	7%
Concrete, structural - C30, foundation	2004+	45	8B	6	8	20	1	**447**	**569**	15	7%
Concrete, structural - C35, beams, columns, slabs	2004+	45	8B	6	8	20	1	**1,024**	**0**	15	7%
Concrete, non-structural - 150 dose lean concrete, protective surface	2004+	45	8B	6	8	20	1	**73**	**26**	15	7%

Concrete, non-structural - 250 dose lean concrete, protective surface	2004+	45	8B	6	8	20	1	77	27	15	7%
Concrete, non-structural - 400 dose leveling concrete, screed, mixed on site	2004+	45	8B	6	23	20	1	1	1	15	7%
Concrete, non-structural - 500 dose leveling concrete, screed, mixed on site	2004+	45	8B	6	23	20	1	23	23	15	7%
Elevator (equipment) - Electric human elevator, 2 units per building	2004+	45	4	10	3	120	1	1	1	15	0%
Glass, flat - Partition wall, interior, modular	2004+	45	4	10	3	60	1	2	2	15	10%
Glass, flat - Window, 4mm heat control coated (low-E) glass + 16mm air space + 4mm flat glass, exterior	2004+	45	7	8	7	60	1	10	10	15	10%
Glass, flat - Partition wall, 90 min. fire resistant with automatic glazed door system	2004+	45	4	10	3	60	1	2	2	15	10%
Gypsum board - Partition wall (with rockwool in between two gypsum panels), interior	2004+	45	4	10	3	180	1	1	76	15	10%
Gypsum board - Suspended ceilings	2004+	45	7	8	7	180	1	6	12	15	10%
Cement fibre board + gypsum board - Wall cladding, external - Only in Steel Building option	2004+	45	4	10	3	180	1	0	92	15	10%
(XPS) Extruded polystyrene foam - Heat insulation for roofs, basement floor, under floor coverings, and exterior façade casing	2004+	45	7	8	7	400	1	4	4	15	10%
Flexible polyolefin (FP) membrane - Horizontal and vertical water insulation at foundation level, basement, and lowered floor	2004+	45	4	10	3	400	1	1	1	15	10%

Polypropylene membrane - Vapor barrier, wet cores	2004+	45	4	10	3	400	1	1	1	15	10%
Rock wool - Sound insulation for suspended ceilings	2004+	45	4	10	3	400	1	2	2	15	10%
Marble - Floor covering tiles, as well as sill, parapet and capping	2004+	45	7	8	7	400	1	79	79	15	5%
Lime washing with quick lime - Ceiling cover	2004+	45	4	10	3	80	1	1	1	15	7%
Paint, water based - Matt paint, interior	2004+	45	4	10	3	80	1	1	1	15	7%
Paint, water based - Semi-matt paint, interior	2004+	45	4	10	3	80	1	2	2	15	7%
Paint, silicone and water based - Grained paint, exterior facade	2004+	45	4	10	3	80	1	1	1	15	7%
Paint, silicone and water based - Decorative paint, interiors	2004+	45	4	10	3	80	1	1	1	15	7%
Paint, silicone and water based - Fasarit brand spray paint, exterior facade surfaces	2004+	45	4	10	3	80	1	4	1	15	7%
Paint_Anti mold - Anti-mold paint	2004+	45	4	10	3	80	1	1	1	15	7%
Plaster, lime-based - Exterior façade surface	2004+	45	4	10	3	80	1	3	6	15	7%
Plaster, gypsum-based - Interior façade surface	2004+	45	7	8	7	80	1	38	7	15	7%
Polyamide - Floor covering (carpet)	2004+	45	4	10	3	120	1	1	1	15	6%
PVC - Floor covering	2004+	45	7	8	7	150	1	2	2	15	6%
Steel, structural - Reinforcing bar (ribbed, in any diameter)	2004+	45	8A	7	11	300	1	177	43	15	0.25%
Steel, structural - Reinforcement mesh	2004+	45	4	10	3	300	1	1	29	15	0.25%
Steel, structural - Hot-dip galvanized with zinc alloy and oil-painted	2004+	45	7	8	7	300	1	2	257	15	0.25%

Steel, non-structural - Hot-dip galvanized steel (TS 914 EN ISO 1461) - various iron, metal sheet, plate, and sections	2004+	45	7	8	7	300	1	3	3	15	0.25%
Steel, non-structural - Steel handrails with 2 layers of oil-paint steel (stairs, balcony)	2004+	45	4	10	3	300	1	1	1	15	0.25%
Steel, stainless - Guardrails, gutters, etc.	2004+	45	7	8	7	300	1	2	2	15	0.25%
Steel, galvanized - 90 min. fire resistant door and subframe _galvanized steel (110x220)	2004+	45	4	10	3	300	1	1	1	15	0%
Stone, natural (basalt andasite and granite) - Façade cladding	2004+	45	7	8	7	400	1	4	4	15	5%
Terrazzo tiles - Floor covering, interior surfaces	2004+	45	7	8	7	120	1	7	7	15	1%
Terrazzo tiles - Floor covering, exterior surfaces	2004+	45	4	10	3	120	1	3	3	15	1%
Wood, laminated - Door, interior	2004+	45	7	8	7	120	1	9	9	15	0%
Wood, laminated - Floor covering (parquet)	2004+	45	4	10	3	120	1	3	3	15	4%
Wood, laminated - Facade cladding, exterior and interior surfaces. Compact, high-pressure (HPL)	2004+	45	7	8	7	120	1	4	4	15	4%
Wood, hard - American panel door leaf + frame (100x220), interior	2004+	45	4	10	3	120	1	3	3	15	0%
Other (Equipment) - Automatic revolving or sliding door, one unit	2004+	45	4	10	3	200	1	1	1	15	0%
Copper wires and conductors	2004+	45	4	10	3	100	1	1	1	15	7%
Temporary Materials to Site											
Fireproofing for steel frame members	2004+	45	7	8	7	300	1	-	2	15	5%
Form release oil	2004+	45	4	10	3	100	1	1	1	15	7%

Plywood formwork material	2004+	45	8A	7	11	100	1	2	1	15	9%
Steel formwork	2004+	45	8A	7	11	100	1	52	-	15	0%
Temporary Materials from Site											
Debris box	2004+	45	8A	7	11	20	1	171	86	15	-
Steel formwork material	2004+	45	8A	7	11	100	1	52	-	15	-
***Equipment to Site**											
Air compressor	2004+	45	4	10	3	50	1	1	1	15	-
Concrete pump	2004+	45	8A	7	N/A	50	0	1	1	15	-
Crane	2004+	45	**8B**	6	N/A	50	0	1	1	15	-
Excavator	2004+	45	8B	6	N/A	50	0	1	1	15	-
Forklift	2004+	45	8B	7	11	50	1	1	1	15	-
Loader	2004+	45	8B	6	N/A	50	0	1	1	15	-
Miscellaneous small equipment	2004+	45	8B	7	11	50	1	1	1	15	-
***Equipment from Site**											
Air compressor	2004+	45	4	10	3	50	1	1	1	15	-
Concrete pump	2004+	45	8A	7	N/A	50	0	1	1	15	-
Crane	2004+	45	**8B**	6	N/A	50	0	1	1	15	-
Forklift	2004+	45	8B	7	11	50	1	1	1	15	-
Excavator	2004+	45	8B	6	N/A	50	0	1	1	15	-
Loader	2004+	45	8B	6	N/A	50	0	1	1	15	-
Miscellaneous small equipment	2004+	45	8B	7	11	50	1	1	1	15	-

Since the dormitory project is located in Istanbul, it would be preferable to use emission factors for the Turkish truck fleet in calculating the related LCI. However, such data do not currently exist for Turkey. Therefore, data from U.S. EPA's diesel-engine heavy duty trucks is commonly applied in LCI calculations which is an acceptable solution. Results are demonstrated hereafter.

5.3.2 Results for Transportation of Building Materials and Equipment to/from Construction Site

Results for the transportation of excavated soil, building materials, and equipment to and from the site are calculated based on input data from Table 5.6, 5.7, and 5.8.

Emission factors for HC, CO, NO_x, PM, and SO_2 are obtained from U.S. EPA's MOBILE 6 model [309, 310, 312]. These factors are provided in grams per miles traveled and vary with the model year and cumulative mileage of the heavy-duty truck type chosen (see Appendix C, Table 9.16 to Table 9.30). By multiplying these emission factors with the total distance traveled in miles, total emissions from transportation are estimated. Therefore, based on the approach described in CDEST, the total distance traveled by a truck to deliver materials is calculated prior to estimating emission factors as follows:

$$\boxed{Total\ Distance_{Mi} = \left(\frac{MW_i}{TC_d}\right) \times (1 + WF_i) \times OD_i \times (1 + RF_i)}$$

Equation 5.4: Calculation of total distance required to deliver a material to/from construction site

Where:

$Total\ Distance_{Mi}$ = Total distance traveled to deliver a building material to/from the construction site, in km;

MW_i = Total weight of building material "i" from Table 5.3, in metric tons;

TC_d= Truck capacity (or cargo weight) of selected heavy-duty diesel truck class "d" from Table 5.5 and Table 5.8, in metric tons for all vehicles; for concrete mixer truck, in m^3;

WF_i = Construction waste factor for material "i" from Table 5.8, in %;

OD_i = Average one-way distance for material "i", from Table 5.8, in km;

RF_i = Return factor for material "i", from Table 5.8, unitless.

For transportation of equipment to the construction site, the distance is calculated in a slightly different way:

$$\boxed{Total\ Distance_{Ee} = \left(\frac{EW_e}{TC_d}\right) \times OD_e \times (1 + RF_e)}$$

Equation 5.5: Calculation of total distance required to deliver equipment to/from construction site

Where:

$Total\ Distance_{Ee}$ = Total distance traveled to deliver equipment to/from the construction site in km;

EW_e = Weight of equipment "e" from Appendix C, Table 9.28, in metric tons;

TC_d= Truck capacity (or cargo weight) of selected heavy-duty diesel truck class “d” from Table 5.5 and Table 5.8, in metric tons;

OD_e = Average one-way distance for equipment “e”, from Table 5.8, in km;

RFe = Return factor for equipment “e”, from Table 5.8, unitless.

Another version of the distance calculation is for equipment which can travel to the site on its own power:

$$Total\ Distance_{Em} = \ Number_{trips} \times OD_{Em} \times (1 + RF_{Em})$$

Equation 5.6: Calculation of total distance traveled by mobile construction equipment

Where:

$Total\ Distance_{Ep}$ = Total distance traveled by a mobile construction equipment, in km;

$Number_{trips}$ = Number of trips to construction site, from Table 5.8, unitless;

OD_{Em} = Average one-way distance for mobile construction equipment “E_m”, from Table 5.8, in km;

RF_{Em} = Return factor for mobile construction equipment “E_m”, from Table 5.8, unitless.

Note that all distances are calculated in “km”. However, distances are converted to miles in emission calculations to match the units of emission factors for HC, CO, NO_x, PM, and SO_2 from MOBILE 6.1. Therefore, total air emissions from transportation of materials and equipment are calculated as follows:

$$HC_{Transport} = Total\ Distance \times 0.62137 \ \times \frac{miles}{km} \times \left[(Table\ 8.20\ Zero\ Mile\ Rates)_{ModelY,WeightC} + CumTruckMileage \times \left((Table\ 8.20\ Deterioration\ Rates)_{ModelY,WeightC}\right)\right] \times 0.001\ \frac{kg}{g}$$

$$CO_{Transport} = Total\ Distance \times 0.62137 \ \times \frac{miles}{km} \times \left[(\text{Table } 8.22\ Zero\ Mile\ Rates)_{ModelY,WeightC} + CumTruckMileage \times \left((Table\ 8.22\ Deterioration\ Rates)_{ModelY,WeightC}\right)\right] \times 0.001\ \frac{kg}{g}$$

$$NO_{x\_Transport} = Total\ Distance \times 0.62137 \ \times \frac{miles}{km} \times \left[(Table\ 8.24\ ZeroMileRates)_{ModelY,WeightC} + CumTruckMileage \times \left((\text{Table } 8.24\ Deterioration\ Rates)_{ModelY,WeightC}\right)\right] \times 0.001\ \frac{kg}{g}$$

$$PM_{Transport} = Total\ Distance \times 0.62137 \ \times \frac{miles}{km} \times \left[Table\ 8.26\ _{ModelY,WeightC}\right] \times 0.001\ \frac{kg}{g}$$

$$SO_{2\_Transport} = Total\ Distance \times 0.62137 \ \times \frac{miles}{km} \times \left[Table\ 8.27\ _{ModelY,WeightC,SulfurContent}\right] \times 0.001\ \frac{kg}{g}$$

Equation 5.7: Calculation of HC, CO, NO_x, PM, and SO_2 emissions from transportation of materials and equipment to/from construction site

Where:

$HC_{Transport}$ = Hydrocarbons from transportation by heavy-duty diesel trucks, in kg;

$CO_{Transport}$ = Carbon monoxide from transportation by heavy-duty diesel trucks, in kg;

$NO_{x\_Transport}$ = Nitrogen oxides from transportation by heavy-duty diesel trucks, in kg;

$PM_{Transport}$ = Particulate matter from transportation by heavy-duty diesel trucks, in kg;

$SO_{2\_Transport}$ = Sulfur dioxide from transportation by heavy-duty diesel trucks, in kg;

Total Distance = Calculated distance in Equation 5.4, Equation 5.5, and Equation 5.6, in km;

0.62137 = Conversion factor from km to miles;

$SO_{2\_Transport}$ = Sulfur dioxide from transportation by heavy-duty diesel trucks, in kg;

Total Distance = Calculated in Equation 5.4, Equation 5.5, and Equation 5.6, in km;

0.62137 = Conversion factor from km to miles;

0.001 = Conversion factor from kg to grams;

CumTruckMileage = Cumulative truck mileage from Table 5.8, in 10K miles.

Additionally, emission factors corresponding to the heavy-duty truck with selected model year (ModelY), weight class (WeightC), and sulfur content (only for SO_2 calculations) are used in the Equation 5.7. Related data for vehicles with zero miles (for all air emission types) and deterioration rates (only for HC, CO, and NO_x) of differing mileages are obtained from Appendix C, Table 9.20, Table 9.22, Table 9.24, Table 9.26, and Table 9.27, respectively.

Moving forward, CO_2 emission from transportation is estimated on the basis of diesel fuel characteristics and the associated equation is developed by US EPA [313]:

$$CO_2rate_{diesel} = \left(\frac{44}{12}\,\frac{g\,CO_2}{g\,C}\right) \times C_{diesel} \times \left(\frac{1}{D_{diesel}}\right) \times (0.453\,\frac{kg}{lb}) \times F_{diesel}$$

Equation 5.8: Calculation of CO_2 emission rate from diesel fuel use by heavy trucks

Where:

CO_2 $rate_{diesel}$ = calculated as 10,157 g CO_2 per gallon of diesel fuel;

Carbon content of diesel fuel (Cdiesel) = 2,770 g C/gal of fuel;

Density of diesel fuel (D_{diesel}) = 7.099 lb/gal;

Fraction of fuel oxidized (F_{diesel}) = 100%

Total amount of diesel fuel use by the heavy-duty truck is required to calculate energy consumption and related CO_2 emissions for transportation of materials and equipment. Fuel use is estimated as follows:

$$Fuel_{Transport} = \frac{Total\ Distance}{Truck\ Fuel\ Efficiency} \times 0.62137\ \frac{miles}{km}$$

Equation 5.9: Calculation of fuel use for transportation of materials and equipment to/from site

Where:

$Fuel_{Transport}$ = Amount of diesel fuel used in heavy-duty trucks, in gallons;

Total Distance = Calculated distance in Equation 5.4, Equation 5.5, and Equation 5.6, in km;

Truck Fuel Efficiency = From Table 5.8 for the heavy-duty truck with selected model year and weight class, in miles per gallons (mpg).

The output from Equation 5.9 is used in calculating the transportation-related direct energy consumption and CO_2 emission as follows:

$$Energy_{Transport} = HHV_{diesel} \times Fuel_{Transport}$$

Equation 5.10: Calculation of energy consumption for transportation of materials and equipment to/from site

Where:

$Energy_{Transport}$ = Direct energy consumption associated with diesel fuel used in heavy-duty trucks, in MJ;

HHV_{diesel} = Higher heating value for diesel fuel [313], equals to 146.326 MJ/gal;

$Fuel_{Transport}$ = Amount of diesel fuel used in heavy-duty trucks from *Equation 5.9*, in gallons.

$$CO_{2\_Transport} = CO_2 rate_{diesel} \times Fuel_{Transport} \times 0.001\ \frac{kg}{g}$$

Equation 5.11: Calculation of total CO_2 emission for transportation of materials and equipment to/from site

Where:

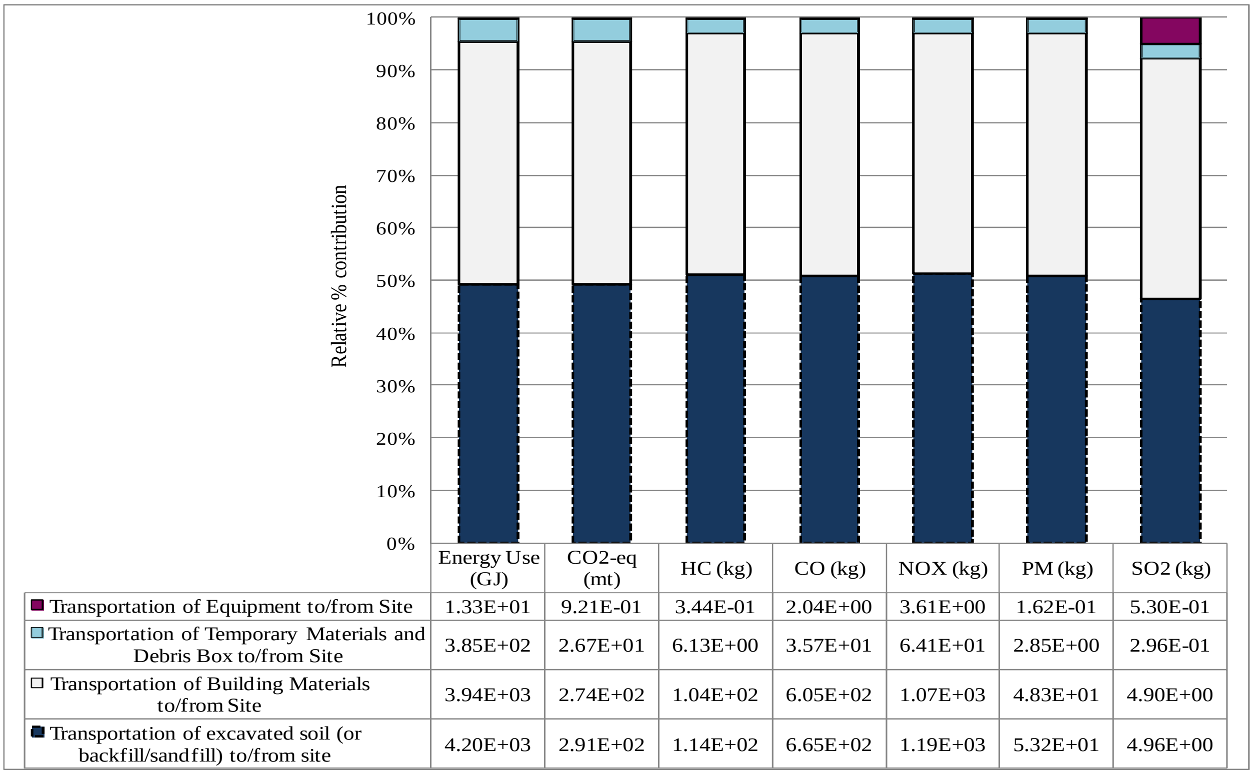
$CO_{2\_Transport}$ = CO_2 emission associated with diesel fuel used in heavy-duty trucks, in kg;

CO_2 $rate_{diesel}$ = calculated as 10,157 g CO_2 per gallon of diesel fuel;

$Fuel_{Transport}$ = Amount of diesel fuel used in heavy-duty trucks from *Equation 5.9*, in gallons;

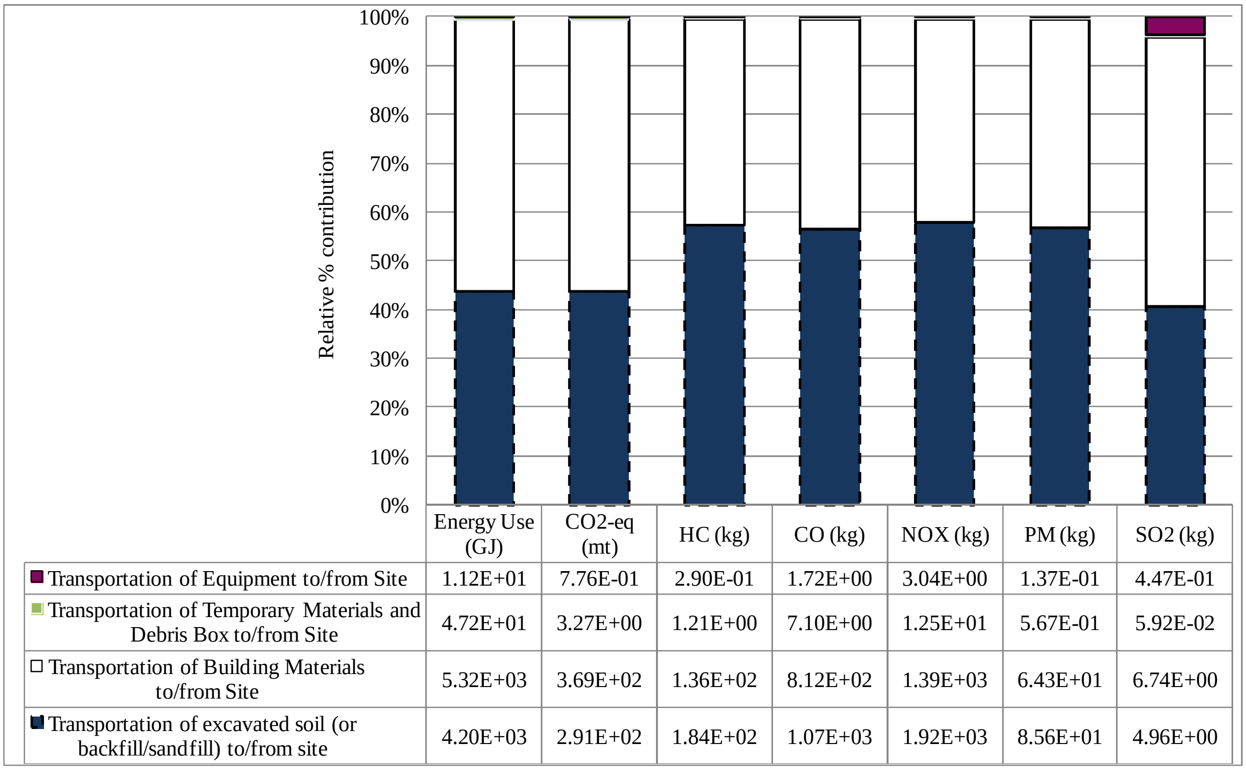
0.001 = Conversion factor from kg to grams.

Total transportation results from the equations above are summarized in Figure 5.6 and Figure 5.7 for both concrete and steel framed buildings.



	Energy Use (GJ)	CO2-eq (mt)	HC (kg)	CO (kg)	NOX (kg)	PM (kg)	SO2 (kg)
🟪 Transportation of Equipment to/from Site	1.33E+01	9.21E-01	3.44E-01	2.04E+00	3.61E+00	1.62E-01	5.30E-01
🟦 Transportation of Temporary Materials and Debris Box to/from Site	3.85E+02	2.67E+01	6.13E+00	3.57E+01	6.41E+01	2.85E+00	2.96E-01
□ Transportation of Building Materials to/from Site	3.94E+03	2.74E+02	1.04E+02	6.05E+02	1.07E+03	4.83E+01	4.90E+00
■ Transportation of excavated soil (or backfill/sandfill) to/from site	4.20E+03	2.91E+02	1.14E+02	6.65E+02	1.19E+03	5.32E+01	4.96E+00

Figure 5.6: LCI results for transportation of building materials, temporary materials, excavated/filling soil, and equipment to/from construction site for concrete frame building



	Energy Use (GJ)	CO2-eq (mt)	HC (kg)	CO (kg)	NOX (kg)	PM (kg)	SO2 (kg)
🟪 Transportation of Equipment to/from Site	1.12E+01	7.76E-01	2.90E-01	1.72E+00	3.04E+00	1.37E-01	4.47E-01
🟩 Transportation of Temporary Materials and Debris Box to/from Site	4.72E+01	3.27E+00	1.21E+00	7.10E+00	1.25E+01	5.67E-01	5.92E-02
□ Transportation of Building Materials to/from Site	5.32E+03	3.69E+02	1.36E+02	8.12E+02	1.39E+03	6.43E+01	6.74E+00
■ Transportation of excavated soil (or backfill/sandfill) to/from site	4.20E+03	2.91E+02	1.84E+02	1.07E+03	1.92E+03	8.56E+01	4.96E+00

Figure 5.7: LCI results for transportation of building materials, temporary materials, soil, and equipment to/from construction site for steel frame building

5.3.3 Construction Phase Input

Generally, construction LCIs include environmental impacts from electricity used for driving power tools, lighting, heating (some construction activities may require heat/steam in cold climate [1]), as well as diesel fuel for operating heavy construction equipment. Various studies in the literature estimate that construction energy constitutes 1.2 to 10 percent of total embodied energy [60, 119, 121, 122, 134]. Among these studies, Cole [134] estimated higher percentages (7 to 10 percent of total embodied energy) for the construction stage. That is mostly because of the inclusion of impacts from transportation of construction workers in the construction energy calculations. In this dissertation, transportation of workers was excluded from the LCA calculations.

Commonly, energy consumption for concrete frame construction was estimated at higher levels compared to steel frame construction. In concrete frames, more temporary materials are required (such as formwork), installation takes longer, meaning longer periods of equipment use, and transportation impacts are larger due to the delivery of heavier materials used in concrete-frame buildings [122, 134].

Construction-related LCIs are calculated on the basis of technical specifications from Prokon and sources such RS Means Building Construction Cost Data (2013), construction equipment manufacturers' websites (see Section 9.3 of Appendix C for the master list of equipment), and construction LCA tools, such as CDEST tool [119]. As first step, major construction activities and related durations for equipment use are determined. For all diesel equipment, model year is assumed to be 2005 for simplicity of calculations. The construction stage starts with the excavation and preparation of the site area after the mobilization of construction equipment. It is assumed there is no major site demolition (e.g. removal of trees, pavements, existing structures, etc.). Hydraulic excavator (or backhoe) and front loader are used for the earthworks. Both the excavator and front loader can move on their own power. Hauling distances on site are estimated at 500 m for the excavator and 175 m for the front loader based on the book by Nunnally [314]. Following the construction site preparation are construction of structural frame and building envelope installation, mechanical, electrical equipment installations, and exterior and interior finishings.

The Table 5.9 summarizes the duration of equipment use in hours and power sources for the major construction activities. Power sources can be diesel, gasoline, or electricity. Based on the equipment power (in horsepower or watts), type of the power source, and the equipment model year (2005 for the case study) information, related energy consumption and major air emissions are estimated. Results are demonstrated in following section.

Table 5.9: Construction equipment use hours and power source input

Material	Equipment	Use (hr)	Power Source	Power (diesel and gasoline: hp) (electricity: watt)
Excavation				
Common earth	Hydraulic excavator (with 1.2 m^3 bucket capacity)	212	Diesel	204
Backfill/Sandfill				
Common earth	Front loader (with 3.5 m^3 bucket capacity)	104	Diesel	211
Sand and gravel	Front loader (with 3.5 m^3 bucket capacity)	0.31	Diesel	211

Concrete Frame Construction Equipment Use				
Concrete	Concrete mixer truck	1,023	Diesel	425
	Concrete pump	1,679	Diesel	131
	Vibrator	1,289	Gasoline	6
Formwork	Air Compressor	6,844	Diesel	140
	Crane	1,290	Diesel	450
	Power Saw	720	Gasoline	3
Misc. Work at Site	Forklift	102	Diesel	135
Steel, reinforcing bars	Crane	771	Diesel	450
	Rebar Bender	214	Electricity	1,500
	Rebar Cutter	214	Electricity	1,400
	Welder	241	Electricity	9,600
Steel Frame Construction Equipment Use				
Concrete	Air Compressor (cleaning formwork)	383	Diesel	140
	Concrete Mixer Truck	1,130	Diesel	425
	Concrete Pump	391	Diesel	131
	Vibrator	1,424	Gasoline	6
Misc. Work at Site	Crane (formwork)	72	Diesel	450
	Forklift	76	Diesel	135
Steel	Air Compressor (fireproofing)	52	Diesel	140
	Crane (structural steel)	863	Diesel	450
	Power Saw	105	Electricity	1,260
	Rebar Bender	52	Electricity	1,200
	Rebar Cutter	52	Electricity	1,200
	Steel Punch	32	Electricity	11,185
	Steel Torch	32	Electricity	36,000
	Welder	270	Electricity	9,600

5.3.4 Construction Phase Results

As mentioned previously, on-site equipment use requires various sources of power which in turn consumes energy and causes major air emissions during the construction phase. Varying with the type (power source and power) of construction equipment and the length of its use, energy consumption is calculated based on the input from Table 5.9:

$$Diesel_{Construction} = Hp \times Time \times BSFC \times HHV_{diesel} \times \left(1{,}055.056 \times \frac{J}{Btu}\right) \times \left(\frac{1}{10^6} \times \frac{MJ}{J}\right)$$

$$Electricity_{Construction} = Watts \times Time \times (Electricity_{Turkish\_mix} \times \frac{MJ}{kWh} \times \left(\frac{1}{10^3} \times \frac{kilowatts}{watts}\right)$$

$$Gasoline_{Construction} = Hp \times Time \times BSFC \times HHV_{gasoline} \times \left(1{,}055.056 \times \frac{J}{Btu}\right) \times \left(\frac{1}{10^6} \times \frac{MJ}{J}\right)$$

Equation 5.12: Calculation of energy consumption by construction equipment use on site

Where:

$\text{Diesel}_{\text{Construction}}$ = Total amount of diesel energy consumed by a construction equipment on site, MJ;

$\text{Electricity}_{\text{Construction}}$ = Total amount of electricity consumed by an electric construction equipment on site, MJ;

$\text{Gasoline}_{\text{Construction}}$ = Total amount of gasoline energy consumed by a construction equipment on site, MJ;

Hp = Horsepower of diesel or gasoline equipment (input from Table 5.9), in hp;

Watts = Power of electric construction equipment (input from Table 5.9), in hp;

Time = Duration of construction equipment use, in hours;

$\text{Electricity}_{\text{Turkish\_mix}}$ = Energy conversion for Turkish electricity grid mix (Appendix C, Table 9.31), equals to 7.98 MJ/kWh;

BSFC = Brake specific fuel consumption, which is a fuel use rate measurement, varies with model year and power (from Appendix C, Table 9.29), in lb/hp-hr;

$\text{HHV}_{\text{diesel}}$ = Higher heating value for diesel fuel [146], equals to 19,300 Btu/lb;

$\text{HHV}_{\text{gasoline}}$ = Higher heating value for gasoline [151, 218] 20,300 Btu/lb.

Applying the necessary unit conversions in Equation 5.12, energy use for the construction equipment is calculated and final results are demonstrated in Table 5.10.

Emission factors for pollutants HCs, CO, NO_x, PM are taken from the EPA's NONROAD model [146] while CO_2 and SO_2 emissions are calculated based on the diesel fuel related data, varying with BSFC values.

$$CO_{2\_Diesel\_Construction} = BSFC \times \frac{1}{D_{diesel}} \times CO_2 rate_{diesel}$$

$$SO_{2\_Diesel\_Construction} = BSFC \times 453.6 \times (1 - 0.02247) - HC_{diesel}) \times 0.0033 \times 2$$

Equation 5.13: Calculation of CO_2 and SO_2 emission factors of non-mobile construction equipment use on site

Where:

$CO_{2\_\text{Diesel\_Construction}}$ = CO_2 emission associated with diesel fuel used in non-mobile construction equipment in g/hp-hr;

$SO_{2\_\text{Diesel\_Construction}}$ = SO_2 emission associated with diesel fuel used in non-mobile construction equipment in g/hp-hr;

BSFC = Brake specific fuel consumption, which is a fuel rate measurement, varies with model year and power (from Appendix C, Table 9.29), in lb/hp-hr;

$CO_2\ \text{rate}_{\text{diesel}}$ = calculated as 10,157 g CO_2 per gallon of diesel fuel (from

Equation 5.8);

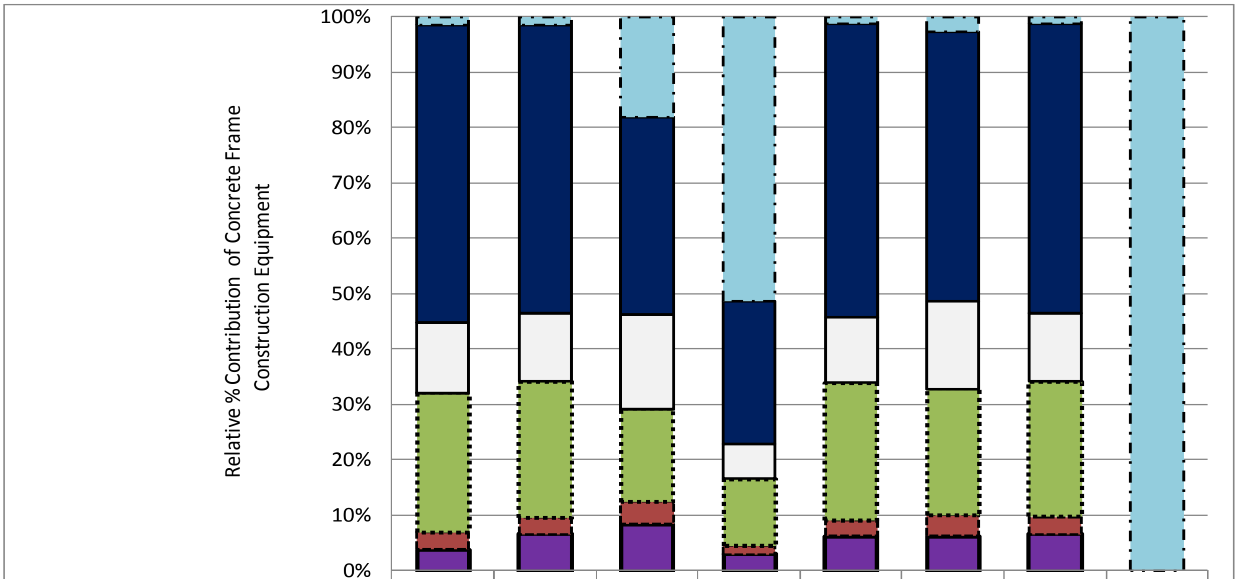
HC_{diesel} = Corresponding hydrocarbon emissions from Table 9.29, in g/hp-hr;

Density of diesel fuel (D_{diesel}) = 7.099 lb/gal;

For gasoline-powered equipment, emission factors of HCs, CO, NO_x, PM, CO_2, and SO_x are obtained from EPA AP-42 [151] while for electric equipment, electricity grid mix factors from Appendix C, Table 9.31 are applied in LCA calculations. Only for welding and torch cutting activity-related PM and heavy metal emissions, data from Table 9.32 are **Error! Reference source not found.**utilized on the basis of approach described in CDEST [119] and added to electricity-related data. Diesel and gasoline fuel related LCI factors are tabulated in Table 9.29 and Table 9.30, respectively, in units of grams/hp-hr. By multiplying these emission factors with the total equipment use duration (hr) and horsepower (hp), total emissions associated with the construction phase are estimated (Table 5.10). Additionally, Figures 5.8 and 5.9 below summarize construction-related impacts for both concrete and steel framed building options.

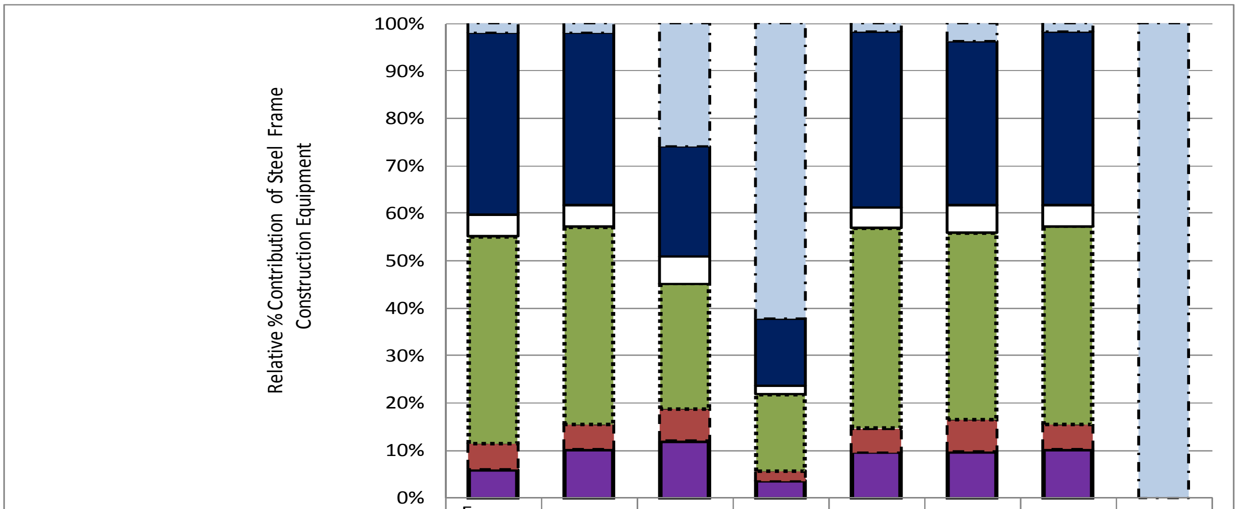
Table 5.10: Construction phase LCI results

	Energy (GJ)	CO_2 (mt)	CO (kg)	HC (kg)	NOx (kg)	PM10 (kg)	SO_2 (kg)	VOC (kg)
Soil Work								
Excavation	3.23E+02	2.27E+01	3.23E+01	1.33E+01	1.73E+02	5.68E+00	4.63E+01	
Loading/Backfilling	1.64E+02	3.88E+01	5.52E+01	2.28E+01	2.95E+02	9.72E+00	7.92E+01	
Concrete Frame								
Air compressor (formwork)	4.01E+02	2.82E+01	4.65E+01	1.81E+01	2.20E+02	9.65E+00	5.75E+01	
Concrete mixer truck	3.25E+03	2.28E+02	3.66E+02	7.26E+01	1.89E+03	5.72E+01	4.67E+02	
Concrete pump	1.64E+03	1.16E+02	1.91E+02	7.44E+01	9.02E+02	3.96E+01	2.36E+02	
Crane (formwork)	4.34E+03	3.05E+02	4.89E+02	9.69E+01	2.52E+03	7.64E+01	6.23E+02	
Crane (rebars)	2.59E+03	1.82E+02	2.92E+02	5.79E+01	1.50E+03	4.56E+01	3.72E+02	
Forklift	9.56E+01	6.71E+00	1.11E+01	4.33E+00	5.24E+01	2.30E+00	1.37E+01	
Power saw	**7.18E+00**	**5.01E-01**	**1.72E-01**		**1.15E+00**	3.75E-01	**1.73E+00**	**1.71E-01**
Rebar bender	**2.56E+00**	**1.79E-01**	**6.13E-02**		**4.12E-01**	1.34E-01	**6.18E-01**	**6.10E-02**
Rebar cutter	**2.39E+00**	**1.67E-01**	**5.72E-02**		**3.84E-01**	1.25E-01	**5.77E-01**	**5.70E-02**
Vibrator	**6.01E+01**	**3.81E+00**	**1.54E+03**	**7.48E+01**	**3.99E+01**	2.53E+00	**2.07E+00**	
Welder	**1.85E+01**	**1.29E+00**	**4.41E-01**		**2.96E+00**	9.62E-01	**4.45E+00**	**4.39E-01**
Steel Frame								
Air compressor (formwork)	4.01E+02	2.82E+01	4.65E+01	1.81E+01	2.20E+02	9.65E+00	5.75E+01	
Concrete mixer truck	3.59E+03	2.52E+02	4.05E+02	8.02E+01	2.08E+03	6.32E+01	5.15E+02	
Concrete pump	3.82E+02	2.69E+01	4.43E+01	1.73E+01	2.10E+02	9.21E+00	5.48E+01	
Crane (formwork)	2.43E+02	1.71E+01	2.74E+01	5.42E+00	1.41E+02	4.28E+00	3.49E+01	
Forklift	7.69E+01	5.40E+00	8.92E+00	3.48E+00	4.22E+01	1.85E+00	1.10E+01	
Vibrator	6.09E+01	3.86E+00	1.56E+03	7.57E+01	4.04E+01	2.56E+00	2.10E+00	
Air compressor (fireproofing)	5.45E+01	3.83E+00	6.32E+00	2.47E+00	2.99E+01	1.31E+00	7.82E+00	
Crane (structural steel frame elements)	2.90E+03	2.04E+02	3.27E+02	6.48E+01	1.68E+03	5.11E+01	4.17E+02	
Power saw	1.06E+00	7.36E-02	2.53E-02		1.93E-01	5.51E-02	2.55E-01	2.52E-02
Rebar bender	4.93E-01	3.44E-02	1.18E-02		9.00E-02	2.57E-02	1.19E-01	1.17E-02
Rebar cutter	4.93E-01	3.44E-02	1.18E-02		9.00E-02	2.57E-02	1.19E-01	1.17E-02
Steel punch	2.81E+00	1.96E-01			5.13E-01	1.47E-01	6.78E-01	6.70E-02
Steel torch	9.05E+00	6.31E-01			1.65E+00	4.72E-01	2.18E+00	2.16E-01
Welder	2.07E+01	1.44E+00			3.77E+00	1.08E+00	4.99E+00	4.92E-01



	Energy Use	CO2-eq	HC	CO	NOX	PM	SO2	NMVOC
🟦 Others (forklift, power saw, rebar bender and cutter, vibrator, welder)	1.86E+02	1.27E+01	7.91E+01	1.55E+03	9.79E+01	6.43E+00	2.32E+01	7.28E-01
🟦 Crane	6.93E+03	4.87E+02	1.55E+02	7.81E+02	4.02E+03	1.22E+02	9.95E+02	0.00E+00
☐ Concrete pump	1.64E+03	1.16E+02	7.44E+01	1.91E+02	9.02E+02	3.96E+01	2.36E+02	0.00E+00
🟩 Concrete mixer truck	3.25E+03	2.28E+02	7.26E+01	3.66E+02	1.89E+03	5.72E+01	4.67E+02	0.00E+00
🟥 Air compressor	4.01E+02	2.82E+01	1.81E+01	4.65E+01	2.20E+02	9.65E+00	5.75E+01	0.00E+00
🟪 Excavator and front loader	4.87E+02	6.15E+01	3.61E+01	8.75E+01	4.68E+02	1.54E+01	1.25E+02	0.00E+00

Figure 5.8: LCI results from construction equipment use for concrete frame building



	Energy Use	CO2-eq	HC	CO	NOX	PM	SO2	NMVOC
🟦 Others (forklift, power saw, rebar bender and cutter, vibrator, welder)	1.72E+02	1.17E+01	7.92E+01	1.57E+03	8.89E+01	6.22E+00	2.15E+01	8.24E-01
🟦 Crane	3.15E+03	2.21E+02	7.03E+01	3.55E+02	1.83E+03	5.54E+01	4.52E+02	0.00E+00
☐ Concrete pump	3.82E+02	2.69E+01	1.73E+01	4.43E+01	2.10E+02	9.21E+00	5.48E+01	0.00E+00
🟩 Concrete mixer truck	3.59E+03	2.52E+02	8.02E+01	4.05E+02	2.08E+03	6.32E+01	5.15E+02	0.00E+00
🟥 Air compressor	4.55E+02	3.20E+01	2.06E+01	5.28E+01	2.50E+02	1.10E+01	6.53E+01	0.00E+00
🟪 Excavator and front loader	4.87E+02	6.15E+01	3.61E+01	8.75E+01	4.68E+02	1.54E+01	1.25E+02	0.00E+00

Figure 5.9: LCI results from construction equipment use for steel frame building

5.4 Building Operation and Maintenance Phase

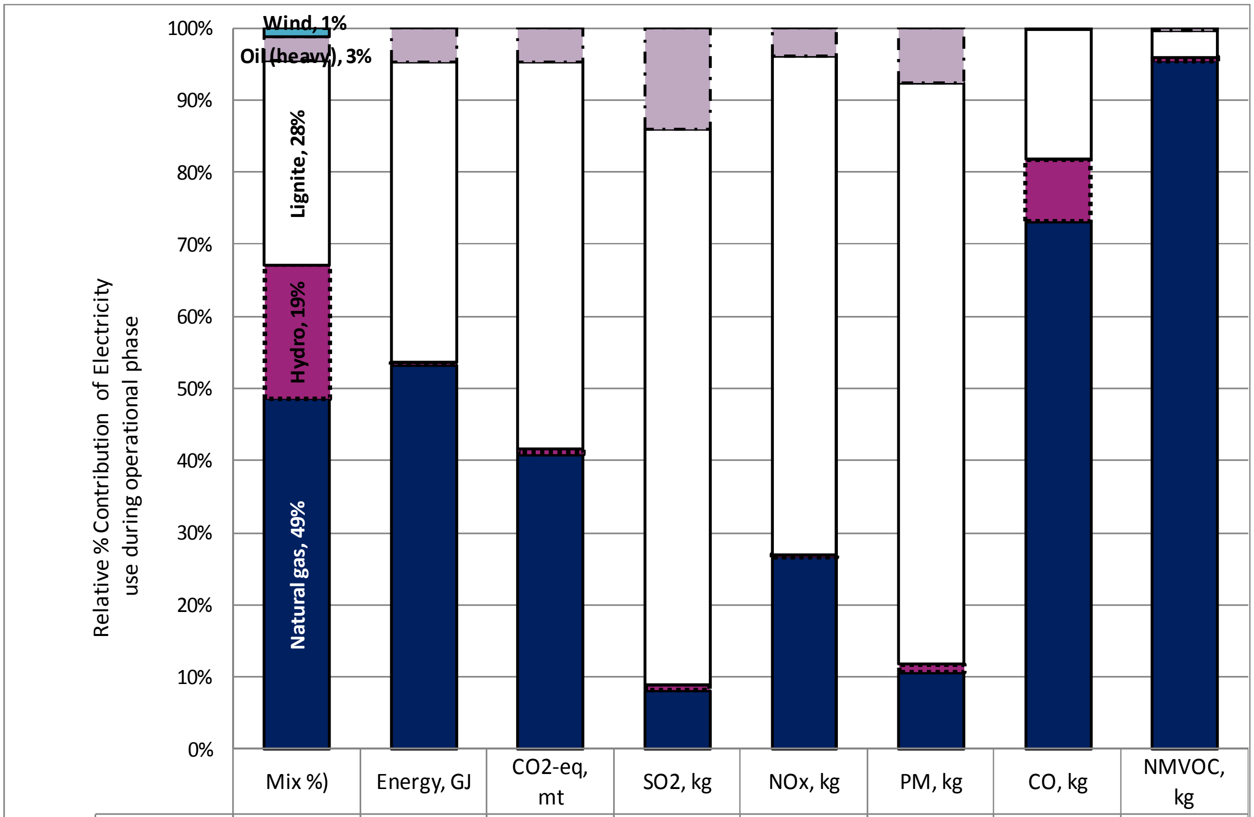
5.4.1 Energy Use for Building Operation

In order to analyze the energy use during the operation phase of the dormitory building, annual electricity (for lighting and appliances) and natural gas consumption (for space heating and domestic hot water) data were obtained from Prokon (Table 5.11).

Table 5.11: Summary of energy supply for building operation phase

Type of Building Operation	Energy Supply	LCA data sources
Space heating	Natural gas	[315, 316]
Hot water	Natural gas, solar energy	[315, 316]
Lighting and appliances	Turkish electricity mix	[316, 317]

The hourly electricity use is given as 780 kilowatts. It is assumed that average use is 12 hours per day, 30 days per month, and 10 months per year (with two months of summer break with little or no electricity use), which add up to about **2,800 MWh/year**. The average electricity use intensity for an office building in a climate (for California) similar to Istanbul's is estimated as **214 kWh/m^2** on the basis of the U.S. EIA Commercial Buildings Energy Consumption survey [318]. When the EIA's data are applied, it is about 2,200 MWh of annual electricity use for the case building. Therefore, measured results appear to be consistent with the estimated values from EIA and literature [319]. The electricity generation is grid-based and Appendix C, Table 9.31 lists the electricity grid mix percentages and associated energy use and emission factors applied in LCA calculations. Figure 5.10 below summarizes the building's electricity use (including both upstream and direct use impacts) over 50 years, together with the percent contribution of electricity grid mix percentages for the Istanbul area.



	Mix %)	Energy, GJ	CO2-eq, mt	SO2, kg	NOx, kg	PM, kg	CO, kg	NMVOC, kg
■ Wind	1%	3.94E+02	3.05E+01	8.40E+01	6.10E+01	4.26E+01	8.15E+01	1.44E+01
▨ Oil (heavy)	3%	5.36E+04	3.91E+03	3.83E+04	7.78E+03	4.49E+03	0.00E+00	1.05E+02
□ Lignite	28%	4.67E+05	4.46E+04	2.08E+05	1.42E+05	4.71E+04	4.82E+03	9.78E+02
▨ Hydro	19%	3.12E+03	6.37E+02	2.14E+03	5.99E+02	6.49E+02	2.32E+03	1.36E+02
■ Natural gas	49%	5.97E+05	3.39E+04	2.19E+04	5.44E+04	6.18E+03	1.96E+04	2.55E+04

Figure 5.10: LCA results related to electricity use (incl. upstream impacts of energy sources) for the building operation over 50 years of its life span

Natural gas boilers provide the space heating for all the campus buildings. Based on Prokon's estimations, total natural gas consumption for winter (the highest consumption is during winter) and summer seasons are 3,162,182 m^3 and 442,705 m^3, respectively. These numbers are total quantities for six building blocks; each has one boiler of its own. Building B, which is composed of two blocks with one boiler for each, consumes one third of the total natural gas, corresponding to 1,201,629 m^3 per year. In the related energy calculations from Prokon, lower heating value (LHV) for natural gas is given as 8,250 kcal /m^3. Using the IPCC guidelines [34], LHV is multiplied by a factor of 1.11 to estimate the HHV value of the fuel. Making all the necessary unit conversions, HHV of the natural gas combustion for the case study is calculated as 38.3 MJ/m^3. Pre-combustion life-cycle energy value for natural gas is 3.39 MJ/m^3 (Table 4.15).

$$Natural\ gas_{annual_{spaceheating}} = (HHV_{naturalgas} + Precombust_{naturalgas}) \times Naturalgas_{volume}$$

Equation 5.14: Annual energy consumption requirement for space heating with natural gas

Where:

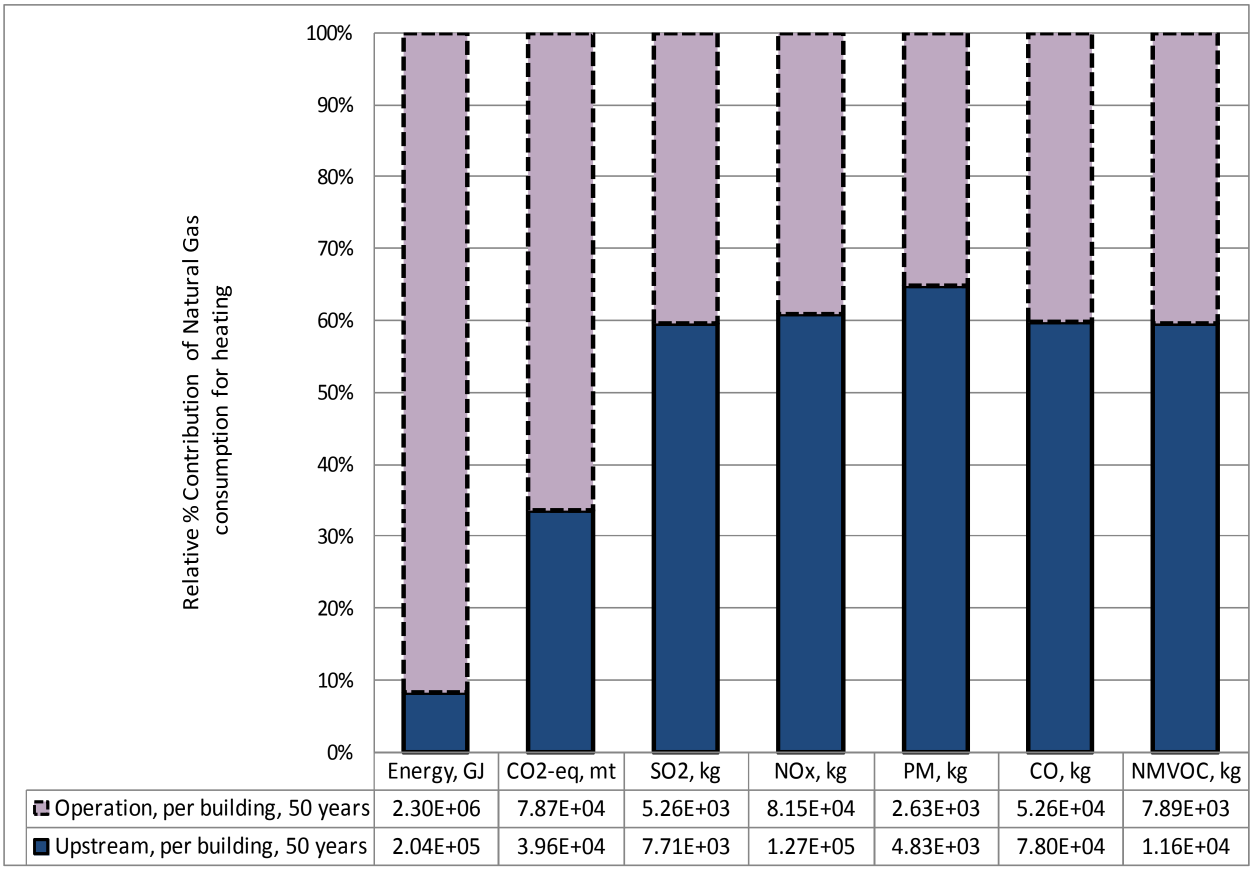
$\text{Naturalgas}_{\text{annual\_space heating}}$ = Annual energy consumption required for space heating with natural gas, in MJ/year;

$\text{HHV}_{\text{natural\_gas}}$ = Higher heating value of natural gas, 38.3 MJ/m^3;

$\text{Precombust}_{\text{natural\_gas}}$ = Pre-combustion life-cycle energy value for natural gas is 3.39 MJ/m^3;

$\text{Naturalgas}_{\text{volume}}$ = Volume of natural gas used in space heating per year, in m^3;

For a complete LCA of natural gas use in the building, both upstream and operation LCI of the heating system are considered. Both upstream and heating data for natural gas delivered in Istanbul, Turkey are based on a European Environment Agency report [315] and shown in Appendix C, Table 9.33. The calculated LCA results (using Equation 5.14) for natural gas use during 50 years of building's life are illustrated below in Figure 5.11:



	Energy, GJ	CO2-eq, mt	SO2, kg	NOx, kg	PM, kg	CO, kg	NMVOC, kg
▨ Operation, per building, 50 years	2.30E+06	7.87E+04	5.26E+03	8.15E+04	2.63E+03	5.26E+04	7.89E+03
■ Upstream, per building, 50 years	2.04E+05	3.96E+04	7.71E+03	1.27E+05	4.83E+03	7.80E+04	1.16E+04

Figure 5.11: Total LCA results related to natural gas use for heating the dormitory building over 50 years of its life-span

For countries with high levels of solar radiation like Turkey, the application of solar energy systems (especially during summer) in buildings can make a significant contribution to reducing GHG emissions from fossil fuels. In the case study, solar collectors are installed to make an input to water heating system instead of depending solely on the natural gas boilers or electricity grid. Therefore, energy consumption for domestic hot water (DHW) supply involves solar thermal collectors and auxiliary heating by a 1,000 kW natural gas boiler. Appendix C, Table 9.35 shows the basic input information regarding the climate, domestic hot water consumption, and system components used in a simulation program developed for calculating energy consumption in "Solar Thermal Heating Systems", namely, T*SOL Pro 4.5. Figure 9.2 and Figure 9.3 in Appendix C illustrate the results of the simulation calculations of DHW-related total energy and solar energy consumption. Accordingly, energy consumption results of the annual DHW simulation are shown in Table 5.12:

Table 5.12: Energy consumption results of DHW simulation (Prokon, 2010)

Results of annual DHW simulation		
Installed collector power	176 kW	
Installed gross solar surface area	252 m^2	
Total active solar surface area	233 m^2	
Collector surface area irradiation (active surface)	387 MWh	1,661 kWh/m^2
Energy produced by collectors	185 MWh	792 kWh/m^2
Energy produced by collector loop	180 MWh	772 kWh/m^2
DHW heating energy supply	555 MWh	
Solar contribution to DHW	179 MWh	
Energy from auxiliary heating	390 MWh	
Natural gas savings	27,150 m^3	
CO_2 emissions avoided	57,412 kg	
DHW solar fraction	31.5%	
Fractional energy saving	33.0%	
System efficiency	46.3%	

Based on Table 5.12, LCA associated with the water heating system is performed for both the solar and natural gas fraction of the system using LCA data from literature. Major air emission factors for upstream and direct combustion (in boilers for the purpose of heating) of natural gas are obtained from Table 9.33 and Table 9.34. Regarding the solar fraction of hot water system, upstream impacts involve extraction of raw materials, solar panel manufacturing, and transportation of panels to the site and their installation with shielded metal arc welding and plasma cutting. Data for the upstream LCA portion of the solar thermal collector are based on an Italian study, which focuses on a similar collector system in Palermo [320]. Functional unit of this study was per one solar thermal collector with a total net surface of 2.13 m^2, which was constituted of the absorbing collector, the water tank, and external support employed to fasten the system on the roof top. Total upstream energy use and emission factors (per 2.13 m^2 of collector system) are provided in Appendix C, Table 9.37. By multiplying these factors with the total active solar surface are around 233 m^2 (Table 5.12), upstream environmental burden of DHW solar fraction is estimated. Direct use impacts of solar panels are negligible. Over 50 years of building's service life, only replacement and maintenance of panels are considered and related results are given in following Section 5.4.2.

Overall, total operation phase energy consumption is calculated by multiplying the total annual energy use which covers electricity, natural gas consumption for heating, combination of natural gas and solar energy use for hot water with the building's life-span that is assumed to be 50 years:

$$Energy_{total\_operation} = Life_{building} \times \left[\left(Electricity_{annual_{operation}} \times e_{conversion} \right) + \sum_{i} Energy_{i} \right]$$

Equation 5.15: Calculation of life-cycle building operational energy consumption

Where:

$Energy_{total\_operation}$ = Life-cycle operational energy consumption by the building, in MJ;

$Life_{building}$ = Useful (service) life of building, which is 50 years for the case building;

$Electricity_{\_annual\_operation}$ = Annual electricity consumption required for the operation of the dormitory building, which is equal to 2,800,000 kWh /year;

$e_{conversion}$ = Conversion factor from electricity to energy, which is equal to 7.98 MJ/kWh (total energy amount calculated per kWh of average Turkish electricity generation), in MJ/kWh

$Energy_{i}$= Annual operational energy consumption of fuel "i", in MJ/year;

In Equation 5.15, "i" is natural gas for space heating, and combination of natural gas and solar energy for DHW supply. In Equation 5.14, annual energy requirement for space heating with natural gas is calculated and included in the equation above in the addition function.

$$Emissions_{Operation_{i,j}} = Life_{building} \times \sum Q_{i} \times EF_{i,j}$$

Equation 5.16: Calculation of life-cycle building operational air emissions

Where:

$Emissions_{Operationi,j}$ = Life-cycle operational emissions from energy sources "i" and "j" denotes one of the emissions, including $CO_{2\text{-eq}}$, SO_2, NO_x, PM, CO, and NMVOC, in kg;

$Life_{building}$ = Useful (service) life of building, which is 50 years for the case building;

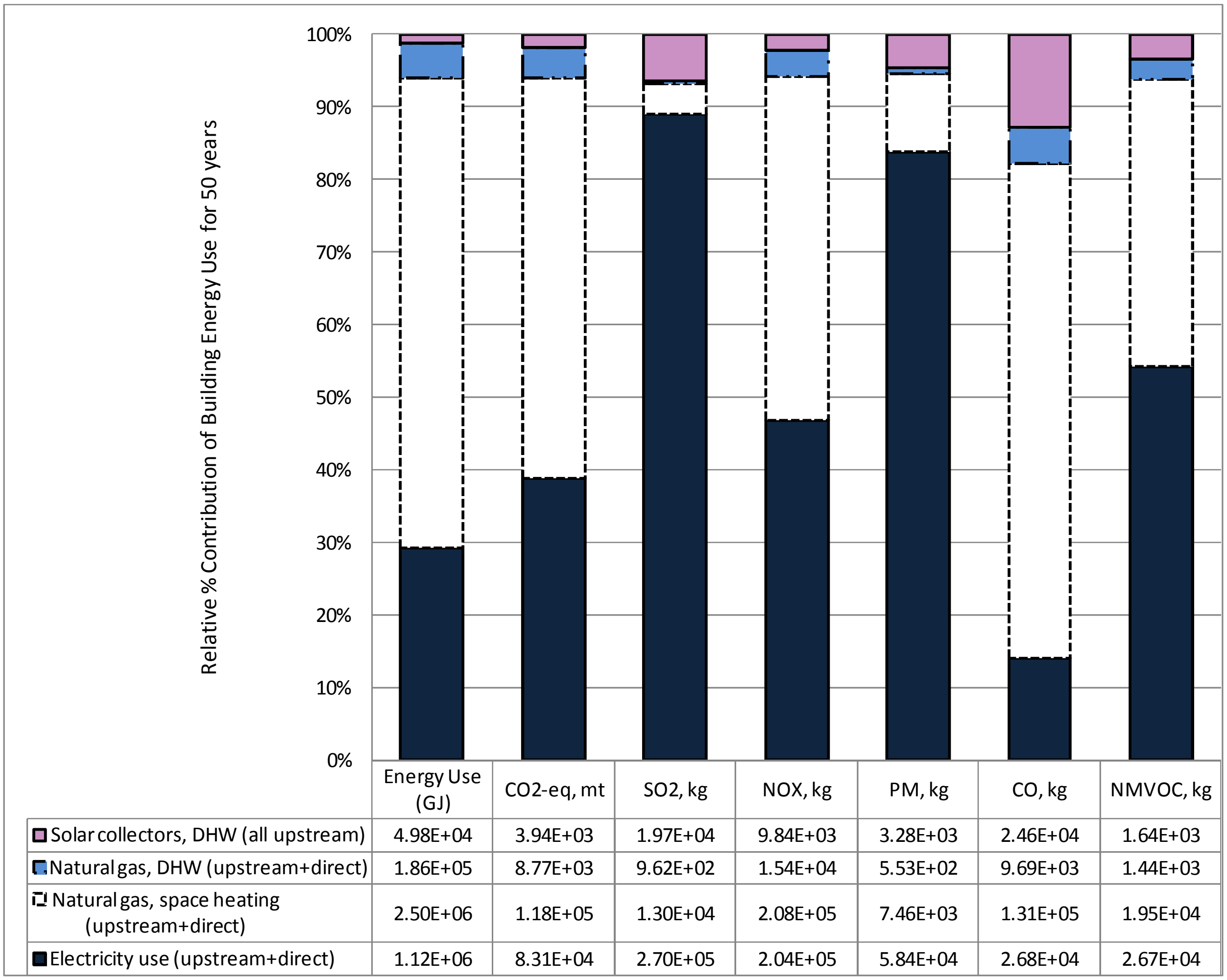
Q_i = Annual quantity of energy source "i" used during the building operation, in kWh for electricity, in m^3 for natural gas, and m^2 of net solar thermal collector irradiation area (limited to only upstream impacts);

$EF_{i,j}$ = Emission factor "j" generated by energy source "I" in kg/kWh for electricity use, kg/m^3 for natural gas, and kg/m^2 of one solar thermal collector area.

Related emission factors are provided in Appendix C, Table 9.31, Table 9.33, Table 9.34, and Table 9.37. Results from the building operational energy use and relevant air emissions over 50 years are summarized in Table 5.13 and Figure 5.12.

Table 5.13: Life-cycle operational energy use and air emission percentages

	Energy Use	**CO_2-eq**	**SO_2**	**NO_X**	**PM**	**CO**	**NMVOC**
Electricity use (upstream + direct)	29%	39%	89%	47%	84%	14%	54%
Natural gas, space heating (upstream + direct)	65%	55%	4%	48%	11%	68%	40%
Natural gas, DHW (upstream + direct)	5%	4%	0.3%	4%	1%	5%	3%
Solar collectors, DHW (all upstream)	1%	2%	6%	2%	5%	13%	3%



	Energy Use (GJ)	CO2-eq, mt	SO2, kg	NOX, kg	PM, kg	CO, kg	NMVOC, kg
■ Solar collectors, DHW (all upstream)	4.98E+04	3.94E+03	1.97E+04	9.84E+03	3.28E+03	2.46E+04	1.64E+03
■ Natural gas, DHW (upstream+direct)	1.86E+05	8.77E+03	9.62E+02	1.54E+04	5.53E+02	9.69E+03	1.44E+03
☐ Natural gas, space heating (upstream+direct)	2.50E+06	1.18E+05	1.30E+04	2.08E+05	7.46E+03	1.31E+05	1.95E+04
■ Electricity use (upstream+direct)	1.12E+06	8.31E+04	2.70E+05	2.04E+05	5.84E+04	2.68E+04	2.67E+04

Figure 5.12: Life-cycle operational phase energy use and related air emissions over 50 years of the case building's useful life

The natural gas use for space heating and DHW accounts for 65% and 5% of the total life cycle primary energy use and 55% and 4% of total $CO_{2\text{-eq}}$, respectively. Natural gas provides all the building's heating and 67% of the energy requirement for the water heating system. As mentioned previously, 33% of the energy for DHW is acquired from solar thermal collectors which results only in 1% of the total primary energy use and 2% of $CO_{2\text{-eq}}$. Grid-based electrical generation accounts for 29 % of the primary energy consumption and 39% of $CO_{2\text{-eq}}$, respectively.

The building consumes about 2.8 million m^3 of water over its useful life or an average 55,553 m^3 per year, based on the water consumption data obtained from a university/hotel mix building LCA study [131] (Table 5.14). Additionally, water is collected in tanks located on the roof top of the dorm buildings. Based on the average 850 mm/year rain data in Istanbul, 3,400 m^3 of water is collected over 4,000 m^2 of roof-top area per year.

Table 5.14: Annual water consumption details

Water Consumption Details:		**units**	**use (m^3/day)**
Number of students	1,326	students (50% female, 50% male)	-
Number of toilet uses	3	per day per person (average)	-
Toilet water consumption:	13.3	l/flush	52.91
Duration of sink use per day	3	min/day	-
Duration of shower use per day	7.5	min/day	-
Flow rate restroom faucet	9.5	l/min	37.79
Flow rate showers	9.5	l/min	94.48
Total water consumption (m^3/day)			185.18
Annual water consumption (m^3/year)			55,552.77
Annual savings from rain water collection (m^3/year)			3,400
Assume 10 months per year, 30 days per month			

Since there is no difference in the operation-phase impacts between the steel- and concrete-framed buildings, the LCA of operational phase is relevant for both building options.

5.4.2 Replacement and Maintenance of Building Materials

Energy required for producing replacement materials as part of maintenance over the life of the building. It is calculated by multiplying the material quantities given in Table 5.3 with their respective embodied energy and GWP factors (from Table 5.4) and number of replacements (also in Table 5.3) over 50 years of building life-time:

$$Energy_{replacement} = \sum_{m}\left[\left(\frac{Life_{building}}{Life_{material\_m}} - 1\right) \times (Q_m \times Energy_m)\right]$$

Equation 5.17: Calculation of building materials replacement energy consumption

Where:

$$Emission_{replacement} = \sum_{m}\left[\left(\frac{Life_{building}}{Life_{material\_m}} - 1\right) \times (Q_m \times EF_m)\right]$$

Equation 5.18: Calculation of building materials replacement air emissions

As observed in Figure 5.13, PVC used as floor covering in both building frames consumes the most amount of material replacement energy (about 28% of total), mostly because of large quantities of consumption and higher rates of replacement. Over 50 years, PVC is estimated to be replaced 6 times, because of its comparably shorter life (average of 8 years). Polyamide carpet is also replaced 6 times but compared to PVC, its quantity is about 25 times less, and so does the energy use and associated GWP. Aluminum used in suspended ceilings and interior door frames ranks the second in replacement energy use, followed by hard wood, laminated wood composition, and ceramic tiles.

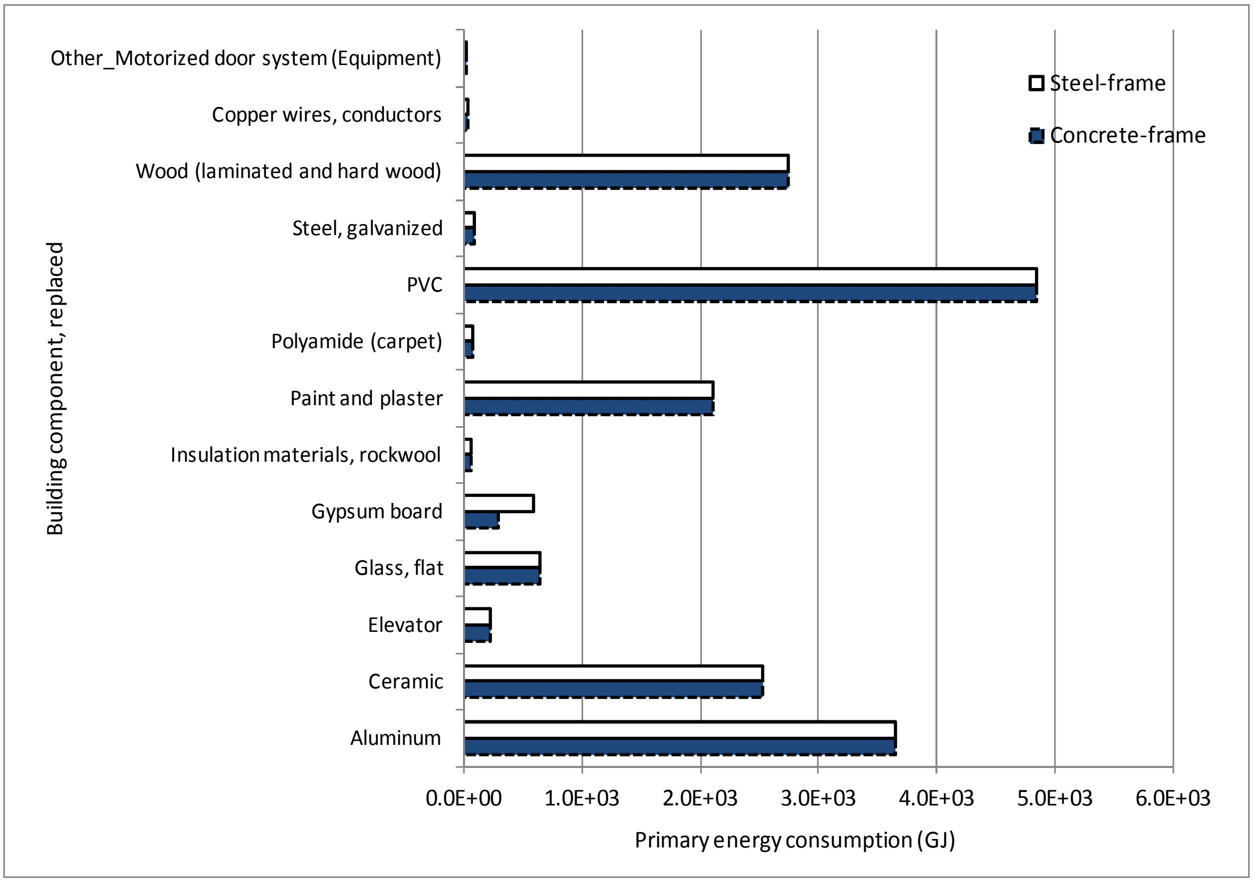


Figure 5.13: Energy consumption results for building materials replacement over 50 years

In terms of GWP percentages (see Figure 5.14), the picture is slightly different. Again, PVC as floor covering contributes to about 31-32% of total replacement GWP. With about 19-20%, ceramic tiles and aluminum come after the PVC-related GWP. In the third place, paint and plaster contributes to about 15% of GWP. As opposed to higher energy requirements for wood replacement, GWP from wood products are much less as it is assumed that wood is a biogenic material (i.e., the CO_2 emitted from decaying wood is absorbed by newly planted trees).

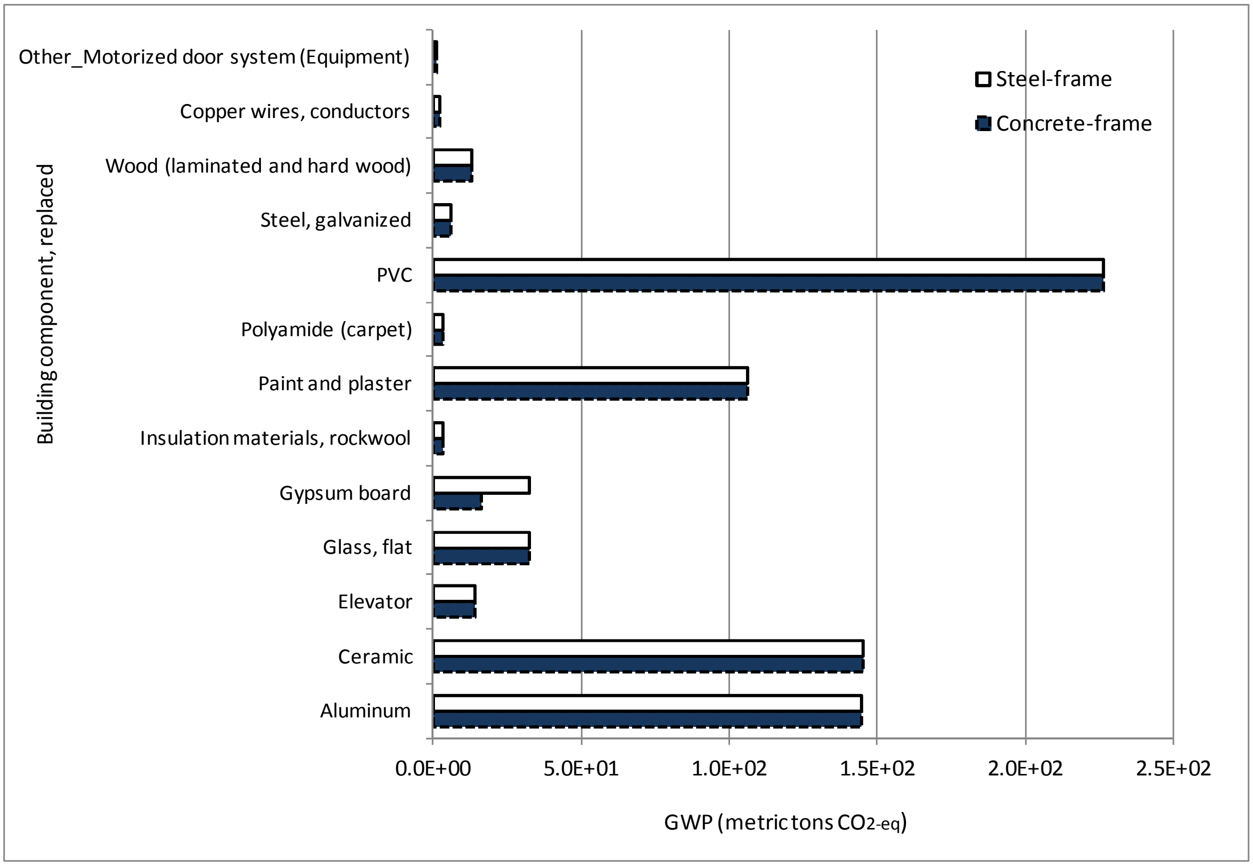


Figure 5.14: GWP results for building materials replacement over 50 years

Finally, percentage contributions to energy use and GWP of each building material replaced over the life of both building frames are summarized in Table 5.15.

Table 5.15: Percentage contributions of replaced building materials to energy use and GWP over 50-years of building's service time

	Primary energy consumption (GJ)		**GWP ($mt\ CO_2$-eq)**	
Material type	**Concrete-frame**	**Steel-frame**	**Concrete-frame**	**Steel-frame**
Aluminum	**21.1%**	**20.7%**	**20.2%**	**19.8%**
Ceramic	**14.6%**	**14.3%**	**20.3%**	**19.9%**
Elevator	1.3%	1.3%	2.0%	1.9%
Glass, flat	3.7%	3.7%	4.6%	4.5%
Gypsum board	1.7%	3.3%	2.3%	4.5%
Insulation materials, rockwool	0.4%	0.4%	0.5%	0.5%
Paint and plaster	12.1%	11.9%	**14.9%**	**14.5%**
Polyamide (carpet)	0.5%	0.5%	0.5%	0.5%
PVC	**27.9%**	**27.5%**	**31.7%**	**31.0%**
Steel, galvanized	0.5%	0.5%	0.8%	0.8%
Wood (laminated and hard wood)	**15.8%**	**15.6%**	1.8%	1.8%
Copper wires, conductors	0.2%	0.2%	0.3%	0.3%
Motorized door system (Equipment)	0.1%	0.1%	0.2%	0.2%
Total	**100.0%**	**100.0%**	**100.0%**	**100.0%**

In addition to replacement of building materials, LCA of delivery of these materials to the building site is calculated in a similar way to the description in Section 5.3.2. Table 5.16 shows the transportation-related LCI results. Energy use and CO_2 emissions are comparably small.

Table 5.16: LCI Results for transportation of building replacement materials

	Energy Use (GJ)	HC (kg)	CO (kg)	NOx (kg)	PM10 (kg)	SO_2 (kg)	CO_2 (mt)
Transportation of Replacement Materials - Concrete frame	329.42	5.00	30.58	51.70	2.41	9.01	22.87
Transportation of Replacement Materials - Steel frame	353.16	5.44	33.01	56.21	2.60	9.66	24.51

5.5 Building End-of-Life Phase

In developing sustainable buildings, minimizing the use of natural resources and maximizing the recycling potential are two important goals to consider. The EOL phase of building materials is an essential part of building LCAs. However, as stated in [308], it is one of the most difficult phases to analyze due to the necessity for forecasting in years, maybe decades for making decisions on demolishing techniques, recycling, prices of recycled and virgin materials, and landfilling options. Therefore, the building EOL LCA literature is very limited [113, 304].

Environmental interventions from the building end-of-life (EOL) phase involve building demolition, removal of metal stream from the waste, and transportation of the scrap metals to recycling facility and the remaining solid waste to landfilling. Additionally, energy use and related air emissions for further management of waste at both recycling facility and the landfill area are considered. Before the case building demolition and EOL LCA calculations, current statistics and issues regarding the construction and demolition waste (C&DW) are discussed.

In recent years, with growing interest in using more environmentally friendly building materials, researchers, policy makers, and other parties have started to pay more attention to reducing the consumption of non-renewable resources while managing growing quantities of demolition waste and increasing the use of secondary materials from construction and demolition waste (C&DW). The U.S. EPA [321] defines C&DW materials as “the materials that are produced during construction, renovation or demolition of structures and include clay bricks, concrete, fly ash, tires, asphalt concrete, asphalt shingles, drywall, fiberglass insulation, vinyl flooring and wood flooring.” In 2011, 117 million mt of C&DW were generated in the U.S., most of which ended up in landfills [322]. In the EU, about 887 million mt of C&DW were generated in 2008 while the level of recycling and reuse of the waste varied greatly (between less than 10% and over 90%) across the EU [323]. The larger rate of C&DW disposal means use of more valuable space in landfills. When Turkey’s situation is investigated, uncontrolled dumping of C&DW not only represents a significant environmental burden but also a financial cost as well. Environmental and economic effects of C&DW can be controlled by waste minimization and appropriate disposal, which both help to reduce negative environmental impacts. However, it is a challenging task to make decisions about C&DW management, especially for the long-term impacts because a thorough analysis is required to understand whether and to what extent recycling waste materials can replace virgin materials. If recycling is not an option, the question is if there will be available landfills in 50 years from now. Even for the current situation, there is lack of adequate Turkish data for C&DW recycling and landfilling rates.

In this dissertation, the U.S. Environmental Protection Agency's Waste Reduction Model (WARM) [321] was used to "…understand and compare the life-cycle GHG and energy implications of materials management options (recycling, source reduction, landfilling, combustion with energy recovery, and composting) for materials commonly found in the waste stream. In the United States, C&DW materials (except for metals) are typically disposed of in landfills which generally do not have methane capture system, which is also representative of the Turkish C&DW management system. Therefore, methane from C&DW landfills is directly released into the atmosphere. Steel and aluminum are assumed to be totally recovered after sorting the waste from demolition and transported to a recycling facility. Based on the WARM tool, it is assumed that the recycled materials replace the virgin material inputs which are used in the manufacturing process. Through recycling, "GHG emissions from making an equivalent amount of material from virgin inputs are avoided" [321] since it may require less energy to produce a material from recycled inputs than from virgin inputs. Generally, materials in WARM are modeled in a closed-loop recycling process where end-of-life products are recycled back into the same product (e.g., a recycled aluminum can becomes a new aluminum can).

For LCA application at the EOL phase, the following information is required in estimating the energy use and the related air emissions associated with the building EOL phase:

1) Energy use associated with demolition equipment used in dismantling the building.

2) Quantity of waste material generated after demolition.

3) Differences in energy use for manufacturing a product from virgin versus recycled inputs.

4) Energy use associated with recycling includes collecting, transporting, and processing at the recycling facility.

5) Energy use associated with collecting, transporting, and processing at landfill.

5.5.1 End-of-life Phase LCA Inputs and Calculations

As the last step of a building LCA, the EOL phase estimates the environmental impacts of demolishing the building and final disposal of waste at either recycling or landfilling facilities. Demolishing operation involves the use of a crane, loader, and other equipment. Energy use and GHG emissions from equipment use are calculated based on the BuiLCA database [4]. The obtained results are in Table 5.17.

Table 5.17: Demolishing LCI results for concrete- and steel-framed buildings

	HC (kg)	CO (kg)	NOx (kg)	PM_{10} (kg)	CO_2 (kg)	SO_2 (kg)	Energy (MJ)	NMVOC (kg)
Crane	5.61E+02	2.83E+03	1.46E+04	4.42E+02	1.76E+06	3.60E+03	2.51E+07	
Forklift	1.37E+01	3.52E+01	1.66E+02	7.30E+00	2.13E+04	4.35E+01	3.03E+05	
Loader	2.50E+01	6.07E+01	3.25E+02	1.07E+01	4.26E+04	8.70E+01	6.06E+05	
Grinder		2.52E+00	1.93E+01	5.51E+00	7.36E+03	2.55E+01	1.06E+05	2.51E+00
Power saw		8.00E-02	6.10E-01	1.75E-01	2.33E+02	8.07E-01	3.35E+03	7.97E-02
Rebar cutter		5.42E-02	4.13E-01	1.18E-01	1.58E+02	5.46E-01	2.27E+03	5.39E-02
Air	1.36E+01	3.49E+01	1.65E+02	7.25E+00	2.11E+04	4.31E+01	3.01E+05	

compressor								
Generator	3.45E+01	1.54E+03	3.99E+01	2.53E+00	3.81E+03	2.07E+00	2.78E+04	
Concrete Frame, Total	6.48E+02	4.50E+03	1.53E+04	4.76E+02	1.86E+06	3.81E+03	2.65E+07	2.65E+00
Crane	3.00E+02	1.52E+03	7.80E+03	2.37E+02	9.45E+05	1.93E+03	1.34E+07	
Forklift	7.35E+00	1.88E+01	8.91E+01	3.91E+00	1.14E+04	2.33E+01	1.62E+05	
Loader	1.34E+01	3.25E+01	1.74E+02	5.72E+00	2.28E+04	4.66E+01	3.25E+05	
Grinder		2.90E+00	2.21E+01	6.33E+00	8.46E+03	2.93E+01	1.21E+05	2.89E+00
Power saw		3.96E-02	3.02E-01	8.64E-02	1.15E+02	4.00E-01	1.66E+03	3.95E-02
Rebar cutter		6.23E-02	4.75E-01	1.36E-01	1.82E+02	6.28E-01	2.61E+03	6.20E-02
Air compressor	7.29E+00	1.87E+01	8.84E+01	3.88E+00	1.13E+04	2.31E+01	1.61E+05	
Generator	1.85E+01	1.54E+03	3.99E+01	2.53E+00	3.81E+03	2.07E+00	1.49E+04	
Steel Frame, Total	3.47E+02	3.13E+03	8.21E+03	2.59E+02	1.00E+06	2.06E+03	1.42E+07	2.99E+00

In most of the commercial building LCAs, the EOL phase ceases after the demolition waste is transported to the disposal area without the consideration of alternative waste management options, such as recycling [99, 119, 129]. It is also not sufficient to conclude by stating that a certain building material is recyclable at the end-of-life phase without realistically quantifying the overall impacts of recycling, reuse, landfilling, or incineration after the decommissioning of a building. "Recycling can avoid landfilling and partially displace the environmental impacts of manufacturing, as recycled products can substitute virgin materials, but, on the other hand, it is also responsible for impacts related to re-processing and transportation. In such a context, it is possible that more energy is spent and more impacts are caused through recycling than energy and impacts saved as a consequence of avoided primary production" [308]. This requires a thorough LCA approach. In some other commercial building LCAs, although the recycling option is considered, such as in Scheuer et al. [131], they do not give credit to recycling for the avoided environmental impacts. "Future embodied energy benefits are attributed to whatever product system," as stated in [131].

In this dissertation, recycling life-cycle impacts are quantified based on the "*avoided products*" approach, meaning that "EOL chain is modeled downstream, including all the activities and processes (and their related impacts) from C&DW collection to substitution of virgin products. The environmental burdens corresponding to manufacturing of the substituted product are subtracted from the system. The balance between environmental impacts and gains in the chain (net gain) might therefore be negative, in case the avoided impacts (benefits) are higher than the induced impacts, or vice versa" [308].

Before using the demolishing equipment, metal parts (aluminum, structural steel and other visible steel parts) are recovered at the construction site and directly sent to the steel or aluminum factory to be recycled. Reinforcing bars are separated from the rest of the rubble by scrap magnetic separation. Therefore, waste materials are examined in two groups: the first group, which consists of mix of concrete, bricks, ceramic tiles, wood, plaster, mortar, gypsum boards, carpet, doors, glass, and everything other than aluminum and steel are disposed in landfill, which is assumed to be 100 km away from the building site. The second group consists of aluminum and steel that are delivered to the recycling facility (again the distance is 100 km) for further manufacturing of steel and aluminum products in related factories. The WARM [321] model (which also considers the avoided impacts in case of recycling) is used to calculate energy use and GWP from landfilling and recycling activities. Results for both concrete and steel buildings are provided in Figure 5.15 and Figure 5.16. Although concrete and other non-metal materials are the largest in terms of material quantities, environmental impacts of steel and aluminum recycling govern the total end-of-life GWP results. The negative results imply that the GWP reduction through recycling due to avoided emissions from manufacturing of virgin materials exceeds the GWP impacts from landfilling and demolishing. The carbon credit given in the WARM model to steel and aluminum recycling is considerably high, 1.80 and 6.97 mt of $CO_{2\text{-eq}}$ per short ton of material, respectively. Therefore, the total GWP from EOL is -1,451 and -3,314 mt $CO_{2\text{-eq}}$ for concrete- and steel-framed buildings, respectively. Table 5.18 and Table 5.19 show results in details.

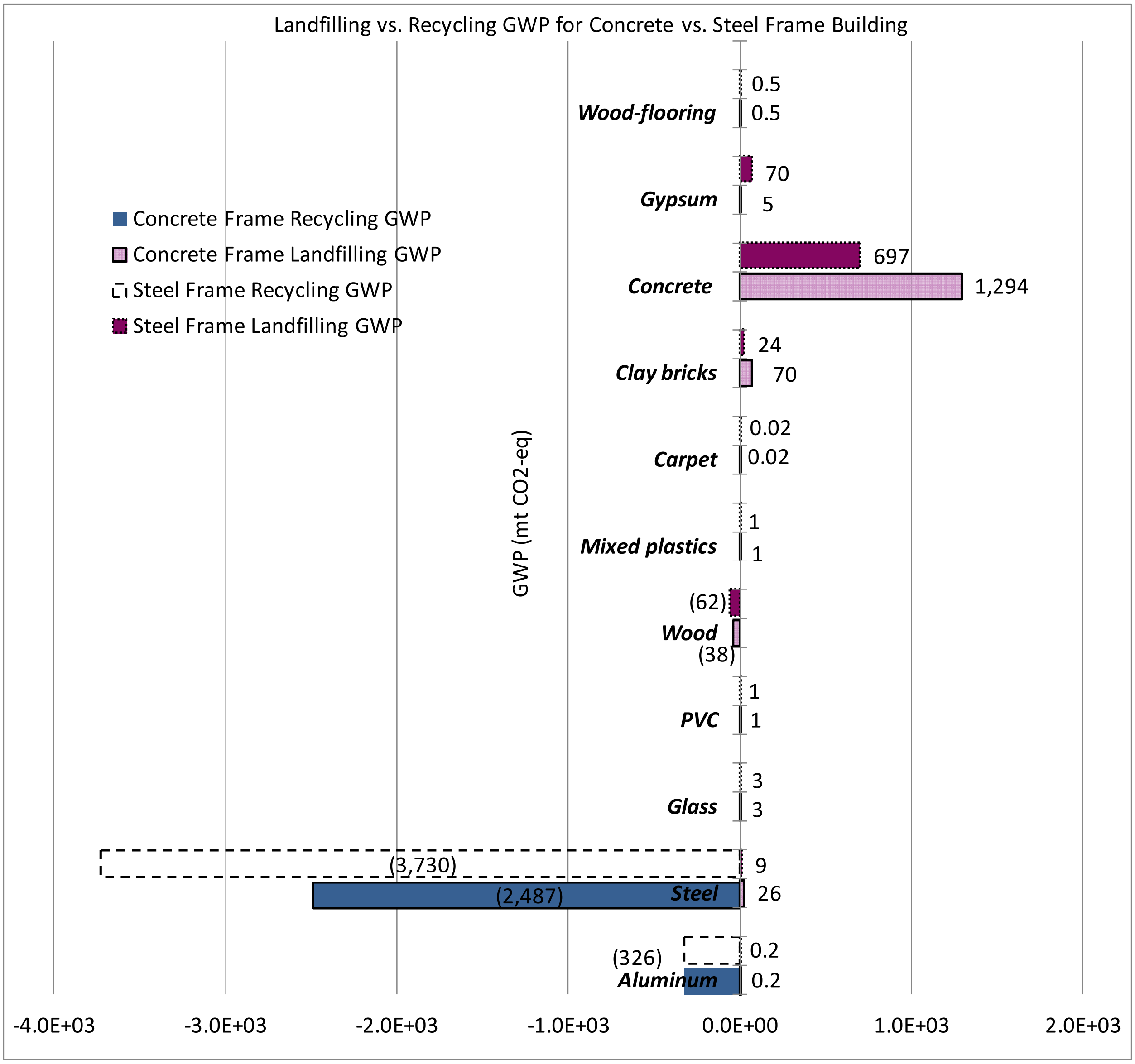


Figure 5.15: GWP for landfilling and recycling of building materials for concrete and steel building options at end-of-life phase

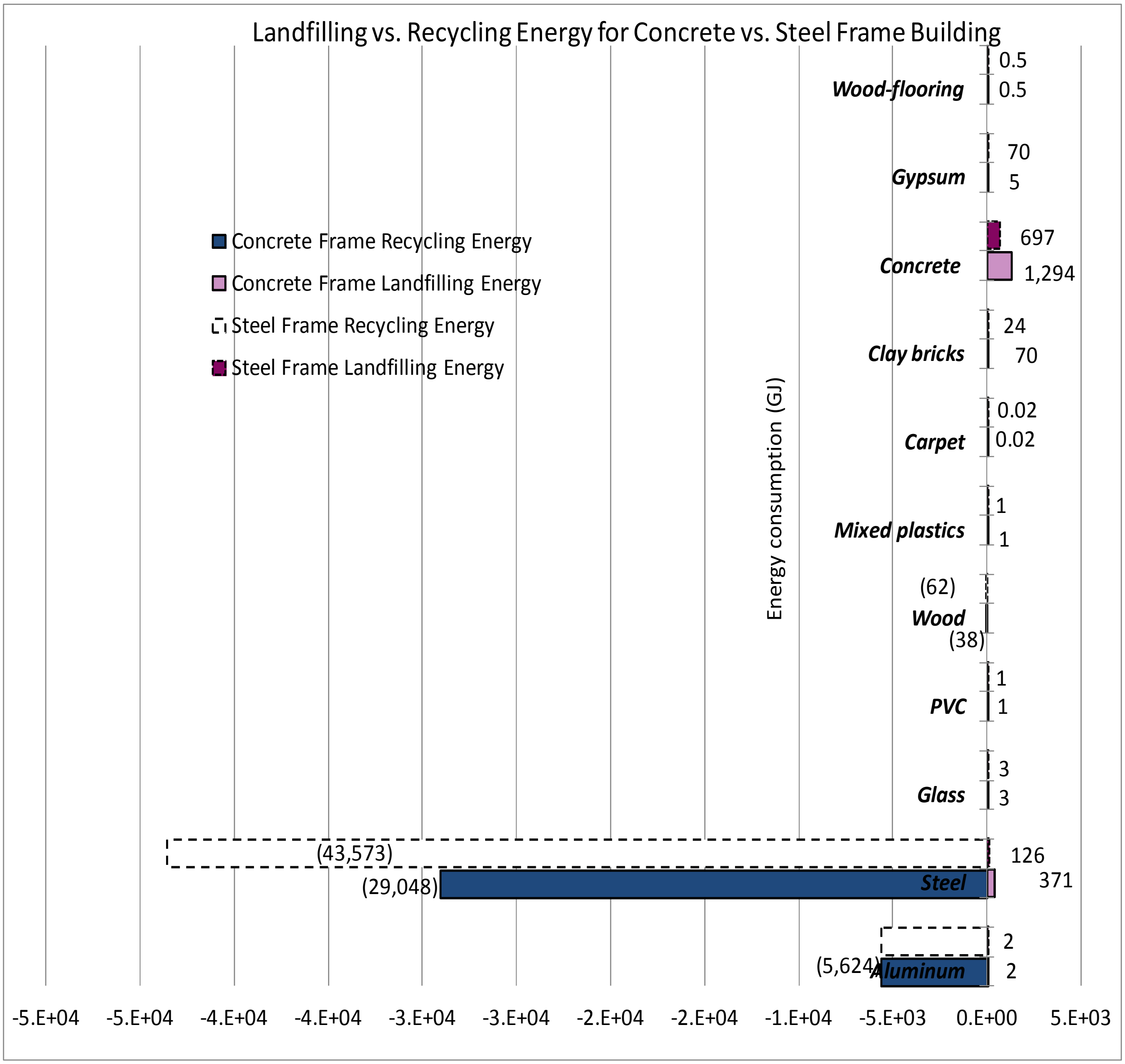


Figure 5.16: Energy consumption for landfilling and recycling of building materials for concrete and steel building options at end-of-life phase

Table 5.18: GWP and energy consumption associated with recycling and landfilling of concrete frame building waste

Material	**Baseline generation of material (tonnes)**	**Estimated recycling (tonnes)**	**GWP from recycling (mt CO_2-eq, yr)**	**Estimated landfilling (tonnes)**	**GWP from landfilling (mt CO_2-eq)**	**Total GWP (mt CO_2-eq)**	**Energy consumption from Recycling (GJ)**	**Energy consumption from landfilling (GJ)**	**Total energy consumption (GJ)**
Aluminum	50.4	46.9	(326.4)	3.5	0.2	**(326.2)**	(5,624.5)	2.3	**(5,622.3)**
Steel	1,963.7	1,384.5	**(2,486.9)**	579.2	25.9	**(2,461.0)**	(29,048.3)	371.4	**(28,677.0)**
Glass	71.5			71.5	3.2	**3.2**	0.0	45.8	**45.8**
PVC	11.4			11.4	0.5	**0.5**	0.0	7.3	**7.3**
Wood	53.3			53.3	(38.5)	**(38.5)**	0.0	22.8	**22.8**
Mixed plastics	30.3			30.3	1.4	**1.4**	0.0	19.4	**19.4**
Carpet	0.4			0.4	0.0	**0.0**	0.0	0.3	**0.3**
Clay bricks	1,559.4			1,559.4	69.8	**69.8**	0.0	1,000.0	**1,000.0**
Concrete (concrete, terrazzo tiles, stones, marble, etc.)	28,929.2			28,929.2	1,294.0	**1,294.0**	0.0	17,855	**17,855**
Drywall, gypsum	39.0			39.0	5.2	**5.2**	0.0	25.0	**25.0**
Wood flooring	6.6			6.6	0.5	**0.5**	0.0	4.2	**4.2**
Total	**32,715.3**	**1,431.4**	**(2,813.3)**	**31,283.9**	**1,362.1**	**(1,451.1)**	**(34,672.9)**	**19,353.2**	**(15,319.6)**

Note that: Negative values denote GWP reductions or carbon storage. Material that is recycled after use is then substituted for virgin inputs in the production of new products. This credit represents the difference in emissions that results from using recycled inputs rather than virgin inputs. The credit accounts for loss rates in collection, processing and remanufacturing. Recycling credit is based on closed- and open-loop recycling, depending on material [321].

Table 5.19: GWP and energy consumption associated with recycling and landfilling of concrete frame building waste

Material	**Baseline generation of material (tonnes)**	**Estimated recycling (tonnes)**	**GWP from recycling (mt CO_2-eq, yr)**	**Estimated landfilling (tonnes)**	**GWP from landfilling (mt CO_2-eq)**	**Total GWP (mt CO_2-eq)**	**Energy consumption from Recycling (GJ)**	**Energy consumption from landfilling (GJ)**	**Total energy consumption (GJ)**
Aluminum	50.4	46.9	(326.3)	3.5	0.2	**(326.2)**	(5,624.5)	2.3	**(5,622.2)**
Steel	2,273.6	2,076.8	(3,730.4)	196.8	8.8	**(3,721.6)**	(43,572.9)	126.2	**(43,446.8)**
Glass	71.5			71.5	3.2	**3.2**		45.8	**45.8**

PVC	11.4			11.4	0.5	**0.5**		7.3	**7.3**
Wood	85.6			85.6	(61.7)	**(61.7)**		36.5	**36.5**
Mixed plastics	30.3			30.3	1.4	**1.4**		19.4	**19.4**
Carpet	0.4			0.4	0.02	**0.02**		0.3	**0.3**
Clay bricks	530.4			530.4	23.7	**23.7**		340.1	**340.1**
Concrete (concrete, terrazzo tiles, stones, marble, etc.)	15,572.7			15,572.7	696.6	**696.6**		9,986.0	**9,986.0**
Drywall, gypsum	527.4			527.4	69.9	**69.9**		338.2	**338.2**
Wood flooring	6.6			6.6	0.5	**0.5**		4.2	**4.2**
Total	**19,160.2**	**2,123.7**	**(4,056.8)**	**17,036.6**	**743.0**	**(3,313.7)**	**(49,197.4)**	**10,906.3**	**(38,291.1)**

Table 5.20: Summary of EOL energy use and GWP percentages for concrete- and steel-framed buildings

	Concrete frame – EOL GWP			**Steel frame – EOL GWP**			**Concrete frame – EOL Energy**			**Steel frame – EOL Energy**		
Material	Recycling	Landfilling	Demolish	Recycling	Landfilling	Demolish	Recycling	Landfilling	Demolish	Recycling	Landfilling	Demolish
Aluminum	-80%	0%		-14%	0%		-48%	0.0%		-23%	0.0%	
Steel	-607%	6%		-161%	0%		-246%	3.1%		-181%	0.5%	
Glass		1%			0%			0.4%			0.2%	
PVC		0%			0%			0.1%			0.0%	
Wood		-9%			-3%			0.2%			0.2%	
Mixed plastics		0%			0%			0.2%			0.1%	
Carpet		0%			0%			0.0%			0.0%	
Clay bricks		17%			1%			8.5%			1.4%	
Concrete		316%			30%			156.8%			41.5%	
Gypsum		1%			3%			0.2%			1.4%	
Wood flooring		0%			0%			0.0%			0.0%	
Demolishing			454%			43%			224%			59%

5.6 Interpretation and Discussion of Results

As expected and stated in the literature review section, the building operation phase over 50 years has the highest percentage of energy consumption and GWP in the life-cycle of a building (Table 5.21). For the concrete building, operational energy use and GWP cause 96% and 94%, respectively of the total impacts while for the steel building, these percentages are 96% and 97%, respectively. Although the operational phase impacts far exceed the impacts from the other life-cycle phases, it is still necessary to investigate major contributors within each phase. Table 5.24 and Table 5.25 summarize the major contributors to energy use and GWP associated with each building phase.

Table 5.21: Summary of GWP and primary energy use for life-cycle stages of concrete- and steel-framed dormitory buildings

	Concrete Frame GWP (mt CO_2-eq)	**Steel Frame GWP (mt CO_2-eq)**	**Concrete Frame Energy (GJ)**	**Steel Frame Energy (GJ)**
Materials Manufacturing	5%	5%	3%	3%
Construction (incl. Transportation)	1%	1%	1%	0.4%
Operation (50 years)	94%	96%	96%	97%
Maintenance	0.3%	0.2%	0.4%	0.3%
EOL (incl. demolishing + recycling + landfilling)	0.2%	-1%	0.3%	-0.6%
Total	**100%**	**100%**	**100%**	**100%**

The materials extraction and manufacturing phases contribute 5% of the total GWP and 3% of the energy consumption for both building types (Table 5.21). When investigated in further detail (Table 5.22), it is observed that structural steel elements consume the highest amount of energy for both building types, 37% and 60% of the total manufacturing phase of concrete and steel buildings, respectively. Concrete and aluminum manufacturing energy use comes after steel elements (Table 5.22). However, within the total life cycle, manufacturing of steel elements consume only 1% and 2% of the total energy in concrete- and steel-framed buildings, respectively. In terms of GWP, concrete elements contribute most in the materials manufacturing phase of the concrete building (59% within the phase, 3% over the life-cycle), while the steel elements have the highest GWP impact during the materials manufacturing phase of the steel-framed building (54% within the phase, 2% overall) (see). Steel and concrete elements rank #2 in concrete and steel buildings, interchangeably, while aluminum is the third material in terms of its contribution to GWP associated with the materials manufacturing phase (see Table 5.22).

Table 5.22: Top-three major contributors to energy use and GWP within the materials manufacturing phase (cradle-to-gate)

Building material	**Energy use, concrete frame (%)**	**Energy use, steel frame (%)**	**GWP, concrete frame (%)**	**GWP, steel frame (%)**
Steel	37%	60%	30%	54%
Concrete	35%	18%	59%	35%
Aluminum	10%	8%	3%	3%
Total phase contribution (%)	**82%**	**86%**	**92%**	**92%**

As for the construction-related phase impacts, crane use is the major contributor to both energy use and GWP in steel and concrete buildings. The other two major contributing construction machines are listed in Table 5.23. They all use diesel as source of power for long hours with considerably high horsepower ratings. In addition to GWP and energy use metrics, I have also calculated the construction-related criteria air pollutants. It is important to note that the equipment listed in the table below also contribute to high percentages of NO_x, PM, and SO_2. However, vibrators are the major source of CO emissions, as they use large amounts of gasoline. Non-methane VOCs are caused by the machinery (such as welders, cutters, etc.) operated by electricity. In the construction-phase LCA, construction waste and its transportation to disposal landfilling areas is also estimated based on the waste factors obtained from literature (see the related Section 5.31. for calculations).

Table 5.23: Top-three major contributors to energy use and GWP within the construction phase (cradle-to-gate)

Construction equipment	Energy use, concrete frame (%)	Energy use, steel frame (%)	GWP, concrete frame (%)	GWP, steel frame (%)
Crane	54%	44%	52%	42%
Concrete mixer truck	25%	38%	24%	37%
Concrete pump	13%		12%	
Excavator, front loader		6%		10%
Total phase contribution (%)	**92%**	**88%**	**89%**	**88%**

The building operation phase was inventoried on the basis of hourly electricity use data, annual simulation data related to natural gas for heating and solar collectors for domestic water heating, as well as rain-water collection data on the basis of Istanbul's annual rain statistics and students' daily water use patterns and quantities. Heating (65% of total operation phase energy use, 62-63% of overall life-cycle energy use impacts) powered by natural gas dominates the total life-cycle energy use and the GWP (55% of the total operation phase GWP and 52-53% of the overall GWP) for 50 years. When calculating the upstream and direct LCI of natural gas, regional (the closest LCI data was for Mediterranean region) data found in a European Environment Agency report [315] were utilized.

Although natural gas for heating (direct and upstream impacts together) dominates the energy use, GWP, and CO results for 50 years of building's life time, electricity use contributes to the highest percentage of emissions of SO_2 (89%), PM (84%), and NMVOC (54%). Natural gas and electricity use for major building activities, such as lighting, cooking, operating appliances, etc., contribute equally to the NO_x emissions, that is, 48% and 47% of overall LCA emissions from each source, respectively. Electricity use LCA is estimated on the basis of the Turkish electricity grid mix. Natural gas and solar collectors used in hot water supply contribute to the remaining smaller fraction of environmental impacts. Table 5.13 and Figure 5.12 summarize the related percentages. The percentages of energy use and GWP impacts estimated for the maintenance and replacement of building materials are relatively small (only about 0.1%) when considered within the overall life cycle of the building's impacts. However, within the maintenance phase, replacement of PVC flooring dominates both energy use (27-28%) and GWP (31%) over other building materials. It is not surprising as both the quantity and replacement frequency (6 times over 50 years) of PVC flooring is considerably high. Aluminum used in suspended ceilings and interior door frames rank the second in replacement energy use, followed by wood (hard wood and laminated), and ceramic tiles. The replacement rates are only one time for aluminum components, while it is one time for wood doors and ceramic wall claddings and two times for laminated wood and ceramic tiles used as flooring materials. Although the replacement rate and quantity of aluminum is relatively small, it is very energy intensive to manufacture this material, which is in the range of 190 – 315 MJ per kg [112, 324, 325]. That is why its manufacturing and maintenance require considerable amount of energy use and come with associated life-cycle impacts.

Finally, the steel recycling impact dominates the end-of-life phase. Results in demonstrate how the EOL corresponds to a negative contribution or, in other terms, to a net achieved environmental gain of 0.7% – 1.1 % of total life-cycle energy use and 246% - 181% of EOL phase energy use for concrete and steel buildings, respectively. For GWP, these numbers correspond to a net gain of 1.1% - 2% of total GWP and 607% - %161% of GWP from EOL phase for concrete and steel buildings, respectively (Table 5.24, Table 5.25). Negative results can be explained in terms of avoided impacts that can be traced back to the secondary construction materials that enter future life cycles in substitution of virgin products. The energy gained during EOL is accounted for by system expansion (avoided burden approach). Here, the net environmental gain from recycling is calculated by the difference between the avoided impacts due to the substitution of virgin building materials (gross credit) and the impacts caused by transportation and recycling processes. When calculating the overall EOL impacts, energy used during demolishing, transportation of waste materials to landfills, and landfilling are considered as an environmental burden, which is subtracted from the net environmental gain from recycling. For the steel building, EOL impacts are negative due to relatively larger quantities of steel and aluminum recycled. For the concrete building, although the final EOL result is a net burden due to the demolishing and landfilling impacts, it is still very small overall, 0.3% of total life-cycle energy use, mostly because of the consideration of recycling of steel and aluminum waste.

Table 5.24: Major sources of energy use by building life-cycle phase

	Concrete Frame			Steel Frame		
Phase	**Largest phase impact**	**% of phase**	**% of total**	**Largest phase impact**	**% of phase**	**% of total**
Materials Manufacturing	Steel elements	37%	1%	Steel elements	60%	2%
Construction	Use of crane	54%	0.2%	Use of mixer truck	44%	0.1%
Transportation	Transportation of soil to/from site	49%	0.1%	Transportation of building materials to/from site	56%	0.1%
Operation	Natural gas, space heating	65%	62%	Natural gas, space heating	65%	63%
Maintenance	PVC floor covering	28%	0.1%	PVC floor covering	27%	0.1%
EOL	Steel recycling	-246%	-0.7%	Steel recycling	-181.1%	-1.1%

Table 5.25: Major sources of GWP by building life-cycle phase

	Concrete Frame			Steel Frame		
Phase	**Largest phase impact**	**% of phase**	**% of total**	**Largest phase impact**	**% of phase**	**% of total**
Materials Manufacturing	Concrete elements	59%	3%	Steel elements	54%	2%

Construction	Use of crane	52%	0.2%	Use of mixer truck	42%	0.1%
Transportation	Transportation of soil to/from site	49%	0.1%	Transportation of building materials to/from site	56%	0.2%
Operation	Natural gas, space heating	55%	52%	Natural gas, space heating	55%	53%
Maintenance	PVC floor covering	31.7%	0.1%	PVC floor covering	31.0%	0.1%
EOL	Steel recycling	-607%	-1.1%	Steel recycling	-161.4%	-2%

Finally, Figure 5.17 and Figure 5.18 summarize the breakdown of energy use and GWP for the life-cycle phases of both concrete- and steel-framed buildings. More or less, both buildings have similar impacts over the course of their life. While energy use during the materials manufacturing and maintenance phase is slightly larger for the steel building, construction and EOL phases for the steel building contribute less to the energy use compared to that of the concrete building. Operation-phase results are equivalent for both building frames as the same operation data were used in estimating the environmental impacts. As part of future work, it is essential to estimate a building's energy use and associated environmental impact on the basis of the building design features such as building size, type, material u-values (concrete vs. steel) and indoor air quality requirements.

In conclusion, the operation phase aside, the choice of materials in terms of their embodied energy, repair and replacement rates, and recyclability potential can have considerable influences on and importance in designing future sustainable buildings.

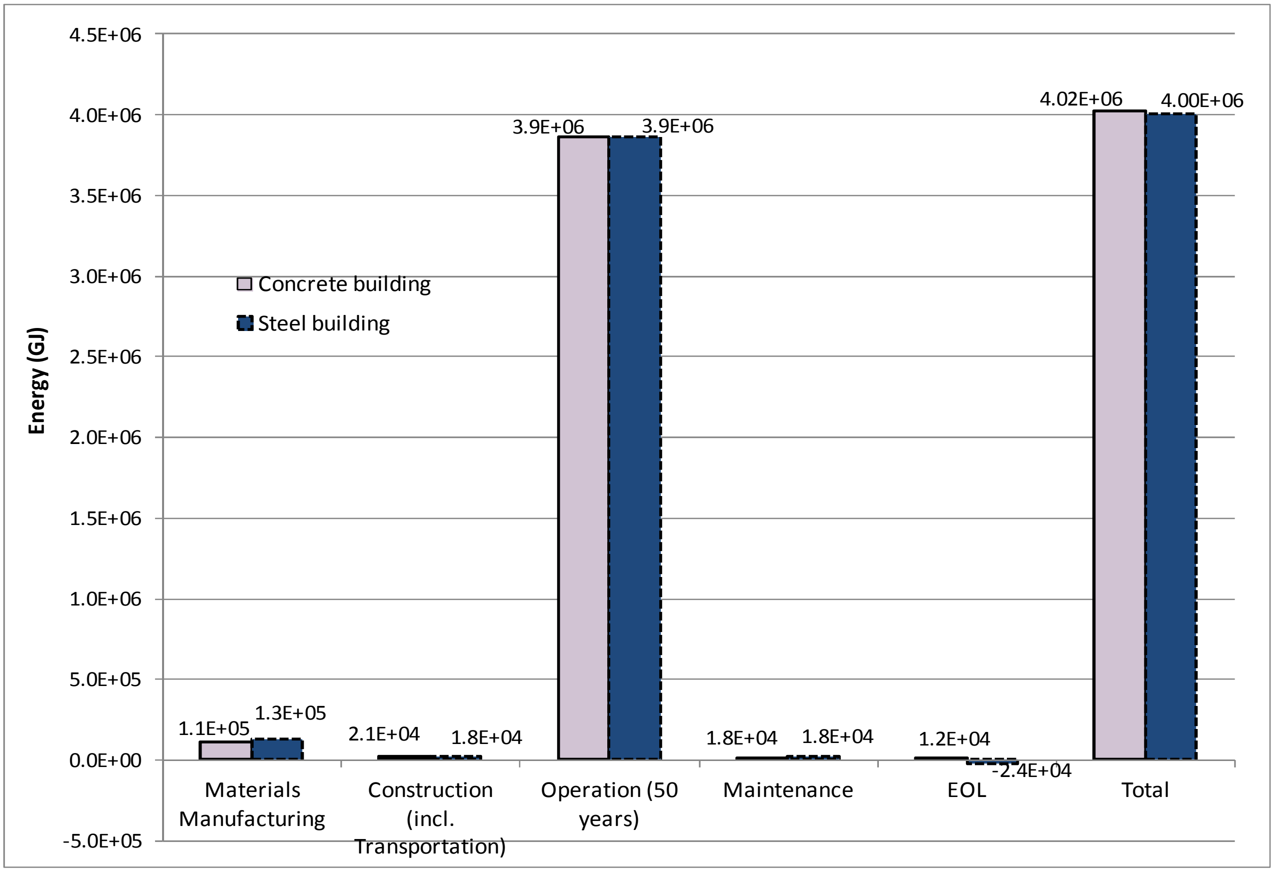


Figure 5.17: Life-cycle primary energy use demonstration of concrete and steel building options

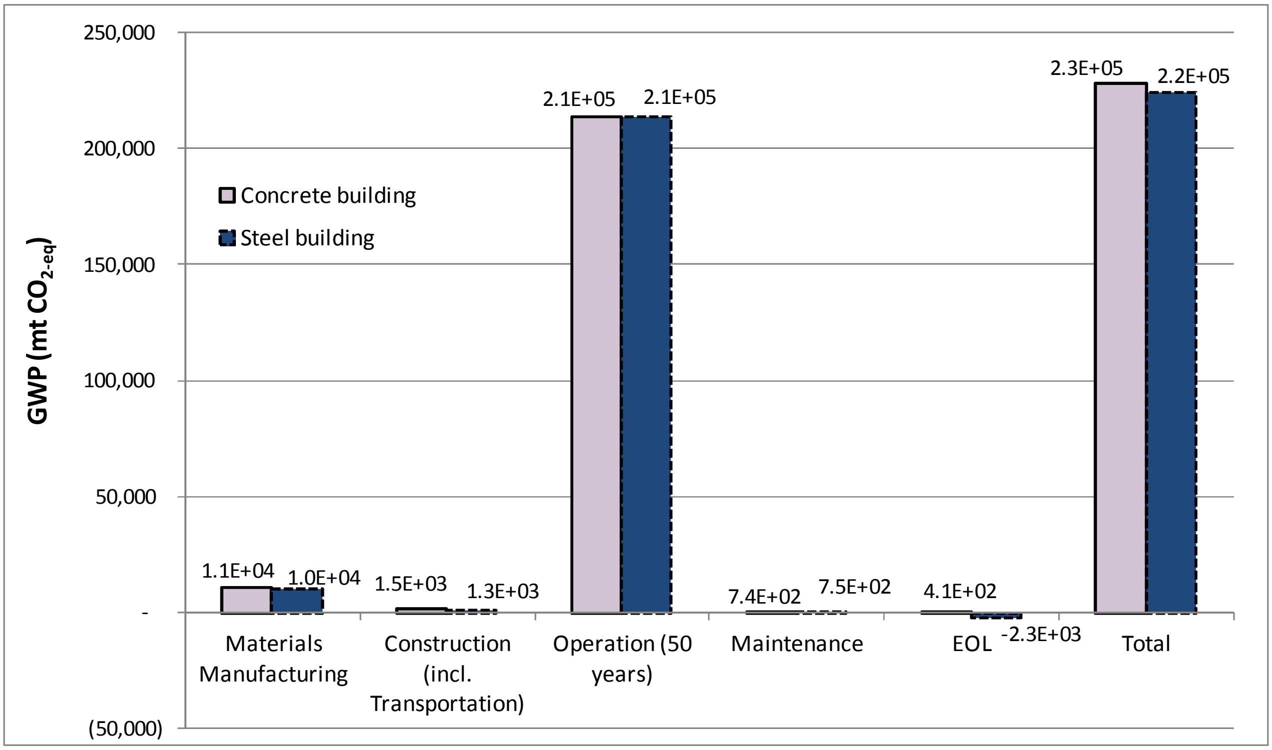


Figure 5.18: Life-cycle GWP demonstration of concrete and steel building options

5.7 Data Quality and Uncertainty

As observed in the literature review, most concrete and building LCAs leave out the uncertainty analysis. Lack of consensus and requirement of additional efforts and, of course, data are among major reasons. The existence of uncertainties in input data and modelling is often mentioned as a crucial drawback to a clear interpretation of LCA results [326]. Uncertainty analysis is the ultimate step towards a complete and reliable LCA. Although its use is not common practice, uncertainty analysis is gaining importance in LCAs. Throughout the LCA of the building case study, uncertainty can be attributed to many factors stemming from inevitable variations. Each phase and each process has its own intrinsic variations. Before describing the case study variations and areas of uncertainty, it would be valuable to understand the types of major uncertainties occurred over the course of LCA. A short classification of uncertainty and variability in LCA according to Huijbregts et al. [327] is useful for the clarifications:

1. *Parameter uncertainty: Obviously, a large amount of data is used when an LCA is performed. Uncertainty in all the parameters causes uncertainty in the results of the study. Empirical inaccuracy (imprecise measurements), unrepresentative data (incomplete or outdated measurements) and lack of data (no measurements) are common sources of parameter uncertainty. Weidema and Wenaes [328] describe a comprehensive procedure to define such uncertainty. Their method is based on expert judgment and is applied for the assessment of the quality of data used in the dormitory case study. However, it is important to note that lack of knowledge about specific*

processes, material and energy source input and related emissions from a production system cannot simply be compensated by the assessment of inaccuracy and unreliability.

2. *Model uncertainty: When a model suffers from large model uncertainties, the results of a parameter uncertainty analysis may be misleading. In LCA, processes and the interaction of these processes with one another and the environment are assumed to be in a linear manner, although sometimes as it is not. Moreover, spatial and temporal characteristics are lost by the aggregation of emissions in the inventory analysis.*
3. *Uncertainty due to choices: Choices are unavoidable in LCAs. A typical example of a choice to do in life cycle assessment is the one of the functional unit and the type of allocation procedure. One option to manage such uncertainty is by the standardisation of LCA procedures. If standardisation is not possible, one option is to seek for expert opinion. Another common solution is to develop scenario analysis. By the scenario analysis, one can show differences in LCA outcomes due to the selection of different system boundaries, application of different allocation procedures, characterization methods and weighting methods.*
4. *Spatial variability: Many LCA software and databases include European or US average data. For example, simply, specific information on cement, natural gas, or heavy-duty diesel truck freight transportation is not available for Turkiye or for any other country outside of US and EU, being used as average data on a European or US scale. The use of these databases is undoubtedly convenient but doesn't take into account the spatial variability of these parameters in the real world. This simplification also introduces model uncertainty. Especially, it is very complicated to estimate spatial variations when it comes to toxic emissions and their hazard to human and environment.*
5. *Temporal variability: Temporal variations commonly exist in production processes in the form of technology applied and related LCI and LCIA data. Temporal variability over the years can be integrated in the analysis when inventory data of several years are collected. However, chances are low as it very difficult to collect all the data used in the, e.g. LCA of a commercial building. LCIA data internalize the temporal variability to a certain extent. For example, GWP factors differ depending on the chosen time horizon to integrate potential effects. As a solution, characterization factors computed for a short time horizon may serve as indicators for short-term effects, while longer time horizons may serve as indicators for longer-term effects." [327]*

Additionally, Williams et al. [329] suggest a roadmap for managing uncertainties in life-cycle assessments, mainly associated with compiling the LCI data. Table 5.26 demonstrates major types of uncertainties encountered in compiling LCIs and which of them are most important for each of the two LCA models, process-based and EIO-LCA. Since the case study is carried out by using process-based LCA, I am not very much concerned about the EIO-LCA related uncertainties. The case study is in Istanbul and EIO-LCA models developed for other countries would add up to another level of uncertainty, therefore, process-based related uncertainties are the major focus of the dissertation.

Table 5.26: Types of uncertainties intrinsic to compiling LCI data

Uncertainty Type	**Brief Description**	**LCI method typically with higher chance of that uncertainty type**
Data	Data collection errors in input parameters	Both
Cut-off	Due to exclusion of processes	Process-based
Aggregation	Lumping of different processes /products in a given sector	EIO-LCA
Geographic	Variations in processes/products in different places.	EIO-LCA
Temporal	Variations in processes/products with time	EIO-LCA (usually five-year scale)

5.7.1 Uncertainty Associated with the Case Study

5.7.1.1 Parameter Uncertainty

The accuracy and the reliability of an LCA require good quality of available data. For the analysis of parameter uncertainty, ranges of LCI data are required for each process to determine the probability distributions and correlations. Accordingly, parameters with the largest spread on the model outcome should have been given the priority. But this is a complicated task, mostly because of lack of essential parameters, required for determination of probability distributions. For the case study, uncertainty analysis can only be developed for concrete manufacturing as the GreenConcrete tool incorporates ranges of LCI data (min, max, average). Stochastic modeling, which can be performed by Monte Carlo simulation is one of the suggested approaches in LCA data uncertainty, according to Weidema [328]. As a result of a Monte Carlo simulation, emissions for each of the building phase can be viewed as a range of values with their own probability distributions. Except for the concrete manufacturing stage, it is very complicated to develop uncertainty analysis for all the life-cycle phases of the building system, which requires hundreds of individual data, most of which are measurements or estimates with no probability distributions. At this point, there is only limited qualitative information on the uncertainty of the different data sources.

Since the bill of quantities is readily available from the engineering company (Prokon), quantity-related data for materials are considerably reliable. However, there is still a significant amount of materials LCA data obtained from EU and US sources. Exceptions are concrete, ceramic tiles, and steel. Concrete manufacturing LCIs are calculated based on the Turkish electricity grid mix, national plant fuel mixes, and technologies using the GreenConcrete LCA tool. Environmental data for ceramic tiles [330, 331] are obtained from a Turkish ceramic manufacturer. Also structural steel [332] and galvanized steel LCI (obtained from an Istanbul-based steel manufacturer [333]) represent the average Turkish steel manufacturing practice [334], which is a mix of electric arc furnace (100% scrap) and basic oxygen furnace (35% scrap). On the other hand, manufacturing LCI for the remaining materials is obtained from sources that utilize similar regional manufacturing practice to that of Turkish practice, if possible. Marble LCI is based on an Italian study [335], while the clay brick data is obtained from a Greek study [336]. However, despite the similarities of final products and manufacturing processes, variations in the electricity grid mixes, and other region-specific parameters are inevitable. When representative data from EU was not available, I used U.S. and Australian LCI data with varying scopes of studies, system boundary differences, technological and regional manufacturing assumptions.

In addition to the materials extraction and manufacturing energy use and GHG data uncertainties and variability, other parameter uncertainty includes estimations about emission factors used for other building life-cycle phases. Emission factors and energy consumption data for heavy-duty diesel trucks, as well as non-road construction equipment used during construction (and also demolishing), are based on the U.S. EPA's MOBILE 6.1 [309-313] tool and AP-42 emission factors for diesel and gasoline engine powered industrial engines [151], respectively. However, AP-42 emission factors are considerably old, from the 1990s. On the other hand, the EPA's data are transparent in terms of methodical recording of data quality. In AP-42, emission factors are qualitatively rated, "…given a rating from A through E, with A being the best. A factor's rating is a general indication of the reliability, or robustness, of that factor… Conversely, a single observation based on questionable methods of testing would be assigned an E." [337]. Such a system of grading by a dependable organization can ascertain reliability. MOBILE 6.1 data used in calculating transportation LCI are more recent in addition to being credible because of US EPA's data quality records. It would be preferable to use emission factors for Turkish truck fleet in calculating related LCI but such data does not currently exist for Turkey. Therefore, the U.S. EPA's data are commonly applied in transportation, construction, and demolishing LCI calculations. As to the construction phase, it was not possible to obtain the real construction data regarding the horsepower and duration of use for construction equipment, site-specific data such as preparation of site prior to construction, distances and modes for transferring the materials and equipment on site, as well as waste amounts and other construction related information. All the related data are either calculated on the basis of RS Means or assumptions from the technical specifications obtained from Prokon. The RS Means data [145] represent the average U.S. construction conditions and again add up to the parameter uncertainty.

The building's operational phase data are considerably the most robust: electricity use, heating by natural gas, and water heating from solar collectors and natural gas are estimated by Prokon on the basis of simulation models and realistic building use patterns. Calculations associated with the LCI of electricity generation (including upstream impacts), direct and indirect fuel use impacts both for natural gas and solar power consider Turkish average conditions. However, there is still uncertainty due to exclusion of LCI related with waste generated during building's use, manufacturing of appliances (radiators and heaters, computers, washing machines, furniture, etc), and indoor air quality. This was an uncertainty introduced by choice to keep the already expanded scope manageable or simply due to lack of data. The choice of building's service life is solely based on the literature and it is assumed that electricity use, heating and other operational use patterns remain constant through 50 years of building's estimated life. New technological developments in future will obviously affect the impacts from use phase but again, how and in what quantities this impact will occur is uncertain. In a recent LCA study by Aktas and Bilec [140], authors calculated lifetime and LCI data for residential buildings and associated interior building materials to quantify the impact of material replacement and to compensate for the uncertainty associated with these parameters. Due to lack of such statistical data for Turkish dormitory buildings, average lifetime values were chosen both for the dormitory building and replaced materials on the basis of literature [155], which introduced another parameter uncertainty.

Finally, the end-of-life phase requires forecasting in years, maybe decades from now for making decisions on demolishing techniques, possible recyclability rates for certain materials, recycling and landfilling options, changes in environmental policies (e.g., lead was commonly used in paints from 20-30 years ago but now is considered toxic to human health) and changes in prices of virgin and recycled materials. Therefore, it is the most difficult phase in terms of calculating the relevant LCI data because of high levels of uncertainty about the future.

All in all, we need more reliable and representative data, which requires additional research, expert judgments, and transparent measurements to reduce parameter uncertainty.

5.7.1.2 Model Uncertainty

Model uncertainty has its inherent implications in the case study LCA. These are summarized briefly in Table 5.26. The “Chapter 3: Research Methodology” briefly describes the advantages and drawbacks of process-based and Input-Output-based LCA in terms of model uncertainty.

In this research, building life-cycle phases are all process-based and much effort was put into making the choice of system boundaries as much inclusive and comprehensive as possible. However, it is not always possible to capture all direct and indirect supply-chain repercussions of a dormitory building over 50 years of its service life in a country where related energy use and emission factor data are still premature or even lacking. Therefore, most of the LCI data are estimated based on data from other parts of the world, mostly from the U.S. and EU (Mediterranean and Eastern European data are the most relevant, when available).

Within each building phase system boundary, some of the factors are excluded mostly because neither does the relevant data exist nor the impacts of such factors are significant. These factors include:

- In the materials manufacturing phase, life-cycle interventions are limited to only energy use and GWP as these two are most commonly studied for the building materials. However, criteria pollutants, and toxic emissions are important as they are specifically hazardous to environment and human health. Although the GreenConcrete LCA tool is very comprehensive in calculating LCI data, PM emissions which are specifically significant during materials quarrying, transferring and loading/unloading of concrete materials, are based on single average data points – which generally does not reflect the regional or technological variations. In the tool, chemical compositions of concrete materials and fuels are also not taken into consideration. However, for example, chemical composition of fly ash can be used in calculating emissions of heavy metals, dioxins or some other raw material related emissions.

- Cradle-to-gate system boundaries obtained for each of the building material item in bill of quantities show variations and it can sometimes be uncertain which manufacturing processes are included within these boundaries as the data are from third parties. Although materials manufacturing LCI data is available, it can be hard to interpret such data without knowing which processes, technologies, materials, fuels, or assumptions are involved (see Appendix B, Table 9.15 for an overview of system boundaries of major building materials analyzed).

- In the construction phase, even though direct CO_2 and criteria air pollutants are calculated from trucks and non-mobile equipment use, their indirect impacts are excluded as this requires a nationwide economic I-O matrix to capture data related to the upstream economic activities. For example, equipment use LCI is limited to on-site activity of construction machinery, without the consideration of upstream LCI of manufacturing this equipment. Wastewater impacts during the construction of the dormitory building can be significant as large amount of water is utilized.
- Life-cycle water consumption and associated energy use impacts are excluded in the dissertation again because of uncertainty involved with the water input data. Only the building's operation phase water consumption data were available, but without knowing the related Turkish water consumption energy use and emission factors, estimation of environmental burden of water consumption is left for future work.
- LCA results do not include toxic emissions (e.g., heavy metals, dioxins, furans, etc.) and process-related PM emissions from materials manufacturing, loading/unloading of materials, and both from construction and demolishing activities taking place on site as there are limited data on such emissions.
- Finally, wastewater due to water consumption for suppressing dust on construction site, washing off from concrete trucks and formwork for reuse, as well as from rain are excluded from the scope of this dissertation due to lack of data.

5.7.1.3 Spatial and Temporal Uncertainty

The possibility of dealing with spatial variability is generally very limited in building LCAs. First of all, in most cases, detailed regional data neither exists nor easy to retrieve. For example, in case of chemical admixtures, only accumulated average environmental LCI is available and for the EU, from one source, EFCA [190]. Moreover, it is not an easy task to collect data of all the individual plants in a country, and environmental LCI associated with fuel use, electricity generation, and distribution are generally national averages (e.g., even most well-known building and materials LCAs such as BEES [6], ATHENA [46] are based on national averages). In case of Turkiye, LCA data for the overall built environment is either very limited or at its earlier stages. Therefore, most of the related LCI factors are quantified on the basis of vast amount of literature sources from all over the world. For the best management of spatial uncertainty, statistics regarding the Turkish electricity grid mix, energy sources, building energy and water consumption trends are obtained from Prokon and related government agencies. Especially, when calculating the LCI for the materials manufacturing phase, as stated in [327], the spatial and temporal differences for each building material are aggregated in the results. When the materials LCI data are investigated, such differences are obvious in data sources (Appendix B, Table 9.11, Table 9.14, and Table 9.15).

End-of-life options for the management of construction and demolition waste is another challenging area in terms of spatial and temporal uncertainty. Related concerns are mentioned in the parameter uncertainty section.

Temporal uncertainty is inherent in LCAs and we all know that many of the parameters used in calculating the LCA of buildings today will most probably change over 50 years. For example in Turkey, there is continuing investments in electricity generation systems, which in turn can change the whole picture in the results from the case study as electricity is consumed in all phases of the building LCA. For example, in a recent article by World Nuclear Association [338] it has been announced that a new nuclear power plant will start its operations in the North Sea region of Turkey by 2014. However, at this point, it is beyond the scope of this dissertation to address future scenarios regarding changes in Turkish electricity grid mix, but it is definitely a part of future research work. Moreover, other future scenarios can be developed regarding improvements in building materials environmental and technical properties, availability of raw materials and material choices, changes in end-of-life management options (recycling crushed concrete instead of landfilling due to changes in future environmental regulations), and improvements in efficiency of truck fleet as well as changes in performance of construction equipment and even climate change trends. Performing scenario analysis in each of these areas improve our understanding of the consequences of near-future dynamics of the building system, while reducing the temporal uncertainty to a certain extent.

Overall, case study LCA results allow one to define major uncertainties stemming from variations in spatial and temporal differences as well as materials manufacturing, replacement, and construction technologies, operation phase impacts, end-of-life decisions, LCA calculation methods, and many other aspects.

5.7.2 Data Quality Assessment

As the input data for the case study are deterministic with little or no data ranges, the evaluation of the data quality is carried out according to the pedigree matrix developed to estimate uncertainty by Weidema and Wesnæs [328]. The authors suggested five independent “data quality indicators” for reliability, representativeness, temporal correlation, geographical correlation, and further technological correlation (shown in Appendix C, Table 9.38). Based on the indicator scores, one can determine how reliable and complete results from a study are given the quality of their data input (e.g., energy use, emission factor data for the life-cycle phases of a commercial building). Additionally, one can highlight the typical data problems and future needs in an LCA study. This subsequently can be used in improving the future data collection process. However, the pedigree matrix has its shortcomings: scores are based on subjective judgments. At this point, expertise from a number of qualified researchers may be helpful to reach a consensus on the scores. In this dissertation, data quality scores for each of the building life-cycle phases are determined based on the information from data sources, as well as expert judgment from the industry (the owner and directors from Prokon).

For the assessment of the overall data quality in the Turkish dormitory building, Junnila’s and Horvath’s [1] approach is used as a guideline. Results from the data quality assessment are shown in Table 5.27a and Table 5.27b. On a scale of 1 to 5, “1” represents the maximum quality of data, while “5” is an indication of minimum quality. Table 5.27a is prepared for only the building materials manufacturing as the quality of individual material data change considerably for all five of the indicators. The last row of the table shows the weighted average score for the corresponding data quality category. These scores are calculated by taking the average of the sum of the weighted material data scores (which is the multiplication of material mass percentages from bill of quantities and data quality scores from the corresponding building material row). Finally, data quality scores for all building life-cycle phases are presented in Table 5.28b. The construction, demolition, and EOL phases scored less than “2” with the geographical correlation, reliability, representativeness, temporal correlation, and technological correlation. These phases include calculated data based on the U.S. technology, and the U.S. database is older than 10 years. As observed, the operational phase and the materials manufacturing phase are considered to have better-than-average data (1-2) quality. These two building phases are the largest contributors to energy consumption and GWP, therefore overall data quality can be considered as "good quality".

Table 5.27a: Data quality assessment for building materials manufacturing [1, 328]

Building materials (extraction and manufacturing	**Reliability (independence of data supplier)**	**Completeness (representativeness)**	**Temporal correlation (data age)**	**Geographical correlation**	**Technological correlation**	**Region**
Aluminum	2	2	2	3	2	EU - Spain and Greece
Brick	1	2	2	2	1	EU, Greece
Ceramic	1	1	1	1	1	TR
Concrete	2	2	1	1	1	TR
Glass	2	3	2	3	3	EU
Gypsum	2	3	4	4	3	Canada
Cement fibre + gypsum board	1	2	1	3	1	EU
Insulation materials	2	2	2	2	1	EU - Greece
Wood	2	2	2	3	3	EU
Marble	1	1	1	2	1	EU - Italy
Paint and plaster	2	2	1	3	1	EU
Polyamide, carpet	2	2	5	4	2	EU
PVC	2	2	5	4	3	EU
Steel, structural	2	2	3	3	2	EU
Steel, hot-dip galvanized	2	2	1	2	1	TR
Steel, non-structural	4	4	3	4	2	World average
Natural stone (andasite, granite)	3	2	3	2	2	EU (adjusted to TR- mix)
Terrazzo tiles	3	3	2	4	3	US
Copper, wires	3	3	1	4	4	US
Weighted average (Concrete building)	**1.9**	**2.0**	**1.2**	**1.3**	**1.1**	
Weighted average (Steel building)	**1.9**	**2.0**	**1.3**	**1.5**	**1.2**	

Table 27b: Data quality assessment for the Turkish dormitory building case study

Building Phase	**Reliability (independence of data supplier)**	**Completeness (representativeness)**	**Temporal correlation (data age)**	**Geographical correlation**	**Technological correlation**
Materials extraction and manufacturing	**2**	**2**	**1**	**2**	**1**
Construction	3	3	3	4	2
Operation (heating)	1	2	1	2	1
Operation (electricity)	1	2	1	2	1
Operation (DHW)	1	2	1	2	1
Maintenance and Replacement	2	2	2	2	2
Demolition	3	3	3	4	3
EOL: Recycling vs. Landfilling	3	3	2	4	4

Maximum quality = 1, minimum quality = 5.

5.8 Sensitivity Analysis

In the coming sections, concrete manufacturing is further analyzed in more detail to understand areas of improvement towards more sustainable materials. In addition to GWP and energy use, criteria air pollutants are estimated for different technology pathways applied in concrete and steel manufacturing. Materials manufacturing scenario analysis is performed using the GreenConcrete LCA tool for concrete technology pathways, while bPATH (developed by Masanet, Stadel and Gursel for PCA) is used for steel manufacturing.

The standard approach to characterizing data-related uncertainty in process LCI is sensitivity analysis [168], "…whereby model results are calculated for a range of parameter values to determine the magnitude of the effect on the overall result. Sensitivity analysis is generally performed to identify parameters that have larger effect on LCA results. In this way, major variables which deserve the most attention are identified. It is done by allowing each of the variables to change within a range of values, while holding all the other variables constant." I will explore how different assumptions/parameters can change the results of an LCA for varying technologies, location, etc.

The comparison of various concrete manufacturing scenarios is probably the most useful and meaningful part of the concrete LCA research. Here the goal is to emphasize the significance of the chosen parameters (that are known to have strong influence on the final results based on the literature) on the LCA results of differing concrete mixes. The influences of following parameters are included in the sensitivity analysis:

- The electricity grid mix: Different energy mixes for electricity production are considered for the U.S, and Turkish national averages in cement manufacturing scenarios.
- Kiln technologies and kiln fuel mix percentages for the U.S. and Turkish cement manufacturing industries.
- Concrete with SCMs: Various concrete mixes with differing percentages of fly ash and

limestone are considered on the basis of an unpublished work. Results are normalized with respect to concrete compressive strength as with the higher percentages of SCMs strength falls below desired levels.

5.8.1 Sensitivity Analysis: Cement Manufacturing LCA

As stated in the literature review section, most of the cement manufacturing emissions are attributable to the production of cement clinker, the active ingredient in concrete [7]. Approximately half of these emissions are through the combustion of fossil fuels and the remaining portion is due to calcination of the limestone for traditional cement manufacturing processes. Improvements in cement manufacturing processes only have limited influence on reducing GHG emissions and using increased fractions of supplementary cementitious materials yield in more sustainable cement products (and eventually concrete mixtures). In this section, the GreenConcrete LCA tool is applied to explore influence of different cement manufacturing pathways (including blended cements with fly ash and slag) on cradle-to-gate life-cycle energy consumption, GHG emissions and major criteria air pollutants for both Turkish and U.S. cement manufacturing industries. The tool is designed to consider likely variations in cement manufacturing technologies. Below, Table 5.28 summarizes the scenarios that are analyzed using the GreenConcrete LCA tool.

Table 5.28: Summary of pathway scenarios for the cement pyroprocessing and cement substitution technology variations, from GreenConcrete LCA tool (Turkish vs. U.S. fuel use and electricity generation LCI)

Scenario	Name	Description
A	Baseline	This scenario assumes cement production at wet kiln; product is OPC (ordinary portland cement, US: Type I or TR: CEM I), average cradle-to-gate data from GreenConcrete LCA tool.
B	Long-dry	This scenario assumes cement manufactured in a long-dry kiln; product is OPC.
C	Preheater	This scenario assumes cement manufactured in a preheater kiln; product is OPC.
D	Preheater/ precalciner kiln	This scenario assumes cement manufactured in preheater/precalciner kiln; product is OPC.
E	Best practice I (blended cement with fly ash)	This scenario assumes best practice, standard fly ash blended cement (US: Type IP/P or TR: CEM IV) kiln technology from scenario (D)
F	Best practice II (blended cement with slag)	This scenario assumes best practice, standard slag blended cement (US: Type S or TR: CEM III), kiln technology from scenario (D)

Table 5.29 shows the average fuel mix percentages used in the Turkish and the U.S. cement kilns for the scenario analysis.

Table 5.29: Average fuel mixes (by % heat) for Turkish and U.S. cement manufacturing

Kiln fuel mix	% by energy, TR	% by energy, US
Bituminous coal	27%	64%

Lignite coal	31%	0%
Distillate (Diesel or Light) oil	0%	1%
Petroleum coke	43%	21%
Residual Fuel (Heavy) oil	0%	0%
Natural gas	0%	4%
Waste Fuels (Total)	0%	10%

Figures from Figure 5.19 to Figure 5.25 summarize the LCA results of different technology scenarios associated with the cradle-to-gate cement manufacturing, using the GreenConcrete LCA tool. Although Turkish cement kilns consume higher amount of energy (mostly during pyroprocessing) in the form of fossil fuels, electricity-related energy use is lower compared to the U.S. practice. Overall, Turkish cement manufacturing sector consumes less energy mostly because of the higher percentages of cleaner energy sources (70% from natural gas and hydro electricity power plants, 28% from lignite) used in the national electricity grid mix as opposed to the U.S. grid mix, which is dependent on coal (45%), natural gas (23%) and nuclear power (20%). Results are shown in Figure 5.19. However, overall GWP results are slightly higher for Turkish cement kilns for all five scenarios due to higher GHG emission factors resulting from the kiln fuel use, which is 100% dependent on coal and petcoke (see Figure 5.20). Once again, the Turkish cement industry needs to consider and support increased use of waste fuels in cement kilns, but this requires regulatory permission regarding the treatment and processing of wastes from other industries and the government. A comparison among the scenarios shows that energy reduction from the worst case (A) to the best case (F) is 77% and 72% for Turkey and the U.S., respectively. The GWP reduction is around 83% for both countries.

Criteria air pollutants from Turkish and the U.S. cement manufacturing processes for six scenarios are also compared (Figure 5.21). Results follow more or less similar trends with the GWP results. Exceptions are slightly lower rates of PM and VOC emissions for the Turkish manufacturing scenarios.

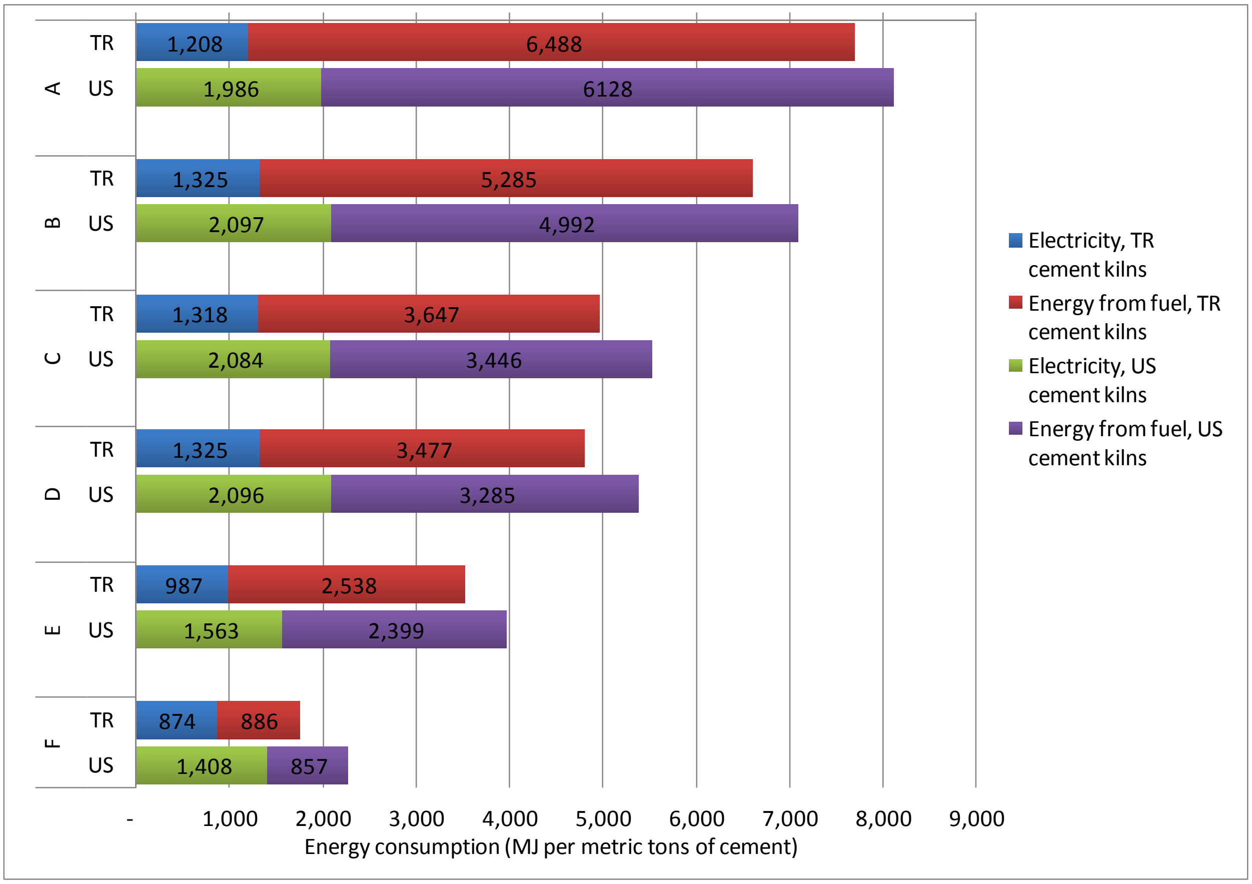


Figure 5.19: Cradle-to-gate energy consumption results of cement production for scenarios A - F for Turkish and U.S. cases

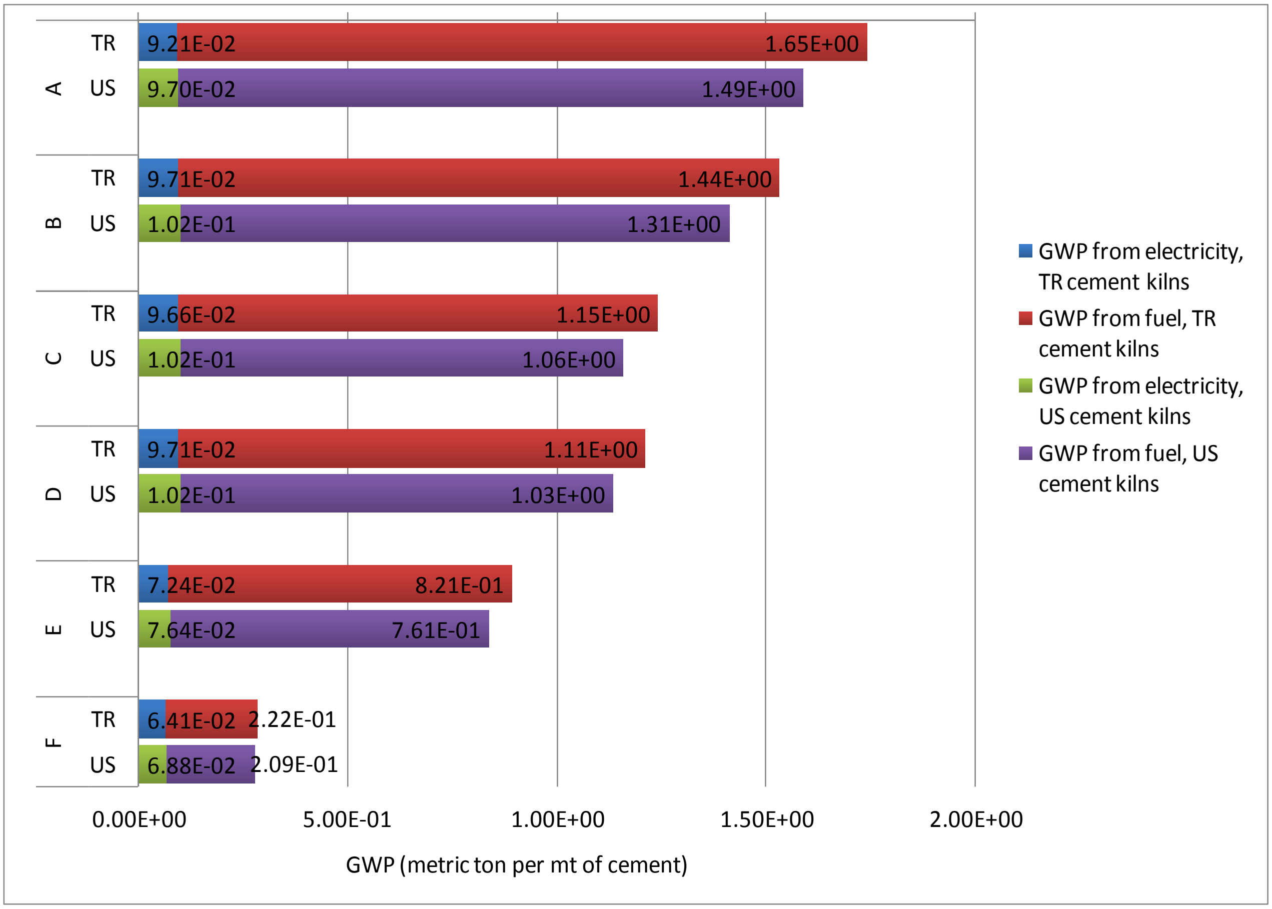
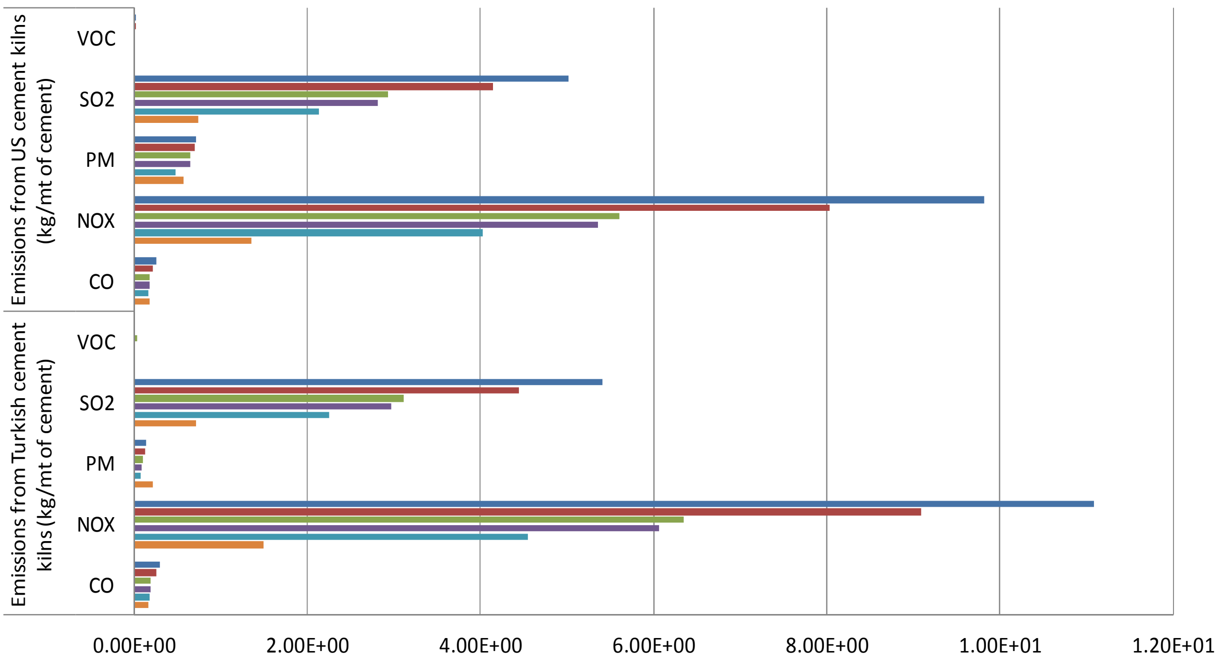


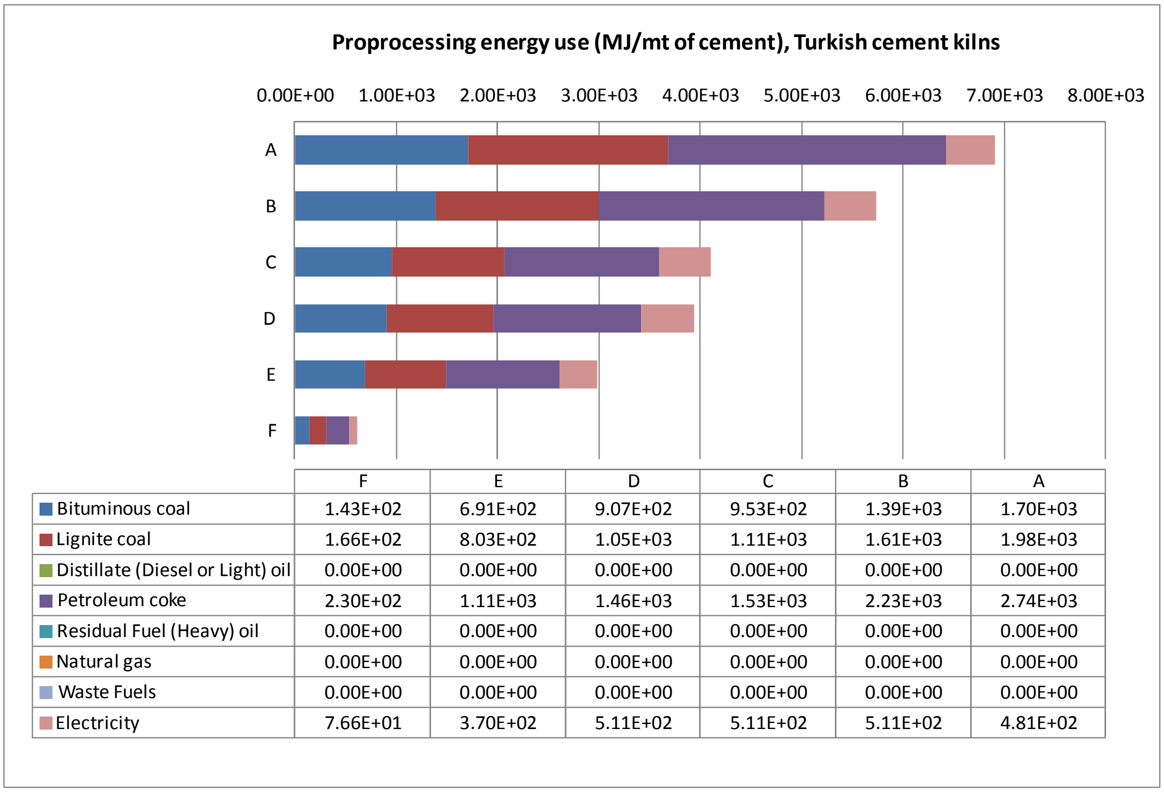
Figure 5.20: Cradle-to-gate GWP of cement production for scenarios A-F for Turkish and U.S. cases



	Emissions from Turkish cement kilns (kg/mt of cement)					Emissions from US cement kilns (kg/mt of cement)				
	CO	NOX	PM	SO2	VOC	CO	NOX	PM	SO2	VOC
🟦 A	3.00E-01	1.11E+01	1.39E-01	5.41E+00	1.67E-02	2.57E-01	9.82E+00	7.18E-01	5.01E+00	2.21E-02
🟥 B	2.58E-01	9.09E+00	1.23E-01	4.45E+00	1.37E-02	2.25E-01	8.04E+00	7.08E-01	4.14E+00	1.83E-02
🟩 C	2.00E-01	6.35E+00	9.74E-02	3.11E+00	3.86E-02	1.80E-01	5.61E+00	6.52E-01	2.94E+00	1.30E-02
🟪 D	1.96E-01	6.07E+00	9.49E-02	2.97E+00	9.52E-03	1.78E-01	5.35E+00	6.50E-01	2.81E+00	1.25E-02
🟦 E	1.85E-01	4.55E+00	7.07E-02	2.25E+00	9.12E-03	1.72E-01	4.03E+00	4.83E-01	2.13E+00	1.17E-02
🟧 F	1.74E-01	1.50E+00	2.23E-01	7.12E-01	6.87E-03	1.77E-01	1.35E+00	5.67E-01	7.44E-01	7.92E-03

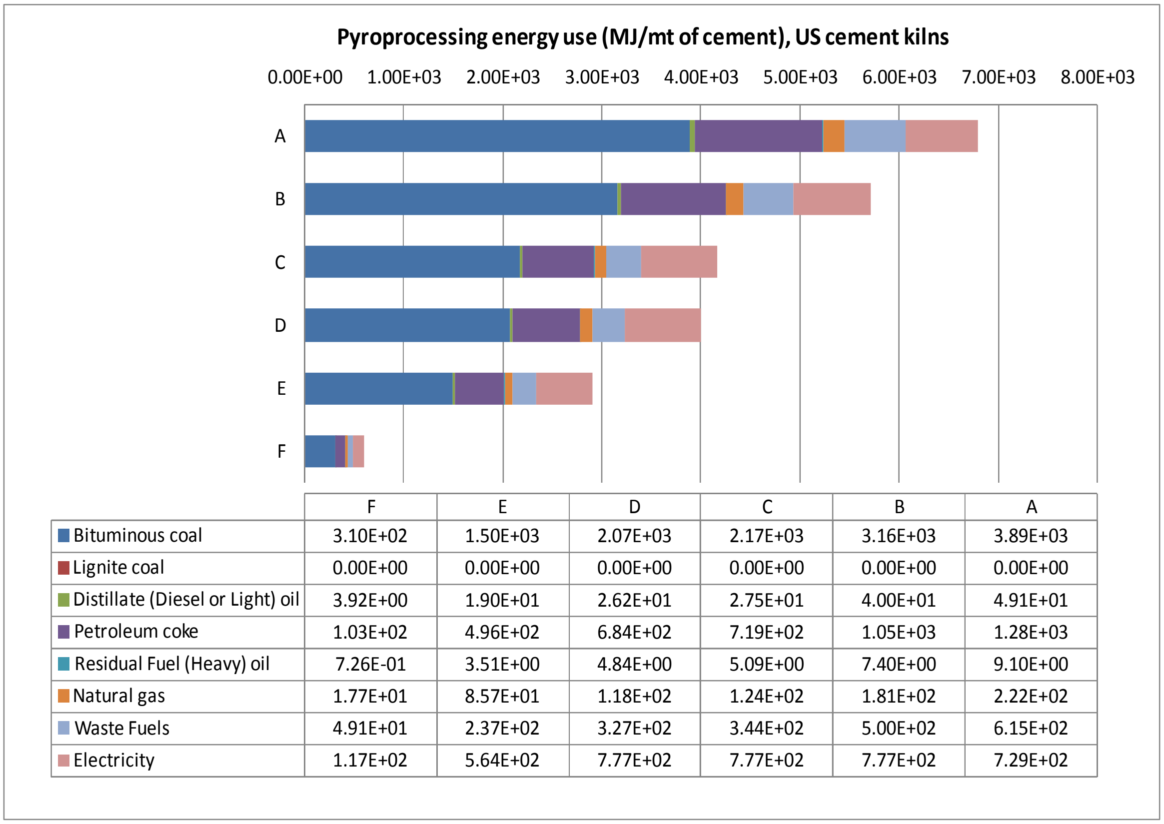
Figure 5.21: Cradle-to-gate criteria air pollutants of cement production for scenarios A-F for Turkish and U.S. cases

Additionally, pyroprocessing, being the most energy-intensive stage of cement manufacturing, is further investigated to understand and quantify the major sources (in addition to the calcination process) of GHG emissions. Fossil fuel (coal and petcoke) combustion and calcination are obviously the major source of GHGs (see Figures 5.22 through 5.25) for all scenarios in Turkey and the U.S. GHGs from kiln electricity use is comparable for both the U.S. and Turkish scenarios, results being in agreement with the literature review. For further details of pyroprocessing-related criteria air pollutants, please refer to Appendix C, Table 9.39 and Table 9.40.



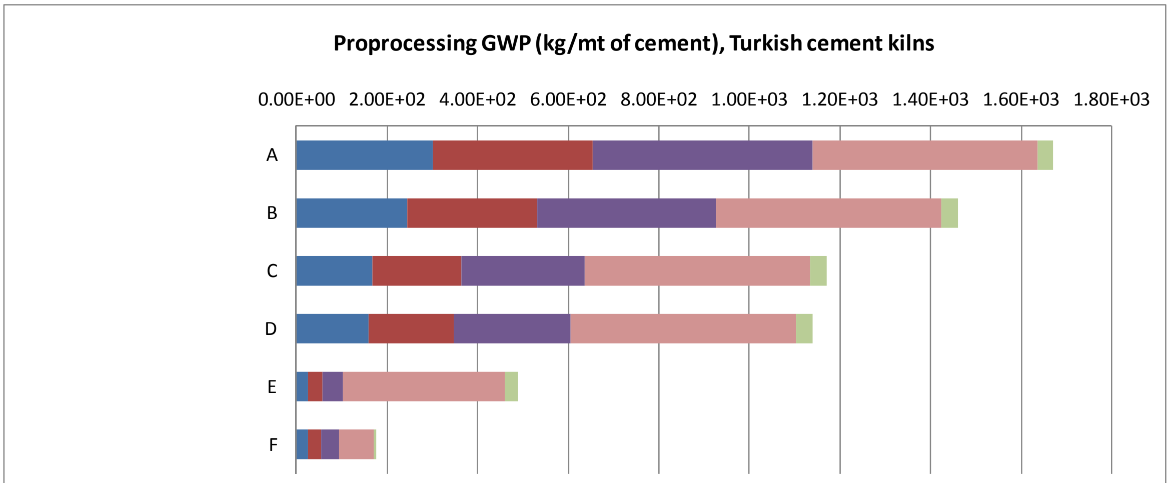
	F	E	D	C	B	A
🟦 Bituminous coal	1.43E+02	6.91E+02	9.07E+02	9.53E+02	1.39E+03	1.70E+03
🟥 Lignite coal	1.66E+02	8.03E+02	1.05E+03	1.11E+03	1.61E+03	1.98E+03
🟩 Distillate (Diesel or Light) oil	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
🟪 Petroleum coke	2.30E+02	1.11E+03	1.46E+03	1.53E+03	2.23E+03	2.74E+03
🟦 Residual Fuel (Heavy) oil	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
🟧 Natural gas	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
🟦 Waste Fuels	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
🟥 Electricity	7.66E+01	3.70E+02	5.11E+02	5.11E+02	5.11E+02	4.81E+02

Figure 5.22: Pyroprocessing kiln energy use distribution for Turkish cement manufacturing scenarios



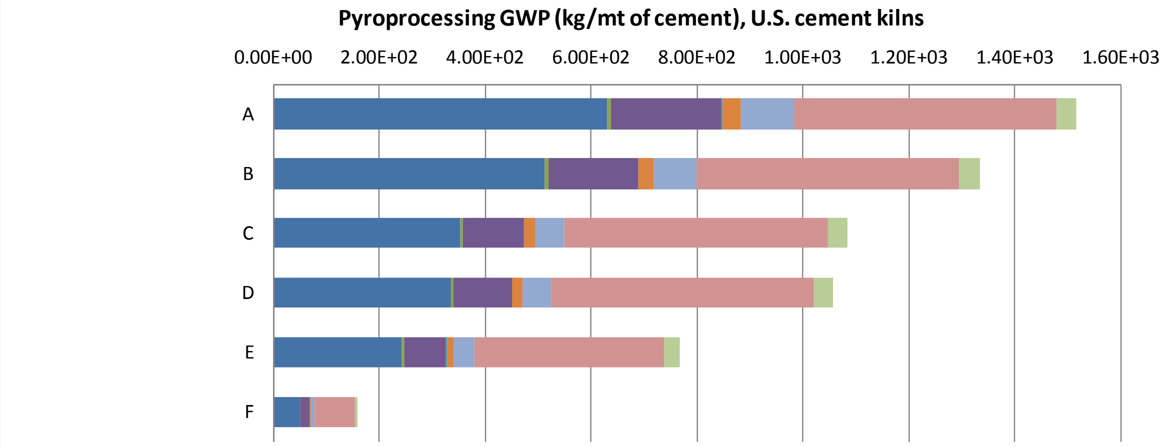
	F	E	D	C	B	A
🟦 Bituminous coal	3.10E+02	1.50E+03	2.07E+03	2.17E+03	3.16E+03	3.89E+03
🟥 Lignite coal	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
🟩 Distillate (Diesel or Light) oil	3.92E+00	1.90E+01	2.62E+01	2.75E+01	4.00E+01	4.91E+01
🟪 Petroleum coke	1.03E+02	4.96E+02	6.84E+02	7.19E+02	1.05E+03	1.28E+03
🟦 Residual Fuel (Heavy) oil	7.26E-01	3.51E+00	4.84E+00	5.09E+00	7.40E+00	9.10E+00
🟧 Natural gas	1.77E+01	8.57E+01	1.18E+02	1.24E+02	1.81E+02	2.22E+02
🟦 Waste Fuels	4.91E+01	2.37E+02	3.27E+02	3.44E+02	5.00E+02	6.15E+02
🟥 Electricity	1.17E+02	5.64E+02	7.77E+02	7.77E+02	7.77E+02	7.29E+02

Figure 5.23: Pyroprocessing kiln energy use distribution for U.S. cement manufacturing scenarios



	F	E	D	C	B	A
Bituminous coal	2.54E+01	2.72E+01	1.61E+02	1.69E+02	2.46E+02	3.02E+02
Lignite coal	2.94E+01	3.16E+01	1.87E+02	1.96E+02	2.86E+02	3.51E+02
Distillate (Diesel or Light) oil	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Petroleum coke	4.08E+01	4.38E+01	2.59E+02	2.72E+02	3.96E+02	4.86E+02
Residual Fuel (Heavy) oil	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Natural gas	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Waste Fuels	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Calcination	7.44E+01	3.60E+02	4.96E+02	4.96E+02	4.96E+02	4.96E+02
Electricity	5.62E+00	2.71E+01	3.74E+01	3.74E+01	3.74E+01	3.52E+01

Figure 5.24: Pyroprocessing GWP distribution for Turkish cement manufacturing scenarios



	F	E	D	C	B	A
Bituminous coal	5.03E+01	2.43E+02	3.35E+02	3.52E+02	5.12E+02	6.30E+02
Lignite coal	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Distillate (Diesel or Light) oil	6.36E-01	3.07E+00	4.24E+00	4.45E+00	6.48E+00	7.96E+00
Petroleum coke	1.66E+01	8.04E+01	1.11E+02	1.16E+02	1.69E+02	2.08E+02
Residual Fuel (Heavy) oil	1.18E-01	5.69E-01	7.85E-01	8.25E-01	1.20E+00	1.47E+00
Natural gas	2.87E+00	1.39E+01	1.92E+01	2.01E+01	2.93E+01	3.60E+01
Waste Fuels	7.95E+00	3.84E+01	5.30E+01	5.57E+01	8.10E+01	9.96E+01
Calcination	7.44E+01	3.60E+02	4.96E+02	4.96E+02	4.96E+02	4.96E+02
Electricity	5.70E+00	2.75E+01	3.80E+01	3.80E+01	3.80E+01	3.56E+01

Figure 5.25: Pyroprocessing GWP distribution for U.S. cement manufacturing scenarios

All in all, "Scenario F", which is the best case scenario using blended cement with slag, results in the lowest energy use and associated air emissions. Once again, the increased use of fly ash and slag is the leading improvement strategy in reducing environmental impacts from cement and eventually concrete manufacturing. However, we should not limit our material choice to these two types of SCMs as their supply is limited with the coal and steel manufacturing industries. Moreover, the quality of fly ash and slag may not always be suitable for replacing the portland cement and may contain trace quantities of some heavy metals, or radioactivity, which requires further research of these byproducts. Therefore, other minerals such as natural pozzolans, limestone or other materials such as alkali-activated alumino-silicates (previously known as geopolymer) are good candidates for replacing cement in concrete mixes.

5.8.2 Analysis of GWP vs. Strength Properties of Self-Consolidating Concrete (SCC) Mixtures with High-Volume Fly Ash (HVFA) and Limestone Powder (LP) using Sensitivity Analysis

Replacing half of the portland cement would require about 1.7 billion metric tons of alternative materials based on the USGS estimates [339]. High-volume fly ash (HVFA) concrete has been used successfully for many years in numerous applications with technical and environmental advantages as compared to conventional portland cement concrete, and its use is expected to keep increasing over time [340-342] However, currently the global availability of fly ash is roughly between 550 and 610 million tonnes [187] , which is about 40% of the overall amount of materials needed. Thus, there is a need for supply of materials, such as limestone powder, to be increasingly brought into the mixture. Limestone powder (LS) as calcite, or crystalline $CaCO_3$ is a widely available resource that has been added to cement and concrete in small volumes for many years, particularly in Europe, and recent research has shown that larger amounts can be successfully used in low water-cementitious materials ratio (*w/cm*) systems to conserve portland cement [343, 344]. This sensitivity analysis is based on an unpublished study [345]. In the collaborative study, the GreenConcrete LCA tool is used to compare the GWP of various concrete mixtures as well as their strength and durability. The tool evaluates both direct and supply-chain environmental impacts of concrete manufacturing, including the related impacts from concrete materials. The following assumptions are made regarding the technology, location of manufacturing, transportation distance and mode selection (Table 5.30) and electricity grid mix percentage (Table 5.31) based on a real case study.

Concrete mixture proportions used in the LCA are shown in Figure 5.32. The *w/cm* ratio for all mixtures was held constant at 0.35. The ratio of portland cement replacement (CR) by fly ash type-F (FAF) and LS was varied between 45% and 75%, by weight. For the OPC-FAF-LS blends, LS content was set at 15% or 25%, by weight, and the amount of fly ash was varied between 20% and 60%, by weight, in order to match the desired total replacement ratio for each mixture. The ratio between coarse and fine aggregates (FA) was kept at 50-50%, and the coarse aggregate consisted of 30% pea gravel and 70% basalt.

Table 5.30: Assumptions for the LCA of HVFA concrete manufacturing

User-Input Data:	**Assumption**
Type of cement	Type I
Type of SCMs	Fly ash, limestone
Type of admixture	Superplasticizer
Electricity grid mix for:	**Location**
Cement supplier	California, US

Fine aggregates supplier	California, US	
Coarse aggregates supplier	Canada, average	
Gypsum supplier	California, US	
Limestone supplier	California, US	
Fly ash supplier	Wyoming, US	
Transportation details for:	**Mode**	**Distance (km)**
Cement raw materials to cement plant	Truck_Class 8b (Model 2005)	1
Gypsum to cement plant	Truck_Class 8b (Model 2005)	200
Cement to concrete plant	Truck_Class 8b (Model 2005)	60
Fine aggregates to concrete plant	Truck_Class 8b (Model 2005)	50
Coarse aggregates to concrete plant	Water_Barge and Truck_Class 8b (Model 2005)	1,000 km by barge, 10 km by truck
Admixture to concrete plant	Truck_Class 8b (Model 2005)	1,000
Fly ash to concrete plant	Rail	1,000
Limestone to concrete plant	Truck_Class 8b (Model 2005)	130
Technology options for:	**Type of technology selected**	**Distance (m)**
Cement raw materials prehomogenization	Dry, raw storing, preblending	
Cement raw materials grinding	Dry, raw grinding, ball mill	
Cement raw meal blending/homogenization	Dry, raw meal blending, storage	
Clinker pyroprocessing	Preheater/Precalciner kiln with US average kiln fuel mix [27]	
Clinker cooling	Reciprocating grate cooler (modern)	
Cement finish milling/grinding/blending	Roller press	
Cement PM control technology	ESP	
Conveying within the cement plant	Screw pump	20 m between process stations
Concrete batching plant loading/mixing	Mixer loading (central mix)	
Concrete batching plant PM control	Fabric filter	

Table 5.31: Electricity grid mix percentage by source of energy adapted from EIA [220, 257] for United States and from CEA [346] for Canada

User-Input Data	**California (%)**	**Wyoming (%)**	**Canada (%)**
Coal	1	91	19
Natural gas	55	1	6
Fuel oil	0.1	0.1	3
Petroleum coke	1		
Nuclear	16		13
Hydropower	14	2	58
Biomass	3		
Geothermal	6		
Solar	0.3		1
Wind	3	5	
Percentages may not add up to 100% because rounding of the numbers during calculations.			

Table 5.32: OPC-FAF-LS concrete mixture proportions

(*w/cm* = 0.35)	**OPC-FAF - LS**	**OPC**	**FAF**	**LS**	**FA**	**CA**	**SP (%)**	**CM (kg/m^3)**	**OPC (kg/m^3)**	**CR (kg/m^3)**
Control mixtures	100-0-0	1.00	-	-	2.00	2.00	1.43	461	461	0
	85-0-15	0.85	-	0.15	2.00	2.00	1.43	458	389	69
	75-0-25	0.75	-	0.25	2.00	2.00	1.32	456	342	114
Binary HVFA blends	70-30-0	0.70	0.30	0.00	2.00	2.00	1.43	453	317	136
	50-50-0	0.50	0.50	0.00	2.00	2.00	1.14	449	224	225
Ternary HVFA-LS blends	55-30-15	0.55	0.30	0.15	2.00	2.00	1.14	451	248	203
	45-40-15	0.45	0.40	0.15	2.00	2.00	1.03	448	202	246
	35-50-15	0.35	0.50	0.15	2.00	2.00	1.00	446	156	290
	25-60-15	0.25	0.60	0.15	2.00	2.00	1.00	444	111	333
	55-20-25	0.55	0.2	0.25	2.00	2.00	1.34	451	248	203
	45-30-25	0.45	0.3	0.25	2.00	2.00	1.14	449	202	247
	35-40-25	0.35	0.4	0.25	2.00	2.00	1.14	447	156	291
	25-50-25	0.25	0.5	0.25	2.00	2.00	1.14	445	111	334

* Keys: *w/cm* = water/cementitious materials ratio; OPC = ordinary portland cement; FAF= fly ash F; LS = limestone powder; SP = superplasticizer; CM = cementitious materials; CR = cement replacement.

For comparison purposes, typical ordinary portland cement concrete (OPCC) having 28-day strength of 18, 30 and 60 MPa (low-strength, medium-strength and high-strength, respectively) are analyzed and found to produce GHG emissions of 218, 304 and 436 kg $CO_{2\text{-eq}}/m^3$, respectively [9, 316].

Based on the GreenConcrete LCA calculations, all self-consolidating FAF-LS mixtures are estimated to be comparable to typical medium-strength OPCC and have lower cement content, and therefore reduced $CO_{2\text{-eq}}$ footprint, than even the low-strength OPCC. Table 5.33 presents the average compressive strength for all mixtures, while Figure 5.26 shows the results in graphical form. As can readily be observed in this figure, a wide range of strengths are attainable depending on the specific replacement ratios and curing time specified for a given project. Similarly, a given strength can be obtained using a variety of mixtures and cement replacement ratios. For example, a strength level of 30 MPa (4,350 psi) can be obtained either at 28 days with a total cement replacement level of up to 55% (either using 15% LS + 40% FAF or 25% LS + 30% FAF), or at 356 days with a replacement level of up to 65%, or at 91 days with a cement replacement level as high as 75%. Higher strengths can also be easily achieved. The 45% replacement with 30% fly ash and 15% limestone powder (30-15) reached approximately 42 MPa (6,030 psi) at 28 days, growing to about 54 MPa (7800 psi) at 91 days.

The early age data are very similar for the 15% LS and 25% LS series. At 7 days, FAF-LS mixtures ranged between 9 MPa for 75% replacement and 20 MPa for 45%. At 28 days, these mixtures reached 19 MPA for 75% replacement and approximately 40 MPa for 45%. At 56 days, this range was 24 MPa to 44 MPa. Finally, at 90 days the FAF-LSF mixtures obtained a minimum of 31 MPa and up to 54 MPa for the 30-15 mixture. As expected, at a fixed *w/cm* ratio, increased FAF content leads to relatively lower early strengths but higher strength gain rates.

Table 5.33: Average compressive strength (MPa) for OPC-FAF-LS mixture designs

OPC-FAF-LS (%)	**7 days**	**28 days**	**91 days**	**365 days**
100-0-0	43.9	53.9	66.3	77.1
85-0-15	28.0	43.2	49.7	53.0
75-0-25	22.2	33.6	38.7	42.2
70-30-0	35.6	51.0	64.6	71.8
50-50-0	27.9	41.6	54.8	64.8
55-30-15	21.5	37.5	47.3	56.8
45-40-15	17.1	33.9	46.2	56.5
35-50-15	12.9	26.0	39.3	49.0
25-60-15	10.3	20.6	29.4	39.5
55-20-25	19.6	36.3	42.9	54.2
45-30-25	14.9	31.5	43.3	55.3
35-40-25	12.4	28.9	41.8	50.4
25-50-25	10.1	20.6	32.8	38.0

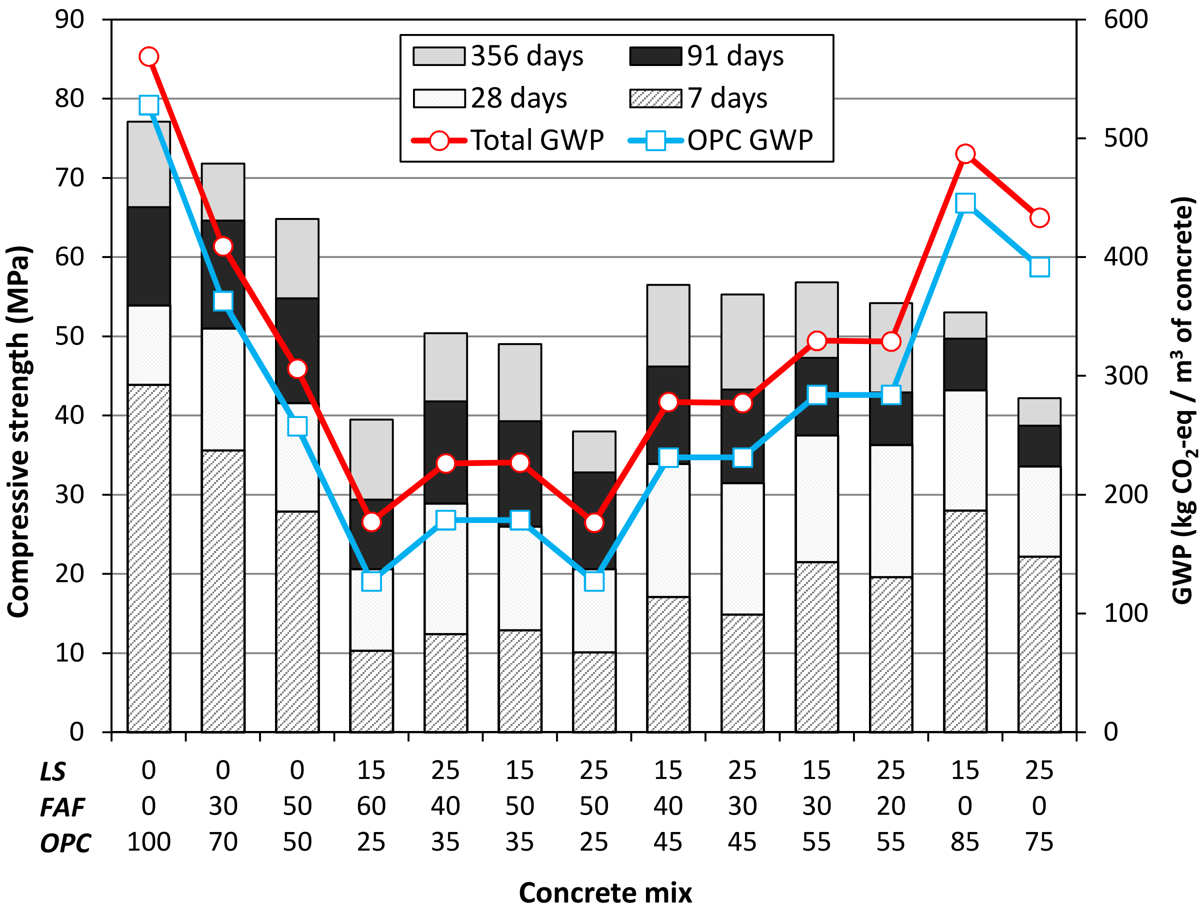


Figure 5.26: Comparison of average compressive strength (MPa) of the concrete mixtures over time (days). Red line shows the calculated total GWP for concrete production (kg CO2-eq/m^3 of concrete); and the blue line shows the contribution of the portland cement used in the mixtures to the GWP

Similarly to the GWP trends, criteria air pollutants increase with the higher weight of portland cement use, mostly attributable to the pyroprocessing stage of the cement manufacturing (see Table 5.34). The only exception is CO emissions which are slightly higher for concrete mixtures with higher fly ash content. Table 5.34 shows the rate of change of CO emissions with the higher fly ash content. This is attributable to the considerable amount of natural gas used during drying of the fly ash. Natural gas combustion has a considerably high CO emission factor.

Table 5.34: GWP and criteria air pollutants for OPC-FAF-LS mixture designs

OPC-FAF-LS	**CO_2.eq (kg /m^3)**	**CO (kg /m^3)**	**NO_X (kg /m^3)**	**PMtotal (kg /m^3)**	**SO_2 (kg /m^3)**
100-0-0	5.69E+02	1.35E-01	2.99E+00	3.64E-01	1.35E+00
85-0-15	4.87E+02	1.26E-01	2.61E+00	3.09E-01	1.15E+00
75-0-25	4.34E+02	1.20E-01	2.36E+00	2.73E-01	1.03E+00
70-30-0	4.12E+02	1.49E-01	2.27E+00	2.62E-01	9.74E-01
50-50-0	3.11E+02	1.57E-01	1.82E+00	1.97E-01	7.31E-01

55-30-15	3.33E+02	1.39E-01	1.91E+00	2.09E-01	7.84E-01
45-40-15	2.82E+02	1.43E-01	1.68E+00	1.77E-01	6.63E-01
35-50-15	2.32E+02	1.47E-01	1.45E+00	1.44E-01	5.44E-01
25-60-15	1.83E+02	1.52E-01	1.23E+00	1.12E-01	4.27E-01
55-20-25	3.32E+02	1.29E-01	1.90E+00	2.07E-01	7.83E-01
45-30-25	2.81E+02	1.33E-01	1.67E+00	1.74E-01	6.61E-01
35-40-25	2.31E+02	1.38E-01	1.44E+00	1.42E-01	5.42E-01
25-50-25	1.82E+02	1.43E-01	1.22E+00	1.10E-01	4.26E-01

GWP contributions of major concrete ingredients are further examined in Figure 5.27 through Figure 5.30. Figure 5.27 reports direct and indirect GWP of concrete mixture designs including quarrying, manufacturing, and transportation processes within the system boundary. The concrete mixture with 100% portland cement (which is responsible for about 93% of the total GWP) causes the highest amount of GWP emissions (Figure 5.27 and Figure 5.28). With the decreasing amount of portland cement and increasing amount of SCM use, e.g., for 60FA-15LS mixture, GWP from portland cement can be as low as 69% by weight of the total GWP emissions. The transportation of materials to the concrete plant is the second highest source of emissions, changing between 4-18% of the total, depending on the weight of the materials delivered and transportation distance and mode (see Figure 5.29). GWP from non-cementitious ingredients and their mass contribution remains almost constant for all mixtures, about 4 kg of fine aggregates (1-2% by weight of concrete mixture), 4-5 kg of superplasticizers (1-2% by weight), 3 kg of coarse aggregates (1% by weight), and 1.5 kg of concrete mixing and batching activities (0.3-1% by weight). Finally, Figure 5.30 summarizes the GWP of limestone production and fly ash preparation, which can be as high as 3% in total for the mixes with the highest cement replacement, e.g. 60FA-15LS mixture. The GWP from fly ash is found to be larger with an order of 5-10 times for the same weight of limestone used in the mixture. This difference can be explained by the higher amount of fuel utilized per unit mass of fly ash during the drying process as part of treatment prior to mixing in concrete [44].

The results show that satisfactory self-consolidating concrete mixtures can be made with high-volumes of fly ash and limestone, with low addition of superplasticisers and without viscosity modifying agents. A wide range of early and long term strengths are attainable depending on the selected mix proportion. GHG emissions and major criteria air pollutants (with only exception being CO emissions) were also successfully reduced and were in all cases similar to and lower than typical OPCC.

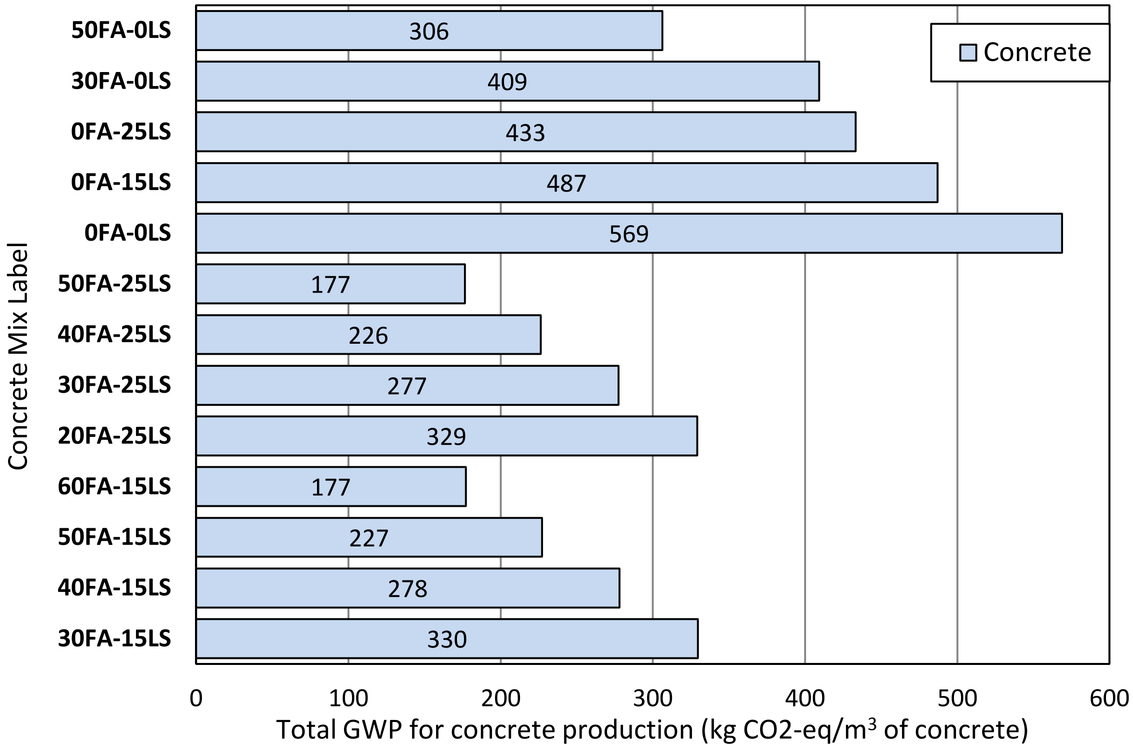


Figure 5.27: Total GWP results of OPC-FAF-LS concrete manufacturing

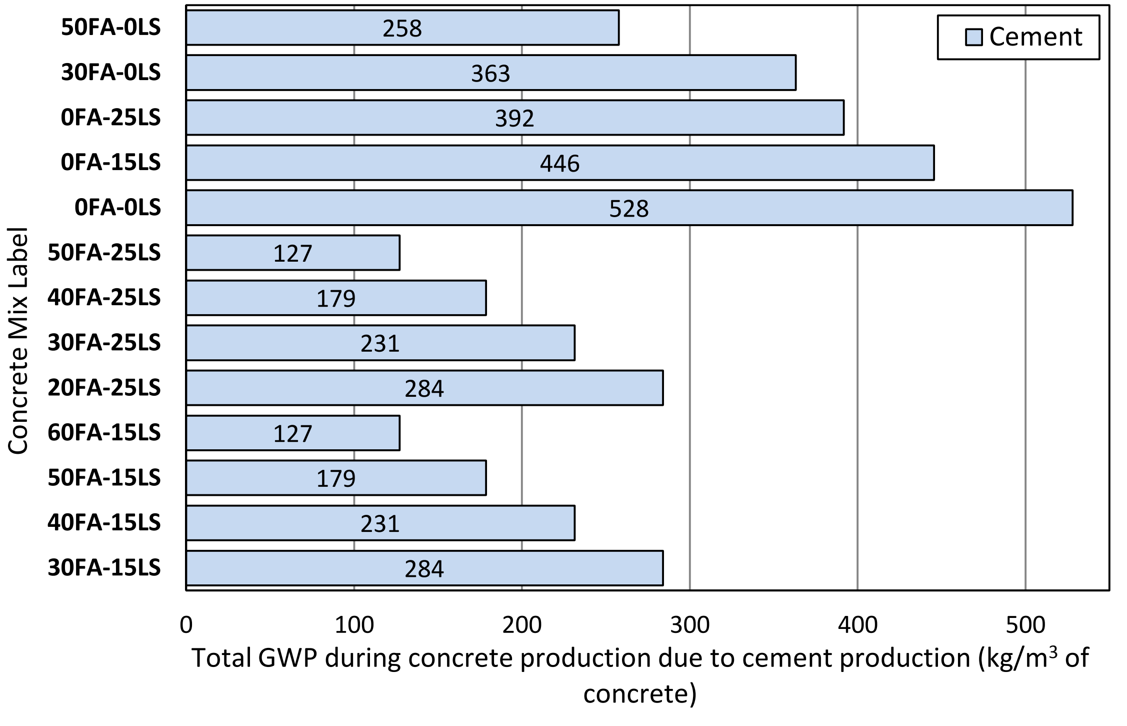


Figure 5.28: Total GWP results associated with portland cement used in OPC-FAF-LS concrete mixture designs

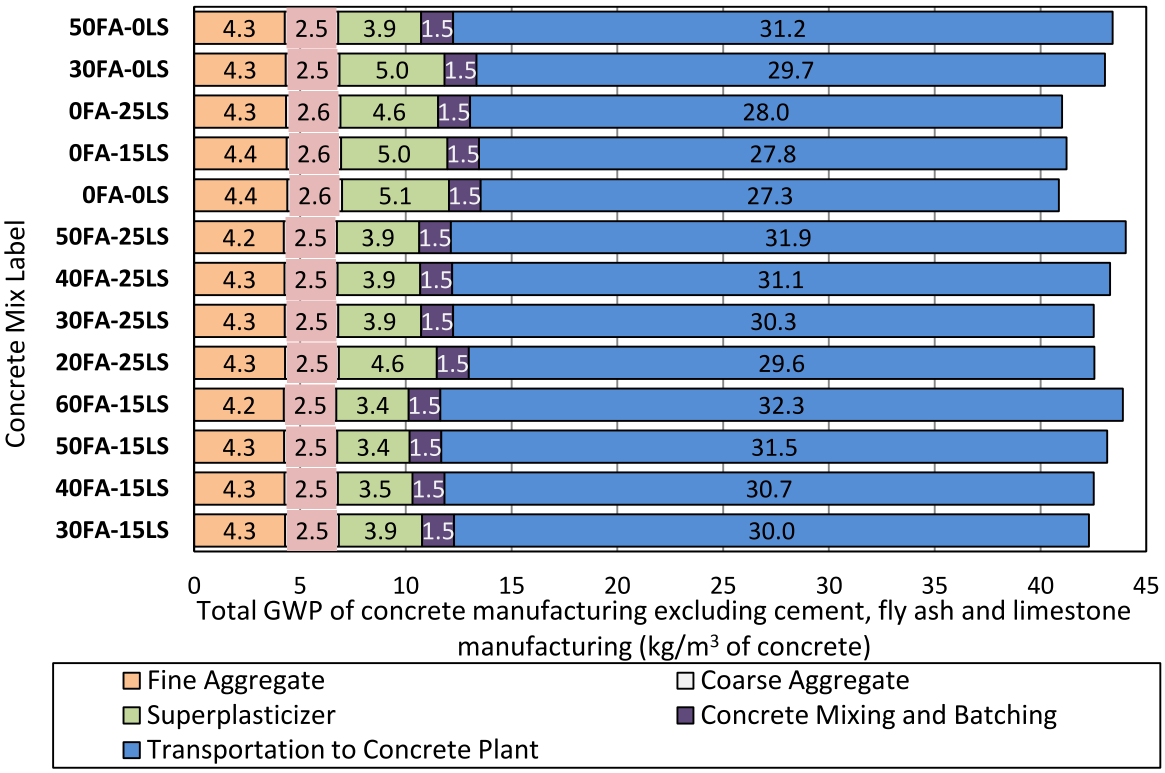


Figure 5.29: Total GWP results associated with concrete manufacturing excluding cement, fly ash and limestone production

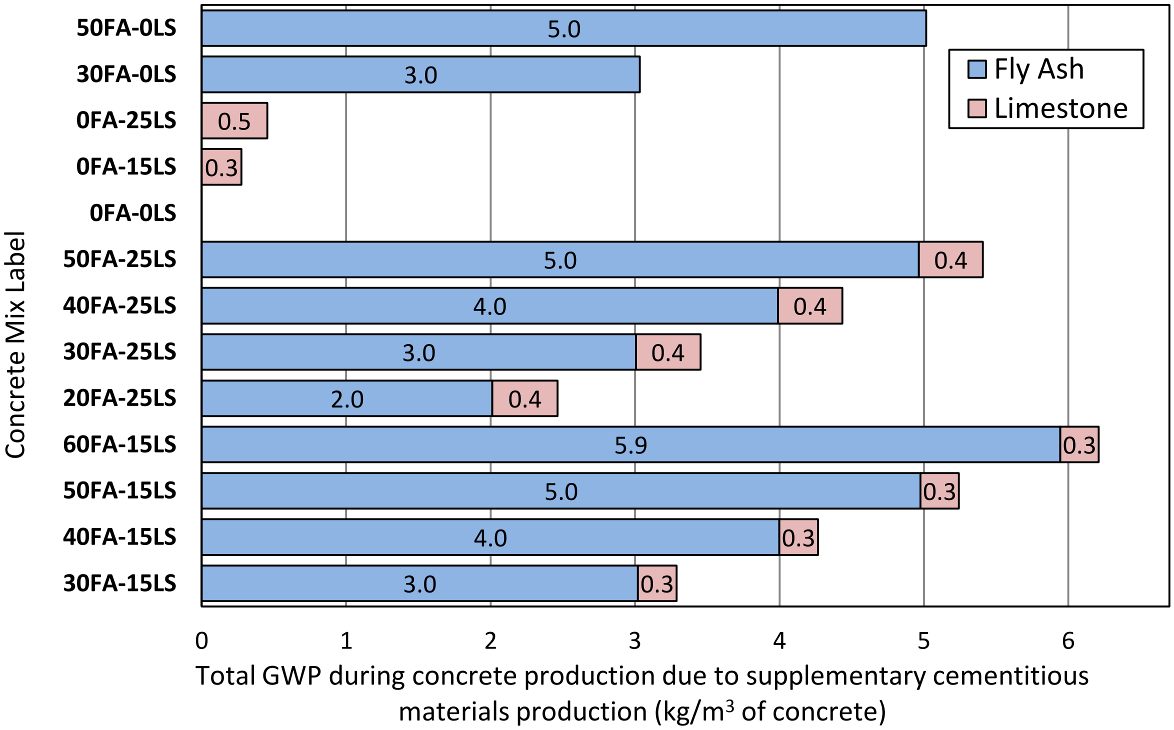


Figure 5.30: Total GWP results associated with fly ash preparation and limestone production processes

5.8.3 Sensitivity Analysis: U.S. Concrete Mixtures with Varying Proportions of Raw Materials

Finally, concrete mixture designs which are representative of about 99% of the U.S. concrete production are analyzed with respect to the influence of replacement of ordinary portland cement with SCMs (fly ash and slag) on GWP. A similar approach to the PCA's analysis was considered [58]. Obviously, cement manufacturing is responsible for most of the GWP (see Figure 5.32) emissions. From Mixture 1 to Mixture 7, portland cement is responsible for 93% (Mixture1), 92% (Mixture2), 90% (Mixture3), 88% (Mixture4), 87% (Mixture5), 83% (Mixture6), and 78% (Mixture7) of overall GWP, respectively. Mixture 1 has the highest amount of cement, while Mixture 7 has the lowest amount. The reduction of total GWP from Mixture 1 to Mixture 7 is considerably high, 60% (Figure 5.31). It is once again demonstrated that concrete LCA results are sensitive to the cement content of the concrete mixture, and overall GWP reduces significantly with the replacement of ordinary portland cement with SCMs such as fly ash and slag.

Table 5.35: Average U.S. Concrete Mixture Designs for 28-day Strengths of 20, 25, and 35 MPa (adapted from [58]

Concrete mix type	Portland cement (kg/m^3)	Fly ash (kg/m^3)	GBFS (kg/m^3)	Water (kg/m^3)	Coarse aggregates (kg/m^3)	Fine aggregates (kg/m^3)	Total weight (kg/m^3)	28-day strength (MPa)
Mixture 1	335	0	0	141	1,187	712	2,375	35
Mixture 2	279	0	0	141	1,187	771	2,378	25
Mixture 3	223	0	0	141	1,127	831	2,322	20
Mixture 4	179	44	0	141	1,127	831	2,322	20
Mixture 5	167	56	0	141	1,127	831	2,322	20
Mixture 6	145	0	78	141	1,127	831	2,322	20
Mixture 7	112	0	112	141	1,127	831	2,323	20

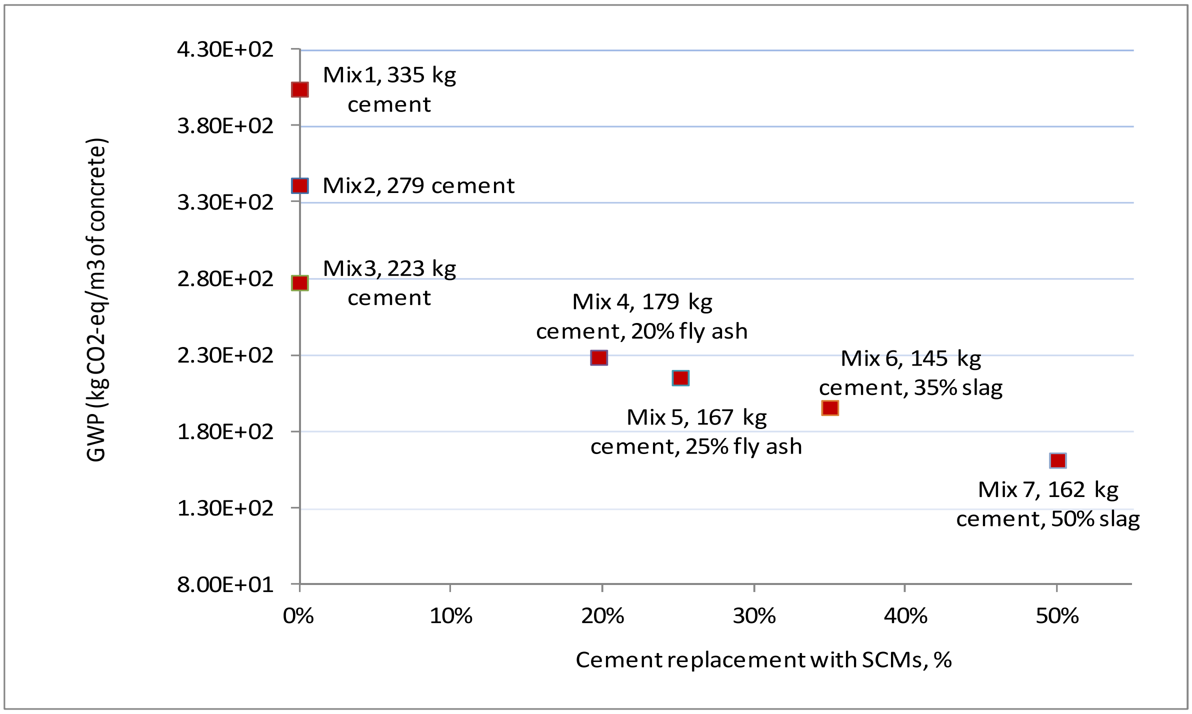
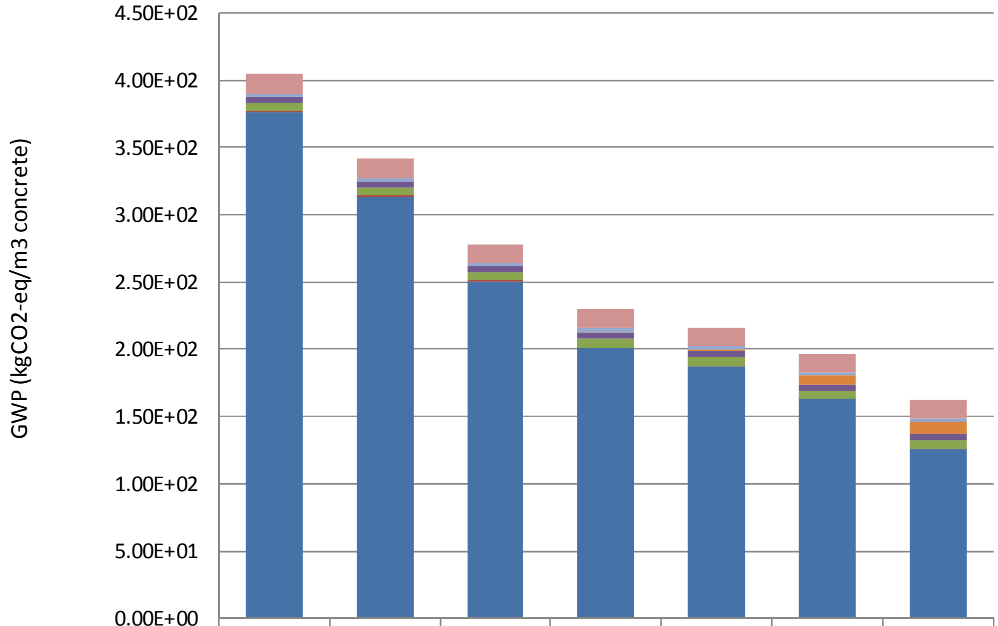


Figure 5.31: GWP reduction by replacing cement with SCMs for the U.S. ready-mixed concrete options



	Mix1	Mix2	Mix3	Mix 4	Mix 5	Mix 6	Mix 7
■ Transportation to Concrete Plant	1.43E+01	1.43E+01	1.40E+01	1.37E+01	1.36E+01	1.35E+01	1.33E+01
■ Concrete Mixing and Batching	2.58E+00	2.58E+00	2.58E+00	2.58E+00	2.58E+00	2.58E+00	2.58E+00
■ SCMs	0.00E+00	0.00E+00	0.00E+00	9.81E-01	1.25E+00	6.62E+00	9.51E+00
■ Admixtures Production	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
■ Coarse Aggregates Production	4.39E+00	4.39E+00	4.17E+00	4.17E+00	4.17E+00	4.17E+00	4.17E+00
■ Fine Aggregates Production	6.28E+00	6.44E+00	6.37E+00	6.37E+00	6.37E+00	6.37E+00	6.37E+00
■ Transportation to Cement Plant	7.11E-01	5.92E-01	4.73E-01	3.80E-01	3.54E-01	3.08E-01	2.38E-01
■ Cement Production (Excl. Transportation)	3.76E+02	3.13E+02	2.50E+02	2.01E+02	1.88E+02	1.63E+02	1.26E+02

Figure 5.32: GWP Results (Mixtures obtained from PCA [58]

6 Policy Scenario Analysis for the Turkish Concrete Manufacturing Sector

6.1 Goal and Approach

The goal of this Chapter is to analyze and understand which key parameters can abate $CO_{2\text{-eq}}$ emissions from the Turkish cement and concrete manufacturing sector. For this purpose, the GreenConcrete LCA tool, which has the capability to consider a full range of parameters, has been applied. Using the tool, eleven scenarios that vary in technology, materials use, electricity mix, and transportation have been developed in order to identify which parameters are the major drivers of variation across a range of circumstances. For each scenario, LCAs of concrete mixture designs with comparable compressive strengths from literature are compared. Results indicate the parameters that are the key contributors to the GHG emissions from cement and concrete plants in Turkey.

Prior to the scenario analysis, the Turkish construction sector and recent industrial developments have been briefly evaluated from a sustainability point of view.

6.2 The Turkish Construction Sector

The construction sector is one of the leading sectors of the Turkish economy, having links to more than 150 other sectors of the economy. It consists mainly of companies engaged in construction of residential buildings, nonresidential buildings, and infrastructure such as hydroelectric power plants (HEPPs), high-speed railways and their signaling and electrification, roads and highways; each has a share of 60%, 20%, and 20% of the sectoral activity, respectively [347]. In recent years, the construction sector in Turkey has become a target of economic policy aimed at achieving price stability, low unemployment, and balanced growth since changes in the construction sector have considerable influence on the nation's macroeconomic variables.

Table 6.1 shows the growth in national GDP as well as the share of construction sector from 2002 to 2012. Following the steep decline of the Turkish economy and the construction industry in 2009, the economy has been experiencing a consistent recovery, as shown in Table 6.2. According to the World Bank's 2013 report [348], Turkey's growth path is predicated on the continuing structural reform agenda.

Following the economic recovery after 2010, the construction and the transportation sectors have continued to increase in their added values. While the construction sector's GDP share in current prices was 4.7% in 2008, it declined to 3.8% in 2009. However, its share in current prices steadily reached 4.4% along 2012. In 2009, the global crisis has played a critical role in declining GDP levels. As observed in Table 6.2, the crisis affected the construction sector profoundly. Although the Turkish construction sector had experienced growth until 2008, it started to shrink by 8.1% and 16.1% in 2008 and 2009, respectively. Starting in the first quarter of 2010, construction continued to grow by 18.5%, 11.5%, and 0.6%, respectively, in years 2010, 2011, and 2012 [349].

Table 6.1: Percent share of Turkish construction industry in GDP, in current prices and national currency for 2002-2012

Year	GDP (national currency, current prices, millions)	Construction sector (national currency, current prices, millions)	% Share of construction in GDP
2002	350,476.1	14,707.3	4.20%
2003	454,780.7	18,405.5	4.05%
2004	559,033.0	24,661.0	4.41%
2005	648,931.7	28,694.1	4.42%
2006	758,390.8	35,849.3	4.73%
2007	843,178.4	41,013.3	4.86%
2008	950,534.3	44,657.6	**4.70%**
2009	952,558.6	36,577.6	**3.84%**
2010	1,098,799.3	45,669.5	**4.16%**
2011	1,297,713.2	57,751.3	**4.45%**
2012	1,415,786.0	62,063.5	**4.38%**
data extracted on 25 Mar 2014 20:15 UTC (GMT) from OECD.Stat **[349]**			

Table 6.2: GDP and construction sector annual growth rates for Turkey, based on constant prices and national currency for 2002-2012

Year	GDP growth rate, based on constant prices (%)	Construction sector growth rate, based on constant prices (%)
2002	6.2%	14.0%
2003	5.3%	8.0%
2004	9.4%	14.1%
2005	8.4%	9.3%
2006	6.9%	18.5%
2007	4.7%	5.7%
2008	0.7%	-8.1%
2009	**-4.8%**	**-16.1%**
2010	9.2%	18.3%
2011	8.8%	11.5%
2012	2.2%	0.6%
data extracted on 25 Mar 2014 19:11 UTC (GMT) from OECD.Stat **[349]**		

Similarly, housing construction permits decreased by 17% in 2008, and 4.7 percent in 2009, respectively. However, together with the economic recovery in 2010, the demand in housing sector started to grow again and construction permits increased by 23.6 percent in 2010 [350], based on the information from Ministry of Development's Ninth Development Plan.

While the Turkish construction industry is growing as a result of the increasing demand for public housing and high-rise office buildings, energy investments, mainly in hydroelectric power plants and transportation-related projects, are also estimated to grow steadily [348].

Concrete and cement manufacturing sectors are considered for the policy scenario analysis, as it is believed to be good representative of the construction sector. Both globally and in Turkey, concrete and cement manufacturing are known to be major contributors to CO_2 emissions (more than 5% of total GHG emissions). The policy scenario analysis is performed based on the recent concrete production volume statistics from the European Ready Mixed Concrete Organization (ERMCO) [351], and results are shown in the following sections.

6.3 Existing Environmental Initiatives of the Turkish Construction Sector

In recent years, Turkey's economic development has been characterized by a relatively low, but rapidly increasing environmental footprint. Total CO_2 emissions from Turkey constitute 2.4% of the OECD total and 0.9% of the world total. When compared to large individual economies, Turkey's CO_2 emissions are 27 times lower than China's CO_2 levels and 18 times lower than the U.S. levels. However, as of 2010, Turkey's total CO_2 emissions reached 298 million tons, an increase of 104% since 1990 (Table 6.3). From 1990 to 2010, the average change in emission levels were 51% in the world, 237% in China, 14% in the United States, and -3.5% in OECD-Europe, based on the data from OECD StatsExtract [349] and World Development Indicators [352].

In terms of carbon intensity, 2.8 kg CO_2 per unit of energy use, Turkey is among the top 28 countries on the list of 135 countries with available data. The high emission intensity could be a result of various reasons, including high emission technologies, the use of energy sources with high emission factors (e.g., coal, diesel), outdated/inefficient emission control technologies, or some combination of them. These factors will be explained in further details in Section 6.5 of this chapter with respect to the cement and concrete manufacturing industries.

On the other hand, the carbon intensity of the Turkish economy has remained flat from 1999 to 2010, at a considerably low level of 0.3 kg per one US dollar of GDP (in 2005 prices and purchasing power parities), roughly equivalent to the average OECD-Europe intensity. Turkey's GDP grew 2.5 times (in current U.S. dollars) from 1999 to 2010 [352]. However, the positive impact of the GDP growth on CO_2 intensity per capita was offset by the increased electricity generation due to industrialization, population and economic growth. TurkStat data indicate that electricity consumption on per capita basis has increased six-folds from 1980 to 2005. From 2005 to 2010, it was observed to increase from 300 kWh per person to 400 kWh per person [353]. Despite the increase in Turkey's carbon intensity factor per capita from 2.7 mt of CO_2 in 1999 to 4.1 mt of CO_2 in 2010, it still remains below OECD-Europe level of 7.4 mt per capita and the world average of 4.9 mt of CO_2 per capita (Table 6.3).

Overall, based on these indicators, one can conclude that there is considerable potential for Turkey to mitigate its emissions. However, it is a challenging process due to the rapid increase in emissions as a result of the expanding economy.

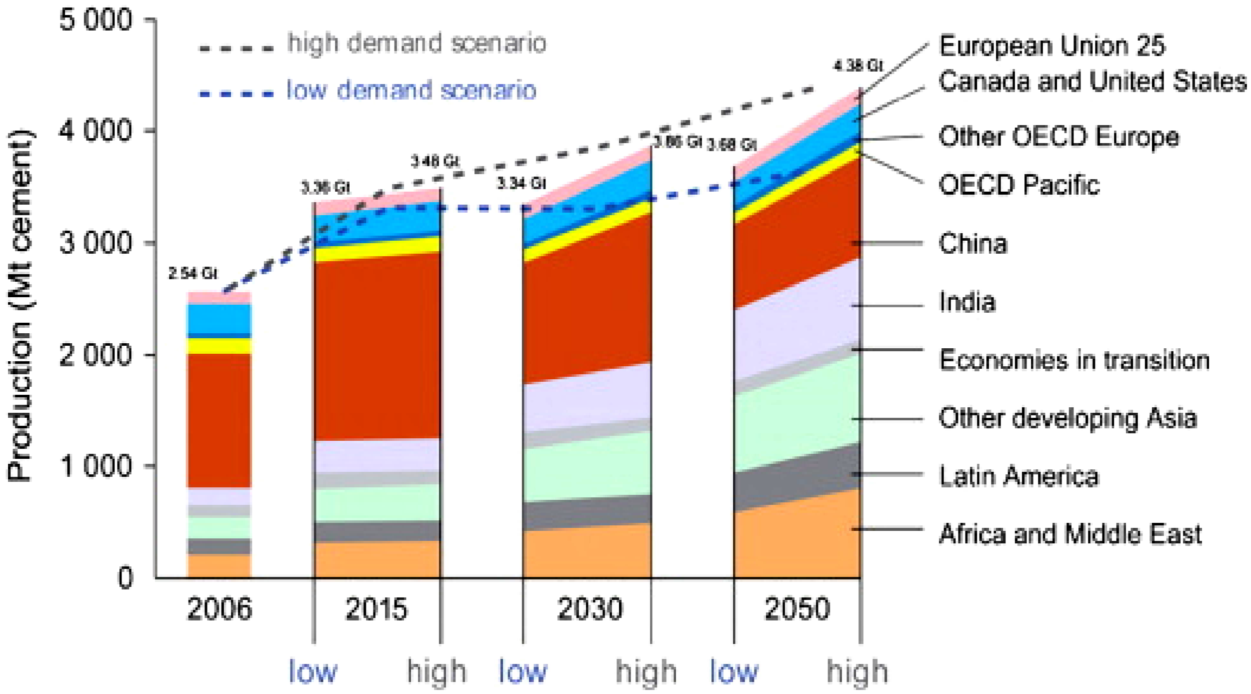
As an emerging market economy, Turkey is still continuing to build institutions that help meet sustainability goals by focusing on policies, particularly those bridging environmental protection, innovation, and meeting local and international obligations /commitments for a greener growth. Turkey has already made considerable progress towards achieving some of these goals: It ratified the Kyoto Protocol in 2009, and declared at the Copenhagen COP 15 that it shall contribute to the effort of tackling climate change. Additionally, the Turkish government approved a National Climate Change Strategy in 2010 for an action plan. Moreover, as part of negotiations for the EU accession process, Turkey has started to harmonize its environmental laws with those of the EU within the Environment Chapter context. Following these initial steps, Turkey has begun implementing the related laws in several areas, such as waste and water management, and environmental impact assessment. Accordingly, the Turkish construction sector, together with other six strategic sectors (including the automotive industry, iron and steel manufacturing, machine building, white goods, electronics and agriculture), have had considerable potential for implementing greater resource efficiency and pollution abatement. In the construction sector, uncertainties regarding the sustainable use of natural resources while protecting the environment without adversely affecting the production process are major initiatives in implementing environmental laws. For the building sector, the potential for energy efficiency over the life-cycle of buildings is gaining attention. Within the construction sector, especially the concrete and cement manufacturing sectors are under close scrutiny because they still require improvements to meet existing EU pollution and emission standards. Specifically, the EU Directive 89/106/EEC on construction materials requires Turkish building material exporters to follow specifications regarding environmental considerations in the production of concrete and cement.

Table 6.3: World Development Indicators in terms of GDP per unit of energy, total CO_2 emissions and carbon intensity [352]

	GDP per unit of energy		**Carbon dioxide emissions**			**Carbon (CO_2) intensity**					
	2005 PPP $ per kg of oil equivalent		**Total, 1000 metric ton**		**% change**	**kg per kg of oil equivalent energy use**		**metric ton per capita**		**kg per 2005 PPP $ of GDP**	
	1990	**2011**	**1990**	**2010**	**1990 - 2010**	**1990**	**2010**	**1990**	**2010**	**1990**	**2010**
Turkey	**8.3**	**8.8**	**145,855**	**298,002**	**104.3**	**2.8**	**2.8**	**2.7**	**4.1**	**0.3**	**0.3**
Brazil	7.7	7.5	208,887	419,754	100.9	1.5	1.6	1.4	2.2	0.2	0.2
Canada	3.6	4.9	450,077	499,137	10.9	2.2	2	16.2	14.6	0.6	0.4
China	1.4	3.7	2,460,744	8,286,892	236.8	2.8	3.3	2.2	6.2	2	0.9
Germany	5.9	9.1	929,973	745,384	..	2.7	2.3	11.6	9.1	0.4	0.3
India	3.3	5.3	690,577	2,008,823	190.9	2.2	2.8	0.8	1.7	0.7	0.5
Japan	7.5	8.5	1,094,834	1,170,715	6.9	2.5	2.3	8.9	9.2	0.3	0.3
Korea, Rep.	5.2	5.3	246,943	567,567	129.8	2.7	2.3	5.8	11.5	0.5	0.4
Mexico	6.9	7.9	314,416	443,674	41.1	2.6	2.5	3.7	3.8	0.4	0.3
Russia	2.1	2.9	2,139,720	1,740,776	..	2.7	2.5	14.4	12.2	1.4	0.9
United States	4.2	6	4,768,138	5,433,057	13.9	2.5	2.5	19.1	17.6	0.6	0.4
World	**4.2**	**5.5**	**22,222,874**	**33,615,389**	**51.3**	**2.5**	**2.5**	**4.2**	**4.9**	**0.6**	**0.5**
Upper middle income	3.4	4.6	5,184,577	12,721,087	145.4	2.7	3	2.7	5.4	0.8	0.7
Low & middle income	3.3	4.6	7,479,994	16,777,539	124.3	2.4	2.7	1.8	3	0.7	0.6
East Asia & Pacific	2	3.9	3,090,436	9,570,523	209.7	2.7	3.1	1.9	4.9	1.4	0.8
Europe & Central Asia	2.5	4.6	1,713,951	1,416,733	..	2.9	2.6	6.8	5.3	1.1	0.6
High income	4.8	6.4	13,509,686	14,901,651	10.3	2.5	2.3	11.9	11.6	0.5	0.4
Euro area/OECD Europe	6.7	8.6	2,561,354	2,472,368	-3.5	2.4	2	8.4	7.4	0.4	0.2

6.4 Turkey's Cement and Concrete Manufacturing Sector Profile

The cement and concrete manufacturing sectors are major CO_2 emitters in Turkey. Although energy intensity per unit of product is less than that of other energy-intense materials such as steel, aluminum and glass, the volume of production is much higher, with an estimated 90 million cubic meters (m^3) of concrete and 63 million metric tons (reaching to 70 mmt in 2013) of cement in 2011 (Table 6.4 and Table 6.6). From 2004 to 2011, Turkish concrete manufacturing and production per capita rates grew by 143% and 138%, despite the decrease of its production (and per capita numbers shown in Table 6.5) by -24% (-25%) and -38% (-41%) in the EU and the United States, respectively, based on the ERMCO data [351]. Cement production followed a similar trend. From 2004 to 2013, Turkish cement manufacturing increased by 84%, somewhat below the world cement production increase of 88%. The world production rates have increased mostly due to the growth in Chinese and Indian construction activities from 2004 to 2013. Especially in China, cement production reached 2.3 billion metric tons in 2013, growing by 146% since 2004. In 2013, China by itself accounted for 58% of the world cement production, while Turkey's contribution was at a level of 1.8%, which is very close to the U.S. production share of 1.9%. In the United States, cement manufacturing decreased significantly at a rate of 21% from 2004 to 2013 (Table 6.6). Despite the decrease in the United States and the EU, the longer-term forecast for cement and concrete manufacturing stays positive, as a result of the rapid growth of developing countries due to increasing demand for the necessary housing and infrastructure. According to a WBCSD/IEA report [354], world cement demand and production are expected to grow from 2,540 million tonnes (Mt) in 2006 to between 3,680 Mt for low-demand scenario and 4,380 Mt for high-demand scenario in 2050. The largest share of this growth will take place in China, India, and other developing countries in Asia and Africa (Figure 6.1). This increase in production will be accompanied by a considerable increase in the cement industry's energy use and CO_2 emissions in the near future.



Note: OECD is an acronym for the Organization for Economic Co-operation and Development

Figure 6.1: Annual world cement production projections [354]

Similarly, the cement and concrete production growth is estimated in Turkey based on the WBCSD/IEA analysis [354]. To continue to grow at the same pace, it is necessary for Turkey to improve its energy and emissions efficiencies. Major areas of improvement include installation of more fuel-efficient cement kilns, more energy-efficient cooling, conveying, grinding, milling, and blending technologies that use considerable amount of electricity. In addition to the improvement in production technologies, partial substitution of SCMs, such as pozzolans (mainly fly ash), slag, limestone for portland cement in the finished cement products (such as blended cements) and in concrete can be promoted. Other measures include reducing transportation impacts by switching to low-environmental impact modes and/or transporting of materials, products, equipment, and labor for shorter distances. At the national level, change in electricity mix, such as converting major energy sources to renewable sources of energy should be considered. Each measure used in policy scenario analysis is explained in following sections.

Table 6.4: Total concrete production from 2004 to 2011, ERMCO [351]

In million m^3	**2004**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**	**2011**	**% change 2004-2011**
Austria	9.90	11.00	11.00	11.30	11.50	10.30	10.20	10.50	6%
Belgium	11.20	11.00	12.20	12.00	11.80	10.40	10.80	11.60	4%
Czech Republic	6.40	7.40	8.00	8.50	9.60	7.30	6.40	7.50	17%
Denmark	2.30	2.60	2.80	2.90	2.70	1.80	1.70	2.10	-9%
Finland	2.40	2.50	2.70	3.10	2.80	2.00	2.60	3.00	25%
France	37.50	39.50	43.30	45.00	44.10	37.00	37.40	41.30	10%
Germany	44.20	40.50	43.40	40.80	41.00	37.70	42.00	48.00	9%
Ireland	8.50	10.00	9.20	7.40	10.00	3.80	2.70	2.40	-72%
Italy	72.70	77.40	77.50	75.20	73.20	54.00	54.40	51.80	-29%
Netherlands	7.80	8.60	8.50	8.90	10.50	9.30	8.10	8.80	13%
Poland	10.50	11.00	14.20	16.00	21.20	17.70	18.60	23.70	126%
Portugal	11.50	12.00	11.00	11.50	11.00	8.50	7.50	6.10	-47%
Slovakia	2.40	2.70	2.90	3.20	3.70	2.60	2.40	2.30	-4%
Spain	82.00	87.60	97.80	95.30	69.00	49.00	39.10	30.80	-62%
Sweden	2.50	2.70	3.00	3.30	3.50	2.80	3.30	3.30	32%
UK	25.00	25.20	25.10	25.60	20.50	15.40	15.70	16.70	-33%
Total / Average EU	**355.80**	**369.60**	**396.60**	**394.00**	**368.10**	**286.50**	**262.90**	**269.90**	**-24%**
Israel	9.30	8.80	8.80	9.80	9.50	9.50	11.00	11.00	18%
Norway	2.70	3.10	3.20	3.80	3.70	2.90	3.00	3.50	30%
Switzerland	9.80	11.10	12.10	12.10	12.10	12.10	11.80	12.50	28%
Turkey	**37.10**	**46.30**	**70.70**	**74.40**	**69.60**	**66.40**	**79.70**	**90.00**	143%
Russia	43.00	40.00	40.00	38.00	52.00	45.00	40.00	40.00	-7%
USA	330.00	345.00	345.00	315.00	270.00	243.00	197.00	203.00	-38%

Table 6.5: Concrete production per capita from 2004 to 2011, ERMCO [351]

m^3/capita	2004	2005	2006	2007	2008	2009	2010	2011	% change 2004-2011
Austria	1.20	1.36	1.34	1.36	1.38	1.24	1.22	1.25	5%
Belgium	1.08	1.05	1.16	1.13	1.11	0.98	1.00	1.01	-7%
Czech Republic	0.63	0.73	0.78	0.83	0.92	0.70	0.61	0.71	13%
Denmark	0.43	0.48	0.52	0.53	0.49	0.33	0.31	0.38	-12%
Finland	0.46	0.48	0.52	0.59	0.53	0.38	0.49	0.56	22%
France	0.63	0.66	0.71	0.71	0.69	0.58	0.58	0.64	1%
Germany	0.54	0.49	0.53	0.50	0.50	0.46	0.51	0.59	9%
Ireland	2.13	2.44	2.24	1.36	1.38	0.86	0.61	0.54	-75%
Italy	1.27	1.34	1.32	1.13	1.11	0.99	0.91	0.86	-32%
Netherlands	0.48	0.53	0.52	0.83	0.92	0.57	0.49	0.53	11%
Poland	0.27	0.29	0.37	0.53	0.49	0.46	0.49	0.62	130%
Portugal	1.11	1.14	1.04	0.59	0.53	0.80	0.71	0.57	-48%
Slovakia	0.44	0.49	0.54	0.71	0.69	0.48	0.44	0.43	-3%
Spain	1.99	2.06	2.25	0.50	0.50	1.08	0.85	0.67	-66%
Sweden	0.28	0.30	0.33	0.36	0.38	0.31	0.36	0.35	26%
UK	0.42	0.42	0.42	0.42	0.34	0.26	0.26	0.27	-36%
Total / Average EU	**0.82**	**0.85**	**0.90**	**0.88**	**0.82**	**0.63**	**0.60**	**0.61**	**-25%**
Israel	1.39	1.29	1.24	1.38	1.30	1.30	1.51	1.51	8%
Norway	0.58	0.66	0.70	0.80	0.77	0.61	0.63	0.73	25%
Switzerland	1.35	1.49	1.64	1.61	1.59	1.53	1.53	1.61	19%
Turkey	**0.52**	**0.65**	**0.97**	**1.07**	**0.99**	**0.94**	**1.11**	**1.24**	**138%**
Russia	0.30	0.27	0.28	0.27	0.37	0.32	0.28	0.28	-6%
USA	1.13	1.18	1.15	1.06	0.89	0.80	0.65	0.67	-41%

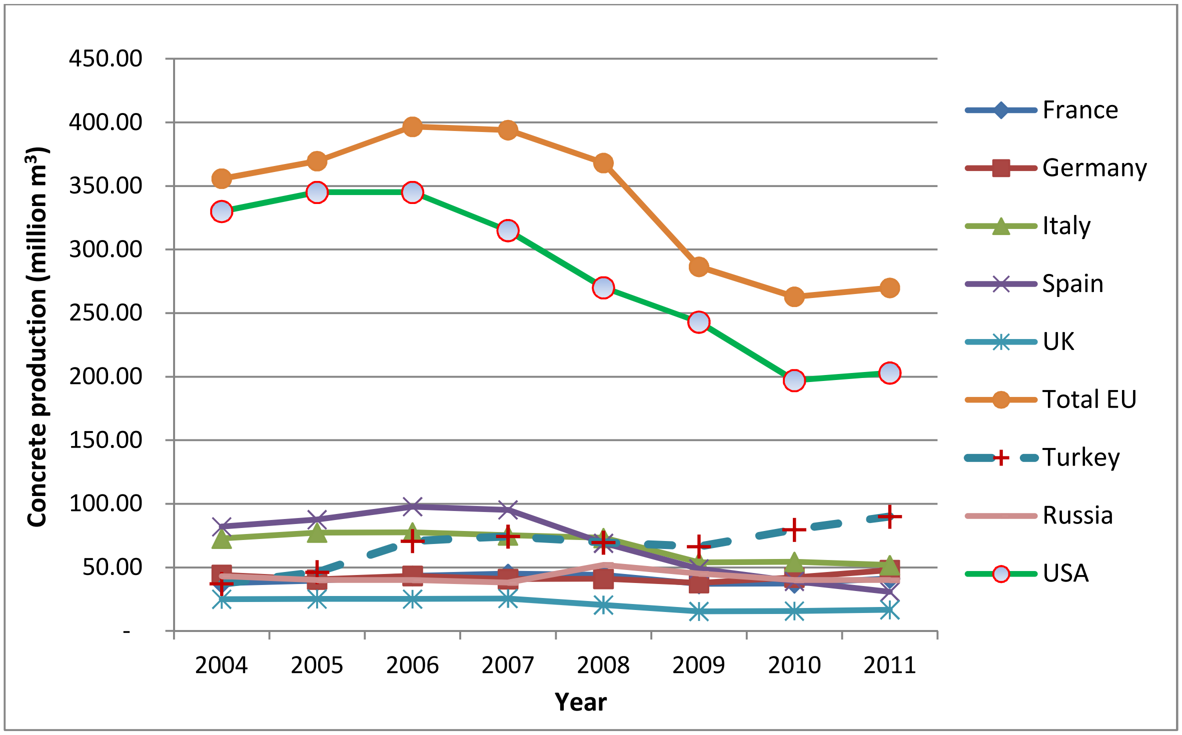


Figure 6.2: 2004-2011 Annual concrete production in major ERMCO members, the United States and Russia [351]

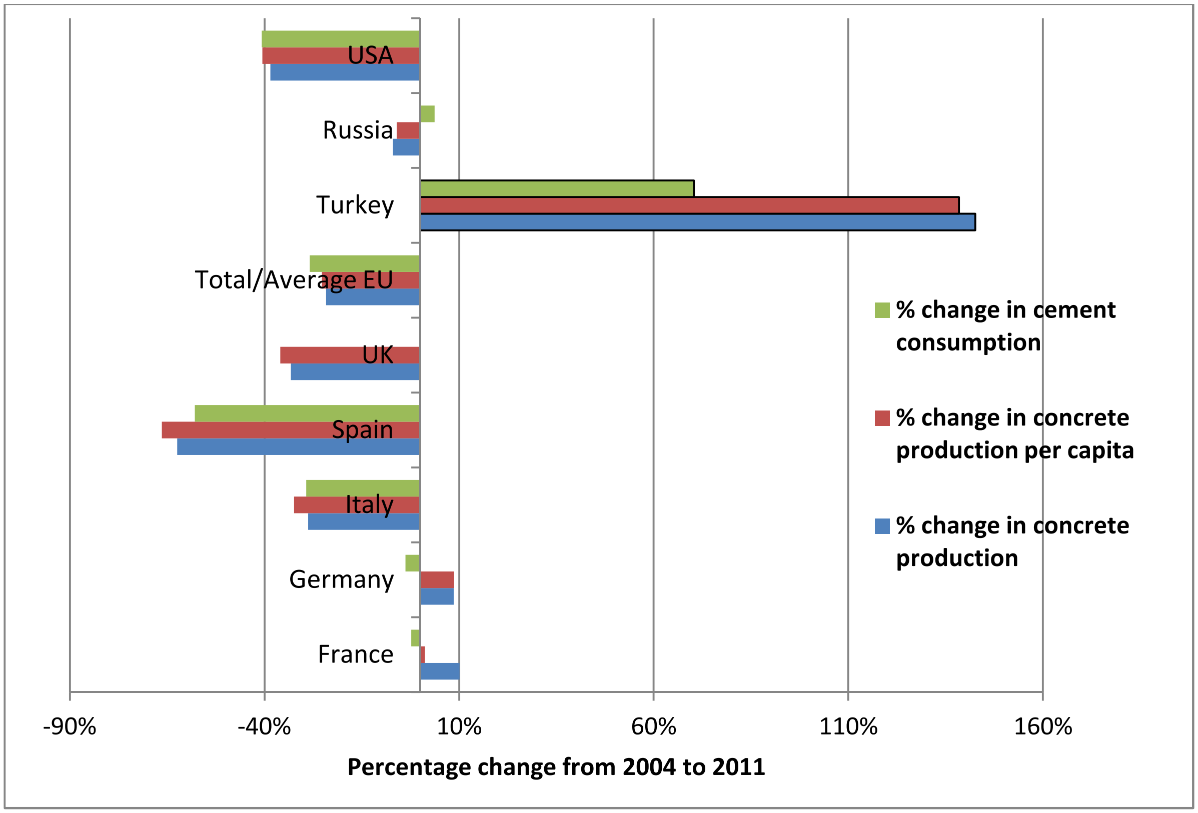


Figure 6.3: Comparison of Turkish concrete manufacturing sector indicators to other major members of the European Ready Mixed Concrete Organization (ERMCO) [351]

Table 6.6: World cement production statistics from 2004 to 2013, USGS Minerals - Cement database [355]

In thousand metric tons	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013 estimated	% change 2004-2013
United States	99,000	101,000	99,700	96,500	87,600	64,900	67,200	68,600	74,900	77,800	-21%
Brazil	38,000	36,700	39,500	46,400	51,900	51,700	59,100	64,100	68,800	70,000	84%
China	934,000	1,040,000	1,200,000	1,350,000	1,390,000	1,629,000	1,880,000	2,100,000	2,210,000	2,300,000	146%
Egypt	28,000	29,000	29,000	38,400	40,000	46,500	48,000	44,000	46,100	46,000	64%
Germany	32,000	21,300	33,400	33,400	33,600	30,400	29,900	33,500	32,400	34,000	6%
India	125,000	145,000	155,000	170,000	177,000	205,000	210,000	240,000	270,000	280,000	124%
Indonesia	36,000	37,000	34,000	36,000	37,000	40,000	22,000	30,000	32,000	35,000	-3%
Iran	30,000	32,700	33,000	36,000	44,400	50,000	50,000	61,000	70,000	75,000	150%
Italy	38,000	46,400	43,200	47,500	43,000	36,300	36,300	33,100	33,000	29,000	-24%
Japan	67,400	69,600	69,900	67,700	62,800	54,800	51,500	51,300	51,300	53,000	-21%
Korea	53,900	51,400	55,000	57,000	53,900	50,100	47,200	48,300	48,000	49,000	-9%
Mexico	35,000	36,000	40,600	40,700	47,600	35,200	34,500	35,400	35,400	36,000	3%
Russia	43,000	48,700	54,700	59,900	53,600	44,300	50,400	55,600	61,500	65,000	51%
Saudi Arabia	23,200	26,100	27,100	30,400	31,800	40,000	42,300	48,400	50,000	50,000	116%
Thailand	35,600	37,900	39,400	35,700	35,600	31,200	36,000	36,700	37,000	35,000	-2%
Turkey	38,000	42,800	47,500	49,500	51,400	54,000	64,000	63,400	63,900	70,000	84%
Vietnam	25,300	29,000	32,000	36,400	37,000	47,900	50,000	59,000	60,000	65,000	157%
Other countries	381,000	400,000	442,000	437,000	459,000	466,000	480,000	470,000	524,000	597,000	57%
World (Total)	2,130,000	2,310,000	2,550,000	2,770,000	2,840,000	3,060,000	3,310,000	3,600,000	3,800,000	4,000,000	88%

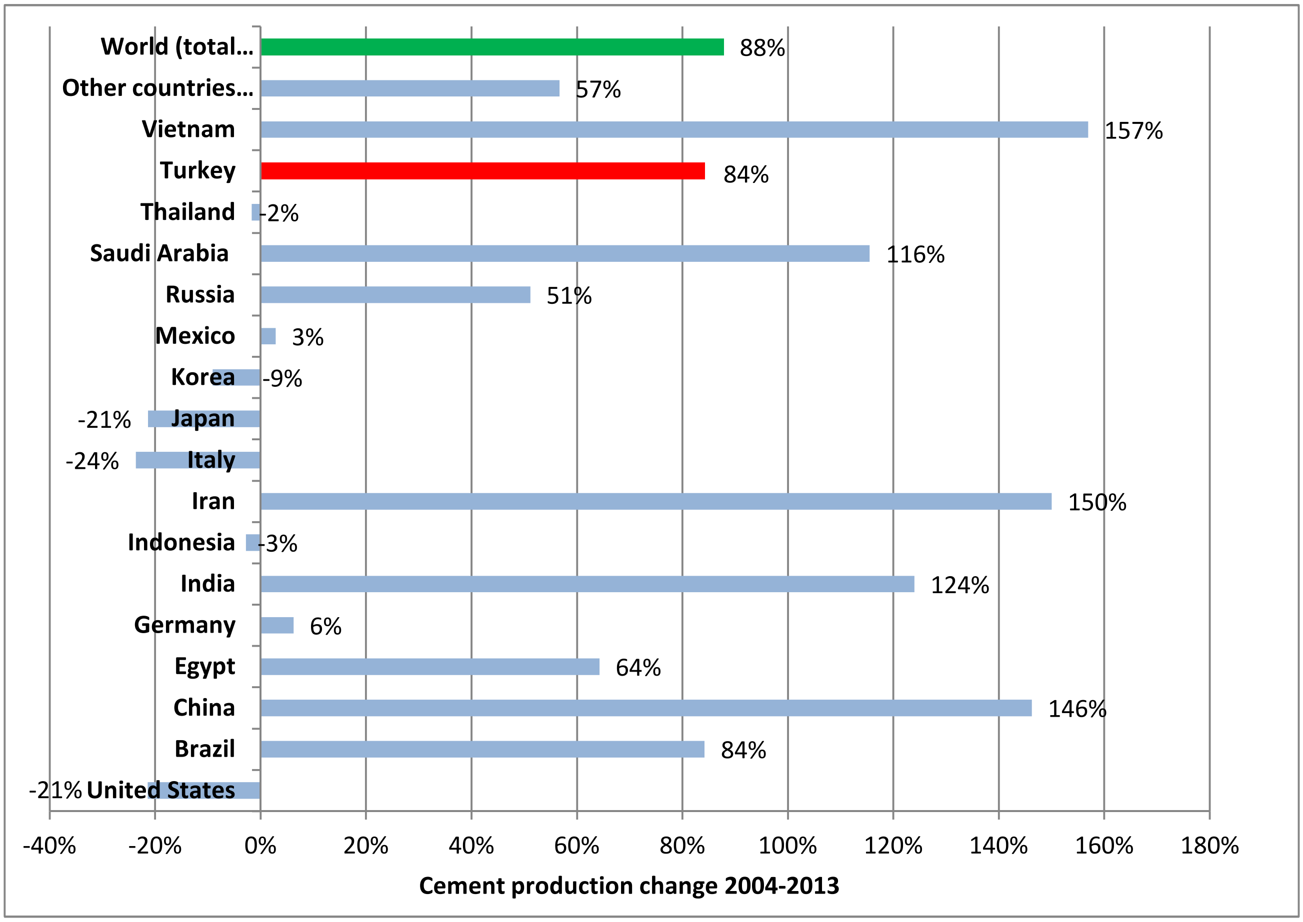


Figure 6.4: Percentage change in world cement production from 2004 to 2013 [355]

From 1972 to 2011, global CO_2 emissions increased from 14.8 $GtCO_2$ to 31.3 $GtCO_2$. According to the IEA 2011 statistics, almost 63% of global CO_2 emissions are caused by industrial activities (such as electricity and heat generation and other industries), showing significant impact on climate change [356]. These emissions are mostly attributed to the combustion of huge quantities of carbon-intensive fossil fuels to generate the required power. In addition, some industrial processes have reactions which chemically transform raw materials to waste gases such as CO_2. These processes include iron, steel and metallurgical coke production, cement manufacturing, ammonia production, lime production, limestone and dolomite use.

Currently, Turkey emits about 1% of overall world's fossil-fuel related CO_2 emissions, rising from 0.3% in 1972. In OECD-Europe countries, Turkey is responsible for 8% of such CO_2 emissions in 2011, which is considerably higher compared to 1% of emissions in 1972, corresponding to about 48 $MtCO_2$ in 1972 and 286 $MtCO_2$ levels in 2011.

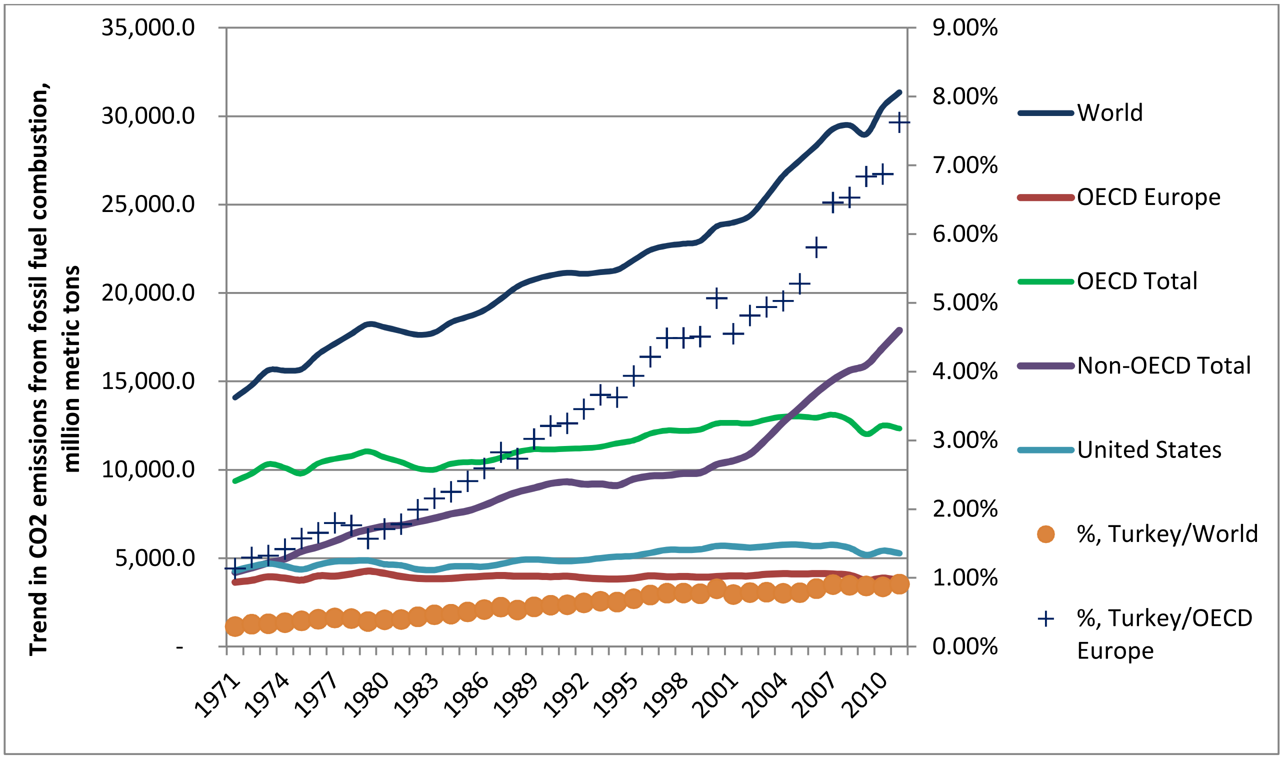


Figure 6.5: Trend in CO_2 emissions from fossil fuel combustion, and Turkey's position with respect to world total and OECD-Europe in terms of CO_2 emissions [356]

Looking at the statistics associated with the total CO_2 emissions from fossil fuels and cement production (Table 6.7, Figure 6.5, and Figure 6.7), cement production-related emissions increased at a higher rate from 2004 to 2010 in parallel with the economic growth. From 2004 to 2010, the change in cement-sector related-CO_2 emissions is 62% in Turkey and 51% in the world, while it is 32% and 16%, respectively, for total industrial activities. Cement production is responsible for 9-10% of total Turkish CO_2 emissions, as opposed to 4-5% of total world emissions. Therefore, it is especially important for Turkey to start acting soon to reduce its emissions from the production of cement and concrete.

Table 6.7: Summary of global and national CO_2 emissions from fossil fuels and cement production for 2004-2010 [357]

	2004			2010			% Change from 2004 to 2010		
(thousand metric tons)	Total CO_2 emissions from fossil-fuels and cement production	CO_2 emissions from cement production	Per capita CO_2 emissions (metric tons)	Total CO_2 emissions from fossil-fuels and cement production	CO_2 emissions from cement production	Per capita CO_2 emissions (metric tons)	% change in total CO_2 emissions	% change in CO_2 emissions from cement production	% change in per capita CO_2 emissions
World (total)	**2.74E+07**	**1.09E+06**	**0.004**	**3.16E+07**	**1.65E+06**	**0.005**	**16%**	**51%**	**8%**
China	5.29E+06	4.84E+05	4.07	8.29E+06	9.37E+05	6.16	57%	94%	51%
India	1.35E+06	6.48E+04	1.21	2.01E+06	1.05E+05	1.65	49%	62%	36%
USA	5.79E+06	4.94E+04	19.43	5.43E+06	3.35E+04	17.27	-6%	-32%	-11%
Turkey	**2.25E+05**	**1.93E+04**	**3.34**	**2.98E+05**	**3.13E+04**	**4.11**	**32%**	**62%**	**23%**
Brazil	3.38E+05	1.72E+04	1.83	4.20E+05	2.95E+04	2.16	24%	72%	18%
Japan	1.26E+06	3.36E+04	9.97	1.17E+06	2.57E+04	9.24	-7%	-24%	-7%
Russia	1.60E+06	2.28E+04	11.11	1.74E+06	2.51E+04	12.17	9%	10%	10%
Iran	4.47E+05	1.61E+04	6.49	5.72E+05	2.49E+04	7.74	28%	55%	19%
Vietnam	9.05E+04	1.30E+04	1.10	1.50E+05	2.49E+04	1.72	66%	91%	57%
Egypt	1.51E+05	1.43E+04	2.05	2.05E+05	2.39E+04	2.53	36%	67%	23%
Korea	4.82E+05	2.84E+04	10.30	5.68E+05	2.36E+04	11.77	18%	-17%	14%
Saudi Arabia	3.96E+05	1.27E+04	17.05	4.64E+05	2.11E+04	16.90	17%	67%	-1%
Thailand	2.52E+05	1.78E+04	3.81	2.95E+05	1.82E+04	4.25	17%	2%	12%
Italy	4.73E+05	2.26E+04	8.10	4.06E+05	1.81E+04	6.71	-14%	-20%	-17%
Mexico	4.11E+05	1.74E+04	3.89	4.44E+05	1.72E+04	3.92	8%	-1%	1%
Pakistan	1.32E+05	7.48E+03	0.84	1.61E+05	1.50E+04	0.92	23%	100%	9%
Germany	8.26E+05	1.59E+04	10.01	7.45E+05	1.49E+04	9.06	-10%	-6%	-10%
Spain	3.39E+05	2.27E+04	7.96	2.70E+05	1.17E+04	5.87	-21%	-49%	-26%
Indonesia	3.38E+05	1.66E+04	1.50	4.34E+05	1.10E+04	1.80	29%	-34%	20%
Algeria	8.95E+04	5.49E+03	2.75	1.23E+05	9.97E+03	3.48	38%	82%	27%
Malaysia	1.67E+05	7.82E+03	6.53	2.17E+05	9.72E+03	7.63	30%	24%	17%
France	3.90E+05	1.05E+04	6.42	3.61E+05	9.13E+03	5.76	-7%	-13%	-10%
UAE	1.13E+05	4.49E+03	30.95	1.68E+05	8.98E+03	22.29	48%	100%	-28%
Taiwan	2.61E+05	9.50E+03	11.48	2.60E+05	8.13E+03	11.22	0%	-14%	-2%
Philippines	7.41E+04	6.66E+03	0.88	8.16E+04	7.93E+03	0.88	10%	19%	0%
Poland	3.05E+05	6.27E+03	7.99	3.17E+05	7.74E+03	8.29	4%	24%	4%
Greece	9.71E+04	7.50E+03	8.73	8.67E+04	7.48E+03	7.63	-10.7%	-0.2%	-13%

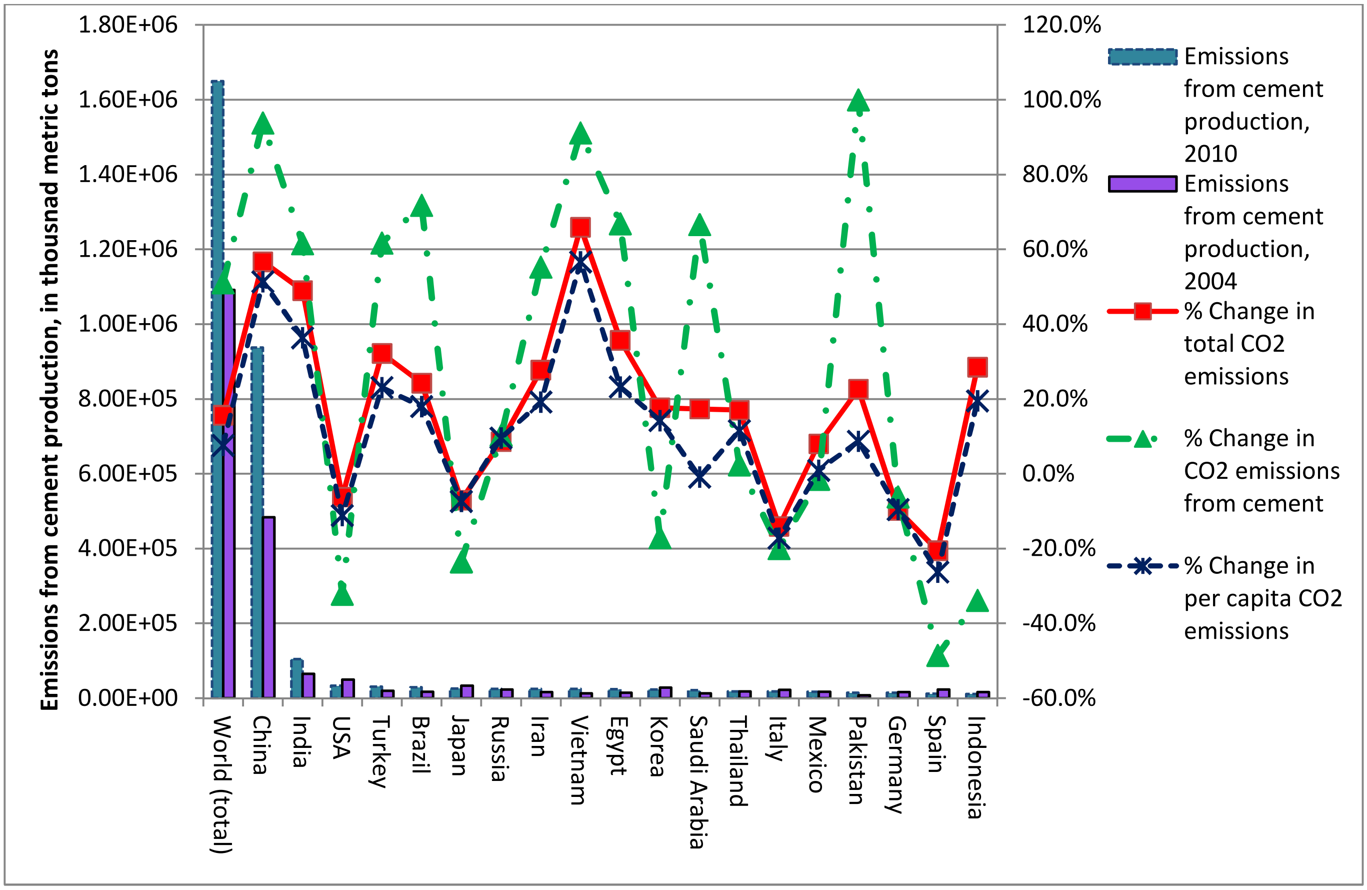


Figure 6.6: Statistics for global and national CO_2 emissions from cement production activities for 2004-2010 [357]

6.5 Policy Scenario Analysis and Findings

Four major strategies for CO_2 reduction, switching to lower-environmental impact transportation modes and logistics; technology and energy efficiency improvements in cement plants; electricity grid mix improvements at national level and electricity consumption reduction by switching to efficient technologies at plant level; as well as partial substitutions of clinker and portland cement in finished cement products and in concrete mixtures have been reviewed.

In case of energy saving approaches, shifting to a more efficient process, for example, from wet to dry process with preheater and precalciner, shows the best results since it potentially reduces up to 50% of the required energy and mitigates more than 25% of CO_2 emissions in the process. In addition to the improvement in production technologies, industrial waste and by-products which can be used as both fuel and raw material simultaneously mitigate emissions in cement plants and landfills. In recent years, partial substitution of SCMs, such as pozzolans (mainly fly ash), slag, limestone for portland cement in the finished cement products (such as blended cements) and in concrete are expanding. Although not included in the scenario analysis due to lack of related Turkish data, utilizing waste-derived fuel (WDF) instead of conventional fuels can result in significant emission mitigation [358, 359].

Other measures include reducing transportation impacts by switching to low-carbon fuels such as biofuels or other alternative fuels. At the national level, change in electricity grid mix, such as converting major energy sources to renewable sources of energy, including wind, and solar, can result in considerable CO_2 emission reductions. From electricity consumption point of view, energy-efficient cooling, conveying, grinding, milling, and blending technologies contribute to further emission reduction.

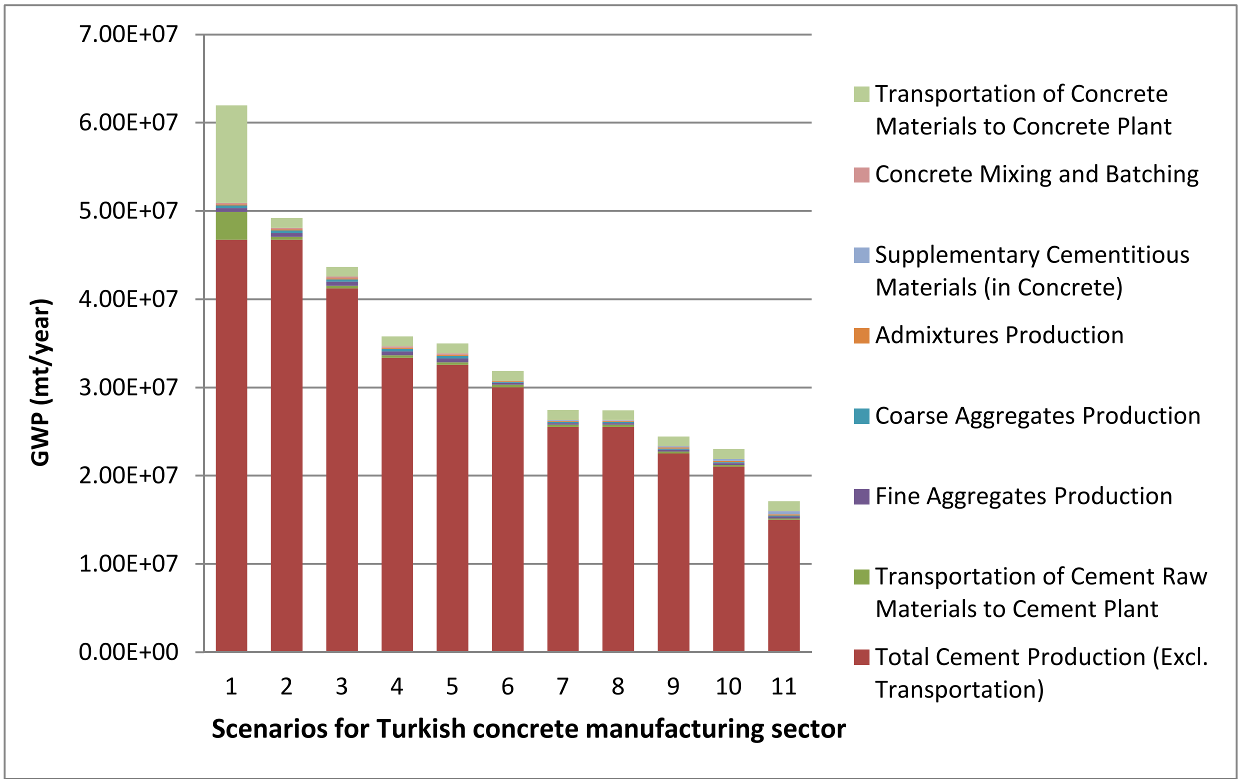
In addition to these four major strategies covered in this section, carbon capture and storage (CCS) is also considered as an effective way to avoid release of CO_2. However, economical and technical challenges still are remarkable obstacles against implementing such processes in the cement and concrete manufacturing plants [359].

For the LCA scenario calculations, the following concrete mixtures (Table 6.8) are used to understand the impacts of differing technology, alternative material use, electricity grid mix, and transportation decisions to identify which parameters can be the major drivers of variation. These mixtures are selected particularly because of their similar strength properties with varying proportions of SCM materials (fly ash and slag) to identify their contribution to GHG emissions.

Table 6.8: Concrete mixtures used in policy scenario analysis [360]

	Mixture 1	**Mixture 2**	**Mixture 3**	**Mixture 4**	**Mixture 5**	**Mixture 6**
Mixture designation (w/b=0.50)	100C	85C15F	75C25F	85C15S	70C30S	50C50S
Binder	340	340	340	340	340	340
Cement (kg/m^3)	340	289	255	289	238	170
Fly ash (kg/m^3)	–	51	85	–	–	–
Slag (kg/m^3)	–	–	–	51	102	170
Fine aggregates (kg/m^3)	819	800	787	819	819	819
Coarse aggregates (kg/m^3)	1,009	1,026	1,043	1,007	999	1,002
Water	170	170	170	170	170	170
Admixture – SP (Ceraplast 300), % by weight of binder	0.50	0.60	0.70	0.60	0.65	0.65
Wet density (kg/m^3)	***2,340***	***2,338***	***2,342***	***2,338***	***2,330***	***2,333***
Compressive strength (MPa) at						
3 days	24	17	16	23	17	14
7 days	29	26	25	30	27	23
28 days	41	35	34	36	38	40
56 days	45	44	44	44	46	46
90 days	46	46	45	46	48	49

In the first scenario, which is the worst case scenario, it is assumed that Type I/II cement is produced in a wet kiln using the average Turkish kiln fuel mix (Table 6.9) and average electricity grid mix (Table 6.10). All cement raw materials and concrete materials are assumed to be delivered by truck from a distance of 500 km. Mixture 1 is a 100% PC concrete that is produced at a central concrete batching plant. All other manufacturing technologies are held constant to focus on major GHG sources such as transportation, pyroprocessing during cement production, electricity grid mix, and the use of alternative raw materials such as GGBF slag and fly ash. Figure 6.7 describes the scenarios together with the total GWP for the Turkish concrete manufacturing sector based on the 2011 sector production volume of about 90 million m^3.



No.	Scenario Description
1 Baseline	Type I/II Cement produced at wet, average fuel mix at kiln, average electricity mix, transportation: 500 km distance, by truck , 100% PC concrete mixture
2	Type I/II Cement produced at wet, average fuel mix at kiln, average electricity mix, transportation: 50 km distance, by truck , 100% PC concrete mixture
3	Type I/II Cement produced at long dry kiln, average fuel mix at kiln, average electricity mix, transportation: 50 km distance, by truck , 100% PC concrete mixture
4	Type I/II Cement produced at preheater kiln, average fuel mix at kiln, average electricity mix, transportation: 50 km distance, by truck , 100% PC concrete mixture
5	Type I/II Cement produced at preheater/precalciner kiln, average fuel mix at kiln, average electricity mix, transportation: 50 km distance, by truck , 100%PC concrete mixture
6	Type I/II Cement produced at preheater/precalciner kiln, average fuel mix at kiln, wind for electricity mix, transportation: 50 km distance, by truck , 100%PC concrete mixture
7	Type I/II Cement produced at preheater/precalciner kiln, average fuel mix at kiln, wind for electricity mix, transportation: 50 km distance, by truck , 85%PC 15%Sconcrete mixture
8	Type I/II Cement produced at preheater/precalciner kiln, average fuel mix at kiln, wind for electricity mix, transportation: 50 km distance, by truck , 85%PC 15%FA concrete mixture
9	Type I/II Cement produced at preheater/precalciner kiln, average fuel mix at kiln, wind for electricity mix, transportation: 50 km distance, by truck , 75%PC 25%FA concrete mixture
10	Type I/II Cement produced at preheater/precalciner kiln, average fuel mix at kiln, wind for electricity mix, transportation: 50 km distance, by truck , as 70%PC 30%S concrete mixture
11	Type I/II Cement produced at preheater/precalciner kiln, average fuel mix at kiln, wind for electricity mix, transportation: 50 km distance, by truck , as 50%PC 50%S concrete mixture

Figure 6.7: Description of scenarios for Turkish concrete manufacturing and associated GWP results

Scenarios and associated GWP are discussed further in the following chapters.

6.5.1 Transportation alternatives and availability of raw materials

In the first scenario analysis, everything being constant, all cement raw materials and concrete materials are assumed to be transported from a 500 km distance to cement and concrete productions facilities. Typically, new cement plants can economically serve a 200 km to 300 km radius [7]. In other scenarios, transportation distance is kept at 50 km. Although a 500 km distance is not very common, limitation and availability of the regional materials can be a major factor contributing to the increased GHG emissions from transportation. For example, in Turkey, admixtures are commonly imported from Europe (e.g., BASF, Sika are major admixture manufacturers located in Switzerland and German). Therefore, transportation distances for some of the concrete materials can be longer, depending on the location of the suppliers. By reducing the transportation distance from 500 km to 50 km, a reduction of 21%, from 62 million tons of $CO_{2\text{-eq}}$ to 49 million tons of $CO_{2\text{-eq}}$, was achieved.

Other alternatives for lowering the transportation-related emissions may include, but are not limited to, utilization of low-carbon transportation modes such as rail, water in delivering cement and concrete materials. Moreover, strategic choice of a location for cement and concrete plants may play an important role, such as plants that are located on large rivers for domestic distribution or on the coastal areas for international distribution [361]. Emissions can also be effectively reduced by the utilization of low-carbon or carbon free types of energy sources, such as electricity, hydrogen, bio-fuels and solar fuels. Analysis of the impacts of these approaches will further be considered as part of future research work.

6.5.2 Technology and energy efficiency improvements

The majority of CO_2 emitted during concrete manufacturing is the result of burning fossil fuels (mostly coal and petroleum coke) in kilns to provide the thermal energy required for calcination. Depending on the kiln technology, the actual thermal energy requirement changes between 3,000 and 7,000 MJ/ton of clinker, based on the kiln technology used to burn the raw material [362]. Table 6.9 shows the average Turkish kiln fuel mix, and this mix is kept constant through the scenario analysis. As evident in Table 4.31, dry manufacturing processes result in energy savings, whereas the wet kilns consume energy in the range of 5,400 - 6,900 MJ/ton of clinker. In the case of a wet process, more energy is required for the water evaporation as the raw material is fed into the kiln in the form of wet slurry. The addition of pre-heaters and pre-calciners to the dry kilns contribute to energy savings, which is about 3,000-3,600 MJ/ton of clinker, in the cement manufacturing process.

Scenarios 2, 3, 4, and 5 analyze the variations in $CO_{2\text{-eq}}$ with respect to the changes in cement kiln technologies. Overall, keeping all other variables constant, switching from a wet kiln process to a dry kiln with pre-heater and pre-calciner resulted in 29% of reduction in $CO_{2\text{-eq}}$ emissions. However, there is limited potential in improving energy efficiency of kiln systems as modern plants are approaching their theoretical limits. In the short term, replacing older plants with newer ones can reduce energy use considerably. In the longer term, fluidized bed kiln (FBK) technology is emerging. A FBK replaces traditional rotary kiln with a stationary vertical vessel (reactor) where the cement raw materials are calcined in a fluidized bed. The advantages of this technology are projected to be lower capital costs (in terms of construction and installation), lower heat use and CO_2 levels, reduced NO_x emissions, improved energy use and more flexibility in use of a wide variety of fuels in the kiln. However, earlier versions of FBKs were not commercially successful due to high rates of clinker recycling and lower clinker production capacities at a level of 1,000 ton per day (tpd). Currently, it is difficult to scale up FBK to the required 5,000-6,000 tpd clinker capacity [38, 359].

Table 6.9: Average fuel mixes (by % heat) for Turkish cement manufacturing

Kiln fuel mix	% by energy, TR
Bituminous coal	27%
Lignite coal	31%
Distillate (Diesel or Light) oil	0%
Petroleum coke	43%
Residual Fuel (Heavy) oil	0%
Natural gas	0%
Waste Fuels (Total)	0%

6.5.3 Electricity grid mix supply and demand improvements

In scenario 6, it is anticipated that the national grid mix is converted to 100% wind power from the average grid mix shown in Table 6.10.

Table 6.10: Turkish electricity grid mix based on Turkish State Planning Organization’s data [347]

Source of energy	Contribution of Electricity Source (%)
Bituminous Coal	-
Natural gas	49%
Residual (Heavy) oil	3%
Distillate (Diesel or Light) fuel oil	-
Nuclear (Uranium)	-
Hydro	19%
Biomass	-
Geothermal	-
Solar	-
Wind	1%
Lignite coal	28%

Independent from the fuel-related energy use during production processes, electricity in terms of MJ-equivalent is reduced by 97% from scenario 5 to scenario 6 when the electricity grid is converted to 100% wind power. In terms of GWP, only about 9% reduction is achieved in ***total*** $CO_{2\text{-eq}}$ emissions. Figure 6.8 demonstrates that the highest reduction in GWP, 97%, is obtained during concrete mixing and batching stage at the concrete plant as most of the processes use electricity exclusively. About 56% and 54% reduction in GWP is attained for fine and coarse aggregates production, respectively. Considerable amount of electricity is required for crushing and grinding of aggregates to achieve desired size and shape for use in concrete mixes. For cement manufacturing, there is only an 8% decrease in GWP. About 60% of this reduction is attributed to the electricity that is used in grinding and milling processes; raw materials grinding 11%, cement finish milling and grinding 23%, and grinding of solid fuels, i.e. coal, 25%. Figure 6.9 summarizes the percentage share of electricity use for Mix 1 with 100% PC concrete production. As observed, cement production is responsible for 85% of the total electricity use, Figure 6.10 shows the percentage share of the electricity utilized in traditional portland cement manufacturing.

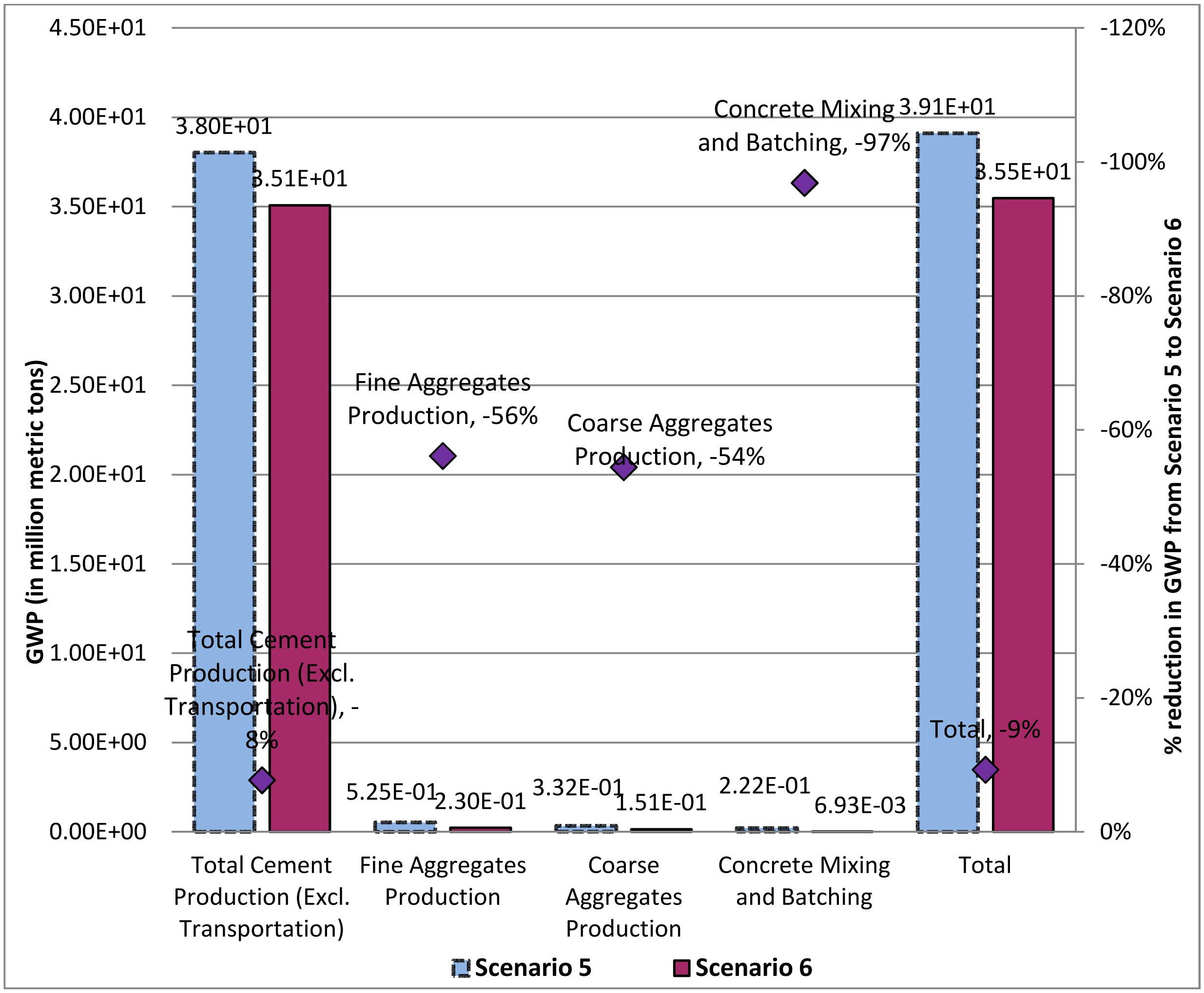


Figure 6.8: Change in GWP resulting from switching to wind power (from Scenario 5 to Scenario 6) by concrete production phases

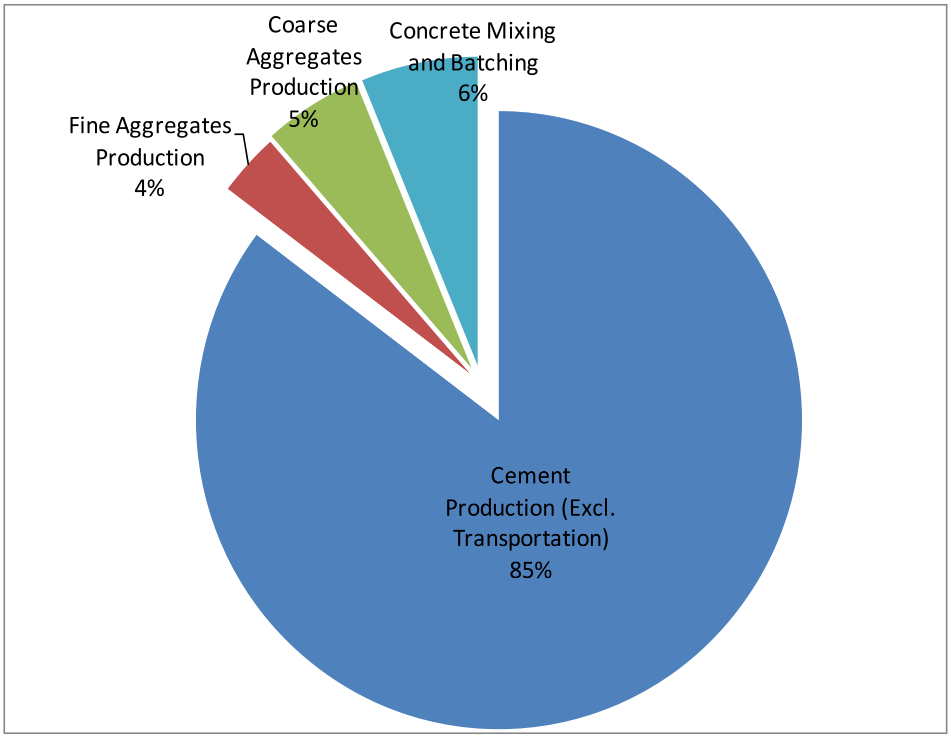


Figure 6.9: Percentage share of electricity use in traditional concrete production made with 100% PC and no SCM addition (GreenConcrete LCA tool)

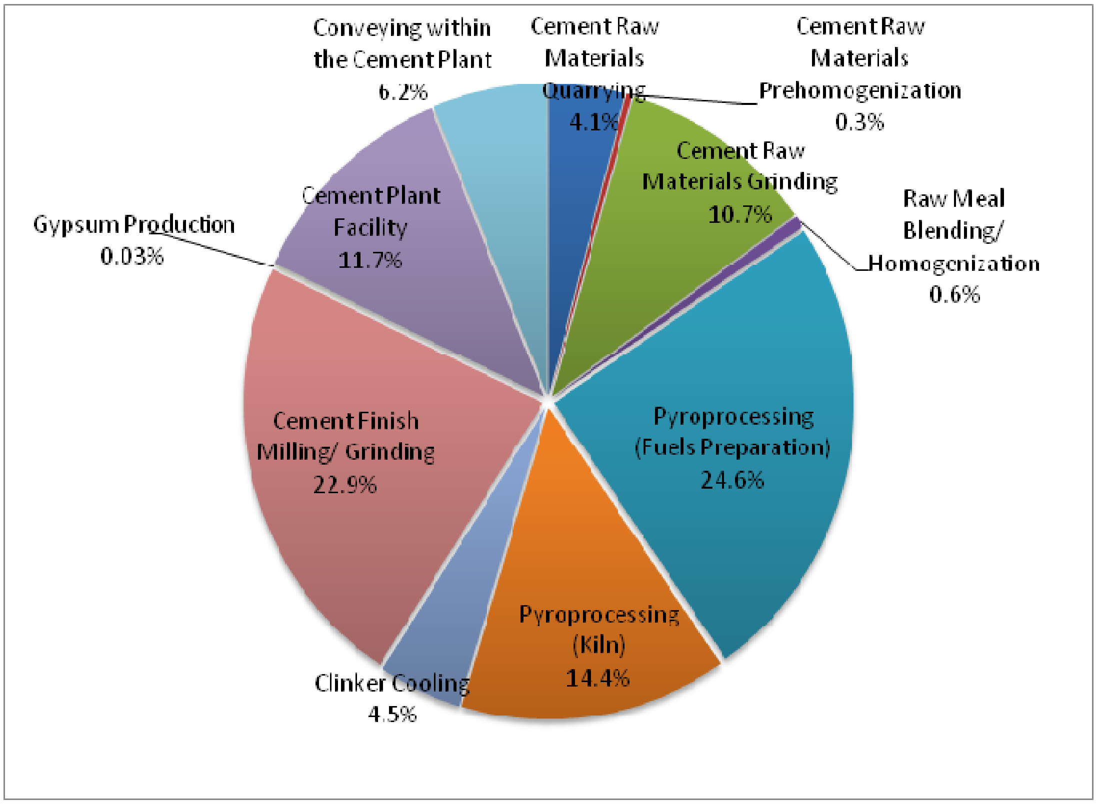


Figure 6.10: Percentage share of electricity use in traditional Type I/II portland cement manufacturing (GreenConcrete LCA tool)

Overall, GWP is lowered by 49% in scenario 6 with respect to the baseline scenario (Figure 6.14). Although it is possible to increase the share of renewable energy sources to an extent in the electricity grid, it is not realistic to switch to a 100% wind powered grid for Turkey. One solution to reduce electricity consumption is the waste heat recovery. Waste heat recovery strategy can also be considered as kiln technology improvement. In China and Japan, boilers for electricity generation are recently integrated to cement kilns, especially very large cement and kiln lines of 10,000 or even 12,000 tpd. As suggested by Schneider et al. [358], a range of specific heat recovery technologies can be applied for the cement industry. In one particular case of a cement plant application, Organic Rankine cycle was used to generate electrical power even with smaller volumes of lower temperature flue gas.

Since electrical energy is required in almost every stage of concrete manufacturing, one way to reduce electricity-related GWP is to utilize equipment with advanced technologies. As mentioned earlier, the crushing and grinding equipment uses more than 60% of the overall electricity (Figure 6.10). The overall efficiency of the grinding process in cement and concrete plants is in the range of 1-5%, and that is certainly unsatisfactory. Ball mills have been used for over 100 years for milling and grinding purposes because of reliability and the favorable properties of cement products ground with them. However, ball mills consume high amounts of energy. In addition to ball mills, vertical roller mills or high pressure grinding rolls are also in use currently. The specific energy demand for these newer technologies is comparatively low but the cement from such mills shows slightly different properties in terms of particle size distribution (PSD) and required fineness [358]. The fineness and PSD properties of cement products are important as they influence water demand, setting time, and strength development of cement in mortar and concrete.

New approaches have been tested and are still under development in improving the grinding systems. High-activation grinding technology is the most promising future technology. By high-energy milling, the reactivity of some of the blended ingredients (e.g., fly ash, slag) is mechanically increased. That is achieved by the combined effect of increasing the surface area of fly ash or slag blended in cement and physicochemical changes obtained by vibratory and attrition milling. In this way, more clinker can be replaced by SCMs with improved compressive strengths of concrete mixes. For example, Kumar et al. studied mechanically-induced reactivity of blast furnace slag and fly ash [359, 363-365]. Authors found that up to 65% of the clinker blended in cement could be replaced with milled fly ash. They showed that the strength of the resulting concrete was comparable to that of a commercial concrete made with cements containing only 20-25% fly ash. Kumar et al. [363] also studied the use of mechanically-activated GBFS substituting 50-95% of the clinker in portland slag cement. Their results showed that portland slag cement blended with 80-85% mechanically-activated GBFS was stronger than typical commercial portland slag cement with only 35% slag.

Another technology under development is ultrasonic comminution which transfers the energy needed for crushing to the material by acoustic pulses that are generated by two counter-rotating disks with special aerodynamic surfaces. The exerted pressure waves pulverize the particles. This approach was introduced by a German manufacturer in 2003 and it was tested with GBFS in model scale only. However, future research remains essential for scaling up to the industrial dimensions. Another development includes plasma comminution which is performed in a liquid by using shock waves, but it has been limited to semiconductor materials [358, 359]. Certainly, the question of how grinding efficiency can be improved still remains open.

6.5.4 Use of SCMs and other alternative raw materials

As mentioned in Chapter 2.3.1 and Chapter 5.8.2 of this dissertation, using alternative binders that replace portland cement in concrete reduces the energy consumption and GHG emissions associated with overall concrete production. Scenarios 7 through 11 investigate the environmental benefits of SCMs (fly ash and slag) used in concrete mixes in terms of their GWP impacts. Figure 6.7 provides properties of concrete mixes with water/binder ratio of 0.50 and 90-day compressive strengths of 45 - 49 MPa used in the scenario analysis. Mix 1 is 100% portland cement while Mix 2 is 85% PC-15% fly ash; Mix 3 is 75% PC-25% fly ash; Mix 4 is 85% PC-15% GBFS; Mix 5 is 70% PC-30% GBFS; and Mix 6 is 50% PC-50% slag.

With the increasing ratios of SCMs replacing cement in concrete, GWP decreases by 56 - 72% with respect to the worst case scenario. The concrete mixes with GBFS result in larger GWP reduction (Scenario 7 vs. Scenario 9) for equal percentage substitutions of PC with fly ash (Figure 6.14), mostly because less amount of slag is required compared to the fly ash per unit volume of concrete of same strength despite slightly higher energy requirement for slag preparation (GreenConcrete LCA tool database).

Fly ash is mainly produced as a by-product in coal power plants. Its use as SCM not only contributes to reducing raw materials and energy requirement, but also can improve durability of concrete through replacing a portion of cement [2, 345]. Blast furnace slag is a non-metallic by-product of iron and steel production process consisting of silicates, alumina-silicates, and calcium-alumina-silicates. Therefore, by utilizing this material as a portion of kiln feed, it both improves raw material burnability and reduces need of limestone, mitigating the associated CO_2 emissions [366]. In Turkey, fly ash has been commonly utilized in cement and concrete through replacing by a portion of clinker in blended cements and cement in concrete mixes. In 2011, in addition to fly ash, GBFS has been introduced as alternative to fly ash (Table 6.11). In Turkey, it is estimated that 14 million tons of fly ash and only 350,000 tons of GBFS are produced annually [367]. Overall, only 1.5 million tons of fly ash and GBFS are utilized in concrete. Average cement content per unit volume of ready mixed concrete in Turkey is estimated to be at a level of 290 kg/m^3, which is close to the EU average of 291 kg/m^3 and the U.S. average of 272 kg/m^3 (Figure 6.12). However, average SCM content per unit volume of Turkish concrete is 50 kg/m^3, same as the EU average, but considerably lower than the U.S. average of 72 kg/m^3 (Figure 6.13). Turkish cement and concrete manufacturers can increase their SCM use, especially the fly ash content, given their annual production rate of 14 million tons and less than the 10% current utilization as SCM. However, slag supply is limited for high rate of usage in cement and concrete manufacturing industries.

Table 6.11: Distribution of type of SCM use in EU, Turkey, Russia, and USA, ERMCO data [351]

	2007	2008	2009	2010	2011
Austria	FA	FA/SF	FA	GGBFS/FA	GGBFS/FA
Belgium	FA	FA	FA	FA	FA
Czech Republic	FA	FA	FA	FA	FA
Denmark	FA	FA	FA	FA	FA
Finland	FA	FA	FA	FA	FA
France	FA	FA	FA	FA	FA
Germany	FA	FA	FA	FA	FA

Ireland	GGBFS	FA	GGBFS	GGBFS	GGBFS
Italy	FA	FA	FA	FA	FA
Netherlands	FA	FA	FA	FA	FA
Poland	FA	FA	FA	FA	FA
Portugal	FA	FA	FA	FA	FA
Slovakia	FA	FA	FA	FA	FA
Spain	-	-	-	-	FA
Sweden	FA	FA	FA	FA	FA
UK	GGBFS/FA	GGBFS/FA	GGBFS/FA	GGBFS/FA	GGBFS
Israel	FA	FA	FA	FA	FA
Norway	FA	FA	MS	FA	FA
Switzerland	-	-	-	-	-
Turkey	**FA**	**FA**	**FA**	FA	GGBFS/FA
Russia	-	FA	FA	-	-
USA	-	-	-	FA	FA

GGBFS: ground granulated blast furnace slag

FA: Fly ash

MS: Micro silica

SF: Silica fume

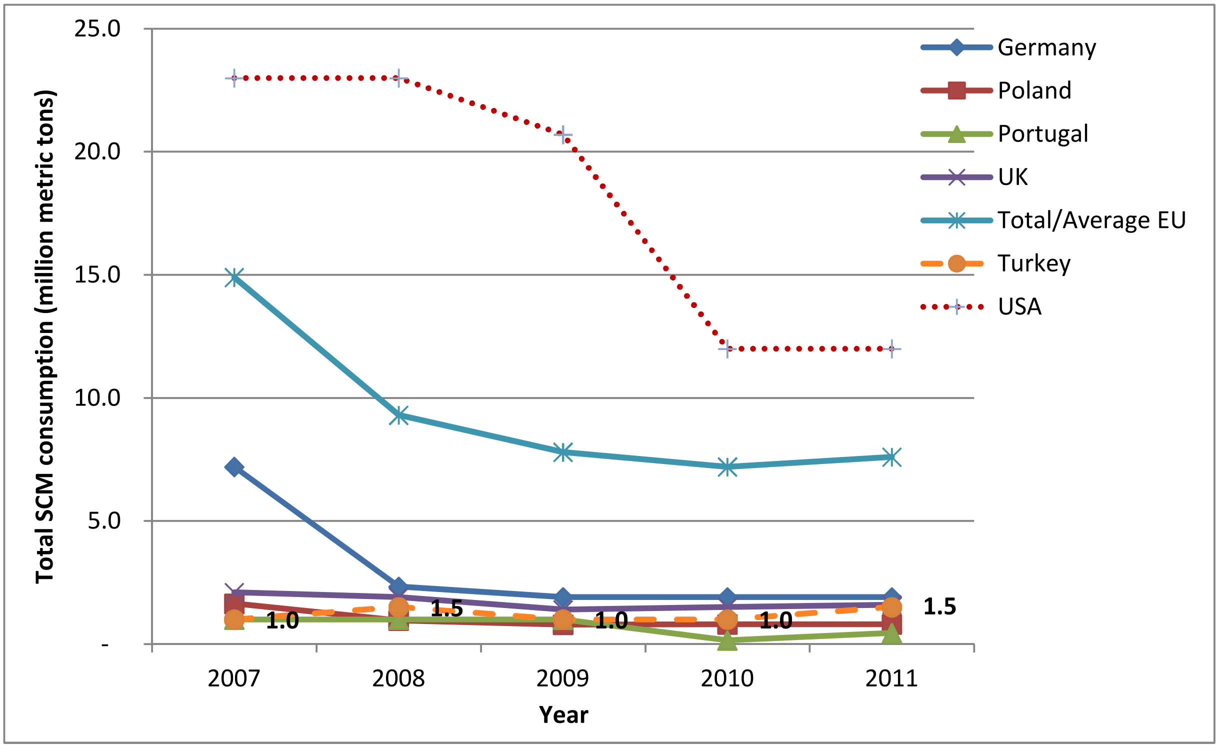


Figure 6.11: Total SCM consumption in concrete production, ERMCO data [351]

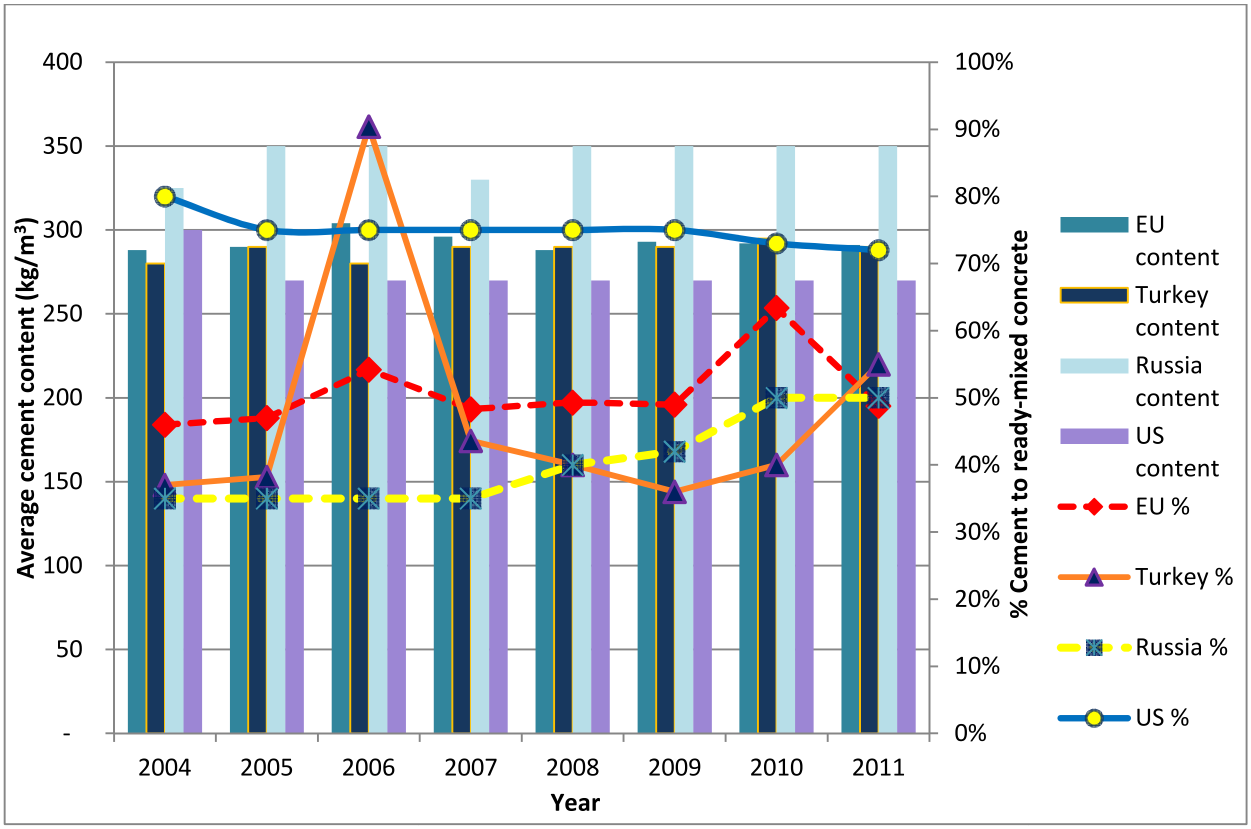


Figure 6.12: Average cement content by percentage and per unit volume of ready-mixed concrete [351]

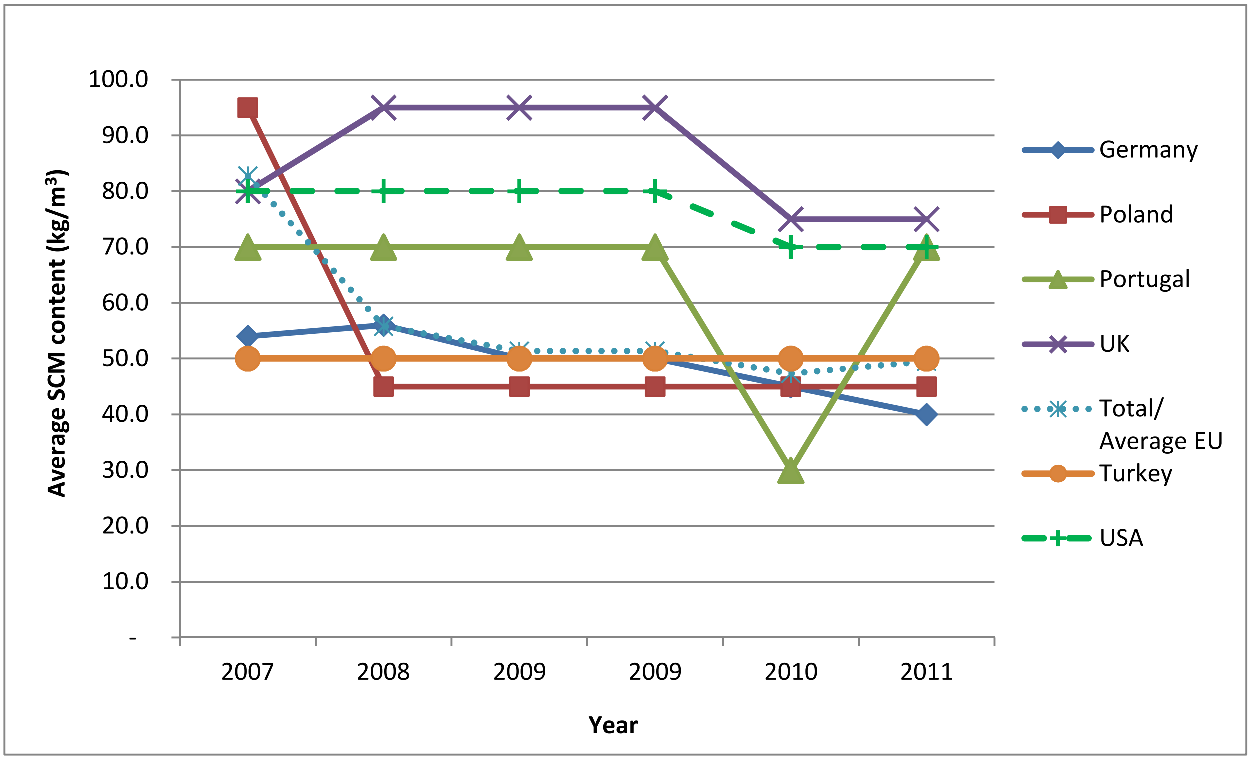


Figure 6.13: Average SCM addition per unit volume of concrete, ERMCO data [351]

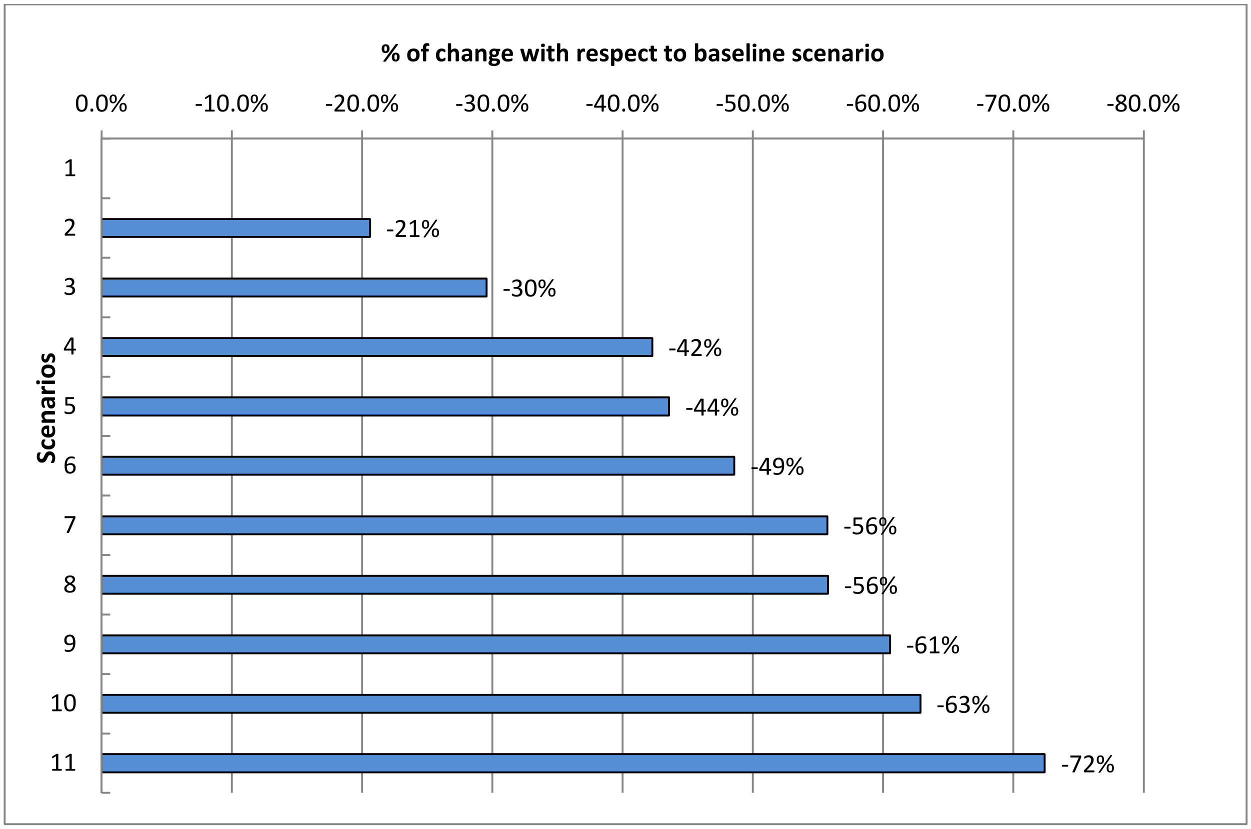


Figure 6.14: Percentage change in $CO_{2\text{-eq}}$ emissions in scenarios with respect to the baseline (worst case scenario)

In addition to the regional availability of suitable SCM materials, there are some limitations of their usage in cement and concrete industries. Using alternative materials can influence strength development of concrete over time; especially concrete with fly ash substitutes has slower strength development compared to concrete with 100% cement. This is mainly because of variation of composition and quality of fly ash obtained from burning different types of coal under varying conditions. National standards and acceptance by industry may be other barrier to utilizing higher rates of SCMs. Further research with well-established quality assurance mechanisms is needed to prove applicability and suitability of utilization of SCMs in cement and concrete. With the expertise and know-how, the cement and concrete industry will be able to further reduce the environmental footprint of their processes and products.

6.6 **Conclusions**

Results from the scenario analysis show that reductions in $CO_{2\text{-eq}}$ emissions can be achieved through:

- Strategic choice of locations for cement and concrete plants for local and international distribution of products by less carbon-intensive modes of transportation, i.e., rail and water;
- Switching to lower-carbon fuels, and expanding the use of biofuels and electric vehicles in delivery of cement and concrete products;
- Improvements in energy efficiency by installation of existing best available technologies for new plants and replacing older technologies for existing plants;

- Switching to less carbon-intensive energy sources for electricity generation;
- Integration of waste heat recovery systems in cement plants for off-grid electricity generation and using more energy efficient equipment in cement and concrete plants;
- Use of alternative raw materials as sustainable waste management and GHG emission reduction options.

Although these strategies have great potential to abate $CO_{2\text{-eq}}$ emissions in cement and concrete industry both in Turkey and globally, technical, regulatory, and economic challenges are still considered obstacles against implementation of such approaches. It is critical to address these regulatory, technical, and institutional obstacles. Cement and concrete producers are generally concerned about the reliability and performance of new technologies and are not willing to take the risk of employing them at the beginning. The industry requires clear technical and operational knowledge, for example, the expanded use of SCMs is held back in some cases either because of lack of awareness of the opportunities to use blended cement in the construction industry or due to outdated building regulations which do not adequately address the use of alternative materials as cement substitutes. To expand the use of alternative materials, building regulations may specify their use in cement and concrete in the construction industry. In case of using alternative fuels in cement kilns, switching to alternative fuels, particularly waste fuels or biomass, offers great opportunities in lowering CO_2 emissions and operating costs. On the other hand, public resistance as well as regulatory/institutional barriers can inhibit the use of alternative fuels at cement kilns.

Beyond regulatory/institutional barriers, the limitation of the regional and global availability of proper raw materials is a major challenge of widespread utilization of alternative materials in cement and concrete products.

Majority of energy saving strategies in cement and concrete industry require large capital investments and due to the limited capital availability, manufacturers can only adopt specific low-priced energy efficiency measures. Moreover, various energy efficiency measures require different types of equipments and facilities. In addition to economic concerns, uncertainty over the quality and performance of such facilities as well as risk of process shutdown can hold back the cement and concrete plants from investing on any kind of energy saving strategies.

Thus, at a national level, collaboration of the government, industry and academia is necessary to develop coherent policy frameworks for the successful implementation of recommended technologies and opportunities.

7 Discussions and Future Research

7.1 Summary and Interpretation

In this section, the major results obtained throughout the dissertation are highlighted although they have been discussed earlier in related chapters in more details.

7.1.1 Discussion and Interpretation of the Case Study LCA Results

While many factors can affect the environmental impact of a building over its life-cycle, only a few of these factors have major influence. For the LCA of the case study buildings, that involves comparison of the LCAs of concrete-framed vs. steel-framed dormitory buildings; the best effort was shown to consider the regional and technological LCIs. For both building types, it was assumed that the life expectancy is 50 years, which is aligned with the literature results demonstrated in Table 2.67, ranging between 25 to 100 years. It is important to note that, the life-span assumption critically influences the relative impact of the total building energy use versus operational energy use and related emissions. Overall, the dormitory building operation phase has the highest percentage of energy consumption and GWP in the life-cycle of a building (Table 5.21). The case study results show that, for the concrete building, operational energy use and GWP cause 96% and 94%, respectively of the total impacts while for the steel building, these percentages are 96% and 97%, respectively. When the literature results are considered, in proportion to the amount of energy consumed, most of the GHG emissions during the operation phase vary between 99% and 81%. The highest percentage of 99% [98] figure in the Chinese building LCA study included aggregated operational and maintenance CO_2 emissions. Accordingly, the case study results are compatible.

The major influential factor for the operation phase was found to be the heating of the building. About 65% of the total operation phase energy use and 63% of overall life-cycle energy use impacts and 55% of the total operation phase GWP and 53% of the overall GWP was from natural gas used for heating over 50 years. When calculating the upstream and direct LCI of natural gas, the regional data (the closest LCI data was for Mediterranean region) developed by the European Environment Agency's report [315] was utilized. On the other hand, building's operational electricity use contributed to the highest percentage of criteria air pollutants of SO_2 (89%), PM (84%), and NMVOC (54%). Natural gas and electricity use for major building activities such as lighting, cooking, operating appliances, etc. contributed equally to the NO_x emissions, which is 48% and 47% of overall LCA emissions from each source, respectively. LCI for the electricity use was estimated on the basis of Turkish electricity grid mix. Natural gas and solar collectors used for the purpose of hot water supply contribute to the remaining smaller fraction of environmental impacts during the building's operation phase (see Table 5.13 and Figure 5.12 for the summary of results). In literature, the most critical factors for the operational phase were consisted of HVAC, hot water and lighting systems because of their high energy requirements (Chapter 2.4).

Although the operational impacts far exceed the impacts from other life-cycle phases, it is still necessary to discuss major contributors within each phase.

Materials extraction and manufacturing phase contributed to the 5% of total GWP and 3% of energy consumption for both building types (Table 5.21). Results for the materials LCA were limited to only two environmental measures since energy use and GWP have currently been the only available data factors for all building materials used in the case study. When investigated in further details (Table 5.22**Error! Reference source not found.**), it was observed that structural materials (and components), which are steel and concrete, consumed the largest amount of energy during their manufacturing. Consequently, same structural materials (and components) were the major sources of GWP. Additional important sources of GWP included non-structural concrete used in surface protection and screeding, aluminum and clay bricks. When considered within the total life-cycle, manufacturing of steel elements consumed only 1% and 2% of total energy in concrete- and steel-framed buildings, respectively. In terms of GWP, concrete elements contributed the most in materials manufacturing phase of the concrete-framed building (59% within the phase, 3% over the life-cycle). Steel elements caused the highest GWP impact during the materials manufacturing phase of the steel-framed building (54% within the phase, 2% overall) as observed in Table 5.25. Two factors contributed to the larger percentages of energy use and related GWP in materials manufacturing: the quantity of the material used and the embodied energy. Although concrete has a lower energy use factor compared to that of aluminum, glass and steel, its quantity is significantly high therefore its contribution to GWP. Therefore, it’s important to give priority to the selection of those materials with lower embodied energy factors as well as smaller quantities for reduction in energy use and associated emissions from materials manufacturing phase. However, one needs to be cautious about the presence of toxic emissions that can be inherent in the properties of such materials

It should also be noted that the materials manufacturing LCI data was obtained from the international sources when Turkish data was not available or limited. Sometimes, these data sources were difficult to interpret as the detailed information was either lacking or incomparable. Obviously, environmental data may differ between different countries as the components involved in the estimation of the environmental interventions related with the transportation, manufacturing processes, energy sources, types of raw materials, etc. may significantly vary. Exceptions are concrete, ceramic tiles, and steel. Concrete manufacturing LCIs are calculated based on the Turkish electricity grid mix, national plant fuel mixes, and technologies using the GreenConcrete LCA tool. Environmental data for ceramic tiles [330, 331] are obtained from a Turkish ceramic manufacturer. Also structural steel [332] and galvanized steel LCI (obtained from an Istanbul-based steel manufacturer [333]) represent the average Turkish steel manufacturing practice [334], which is a mix of electric arc furnace (100% scrap) and basic oxygen furnace (35% scrap). The best effort was shown to capture the most recent and representative data, regionally and technologically. When Turkish materials LCI data was lacking, I used those sources that utilized the similar regional manufacturing practice to that of Turkish practice. For example, marble manufacturing LCI was based on an Italian study [335], while the clay brick data was obtained from Greek sources [336]. However, despite the similarities of final products and manufacturing processes, variations in the electricity grid mixes, and other region-specific parameters were inevitable. When representative data from EU was not available, inevitably, I used the U.S. and Australian LCI data based on varying scope, technological, regional, and other manufacturing assumptions.

For the construction stage, the first step of LCA calculations required construction equipment power and duration information. However, it was not possible to obtain the real construction data regarding the hp and duration of construction equipment use, site-specific data such as the preparation of site prior to construction, as well as the waste amounts and other construction related information. All the related data were either calculated on the basis of RS Means or assumptions from the technical specifications obtained from Prokon. The RS Means data represent the average U.S. construction conditions, which introduces parameter uncertainty to the results.

Generally, construction LCIs include environmental impacts from electricity used for driving power tools, lighting, heating (some construction activities may require heat/steam in cold climate [1], as well as diesel fuel for operating heavy construction equipment. Various studies in literature estimate that construction energy constitutes 1.2 to 10 percent of total embodied energy [60, 119, 121, 122, 134]. For the case study, this value is about one percent of the total building energy use and related GWP. Overall, energy consumption for the concrete frame construction was estimated at higher levels compared to the construction of steel frame. In concrete frames, more temporary materials are required (such as formwork); installation takes longer, meaning longer periods of equipment use; and transportation impacts are larger due to the delivery of heavier materials used in concrete-frame buildings. When examined in details, the construction LCA results show that the crane is the major contributor to both energy use and GWP in steel- and concrete-framed buildings. Among the other major contributors are concrete mixer trucks and pump (see Table 5.23). The entire machinery used diesel as source of power for long hours with considerably high horsepower ratings. In addition to the GWP and energy use metrics, construction-related criteria air pollutants were quantified. It is important to note that, all the top three equipment listed above also contribute to higher percentages of NO_x, PM, and SO_2. On the other hand, vibrators are the major source of CO emissions, as they use large amounts of gasoline. Non-methane VOCs are caused by the machinery (such as welders, cutters, etc.) operated by electricity. As part of the construction phase, construction waste and its transportation to disposal landfilling areas were estimated based on the waste factors obtained from literature. Due to lack of related Turkish data, emission factors for pollutants HCs, CO, NOx, PM were taken from the EPA's NONROAD model while CO_2 and SO_2 emissions were calculated based on the diesel fuel related data, varying with BSFC values. For the gasoline-powered equipment, emission factors of HCs, CO, NO_x, PM, CO_2, and SO_x were adapted from EPA AP-42 while for the electric equipment, electricity grid mix factors for Turkiye (from Turkish government sources) were applied in LCA calculations. Since the technical properties of the construction equipment are similar to those used in Istanbul, Turkiye there is still a need for the development of regional LCI database for Turkish construction equipment fleet and practice.

Here, it should be mentioned that air emissions from transportation to/from construction site are included in the construction LCI results. Again, the EPA's MOBILE 6.1 database was used for calculating the transportation-related emission factors. Since the dormitory project is located in Istanbul, it would be preferable to use emission factors for the Turkish truck fleet in calculating related LCI. However, such data does not currently exist for Turkey.

The literature results demonstrate that the maintenance phase causes about 2%-5% of total CO_2 emissions. On the other hand, the case study percentages for energy use and GWP impacts estimated for the maintenance and replacement of building materials were relatively small (only about 0.1%) when considered within the overall life-cycle of building's impacts. There is considerable uncertainty involved in estimating the impacts from this phase. The selection of lifetime (also replacement rates) for building materials affects the maintenance and replacement results. New technological developments that may influence materials lifetime in future are impossible to estimate today. However, major sources such as BCIS [155] provide lifetime data for building materials. For the case study, material replacement rates were calculated based on international sources like BCIS. During the maintenance phase, the replacement of PVC flooring dominates both energy use (27-28%) and GWP (31%) over other building materials. It is not surprising as both the quantity and replacement frequency (6 times over 50 years) of PVC flooring is considerably high. Aluminum used in suspended ceilings and interior door frames rank the second in replacement energy use, followed by wood (hard wood and laminated), and ceramic tiles. The replacement rates are only once for aluminum components while it is also one time for wood doors and ceramic wall claddings and two times for laminated wood and ceramic tiles used as flooring materials. Although the replacement rate and the quantity of aluminum is relatively smaller, it is very energy intensive to manufacture this material, which is within the range of 190 – 315 MJ per kg [112, 324, 325]. That is why its manufacturing and maintenance require considerable amount of energy use and associated life-cycle impacts.

The end-of-life stage, the building's last life-cycle stage, involves environmental consequences of demolishing the building and the final disposal of waste at either recycling or landfilling facilities. When the literature is investigated, building EOL phase ceases after the demolition waste is transported to the disposal area without the consideration of alternative waste management options, such as recycling. Some studies conclude that a certain building material is recyclable at the end-of-life phase without realistically quantifying the overall impacts of recycling, reuse, landfilling, or incineration after the decommissioning of a building. In few other commercial building LCAs, although recycling option is considered, such as Scheuer et al. [131], they do not give credit to the recycling for the avoided environmental impacts, stating that "Future embodied energy benefits are attributed to whatever product system."

In the dissertation, the recycling life-cycle impacts were quantified based on the "*avoided products*" approach. The environmental impact for the manufacturing of the substituted product is subtracted from the system in case of recycling. The balance between environmental impacts and gains in the chain (net gain) might therefore be negative, in case the avoided impacts (benefits) are higher than the induced impacts, or vice versa. For the case study, only aluminum and steel parts were assumed to be recycled while the rest was landfilled at the end-of-life stage. For calculations, EPA's WARM model (which also considers the avoided impacts in case of recycling) was used for landfilling and recycling activities. Although concrete and other non-metal materials outweighed in terms of material quantities, environmental impacts of steel and aluminum recycling governed the total end-of-life GWP results. Steel recycling impacts dominated the end-of-life phase. Results showed a net environmental gain of 0.7 – 1.1 % of total life-cycle energy use and 246% - 181% of EOL phase energy use for concrete and steel buildings, respectively. This can be explained in terms of avoided impacts that can be traced back to the secondary construction materials that enter future life cycles in substitution of virgin products. The energy gained during EOL is accounted for by system expansion (avoided burden approach). Here, the net environmental gain from recycling was calculated by the difference between avoided impacts due to the substitution of virgin building materials (gross credit) and impacts caused by the transportation and recycling processes. When calculating the overall EOL impacts, energy used during demolition, transportation of waste materials to landfills, and processes taking place at landfill were subtracted from the net environmental gain from recycling. For the steel-framed building, EOL impacts were negative due to relatively larger quantities of steel and aluminum recycled. For concrete-framed building, although the final EOL result is a net burden due to the demolition and landfilling impacts, it was still very small overall, which was 0.3% of the total life-cycle energy use. Here, the negative results imply that GWP reduction through recycling due to the avoided emissions from manufacturing of virgin materials exceeded the GWP impacts from landfilling and demolishing together.

Overall, both building types resulted in similar environmental impacts over the course of their life. While the energy use during the materials manufacturing and maintenance phase was slightly larger for the steel-framed building, the construction and EOL phase resulted in slightly higher energy use for the concrete building. Operation phase results were equivalent for both building frames as the same operation data was used in estimating the environmental impacts. As part of future work, it is essential to estimate a building's energy use and associated environmental impact on the basis of the building design features such as building size, type, material u-values (concrete vs. steel) and indoor air quality requirements, with varying degrees of depth and breadth. In conclusion, the operation phase set aside, the choice of materials in terms of their embodied energy, repair and replacement rates, and recyclability potential can have considerable consequences and importance in designing future sustainable buildings.

7.1.2 Importance of Regional and Technological Aspects in Buildings and Materials LCAs

In the case study, one of the most challenging tasks was the access to regionalized LCI data for Turkish commercial buildings from materials manufacturing the end-of-life phase impacts. The building life-cycle phases were analyzed by applying the process-based LCA and much effort was put to make the choice of system boundaries as much inclusive and comprehensive as possible. However, it was not possible to capture all direct and indirect supply-chain repercussions of a dormitory building over 50 years of its service life in a country where related energy use and emission factor data are still premature or even lacking. Therefore, most of the LCI data were estimated based on the data from other parts of the world, mostly from the U.S. and EU (Mediterranean and Eastern European data are the most relevant, when available. Although it was not possible to regionalize all aspects of the case study building, the best effort was given to capture the regional aspects of the major GWP contributors. Operation phase was the major source of energy use and GWP (about %95 of total impacts over 50 years) as mentioned before. For the operation phase, regionalization was captured to an agreeable extent: The hourly electricity use of the building was provided from the design company. The electricity generation was grid-based and covered the electricity grid mix percentages for Turkiye. Natural gas boilers were used for the space heating of campus buildings. Again, natural gas consumption data for both summer and winter seasons were obtained from Prokon. In calculations, both upstream and heating data for natural gas delivered in Istanbul, Turkey were based on European Environment Agency's report which included Turkish natural gas LCI. Hot water supply also involves natural gas boilers supported with solar thermal collectors. Energy consumption from solar system was calculated using a simulation program based on the data provided by Prokon. But for other building life-cycle stages, spatial variability was not well-captured. For example, construction phase is very unique with complex processes and these processes may require participation of different parties, different equipment, and practices while many assumptions have to be made for estimating the environmental impacts. Since there is no known Turkish LCI database for the construction (as well as demolition) machinery and freight transportation, the U.S. EPA (such as NONROAD, MOBILE 6.1, WARM) databases were excessively used. End-of-life options for the management of construction and demolition waste was another challenging area in terms of spatial and temporal uncertainty. Related concerns were mentioned in the parameter uncertainty section: Emission factors and energy consumption data for heavy-duty diesel trucks, as well as non-road construction equipment used during construction (and also demolishing) are based on U.S. EPA's MOBILE 6.1 [309-313] tool and AP-42 emission factors for diesel and gasoline engine powered industrial engines [151], respectively. However, AP-42 emission factors are considerably old, from 1996's. On the other hand, US EPA's data are transparent in terms of methodical recording of data quality. In AP-42, emission factors are qualitatively rated "…given a rating from A through E, with A being the best. A factor's rating is a general indication of the reliability, or robustness, of that factor…Conversely, a single observation based on questionable methods of testing would be assigned an E." [337]. Such a system of grading by a dependable organization can ascertain reliability. MOBILE 6.1 data used in calculating transportation LCI are more recent and also representative of the technology used in the dormitory building construction, in addition to being credible because of the U.S. EPA's data quality records. Overall, although I was unable to regionalize construction, transportation, and end-of-life demolition and waste management processes, technological representation was more robust as the Turkish construction and transportation system has similar standards to that of EU and U.S. due to the country's considerably active trade relationship with Europe. Moreover, contribution of construction (including transportation) and end-of-life phases together were significantly low (about 1.2% of overall energy use and GWP for concrete building, and even negative (-0.1%) for steel building).

In case of materials manufacturing stage, except for a few building materials, regional LCI data neither exists nor easy to retrieve. Since the concrete and its raw materials manufacturing are the focus of this dissertation, LCA of this building material is thoroughly covered, considering many dimensions of concrete from its design properties to technological variations in manufacturing processes as well as regional aspects.

Compared to other major construction materials, concrete is a complex composite with varying mix designs. Depending on the designer's requirements and type of concrete application, concrete mix designs and properties vary considerably. To be able to assess these properties accurately, certain concrete properties should be defined prior to LCAs. These properties include compressive strength, unit weight, permeability, workability, thermal conductivity, etc. Each of these properties vary considerably depending on the mix design [9, 79]. This variability offers an infinite range of concrete mixes, each of which will have its own life-cycle inventory. Despite the substantial amount of literature about the LCA of concrete, none of the current studies provided systematic details about mix proportions of concrete ingredients and properties (e.g. strength, permeability) of resulting concrete products and their associated life-cycle inventories. Generally, concrete production LCAs offered LCI data in terms of single values [63, 80, 81] or a range of values [56-59, 82] per unit volume of concrete. Of all the concrete studies, the recent ones [44, 56, 59, 61, 65] included different mix designs to formulate the effect of fly ash, GBFS, metakaolin, and other cement substitutions in reducing the concrete's environmental impacts but the results are still limited to the given concrete mix designs with no systematic recipe.

For both the case study and various scenario analyses, the capabilities of GreenConcrete LCA tool were described in capturing structural, technological, and regional properties of various concrete products. The tool can evaluate both direct and supply-chain environmental impacts of concrete manufacturing; including the related impacts from concrete materials (especially cement manufacturing).

In the case study, concrete was applied in both structural and non-structural elements of concrete- and steel-framed dormitory buildings. For the concrete-frame building, reinforced concrete that was used in foundations, beams, slabs, and columns constituted almost 80% of the total weight of the building materials. For the steel-frame, C30 type reinforced concrete which was used in foundation contributed to the 68% of the total weight, whereas the share of structural steel was only 9%. Accordingly, the life-cycle impacts of concrete was significant: about 60% and 35% of total GWP was from concrete manufacturing in concrete and steel building, respectively. Design mixes for the three structural (C25, C30, and C35) and four non-structural (as protective surface and screed) concrete elements were obtained from one of the Turkiye's leading concrete manufacturers. The energy consumption and GWP calculations involved average Turkish cement (including Turkish cement kiln fuel details) and concrete manufacturing technologies, as well as the Turkish electricity grid mix and fossil fuel properties relevant to Turkiye. The results from the Excel version of the tool were not limited to only GWP and energy consumption. The results were broken down by life-cycle phases from cradle-to-gate and further by sources of environmental effects (pre-combustion and combustion fuel use, electricity use, water consumption, and process itself), and environmental effects (solid waste, antimony (Sb), arsenic (As), beryllium (Be), cadmium (Cd), CO_2, CO, chromium (Cr), cobalt (Co), copper (Cu), formaldehyde (CH_2O), lead (Pb), manganese (Mn), mercury (Hg), CH_4, nickel (Ni), NO_x, N_2O, non-methane volatile organic compounds (NMVOC), particulates (PM_{10} and total), selenium (Se), SO_2, VOCs, zinc. However, impacts from superplasticizers were based on an EU database, EFCA [190] and related admixtures LCI was aggregated data, making it impossible to include technical and spatial variations.

Although the GreenConcrete LCA tool is very comprehensive in calculating LCI data, PM emissions which are specifically significant during materials quarrying, transferring and loading/unloading of concrete materials, are based on single average data points – which generally does not reflect the regional or technological variations. In the tool, chemical compositions of concrete materials and fuels are also not taken into consideration. However, for example, chemical composition of fly ash can be used in calculating emissions of heavy metals, dioxins or some other raw material related emissions.

Overall, the case study LCA results allowed defining major uncertainties stemming from variations in spatial and temporal differences as well as materials manufacturing, replacement, and construction technologies, operation phase impacts, end-of-life decisions, LCA calculation methods, and many other aspects.

7.1.3 Environmental Significance of Cement and Concrete Manufacturing

As stated in the literature review section, most of the cement manufacturing emissions are attributable to the production of cement clinker, the active ingredient in concrete [7]. Approximately half of these emissions are due to the combustion of fossil fuels and the remaining portion is from the calcination of the limestone for traditional cement manufacturing processes. Improvements in cement manufacturing processes only have limited influence on reducing GHG emissions and using increased fractions of supplementary cementitious materials yield in more sustainable cement products (and eventually concrete mixtures). The influence of varying cement production processes (mainly cement kiln technology, fuel mixes) and replacement of cement with SCMs can be validated with a sensitivity analysis.

In the first scenario analysis, GreenConcrete LCA tool was applied to explore the influence of different cement manufacturing pathways (including blended cements with fly ash and slag) on cradle-to-gate life-cycle energy consumption, GHG emissions and major criteria air pollutants for both the Turkish and the U.S. cement manufacturing industries. The tool was designed to consider likely variations in cement manufacturing technologies, making it possible to repetitively calculate varying system inputs and outputs. The major input variables for each scenario involves kiln technology and cement types for technological variations and cement kiln fuel and electricity grid mix variations for the U.S. and Turkiye. The five technological scenarios were tabulated in Table 5.28. The best case scenario (slag cement production with precalciner/preheater kilns) resulted in the lowest energy use and associated air emissions. Results from the analysis prove that the increased use of fly ash and slag would be the most efficient way in reducing environmental impacts from cement manufacturing. However, we should not limit our material choice to these two types of SCMs as their supply is limited with the coal and steel manufacturing industries. Moreover, the quality of fly ash and slag may not always be suitable for replacing the portland cement and may contain trace quantities of some heavy metals, radioactivity which requires further research of these by-products use. Therefore, other minerals such as natural pozzolans, limestone or other materials such as alkali-activated alumino-silicates (previously known as geopolymer) are good candidates for replacing cement in concrete mixes.

Additionally, the pyroprocessing, the most energy-intensive stage of cement manufacturing was further investigated to understand and quantify the major sources (in addition to calcination process) of GHG emissions. Fossil fuel (coal and petcoke) combustion and calcination were obviously the major source of GHGs for all scenarios in Turkiye and in the U.S., confirming the results from the literature. ***It was also shown that a shift in energy mix (TR vs. U.S.) could yield significantly different results*** without changing the amount of energy consumption (that was true for both electricity and fuel use) in manufacturing processes (see Figure 5.19). Although Turkish cement kilns burn more coal and petcoke, resulting in higher amount of energy consumption (despite the fact that the kiln fuel energy requirement is fixed for the corresponding kiln type) electricity-related energy values were lower compared to the U.S. practice. Overall, Turkish cement manufacturing consume less energy mostly because of the higher percentages of cleaner energy sources (70% from natural gas and hydro electricity power plants, 28% from lignite) used in national electricity grid mix as opposed to the U.S. grid mix which was dependent on coal (45%), natural gas (23%) and nuclear (20%). However, overall GWP results were slightly higher for Turkish cement kilns for all five scenarios, as petcoke and lignite have higher GHG emission factors (see Figure 5.20).

The concrete mixes are further considered in terms of their strength and GWP aspects by using a sensitivity analysis. In recent years, *high-volume fly ash (HVFA) concrete* has been used successfully for many years in numerous applications with technical and environmental advantages as compared to conventional portland cement concrete, and its use is expected to keep increasing over time [340-342]. This sensitivity analysis was based on an unpublished study [345]. In the collaborative study, GreenConcrete LCA tool was used to compare the GWP of various concrete mixes as well as their strength and durability. The tool evaluated both direct and supply-chain environmental impacts of concrete manufacturing, including the related impacts from concrete materials. Table 5.30 and Table 5.31 summarize the variables used as inputs in the analysis. Concrete mix proportions were given in Table 5.32, all with a constant water/ cementitious material (*w/cm*) ratio of 0.35. The ratio of portland cement replacement (CR) by fly ash type-F (FAF) and LS was varied between 45% and 75%, by weight. For the OPC-FAF-LS blends, LS content was set at 15% or 25%, by weight, and the amount of fly ash was varied between 20% and 60%, by weight, in order to match the desired total replacement ratio for each mix. The ratio between coarse and fine aggregates (FA) was kept at 50:50%, and the coarse aggregate consisted of 30% pea gravel and 70% basalt. Results showed that all FAF-LS mixes were compatible with typical medium-strength OPCC and they had lower cement content, and therefore reduced $CO_{2\text{-eq}}$ footprint, that is even less than the GWP of low-strength OPCC. Ultimately, a wide range of strengths were attained depending on the specific replacement ratios and curing time specified for a given project. At a fixed *w/cm* ratio, increased FAF content led to relatively lower early strengths but higher strength gain rates. Similar to the GWP trend, criteria air pollutants increased with the higher weight of portland cement, again mostly attributable to the pyroprocessing stage of cement manufacturing (Table 5.34). Only exception was the CO emission which was slightly higher for concrete mixes with higher fly ash content. This result was attributed to natural gas used for drying of fly ash since natural gas combustion has considerably higher CO emission factor. When the limestone and fly ash impacts were examined separately, the GWP from fly ash was larger with an order of 5-10 times for the same weight of limestone used in the mix. This difference was due to the fuel utilized while drying the fly ash prior to mixing in concrete. ***Results showed that environmentally and structurally advantageous concrete mixtures could be made with high-volumes of fly ash and limestone, with low addition of superplasticisers and without viscosity modifying agents*. A wide range of early and long term strengths were attainable depending on the selected mix proportion. *GHG emissions and major criteria air pollutants (with only exception being CO emissions) were also successfully reduced and were in all cases similar to and lower than the typical OPCC.***

Finally, GWP from average U.S. concrete mix designs are analyzed with respect to the influence of replacement of ordinary portland cement with SCMs (fly ash and slag). Mix designs were obtained from PCA and a similar approach was applied using the GreenConcrete LCA tool [58]. The sensitivity analysis once again demonstrated that the concrete LCA results are sensitive to the cement content of the concrete mix. Overall GWP reduces significantly with the replacement of ordinary portland cement with SCMs such as fly ash and slag.

In addition to the conducted sensitivity analysis, the influence of many more factors can be calculated using the GreenConcrete LCA tool and database sources. However, it is believed that most important factors were captured in the dissertation.

7.1.4 Summary of Results

The comprehensive LCA results from the dormitory building case study identify the major activities that contribute to energy consumption and environmental impacts, e.g. GWP. By recognizing these activities, it is possible to improve their sustainability, by reducing the energy use and associated emissions. Results from the case study once again show that: operation phase dominates in GWP and energy consumption, which is consistent with the literature results. By trying to include as many factors as possible in the LCA study while considering the most recent, and representative data in terms of geography, technology, use patterns, and climatic conditions, I tried to minimize the uncertainty in the research. However, there is always a need for future research in the LCAs of building systems, especially in countries such as Turkiye where sustainability-related studies are in their premature stages with so many opportunities to come in the near future.

7.2 Contributions

7.2.1 Contribution to the Knowledge of Concrete and Building LCA Research

The exhaustive review of the literature about building and concrete manufacturing LCAs provide an insight about the weaknesses and strengths of related studies, contributing to the knowledge in this area. Results from the literature reveal that building LCA studies diverge in so many areas: included but not limited to the scope and functional unit definition; LCA approach designated; life-cycle phase inclusion; type of building elements, building envelope materials, or structural frame analyzed; the climate zone and the social and natural environment where the building system is operated; the purpose of the building use (office, university, hospital, etc.) and the behavior of users; environmental loads addressed; the choice of method used in impact assessment; interpretation of results; the end-of-life destiny of construction and demolition waste, and so on. This creates a challenge for comparing building LCAs. Furthermore, gaps in data availability and the representation of life-cycle phase and associated inventory and impact categories are collected and provided in details as part of the dissertation. All the background research led to the idea of development of a new LCA methodology for a comprehensive and transparent environmental assessment of concrete and its applications in building projects. This dissertation comprises as an initial step towards developing a new building material LCA tool.

7.2.2 Development of GreenConcrete LCA Tool

Beyond expanding the concrete LCA knowledge in academia, one of the important deliverables of this dissertation is a practical, process-based concrete manufacturing LCA tool, namely GreenConcrete LCA. Both, MS Excel and web versions can assess the environmental profiles of almost infinite number of concrete mixes. When compared with other major building material LCAs such as NIST's BEES, Athena software, the new tool is dynamic as opposed to the static nature of current tools in the market. The tool's dynamism is due to its capability to calculate and compare the LCA of different concrete mixes designed for specific project purposes. Not only the direct but also the supply-chain impacts of each process during the production of concrete and its materials are evaluated within the context of the tool. The scope of the tool covers cement raw materials quarrying and cements production, fine aggregates and coarse aggregates quarrying and processing, processing of supplementary cementitious materials (SCMs), production of major chemical admixtures, and electricity generation impacts associated with the processes considered and transportation of materials within the system. The integration of regional variations and technological alternatives in the scope of material production processes within the tool offers a wide range of applicability and flexibility for cement and concrete manufacturers in the U.S. and worldwide.

GreenConcrete LCA tool is specifically designed for cement and concrete manufacturers for the purpose of quantifying and comparing environmental impacts of their products. Decision makers in the construction sector including construction managers, contractors, civil engineers, architects, and owners can also make use of the output of the GreenConcrete as a decision-support tool for the selection of materials or concrete mixes based on their calculated environmental impacts. Results from the tool can be used to identify the processes and LCA material and energy inputs that should be given priority if achieving sustainability is one of the goals in addition to material properties and cost.

Overall, the LCA database and results from the new tool are arranged in a systematic way which makes the interpretation of the results easier, in addition to tool itself being user-friendly and comprehensive. As stated in the thesis proposal, one of the major goals of this research was to understand the environmental impacts of concrete and its raw materials properly. ***This new LCA approach, as a tool, can bring holistic and comprehensive framework to policy making in the future. Results from the concrete LCA can be further used for identifying major impact areas in terms of pollutants, energy use, and construction and demolition waste and make transparent decisions towards policy recommendations.*** Policy implementation is essential to achieve sustainable concrete applications (e.g. buildings).

7.2.3 Turkish Dormitory Building Case Study and the Related Database

The case study is an important contribution to the building LCA arena, in terms of LCA database coverage, knowledge and methodology applied. It is the first comprehensive LCA study that focused on the environmental impacts of a Turkish dormitory building, considering geographical variations as well as technological variations in all phases of the building.

First of all, a process-based LCA was applied in calculating environmental interventions from all building phases. For the materials manufacturing phase, quantities and descriptions of materials and building products were required and obtained from a Turkish design company. Based on the descriptions of these materials, weight per unit of each material, service life, construction waste, as well as application and technical characteristics were obtained from technical specifications, as well as, from both local and international manufactures (see Appendiex B, Table 9.11 for list of materials and data sources). When available, both LCI and LCIA factors were tabulated for each of these materials, resulting in a comprehensive building materials database which can be utilized in future building LCA studies (Appendix B, Table 9.14 and Table 9.15). Case study results were limited to only two environmental measures since energy use and GWP were currently the only available data for all building materials.

The construction phase LCA calculations involved information regarding the on-site equipment use and heavy-duty trucks for transportation of materials to/from the construction phase. Although the related equipment and truck pool database included LCI data from the latest U.S. EPA sources, the technical information (model, year, horsepower, capacity, power sources, and output) for the construction equipment constitutes a well-organized and comprehensive dataset obtained from all over the world. The information in database and the construction phase LCA calculations/approach can easily be adapted to future construction LCA research.

The operation phase input data (electricity, space heating, and hot water) were obtained from Prokon based on a realistic energy use simulation model, considering climate and use patterns. Associated LCA calculations again required hundreds of data points (and their sources) to cover electricity grid mix and fuel use (both direct and upstream) impacts that are geographically representative of Istanbul region. Once again, the operation-phase related calculations and database is another contribution that can be utilized in Turkish building LCA projects. The end-of-life phase LCA approach and calculations, together with the database are similarly important.

All these described contributions provide an opportunity to understand differences/similarities in building LCAs from one country to another with the objective of determining the best policy option for each building project as well as for each country for sustainable building development. Especially, a policy framework recommendation for sustainable Turkish buildings, such as carbon footprint, standards in building appliances, etc. will totally be a new area that constitutes a promising future work.

7.3 Limitations of the Tool and Future Research

Concrete and buildings LCA research will continue as long as there is demand for greener products and systems. Although the GreenConcrete LCA tool and building LCA case study are comprehensive both in depth and width, some limitations are inevitable due to the nature of LCA work. Therefore, improvements are necessary as part of future research.

Starting with the cement manufacturing, although energy consumption, GHG emissions and criteria air pollutants are well-covered, there is still need for research on impacts from toxic emissions, water effluents, solid waste (e.g. cement kiln dust), and water consumption. These environmental factors are generally overlooked either because of the expertise, time, and data constraints or they are assumed insignificant (without a thorough analysis). These limitations preclude robust environmental analysis of cement production across the full range of energy and emissions issues that should be considered. This problem can be overcome by working together with cement manufacturers who can provide the necessary testing data on these properties, such as chemical analysis of cement raw materials can give an insight on heavy metal content of certain materials. Moreover, there is still need for incorporating a wider range of technology options applied in cement manufacturing processes, as well as cement plant operation details in the concrete LCA tool.

For the aggregates processing part, the tool still lacks the details about different types of aggregates and their energy requirements for their extraction and processing on the basis of their hardness, water content, etc. This is especially important since the major energy consumption in aggregates processing is mostly from crushing and the electricity required for crushing can considerably change with the hardness of aggregates. The tool uses average energy values for fine and coarse aggregates processing with no further distinction based on the properties of these materials. Again, collaboration with the industries of stone and aggregates can improve these limitations.

Extensive research and market analysis will be needed for the development/improvement of chemical admixtures production processes and their associated life cycle inventory. In the tool, aggregated LCI data for admixtures were obtained from one source with no details about the overall manufacturing processes, inputs and outputs. There is requirement for reliable data sources for understanding admixture production processes and related environmental impacts.

Another improvement should be in environmental impacts of the use of secondary materials in cement and concrete (SCMs, recycled concrete, alternative fuels) manufacturing. There is limited amount of research in LCAs of such alternative materials, which requires extensive material test results regarding their chemical and mineral compositions, processing techniques, as well as their regulative and market requirements. Although it is possible to calculate influence of different allocation methods on the environmental impacts of by-products or secondary materials separately, calculations would be easier if allocation would be integrated in the GreenConcrete LCA tool (for both MS Excel and Web versions). This can be achieved in the near future.

Water consumption uncertainty is evident in all life-cycle phases of materials and buildings since regionalized withdrawals and consumption data are somewhat missing.

Regarding the concrete manufacturing overall, environmental impacts from the production of concrete materials other than portland cement; such as, admixtures, and water consumption are rarely analyzed in concrete LCAs. Functional unit choice in concrete LCAs is seen as one of the most influencing factors in interpretation of LCA results. This unit, preferably (but very rarely in literature) includes all relevant concrete aspects, such as strength, durability, unit weight, etc. As developed into "GreenConcrete LCA" tool, the concrete mix proportions are defined on the basis of its cement content and strength according to the applicable standards so that different concrete types can be compared for "green" concrete design requirements. However, a further step should be taken to consider the manufacturing of a structural concrete element or even a whole building with a predefined service life to determine the life-span of concrete for future end-of-life scenarios and design load. Besides concrete material aspects, LCA system boundary (cradle-to-gate, gate-to-gate, and cradle-to-grave) selection is also important. For durability properties and carbon uptake by concrete surface issues, building use, maintenance, and EOL phases should be preferably considered within the system boundary and be integrated in the future building LCA tools.

Regarding the transportation module in the tool, barely one data source by Facanha and Horvath [368] was used to calculate the transportation LCI as it was the only total (direct plus supply-chain impacts) LCI source with representative and common freight transportation options. Improvements should require merging with other freight transportation LCAs that consider different scenarios of vehicle year/capacity/model as well as infrastructure impacts that are adjustable to not only the U.S. conditions but also to other countries worldwide.

In commercial building LCAs, building's energy use and associated environmental impacts should be analyzed not only on the basis of estimated energy demand of the building but also building design features such as building size, type, material u-values, location, and indoor air quality, thermal climate, etc. requirements. As well, there is significant inconsistency in the assumption of building life-span (ranging between 25 to 100 years) and system boundary coverage. The life-span assumption critically influences the relative impact of embodied energy versus operational energy. The criterion also affects the maintenance and replacement considerations with respect to building material life-span considerations. Therefore, in addition to the comparably well-studied operation phase, the system boundary should be inclusive of maintenance and repair phases. Also, more research is necessary to compare end-of-life scenarios after the demolition of the buildings. Improved data regarding end-of-life statistics, e.g., rates of landfilling versus recycling as well as national variations in end-of-life options are essential. In addition statistical information, research should be conducted about major demolition, recycling and landfilling processes and their environmental impacts. Focus should be on leaching, toxic wastes, land use impacts, etc. It is also necessary to understand regional variations in regulations and their effects on the selection of end-of-life strategies.

The research in concrete and building LCAs has shown that minimal emphasis was given on life-cycle impact factors of ozone depletion, eco-toxicity, human toxicity, and abiotic depletion. One important problem with human toxicity and eco-toxicity categories is the lack of exposure data – from one study to another human exposure to pollutants vary considerable depending on the proximity, concentration of pollutant, existence of other sources of pollutant as well as regional differences in climate, geography, population density and so on. There is requirement for ranges of possible values for those impact categories and the conditions they represent. Additionally, due to lack of information about chemical composition of some common air pollutants throughout the life of the building, it is almost impossible to categorize these pollutants provided in the inventory in terms of their toxicity, carcinogenicity, and bioaccumulation and so on.

Above all, impacts from heavy metals and other toxic emissions are mostly omitted in building materials (especially for concrete) LCIAs since their quantities are deemed insignificant however it’s their severity that could be of significant in terms of damage to human and environment.

Although uncertainty and data quality analysis were considered for the building case study, it was still inadequate as only consequences of certain uncertainties were covered in a qualitative style. A complete risk and uncertainty analysis is two dimensional, meaning that both consequences (qualitative information) and probability of occurrence (quantitative information) of them should be considered as part of future work. The remedy for this omission starts at the data collection level. Ranges of LCI data are required for each process to determine probability distributions. One of the suggested approaches is the stochastic modeling which can be performed by Monte Carlo simulation [328]. As a result of this approach, emissions for each building phase can be demonstrated with probability distributions. However, this improvement requires great amount of individual data points and considerable amount of time.

Additionally, the future research should consider the integration of GreenConcrete LCA tool with CAD tools, BIM programs or cost estimating program would be advisable. In addition to the integration of design and construction phase related tools, output from building operation phase energy simulation programs or tools can be applied to establish overall building performance as part of the LCA. One example is the U.S.DOE’s eQuest [130] which determines primary energy consumption for heating, cooling, ventilation, lighting, hot water and sanitary water consumption during the use phase of a building. Another tool that can be developed is a climate model. For example, Dynamic Thermal Model and UK Climate Projections ‘09 Weather Generator software establishes potential building performance in various weather scenarios defined [101]. This study allowed “the influence of climate change to be included in the LCA of building GHG emissions.”

All in all, topics of future work include further development of regionalized life-cycle inventories and their corresponding life-cycle impact categories (such as acidification, eutrophication, eco-toxicity, and human toxicity – as these impact vary highly with the local conditions). New concepts such as albedo (urban heat island) effect on energy use of concrete buildings and land use effects from materials extraction/production constitute other areas that need further research. Finally, as mentioned in the prior paragraphs, integration of building and materials LCA tools with the mentioned design (AUTOCAD), cost (RS Means database), building information management (BIM), and building energy use (DOE’s eQuest) and climate simulation programs (Weather Generator) would eventually result in accurate and timely assessment of building projects, given their one-of-a kind and complex nature.

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9 Appendix

9.1 Appendix A: GreenConcrete LCA Tool – Calculations and Data

Electricity generation from each of the three petroleum-based fuel sources (residual fuel oil, distillate fuel oil, and petroleum coke) are calculated by proportioning the fuel consumption (in MJ) data given for each of the petroleum-based fuels and total amount of electricity (in kWh) generated by all petroleum-based fuel sources, that is also given. The following equation is applied for the calculation:

$$ESOURCE_{PETROLEUMk,j} = \left(ESOURCE_{TOTALPETROLEUM,j} \times \mathrm{ECONSUMPT}_{PETROLEUMk,j}\right) \Big/ \sum_{k}^{3} ECONSUMPT_{PETROLEUMk,j}$$

Equation 9.1: Calculation of net annual electricity generated by petroleum-based fuels

Where:

k represents petroleum-based fuel sources used in electricity generation, that is; k=1: residual fuel oil, k=2: distillate fuel oil, k=3: petcoke;

$\mathrm{ESOURCE}_{\mathrm{PETROLEUMk,j}}$ = Net annual electricity generated by petroleum-based fuel source “k” in State “j”, in kWh;

$\mathrm{ESOURCE}_{\mathrm{TOTALPETROLEUM,j}}$ = Net annual electricity generated by all petroleum-based fuel sources in State “j”, in kWh (given in “Petroleum, Total” column of Table 9.1;

$\mathrm{ECONSUMPT}_{\mathrm{PETROLEUMk,j}}$ = Petroleum-based fuel source “k” consumption estimate for electric power generation in State “j”, in MJ (given in columns “Residual (Heavy) Fuel Oil”, “Distillate (Light) Fuel Oil”, “Petcoke”.

Table 9.1: 2009 Net Electricity Generation (in kWh) by State, by Energy Source

State	Net Annual Electricity Generation	Coal	Natural Gas	Residual (Heavy) Fuel Oil	Distillate (Light) Fuel Oil	Petcoke	Petroleum, Total	Nuclear	Hydro electric	Biomass	Geo thermal	Solar	Wind
AK	6.70E+09	6.31E+08	3.58E+09	5.70E+08	5.87E+08	0.00E+00	1.16E+09	0.00E+00	1.32E+09	6.51E+06	0.00E+00	0.00E+00	7.03E+06
AL	1.43E+11	5.56E+10	3.16E+10	0.00E+00	2.19E+08	0.00E+00	2.19E+08	3.97E+10	1.25E+10	3.05E+09	0.00E+00	0.00E+00	0.00E+00
AR	5.75E+10	2.51E+10	1.12E+10	4.92E+07	3.93E+07	0.00E+00	8.85E+07	1.52E+10	4.19E+09	1.59E+09	0.00E+00	0.00E+00	0.00E+00
AZ	1.12E+11	3.97E+10	3.47E+10	0.00E+00	6.27E+07	0.00E+00	6.27E+07	3.07E+10	6.43E+09	1.59E+08	0.00E+00	1.41E+07	2.95E+07
CA	2.05E+11	2.05E+09	1.13E+11	8.34E+06	5.84E+07	1.48E+09	1.54E+09	3.18E+10	2.79E+10	6.20E+09	1.29E+10	6.47E+08	5.84E+09
CO	5.06E+10	3.16E+10	1.38E+10	0.00E+00	1.35E+07	0.00E+00	1.35E+07	0.00E+00	1.89E+09	5.66E+07	0.00E+00	2.56E+07	3.16E+09
CT	3.12E+10	2.45E+09	9.81E+09	2.73E+08	2.64E+07	0.00E+00	2.99E+08	1.67E+10	5.10E+08	7.59E+08	0.00E+00	0.00E+00	0.00E+00
DC	3.55E+07	0.00E+00	0.00E+00	0.00E+00	3.55E+07	0.00E+00	3.55E+07	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
DE	4.84E+09	2.85E+09	1.38E+09	1.08E+08	1.51E+08	0.00E+00	2.58E+08	0.00E+00	0.00E+00	1.26E+08	0.00E+00	0.00E+00	0.00E+00
FL	2.18E+11	5.40E+10	1.18E+11	5.68E+09	5.79E+08	2.96E+09	9.22E+09	2.91E+10	2.08E+08	4.33E+09	0.00E+00	9.47E+06	0.00E+00
GA	1.29E+11	6.95E+10	2.05E+10	0.00E+00	6.50E+08	0.00E+00	6.50E+08	3.17E+10	3.26E+09	2.83E+09	0.00E+00	0.00E+00	0.00E+00
HI	1.10E+10	1.50E+09	0.00E+00	6.94E+09	1.35E+09	0.00E+00	8.29E+09	0.00E+00	1.13E+08	2.84E+08	1.68E+08	1.39E+06	2.51E+08
IA	5.19E+10	3.74E+10	1.18E+09	0.00E+00	5.97E+07	2.56E+07	8.53E+07	4.68E+09	9.71E+08	1.68E+08	0.00E+00	0.00E+00	7.42E+09
ID	1.31E+10	8.26E+07	1.64E+09	0.00E+00	0.00E+00	0.00E+00	4.10E+04	0.00E+00	1.04E+10	4.78E+08	7.60E+07	0.00E+00	3.13E+08
IL	1.94E+11	9.00E+10	4.49E+09	0.00E+00	1.13E+08	0.00E+00	1.13E+08	9.55E+10	1.36E+08	7.10E+08	0.00E+00	1.60E+04	2.82E+09
IN	1.17E+11	1.08E+11	3.83E+09	0.00E+00	1.47E+08	9.80E+06	1.57E+08	0.00E+00	5.03E+08	3.03E+08	0.00E+00	0.00E+00	1.40E+09
KS	4.67E+10	3.22E+10	2.67E+09	0.00E+00	2.88E+07	9.20E+07	1.21E+08	8.77E+09	1.28E+07	0.00E+00	0.00E+00	0.00E+00	2.86E+09
KY	9.06E+10	8.40E+10	8.78E+08	0.00E+00	1.33E+08	1.88E+09	2.02E+09	0.00E+00	3.32E+09	3.64E+08	0.00E+00	0.00E+00	0.00E+00
LA	9.10E+10	2.31E+10	4.40E+10	4.15E+07	4.15E+07	1.77E+09	1.86E+09	1.68E+10	1.24E+09	2.36E+09	0.00E+00	0.00E+00	0.00E+00
MA	3.90E+10	9.03E+09	2.10E+10	7.49E+08	1.48E+08	0.00E+00	8.97E+08	5.40E+09	1.20E+09	1.22E+09	0.00E+00	4.30E+04	5.96E+06
MD	4.38E+10	2.42E+10	1.77E+09	1.56E+08	1.74E+08	0.00E+00	3.30E+08	1.46E+10	1.89E+09	5.51E+08	0.00E+00	0.00E+00	0.00E+00
ME	1.63E+10	7.21E+07	7.36E+09	4.20E+08	1.35E+07	0.00E+00	4.33E+08	0.00E+00	4.21E+09	3.64E+09	0.00E+00	0.00E+00	2.99E+08
MI	1.01E+11	6.68E+10	8.42E+09	8.63E+07	1.62E+08	1.51E+08	3.99E+08	2.19E+10	1.37E+09	2.32E+09	0.00E+00	0.00E+00	3.00E+08
MN	5.25E+10	2.93E+10	2.85E+09	0.00E+00	6.53E+07	0.00E+00	6.53E+07	1.24E+10	8.09E+08	1.68E+09	0.00E+00	0.00E+00	5.05E+09
MO	8.84E+10	7.16E+10	3.42E+09	0.00E+00	6.06E+07	2.69E+07	8.75E+07	1.02E+10	1.82E+09	7.54E+07	0.00E+00	0.00E+00	4.99E+08

MS	4.87E+10	1.30E+10	2.33E+10	8.30E+06	8.30E+06	0.00E+00	1.66E+07	1.10E+10	0.00E+00	1.42E+09	0.00E+00	0.00E+00	0.00E+00
MT	2.67E+10	1.56E+10	7.78E+07	0.00E+00	5.98E+06	4.84E+08	4.90E+08	0.00E+00	9.51E+09	9.46E+07	0.00E+00	0.00E+00	8.21E+08
NC	1.18E+11	6.51E+10	4.85E+09	0.00E+00	2.97E+08	0.00E+00	2.97E+08	4.08E+10	5.17E+09	1.89E+09	0.00E+00	4.56E+06	0.00E+00
ND	3.42E+10	2.96E+10	1.66E+07	0.00E+00	4.50E+07	0.00E+00	4.50E+07	0.00E+00	1.48E+09	1.16E+07	0.00E+00	0.00E+00	3.00E+09
NE	3.40E+10	2.33E+10	3.12E+08	0.00E+00	2.29E+07	0.00E+00	2.29E+07	9.44E+09	4.34E+08	6.62E+07	0.00E+00	0.00E+00	3.83E+08
NH	2.02E+10	2.89E+09	5.34E+09	1.73E+08	9.64E+06	0.00E+00	1.83E+08	8.82E+09	1.68E+09	1.14E+09	0.00E+00	0.00E+00	6.25E+07
NJ	6.18E+10	5.10E+09	2.06E+10	1.74E+08	1.04E+08	0.00E+00	2.78E+08	3.43E+10	3.21E+07	9.28E+08	0.00E+00	1.07E+07	2.09E+07
NM	3.97E+10	2.91E+10	8.66E+09	0.00E+00	4.46E+07	0.00E+00	4.46E+07	0.00E+00	2.71E+08	3.37E+07	0.00E+00	0.00E+00	1.55E+09
NV	3.77E+10	7.54E+09	2.59E+10	0.00E+00	1.62E+07	0.00E+00	1.62E+07	0.00E+00	2.46E+09	8.90E+05	1.63E+09	1.74E+08	0.00E+00
NY	1.33E+11	1.28E+10	4.18E+10	2.04E+09	4.28E+08	1.79E+08	2.65E+09	4.35E+10	2.76E+10	2.20E+09	0.00E+00	0.00E+00	2.27E+09
OH	1.36E+11	1.14E+11	4.65E+09	0.00E+00	2.72E+08	1.04E+09	1.31E+09	1.52E+10	5.28E+08	6.19E+08	0.00E+00	0.00E+00	1.41E+07
OK	7.51E+10	3.41E+10	3.46E+10	0.00E+00	9.46E+06	0.00E+00	9.46E+06	0.00E+00	3.55E+09	2.31E+08	0.00E+00	0.00E+00	2.70E+09
OR	5.67E+10	3.20E+09	1.61E+10	0.00E+00	0.00E+00	0.00E+00	7.96E+06	0.00E+00	3.30E+10	8.03E+08	0.00E+00	0.00E+00	3.47E+09
PA	2.19E+11	1.05E+11	2.92E+10	4.93E+08	3.42E+08	8.04E+07	9.15E+08	7.73E+10	2.68E+09	2.27E+09	0.00E+00	3.56E+06	1.07E+09
RI	7.70E+09	0.00E+00	7.53E+09	0.00E+00	1.71E+07	0.00E+00	1.71E+07	0.00E+00	4.74E+06	1.45E+08	0.00E+00	0.00E+00	0.00E+00
SC	1.00E+11	3.45E+10	9.78E+09	2.09E+07	1.05E+08	3.98E+08	5.23E+08	5.21E+10	2.33E+09	1.75E+09	0.00E+00	0.00E+00	0.00E+00
SD	8.20E+09	3.22E+09	8.03E+07	0.00E+00	8.32E+06	0.00E+00	8.32E+06	0.00E+00	4.43E+09	5.78E+06	0.00E+00	0.00E+00	4.21E+08
TN	7.97E+10	4.16E+10	4.09E+08	0.00E+00	1.87E+08	0.00E+00	1.87E+08	2.70E+10	1.02E+10	8.99E+08	0.00E+00	0.00E+00	5.17E+07
TX	3.97E+11	1.39E+11	1.89E+11	0.00E+00	6.94E+07	1.34E+09	1.40E+09	4.15E+10	1.03E+09	1.08E+09	0.00E+00	0.00E+00	2.00E+10
UT	4.35E+10	3.55E+10	6.44E+09	0.00E+00	3.61E+07	0.00E+00	3.61E+07	0.00E+00	8.35E+08	4.79E+07	2.79E+08	0.00E+00	1.60E+08
VA	7.01E+10	2.56E+10	1.22E+10	4.87E+08	6.01E+08	0.00E+00	1.09E+09	2.82E+10	1.48E+09	2.42E+09	0.00E+00	0.00E+00	0.00E+00
VT	7.28E+09	0.00E+00	4.43E+06	0.00E+00	0.00E+00	0.00E+00	2.44E+06	5.36E+09	1.49E+09	4.17E+08	0.00E+00	0.00E+00	1.16E+07
WA	1.04E+11	7.48E+09	1.20E+10	0.00E+00	5.36E+07	0.00E+00	5.36E+07	6.63E+09	7.29E+10	1.47E+09	0.00E+00	0.00E+00	3.57E+09
WI	6.00E+10	3.73E+10	5.48E+09	0.00E+00	5.57E+07	6.57E+08	7.12E+08	1.27E+10	1.39E+09	1.29E+09	0.00E+00	0.00E+00	1.05E+09
WV	7.08E+10	6.81E+10	1.09E+08	0.00E+00	1.69E+08	0.00E+00	1.69E+08	0.00E+00	1.65E+09	-8.38E+05	0.00E+00	0.00E+00	7.42E+08
WY	4.60E+10	4.20E+10	4.88E+08	0.00E+00	5.02E+07	0.00E+00	5.02E+07	0.00E+00	9.67E+08	0.00E+00	0.00E+00	0.00E+00	2.23E+09
U.S. average	3.95E+12	1.76E+12	9.21E+11	1.81E+10	7.00E+09	1.39E+10	3.89E+10	7.99E+11	2.73E+11	5.45E+10	1.50E+10	8.91E+08	7.39E+10
Source	[220]	[220]	[220]	calculated (Eqn. 4.44)	calculated (Eqn. 4.44)	calculated (Eqn. 4.44)	[220]	[257]	[257]	[257]	[257]	[257]	[257]

Table 9.2: 2009 Energy Source Consumption Estimates (in MJ) for Electric Power Generation by State, by Energy Source – in Energy Units

State	Coal[1]	Natural Gas[2]	Residual (Heavy) Fuel Oil[3]	Distillate (Light) Fuel Oil[4]	Petcoke[5]	Petroleum, Total	Nuclear	Hydro electric[6]	Biomass[7]	Geo thermal	Solar	Wind
AK	6.65E+09	4.04E+10	3.59E+09	3.69E+09	0.00E+00	7.28E+09	0.00E+00	1.36E+10	0.00E+00	0.00E+00	0.00E+00	1.06E+08
AL	6.03E+11	2.46E+11	0.00E+00	1.06E+09	0.00E+00	1.06E+09	4.38E+11	1.29E+11	5.17E+09	0.00E+00	0.00E+00	0.00E+00
AR	2.71E+11	9.00E+10	5.28E+08	4.22E+08	0.00E+00	9.50E+08	1.67E+11	4.32E+10	5.28E+08	0.00E+00	0.00E+00	0.00E+00
AZ	4.27E+11	2.82E+11	0.00E+00	6.33E+08	0.00E+00	6.33E+08	3.38E+11	6.62E+10	1.79E+09	0.00E+00	1.06E+08	3.17E+08
CA	2.23E+10	8.77E+11	1.06E+08	7.39E+08	1.87E+10	1.95E+10	3.50E+11	2.87E+11	8.18E+10	1.32E+11	6.65E+09	6.01E+10
CO	3.59E+11	1.26E+11	0.00E+00	1.06E+08	0.00E+00	1.06E+08	0.00E+00	1.94E+10	8.44E+08	0.00E+00	2.11E+08	3.26E+10
CT	2.77E+10	7.56E+10	3.27E+09	3.17E+08	0.00E+00	3.59E+09	1.84E+11	5.28E+09	1.42E+10	0.00E+00	0.00E+00	0.00E+00
DC	0.00E+00	0.00E+00	0.00E+00	5.28E+08	0.00E+00	5.28E+08	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
DE	3.52E+10	1.19E+10	5.28E+08	7.39E+08	0.00E+00	1.16E+09	0.00E+00	0.00E+00	1.69E+09	0.00E+00	0.00E+00	0.00E+00
FL	5.88E+11	9.87E+11	6.31E+10	6.44E+09	3.29E+10	1.02E+11	3.21E+11	2.11E+09	5.64E+10	0.00E+00	1.06E+08	0.00E+00
GA	7.35E+11	1.56E+11	0.00E+00	1.16E+09	0.00E+00	1.16E+09	3.50E+11	3.34E+10	4.22E+08	0.00E+00	0.00E+00	0.00E+00
HI	1.78E+10	0.00E+00	7.10E+10	1.38E+10	0.00E+00	8.48E+10	0.00E+00	8.44E+08	3.59E+09	1.69E+09	0.00E+00	2.64E+09
IA	4.07E+11	1.07E+10	0.00E+00	7.39E+08	3.17E+08	1.16E+09	5.16E+10	1.00E+10	1.58E+09	0.00E+00	0.00E+00	7.64E+10
ID	0.00E+00	1.35E+10	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.07E+11	1.58E+09	7.39E+08	0.00E+00	3.27E+09
IL	9.89E+11	3.57E+10	0.00E+00	1.37E+09	0.00E+00	1.37E+09	1.05E+12	1.37E+09	9.92E+09	0.00E+00	0.00E+00	2.90E+10
IN	1.20E+12	3.90E+10	0.00E+00	1.58E+09	1.06E+08	1.69E+09	0.00E+00	5.17E+09	3.17E+09	0.00E+00	0.00E+00	1.45E+10
KS	3.73E+11	3.43E+10	0.00E+00	5.28E+08	1.69E+09	2.22E+09	9.67E+10	1.06E+08	0.00E+00	0.00E+00	0.00E+00	2.94E+10
KY	9.42E+11	9.07E+09	0.00E+00	1.69E+09	2.38E+10	2.55E+10	0.00E+00	3.42E+10	8.44E+08	0.00E+00	0.00E+00	0.00E+00

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[1] Coal covers anthracite, bituminous, subbituminous, lignite, waste coal, and coal synfuel.

[2] Natural gas as it is consumed; includes supplemental gaseous fuels that are mixed with natural gas.

[3] Residual fuel oil includes No. 5 and No. 6 fuel oils and bunker C fuel oil.

[4] Distillate fuel oil includes all diesel, No. 1, No. 2, and No. 4 fuel oils.

[5] Coke from petroleum has a heating value of 6.024 million Btu per barrel. See http://www.eia.gov/dnav/pet/TblDefs/pet_cons_psup_tbldef2.asp

[6] Conventional hydroelectric power and does not include pumped-storage hydroelectricity.

[7] Wood, wood-derived fuels, and biomass waste.

LA	2.66E+11	2.42E+11	4.22E+08	4.22E+08	1.80E+10	1.89E+10	1.85E+11	1.28E+10	1.16E+09	0.00E+00	0.00E+00	0.00E+00
MA	9.57E+10	1.64E+11	8.02E+09	1.58E+09	0.00E+00	9.60E+09	5.95E+10	1.22E+10	2.21E+10	0.00E+00	0.00E+00	1.06E+08
MD	2.57E+11	1.99E+10	1.90E+09	2.11E+09	0.00E+00	4.01E+09	1.61E+11	1.94E+10	7.81E+09	0.00E+00	0.00E+00	0.00E+00
ME	9.50E+08	4.06E+10	3.27E+09	1.06E+08	0.00E+00	3.38E+09	0.00E+00	3.56E+10	3.19E+10	0.00E+00	0.00E+00	3.06E+09
MI	7.20E+11	8.98E+10	8.44E+08	1.58E+09	1.48E+09	3.90E+09	2.41E+11	1.39E+10	2.32E+10	0.00E+00	0.00E+00	3.06E+09
MN	3.22E+11	2.52E+10	0.00E+00	7.39E+08	0.00E+00	7.39E+08	1.37E+11	6.96E+09	2.21E+10	0.00E+00	0.00E+00	5.20E+10
MO	7.85E+11	3.20E+10	0.00E+00	9.50E+08	4.22E+08	1.37E+09	1.13E+11	1.87E+10	8.44E+08	0.00E+00	0.00E+00	5.17E+09
MS	1.47E+11	1.96E+11	1.06E+08	1.06E+08	0.00E+00	2.11E+08	1.21E+11	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
MT	1.81E+11	7.39E+08	0.00E+00	1.06E+08	8.55E+09	8.65E+09	0.00E+00	9.79E+10	0.00E+00	0.00E+00	0.00E+00	8.44E+09
NC	6.86E+11	4.24E+10	0.00E+00	2.95E+09	0.00E+00	2.95E+09	4.51E+11	5.31E+10	1.16E+10	0.00E+00	0.00E+00	0.00E+00
ND	3.46E+11	0.00E+00	0.00E+00	5.28E+08	0.00E+00	5.28E+08	0.00E+00	1.52E+10	0.00E+00	0.00E+00	0.00E+00	3.09E+10
NE	2.56E+11	3.48E+09	0.00E+00	3.17E+08	0.00E+00	3.17E+08	1.04E+11	4.43E+09	6.33E+08	0.00E+00	0.00E+00	3.90E+09
NH	3.46E+10	4.16E+10	1.90E+09	1.06E+08	0.00E+00	2.00E+09	9.73E+10	1.72E+10	1.83E+10	0.00E+00	0.00E+00	6.33E+08
NJ	6.29E+10	1.78E+11	5.28E+08	3.17E+08	0.00E+00	8.44E+08	3.79E+11	3.17E+08	1.13E+10	0.00E+00	1.06E+08	2.11E+08
NM	3.21E+11	7.60E+10	0.00E+00	5.28E+08	0.00E+00	5.28E+08	0.00E+00	2.74E+09	5.28E+08	0.00E+00	0.00E+00	1.59E+10
NV	8.48E+10	2.09E+11	0.00E+00	2.11E+08	0.00E+00	2.11E+08	0.00E+00	2.53E+10	0.00E+00	1.68E+10	1.79E+09	0.00E+00
NY	1.39E+11	3.96E+11	2.16E+10	4.54E+09	1.90E+09	2.81E+10	4.80E+11	2.83E+11	3.32E+10	0.00E+00	0.00E+00	2.33E+10
OH	1.23E+12	4.10E+10	0.00E+00	2.95E+09	1.13E+10	1.42E+10	1.68E+11	5.49E+09	3.17E+09	0.00E+00	0.00E+00	1.06E+08
OK	3.81E+11	3.10E+11	0.00E+00	1.06E+08	0.00E+00	1.06E+08	0.00E+00	3.66E+10	0.00E+00	0.00E+00	0.00E+00	2.77E+10
OR	3.29E+10	1.17E+11	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	3.40E+11	5.49E+09	0.00E+00	0.00E+00	3.58E+10
PA	1.13E+12	2.29E+11	5.17E+09	3.59E+09	8.44E+08	9.71E+09	8.53E+11	2.76E+10	3.01E+10	0.00E+00	0.00E+00	1.11E+10
RI	0.00E+00	5.97E+10	0.00E+00	1.06E+08	0.00E+00	1.06E+08	0.00E+00	0.00E+00	1.90E+09	0.00E+00	0.00E+00	0.00E+00
SC	3.68E+11	8.13E+10	2.11E+08	1.06E+09	4.01E+09	5.38E+09	5.76E+11	2.39E+10	8.97E+09	0.00E+00	0.00E+00	0.00E+00
SD	3.71E+10	9.50E+08	0.00E+00	1.06E+08	0.00E+00	1.06E+08	0.00E+00	4.57E+10	1.06E+08	0.00E+00	0.00E+00	4.33E+09
TN	4.32E+11	4.01E+09	0.00E+00	2.11E+09	0.00E+00	2.11E+09	2.98E+11	1.05E+11	3.17E+08	0.00E+00	0.00E+00	5.28E+08
TX	1.56E+12	1.49E+12	0.00E+00	8.44E+08	1.62E+10	1.70E+10	4.58E+11	1.06E+10	4.64E+09	0.00E+00	0.00E+00	2.06E+11
UT	3.68E+11	5.47E+10	0.00E+00	4.22E+08	0.00E+00	4.22E+08	0.00E+00	8.65E+09	1.16E+09	2.85E+09	0.00E+00	1.69E+09
VA	2.83E+11	1.04E+11	4.96E+09	6.12E+09	0.00E+00	1.11E+10	3.11E+11	1.51E+10	1.66E+10	0.00E+00	0.00E+00	0.00E+00
VT	0.00E+00	1.06E+08	0.00E+00	0.00E+00	0.00E+00	0.00E+00	5.92E+10	1.51E+10	6.01E+09	0.00E+00	0.00E+00	1.06E+08
WA	8.49E+10	9.92E+10	0.00E+00	4.22E+08	0.00E+00	4.22E+08	7.32E+10	7.51E+11	8.23E+09	0.00E+00	0.00E+00	3.68E+10
WI	4.10E+11	4.39E+10	0.00E+00	5.28E+08	6.22E+09	6.75E+09	1.40E+11	1.32E+10	1.03E+10	0.00E+00	0.00E+00	1.09E+10

WV	7.34E+11	1.27E+09	0.00E+00	1.90E+09	0.00E+00	1.90E+09	0.00E+00	1.06E+10	0.00E+00	0.00E+00	0.00E+00	7.60E+09
WY	4.67E+11	1.16E+09	0.00E+00	5.28E+08	0.00E+00	5.28E+08	0.00E+00	9.92E+09	0.00E+00	0.00E+00	0.00E+00	2.29E+10
U.S. average	1.91E+13	7.43E+12	1.91E+11	7.40E+10	1.47E+11	4.11E+11	8.82E+12	2.80E+12	4.65E+11	1.55E+11	9.18E+09	7.61E+11
Source	[258]	[258]	[258]	[258]	[258]	[258]	[258]	[258]	[258]	[258]	[258]	[258]

Table 9.3: 2009 Fossil Fuel Consumption Rates for State Electric Power Generation, in Physical Units (excludes renewable sources as they are given in energy units)

State	Coal (kg)	Natural Gas (m^3)	Residual (Heavy) Fuel Oil (l)	Distillate (Light) Fuel Oil (l)	Petcoke (l)	Nuclear (kg)[8]
AK	3.96E+08	1.08E+09	1.02E+07	9.44E+07	0.00E+00	0.00E+00
AL	2.50E+10	6.43E+09	0.00E+00	2.81E+07	0.00E+00	1.32E+06
AR	1.36E+10	2.36E+09	1.22E+07	1.02E+07	0.00E+00	5.05E+05
AZ	1.88E+10	7.42E+09	0.00E+00	1.65E+07	0.00E+00	1.02E+06
CA	7.97E+08	2.29E+10	1.43E+06	1.84E+07	4.68E+08	1.06E+06
CO	1.57E+10	3.26E+09	0.00E+00	3.97E+06	0.00E+00	0.00E+00
CT	1.08E+09	2.01E+09	7.79E+07	7.95E+06	0.00E+00	5.54E+05
DC	0.00E+00	0.00E+00	0.00E+00	1.35E+07	0.00E+00	0.00E+00
DE	1.23E+09	3.11E+08	1.16E+07	1.81E+07	0.00E+00	0.00E+00
FL	2.13E+10	2.59E+10	1.51E+09	1.66E+08	8.22E+08	9.68E+05
GA	2.97E+10	4.03E+09	6.36E+05	3.02E+07	0.00E+00	1.05E+06
HI	7.17E+08	0.00E+00	1.70E+09	3.58E+08	0.00E+00	0.00E+00
IA	2.05E+10	2.84E+08	0.00E+00	2.04E+07	8.43E+06	1.56E+05
ID	0.00E+00	3.56E+08	0.00E+00	0.00E+00	0.00E+00	0.00E+00
IL	4.87E+10	9.41E+08	1.59E+05	3.61E+07	0.00E+00	3.18E+06
IN	4.94E+10	1.04E+09	0.00E+00	3.97E+07	2.86E+06	0.00E+00
KS	1.89E+10	9.07E+08	1.37E+07	4.26E+07	5.61E+07	2.92E+05
KY	3.56E+10	2.38E+08	0.00E+00	4.47E+07	5.97E+08	0.00E+00
LA	1.43E+10	6.30E+09	9.54E+06	1.21E+07	4.50E+08	5.58E+05

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[8] Calculated as per kg of uranium based on the thermal conversion factor for nuclear steam electric power plants, which is 10,460 Btu/kWh. Assumption: 13,638 kWh of electricity is generated per lbs of uranium fuel used in the U.S.

MA	3.53E+09	4.25E+09	1.92E+08	4.04E+07	0.00E+00	1.79E+05
MD	8.89E+09	5.11E+08	4.45E+07	5.58E+07	0.00E+00	4.84E+05
ME	3.08E+07	1.04E+09	7.81E+07	1.91E+06	0.00E+00	0.00E+00
MI	3.21E+10	2.37E+09	2.02E+07	4.09E+07	3.72E+07	7.27E+05
MN	1.57E+10	6.70E+08	7.95E+05	1.94E+07	0.00E+00	4.12E+05
MO	3.87E+10	8.44E+08	0.00E+00	2.46E+07	1.13E+07	3.41E+05
MS	7.64E+09	5.19E+09	1.91E+06	3.66E+06	0.00E+00	3.66E+05
MT	9.21E+09	1.86E+07	0.00E+00	2.70E+06	2.14E+08	0.00E+00
NC	2.40E+10	1.13E+09	0.00E+00	7.69E+07	0.00E+00	1.36E+06
ND	2.23E+10	2.83E+04	0.00E+00	1.27E+07	0.00E+00	0.00E+00
NE	1.29E+10	9.43E+07	1.59E+05	7.00E+06	0.00E+00	3.14E+05
NH	1.10E+09	1.08E+09	4.47E+07	3.66E+06	0.00E+00	2.93E+05
NJ	2.31E+09	4.65E+09	1.21E+07	9.38E+06	0.00E+00	1.14E+06
NM	1.50E+10	1.99E+09	0.00E+00	1.35E+07	0.00E+00	0.00E+00
NV	3.47E+09	5.44E+09	0.00E+00	5.09E+06	0.00E+00	0.00E+00
NY	5.54E+09	1.04E+10	5.18E+08	1.17E+08	4.75E+07	1.45E+06
OH	4.64E+10	1.07E+09	0.00E+00	7.69E+07	2.81E+08	5.06E+05
OK	1.90E+10	8.06E+09	0.00E+00	3.66E+06	0.00E+00	0.00E+00
OR	1.68E+09	3.08E+09	0.00E+00	9.54E+05	0.00E+00	0.00E+00
PA	4.43E+10	5.96E+09	1.23E+08	9.41E+07	2.23E+07	2.57E+06
RI	0.00E+00	1.57E+09	0.00E+00	3.66E+06	0.00E+00	0.00E+00
SC	1.28E+10	2.10E+09	5.56E+06	2.85E+07	1.00E+08	1.73E+06
SD	1.91E+09	2.60E+07	0.00E+00	3.82E+06	0.00E+00	0.00E+00
TN	1.77E+10	1.04E+08	0.00E+00	5.53E+07	0.00E+00	8.97E+05
TX	8.66E+10	3.93E+10	0.00E+00	2.15E+07	4.05E+08	1.38E+06
UT	1.44E+10	1.42E+09	0.00E+00	1.00E+07	0.00E+00	0.00E+00
VA	9.80E+09	2.69E+09	1.19E+08	1.59E+08	0.00E+00	9.38E+05
VT	0.00E+00	1.81E+06	1.59E+05	4.77E+05	0.00E+00	1.78E+05
WA	4.51E+09	2.59E+09	0.00E+00	1.13E+07	0.00E+00	2.21E+05
WI	2.01E+10	1.16E+09	0.00E+00	1.49E+07	1.55E+08	4.22E+05
WV	2.65E+10	3.14E+07	0.00E+00	4.83E+07	0.00E+00	0.00E+00

WY	2.31E+10	3.06E+07	0.00E+00	1.45E+07	0.00E+00	0.00E+00
U.S. average	8.47E+11	1.95E+11	4.61E+09	1.91E+09	3.66E+09	2.66E+07
Source	[194]	[369]	[258]	[258]	[258]	Calculated [258]

Table 9.4: Calculated Energy Source Consumption Factors per kWh of Electricity by State, by Energy Source

State	**Coal (kg/kWh)**	**Natural Gas (m^3/kWh)**	**Residual Fuel Oil (l/kWh)**	**Distillate (Light) Fuel Oil (l/kWh)**	**Petcoke (l/kWh)**	**Nuclear (kg/kWh)**	**Hydro electric (kWh/kWh)**	**Biomass (kg/kWh)**	**Geothermal (kWh/kWh)**	**Solar (kWh/kWh)**	**Wind (kWh/kWh)**
AK	5.92E-02	1.61E-01	1.52E-03	1.41E-02	0.00E+00	0.00E+00	1.98E-01	0.00E+00	0.00E+00	0.00E+00	1.05E-03
AL	1.75E-01	4.49E-02	0.00E+00	1.96E-04	0.00E+00	9.22E-06	8.75E-02	3.13E-03	0.00E+00	0.00E+00	0.00E+00
AR	2.37E-01	4.10E-02	2.13E-04	1.77E-04	0.00E+00	8.78E-06	7.30E-02	7.97E-04	0.00E+00	0.00E+00	0.00E+00
AZ	1.68E-01	6.62E-02	0.00E+00	1.48E-04	0.00E+00	9.11E-06	5.74E-02	1.39E-03	0.00E+00	1.26E-04	2.64E-04
CA	3.89E-03	1.12E-01	6.99E-06	9.01E-05	2.28E-03	5.16E-06	1.36E-01	3.46E-02	6.28E-02	3.16E-03	2.85E-02
CO	3.11E-01	6.45E-02	0.00E+00	7.86E-05	0.00E+00	0.00E+00	3.73E-02	1.45E-03	0.00E+00	5.06E-04	6.26E-02
CT	3.48E-02	6.43E-02	2.50E-03	2.55E-04	0.00E+00	1.78E-05	1.63E-02	3.96E-02	0.00E+00	0.00E+00	0.00E+00
DC	0.00E+00	0.00E+00	0.00E+00	3.81E-01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
DE	2.53E-01	6.43E-02	2.40E-03	3.74E-03	0.00E+00	0.00E+00	0.00E+00	3.03E-02	0.00E+00	0.00E+00	0.00E+00
FL	9.77E-02	1.19E-01	6.94E-03	7.61E-04	3.77E-03	4.44E-06	9.55E-04	2.25E-02	0.00E+00	4.34E-05	0.00E+00
GA	2.31E-01	3.13E-02	4.94E-06	2.35E-04	0.00E+00	8.19E-06	2.53E-02	2.85E-04	0.00E+00	0.00E+00	0.00E+00
HI	6.51E-02	0.00E+00	1.55E-01	3.25E-02	0.00E+00	0.00E+00	1.02E-02	2.83E-02	1.52E-02	1.26E-04	2.28E-02
IA	3.95E-01	5.47E-03	0.00E+00	3.92E-04	1.62E-04	3.00E-06	1.87E-02	2.65E-03	0.00E+00	0.00E+00	1.43E-01
ID	0.00E+00	2.72E-02	0.00E+00	0.00E+00	0.00E+00	0.00E+00	7.96E-01	1.05E-02	5.80E-03	0.00E+00	2.39E-02
IL	2.51E-01	4.85E-03	8.20E-07	1.86E-04	0.00E+00	1.64E-05	7.03E-04	4.44E-03	0.00E+00	8.25E-08	1.45E-02
IN	4.23E-01	8.88E-03	0.00E+00	3.41E-04	2.45E-05	0.00E+00	4.32E-03	2.35E-03	0.00E+00	0.00E+00	1.20E-02
KS	4.04E-01	1.94E-02	2.93E-04	9.13E-04	1.20E-03	6.25E-06	2.74E-04	0.00E+00	0.00E+00	0.00E+00	6.13E-02
KY	3.93E-01	2.62E-03	0.00E+00	4.93E-04	6.59E-03	0.00E+00	3.66E-02	8.08E-04	0.00E+00	0.00E+00	0.00E+00
LA	1.57E-01	6.92E-02	1.05E-04	1.33E-04	4.95E-03	6.13E-06	1.36E-02	1.11E-03	0.00E+00	0.00E+00	0.00E+00
MA	9.06E-02	1.09E-01	4.93E-03	1.04E-03	0.00E+00	4.61E-06	3.08E-02	4.91E-02	0.00E+00	1.10E-06	1.53E-04
MD	2.03E-01	1.17E-02	1.02E-03	1.27E-03	0.00E+00	1.11E-05	4.31E-02	1.55E-02	0.00E+00	0.00E+00	0.00E+00
ME	1.89E-03	6.36E-02	4.77E-03	1.17E-04	0.00E+00	0.00E+00	2.58E-01	1.69E-01	0.00E+00	0.00E+00	1.83E-02

MI	3.17E-01	2.34E-02	2.00E-04	4.04E-04	3.68E-04	7.18E-06	1.36E-02	1.99E-02	0.00E+00	0.00E+00	2.97E-03
MN	3.00E-01	1.28E-02	1.51E-05	3.70E-04	0.00E+00	7.85E-06	1.54E-02	3.64E-02	0.00E+00	0.00E+00	9.63E-02
MO	4.38E-01	9.55E-03	0.00E+00	2.79E-04	1.28E-04	3.86E-06	2.06E-02	8.29E-04	0.00E+00	0.00E+00	5.65E-03
MS	1.57E-01	1.07E-01	3.92E-05	7.51E-05	0.00E+00	7.51E-06	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
MT	3.45E-01	6.95E-04	0.00E+00	1.01E-04	8.02E-03	0.00E+00	3.56E-01	0.00E+00	0.00E+00	0.00E+00	3.07E-02
NC	2.02E-01	9.55E-03	0.00E+00	6.50E-04	0.00E+00	1.15E-05	4.37E-02	8.50E-03	0.00E+00	3.85E-05	0.00E+00
ND	6.52E-01	8.28E-07	0.00E+00	3.72E-04	0.00E+00	0.00E+00	4.31E-02	0.00E+00	0.00E+00	0.00E+00	8.77E-02
NE	3.78E-01	2.77E-03	4.68E-06	2.06E-04	0.00E+00	9.23E-06	1.28E-02	1.62E-03	0.00E+00	0.00E+00	1.13E-02
NH	5.43E-02	5.35E-02	2.22E-03	1.81E-04	0.00E+00	1.45E-05	8.33E-02	7.85E-02	0.00E+00	0.00E+00	3.10E-03
NJ	3.73E-02	7.52E-02	1.95E-04	1.52E-04	0.00E+00	1.85E-05	5.19E-04	1.58E-02	0.00E+00	1.73E-04	3.38E-04
NM	3.78E-01	5.00E-02	0.00E+00	3.41E-04	0.00E+00	0.00E+00	6.83E-03	1.15E-03	0.00E+00	0.00E+00	3.90E-02
NV	9.20E-02	1.44E-01	0.00E+00	1.35E-04	0.00E+00	0.00E+00	6.53E-02	0.00E+00	4.33E-02	4.62E-03	0.00E+00
NY	4.16E-02	7.82E-02	3.89E-03	8.79E-04	3.57E-04	1.09E-05	2.07E-01	2.17E-02	0.00E+00	0.00E+00	1.70E-02
OH	3.41E-01	7.84E-03	0.00E+00	5.65E-04	2.07E-03	3.72E-06	3.88E-03	2.02E-03	0.00E+00	0.00E+00	1.04E-04
OK	2.53E-01	1.07E-01	0.00E+00	4.87E-05	0.00E+00	0.00E+00	4.73E-02	0.00E+00	0.00E+00	0.00E+00	3.59E-02
OR	2.97E-02	5.43E-02	0.00E+00	1.68E-05	0.00E+00	0.00E+00	5.83E-01	8.40E-03	0.00E+00	0.00E+00	6.12E-02
PA	2.02E-01	2.72E-02	5.62E-04	4.29E-04	1.01E-04	1.17E-05	1.22E-02	1.19E-02	0.00E+00	1.62E-05	4.90E-03
RI	0.00E+00	2.04E-01	0.00E+00	4.75E-04	0.00E+00	0.00E+00	6.15E-04	2.14E-02	0.00E+00	0.00E+00	0.00E+00
SC	1.27E-01	2.10E-02	5.56E-05	2.84E-04	9.99E-04	1.73E-05	2.33E-02	7.77E-03	0.00E+00	0.00E+00	0.00E+00
SD	2.33E-01	3.17E-03	0.00E+00	4.66E-04	0.00E+00	0.00E+00	5.41E-01	1.12E-03	0.00E+00	0.00E+00	5.14E-02
TN	2.21E-01	1.30E-03	0.00E+00	6.94E-04	0.00E+00	1.12E-05	1.28E-01	3.45E-04	0.00E+00	0.00E+00	6.49E-04
TX	2.18E-01	9.89E-02	0.00E+00	5.40E-05	1.02E-03	3.48E-06	2.59E-03	1.01E-03	0.00E+00	0.00E+00	5.04E-02
UT	3.32E-01	3.25E-02	0.00E+00	2.30E-04	0.00E+00	0.00E+00	1.92E-02	2.31E-03	6.41E-03	0.00E+00	3.66E-03
VA	1.40E-01	3.83E-02	1.69E-03	2.26E-03	0.00E+00	1.34E-05	2.12E-02	2.05E-02	0.00E+00	0.00E+00	1.65E-04
VT	0.00E+00	2.49E-04	2.18E-05	6.55E-05	0.00E+00	2.45E-05	2.03E-01	7.17E-02	0.00E+00	0.00E+00	0.00E+00
WA	4.32E-02	2.47E-02	0.00E+00	1.08E-04	0.00E+00	2.11E-06	6.98E-01	6.83E-03	0.00E+00	0.00E+00	3.42E-02
WI	3.36E-01	1.94E-02	0.00E+00	2.49E-04	2.58E-03	7.04E-06	2.32E-02	1.50E-02	0.00E+00	0.00E+00	1.75E-02
WV	3.75E-01	4.44E-04	0.00E+00	6.83E-04	0.00E+00	0.00E+00	2.33E-02	0.00E+00	0.00E+00	0.00E+00	1.05E-02
WY	5.03E-01	6.64E-04	0.00E+00	3.14E-04	0.00E+00	0.00E+00	2.10E-02	0.00E+00	0.00E+00	0.00E+00	4.84E-02
U.S. Average	2.14E-01	4.93E-02	1.17E-03	4.83E-04	9.26E-04	6.73E-06	6.92E-02	1.02E-02	3.80E-03	2.26E-04	1.87E-02

Table 9.5: 2009 Fuel Heat Contents for the U.S. Electric Power Generation

State	Coal (MJ/kg)	Natural Gas (MJ/m^3)	Residual (Heavy) Fuel Oil (MJ/l)	Distillate (Light) Fuel Oil (MJ/l)	Petcoke (MJ/l)	Nuclear (MJ/kg)	Hydro Electric (MJ/kWh)	Biomass (MJ/kg)	Geo thermal (MJ/kWh)	Solar (MJ/kWh)	Wind (MJ/kWh)
AK	1.98E+01	3.75E+01	3.92E+01	3.79E+01	3.78E+01	3.32E+05	1.03E+01	1.24E+01	2.22E+01	1.04E+01	1.04E+01
AL	2.44E+01	3.82E+01	4.19E+01	3.81E+01	3.78E+01	3.32E+05	1.03E+01	1.24E+01	2.22E+01	1.04E+01	1.04E+01
AR	2.02E+01	3.82E+01	4.21E+01	3.89E+01	3.78E+01	3.32E+05	1.03E+01	1.24E+01	2.22E+01	1.04E+01	1.04E+01
AZ	2.26E+01	3.81E+01	4.19E+01	3.79E+01	3.78E+01	3.32E+05	1.03E+01	1.24E+01	2.22E+01	1.04E+01	1.04E+01
CA	2.76E+01	3.83E+01	4.29E+01	3.86E+01	3.82E+01	3.32E+05	1.03E+01	1.24E+01	2.22E+01	1.04E+01	1.04E+01
CO	2.28E+01	3.85E+01	4.19E+01	3.72E+01	3.78E+01	3.32E+05	1.03E+01	1.24E+01	2.22E+01	1.04E+01	1.04E+01
CT	2.57E+01	3.77E+01	4.14E+01	3.84E+01	3.78E+01	3.32E+05	1.03E+01	1.24E+01	2.22E+01	1.04E+01	1.04E+01
DC	0.00E+00	0.00E+00	4.19E+01	3.82E+01	3.78E+01	3.32E+05	1.03E+01	1.24E+01	2.22E+01	1.04E+01	1.04E+01
DE	2.92E+01	3.82E+01	4.19E+01	3.84E+01	3.78E+01	3.32E+05	1.03E+01	1.24E+01	2.22E+01	1.04E+01	1.04E+01
FL	2.78E+01	3.82E+01	4.26E+01	3.86E+01	3.77E+01	3.32E+05	1.03E+01	1.24E+01	2.22E+01	1.04E+01	1.04E+01
GA	2.54E+01	3.86E+01	4.14E+01	3.82E+01	3.78E+01	3.32E+05	1.03E+01	1.24E+01	2.22E+01	1.04E+01	1.04E+01
HI	2.47E+01	0.00E+00	4.13E+01	3.85E+01	3.78E+01	3.32E+05	1.03E+01	1.24E+01	2.22E+01	1.04E+01	1.04E+01
IA	2.01E+01	3.76E+01	4.19E+01	3.84E+01	3.74E+01	3.32E+05	1.03E+01	1.24E+01	2.22E+01	1.04E+01	1.04E+01
ID	2.55E+01	3.78E+01	4.19E+01	3.84E+01	3.78E+01	3.32E+05	1.03E+01	1.24E+01	2.22E+01	1.04E+01	1.04E+01
IL	2.06E+01	3.80E+01	4.19E+01	3.82E+01	3.78E+01	3.32E+05	1.03E+01	1.24E+01	2.22E+01	1.04E+01	1.04E+01
IN	2.44E+01	3.77E+01	4.17E+01	3.83E+01	3.80E+01	3.32E+05	1.03E+01	1.24E+01	2.22E+01	1.04E+01	1.04E+01
KS	1.98E+01	3.78E+01	4.19E+01	3.84E+01	3.83E+01	3.32E+05	1.03E+01	1.24E+01	2.22E+01	1.04E+01	1.04E+01
KY	2.67E+01	3.82E+01	4.19E+01	3.86E+01	3.75E+01	3.32E+05	1.03E+01	1.24E+01	2.22E+01	1.04E+01	1.04E+01
LA	1.91E+01	3.84E+01	4.24E+01	3.88E+01	3.81E+01	3.32E+05	1.03E+01	1.24E+01	2.22E+01	1.04E+01	1.04E+01
MA	2.73E+01	3.85E+01	4.19E+01	3.85E+01	3.78E+01	3.32E+05	1.03E+01	1.24E+01	2.22E+01	1.04E+01	1.04E+01
MD	2.91E+01	3.90E+01	4.23E+01	3.86E+01	3.78E+01	3.32E+05	1.03E+01	1.24E+01	2.22E+01	1.04E+01	1.04E+01
ME	2.97E+01	3.91E+01	4.19E+01	3.89E+01	3.78E+01	3.32E+05	1.03E+01	1.24E+01	2.22E+01	1.04E+01	1.04E+01
MI	2.27E+01	3.78E+01	4.22E+01	3.84E+01	3.73E+01	3.32E+05	1.03E+01	1.24E+01	2.22E+01	1.04E+01	1.04E+01
MN	2.07E+01	3.77E+01	4.19E+01	3.82E+01	3.78E+01	3.32E+05	1.03E+01	1.24E+01	2.22E+01	1.04E+01	1.04E+01
MO	2.05E+01	3.79E+01	4.19E+01	3.84E+01	3.86E+01	3.32E+05	1.03E+01	1.24E+01	2.22E+01	1.04E+01	1.04E+01
MS	1.99E+01	3.78E+01	4.35E+01	3.89E+01	3.78E+01	3.32E+05	1.03E+01	1.24E+01	2.22E+01	1.04E+01	1.04E+01

MT	1.96E+01	3.79E+01	4.19E+01	3.92E+01	3.89E+01	3.32E+05	1.03E+01	1.24E+01	2.22E+01	1.04E+01	1.04E+01
NC	2.87E+01	3.75E+01	4.23E+01	3.86E+01	3.78E+01	3.32E+05	1.03E+01	1.24E+01	2.22E+01	1.04E+01	1.04E+01
ND	1.55E+01	3.87E+01	4.19E+01	3.88E+01	3.78E+01	3.32E+05	1.03E+01	1.24E+01	2.22E+01	1.04E+01	1.04E+01
NE	1.99E+01	3.72E+01	3.98E+01	3.88E+01	3.78E+01	3.32E+05	1.03E+01	1.24E+01	2.22E+01	1.04E+01	1.04E+01
NH	2.99E+01	3.86E+01	4.27E+01	3.88E+01	3.78E+01	3.32E+05	1.03E+01	1.24E+01	2.22E+01	1.04E+01	1.04E+01
NJ	2.67E+01	3.83E+01	4.15E+01	3.82E+01	3.78E+01	3.32E+05	1.03E+01	1.24E+01	2.22E+01	1.04E+01	1.04E+01
NM	2.15E+01	3.83E+01	4.19E+01	3.74E+01	3.78E+01	3.32E+05	1.03E+01	1.24E+01	2.22E+01	1.04E+01	1.04E+01
NV	2.44E+01	3.84E+01	4.19E+01	3.86E+01	3.78E+01	3.32E+05	1.03E+01	1.24E+01	2.22E+01	1.04E+01	1.04E+01
NY	2.60E+01	3.80E+01	4.19E+01	3.88E+01	3.72E+01	3.32E+05	1.03E+01	1.24E+01	2.22E+01	1.04E+01	1.04E+01
OH	2.74E+01	3.85E+01	4.19E+01	3.84E+01	3.76E+01	3.32E+05	1.03E+01	1.24E+01	2.22E+01	1.04E+01	1.04E+01
OK	2.02E+01	3.85E+01	4.17E+01	3.92E+01	3.99E+01	3.32E+05	1.03E+01	1.24E+01	2.22E+01	1.04E+01	1.04E+01
OR	1.96E+01	3.81E+01	4.19E+01	3.85E+01	3.78E+01	3.32E+05	1.03E+01	1.24E+01	2.22E+01	1.04E+01	1.04E+01
PA	2.54E+01	3.83E+01	4.21E+01	3.85E+01	3.43E+01	3.32E+05	1.03E+01	1.24E+01	2.22E+01	1.04E+01	1.04E+01
RI	0.00E+00	3.81E+01	4.19E+01	3.84E+01	3.78E+01	3.32E+05	1.03E+01	1.24E+01	2.22E+01	1.04E+01	1.04E+01
SC	2.90E+01	3.87E+01	4.18E+01	3.86E+01	4.07E+01	3.32E+05	1.03E+01	1.24E+01	2.22E+01	1.04E+01	1.04E+01
SD	1.95E+01	3.71E+01	4.19E+01	3.84E+01	3.78E+01	3.32E+05	1.03E+01	1.24E+01	2.22E+01	1.04E+01	1.04E+01
TN	2.57E+01	3.83E+01	4.19E+01	3.76E+01	3.78E+01	3.32E+05	1.03E+01	1.24E+01	2.22E+01	1.04E+01	1.04E+01
TX	1.81E+01	3.80E+01	4.19E+01	3.84E+01	3.80E+01	3.32E+05	1.03E+01	1.24E+01	2.22E+01	1.04E+01	1.04E+01
UT	2.55E+01	3.86E+01	4.19E+01	3.84E+01	3.78E+01	3.32E+05	1.03E+01	1.24E+01	2.22E+01	1.04E+01	1.04E+01
VA	0.00E+00	3.74E+01	4.19E+01	3.84E+01	3.78E+01	3.32E+05	1.03E+01	1.24E+01	2.22E+01	1.04E+01	1.04E+01
VT	2.91E+01	3.87E+01	4.24E+01	3.84E+01	3.78E+01	3.32E+05	1.03E+01	1.24E+01	2.22E+01	1.04E+01	1.04E+01
WA	1.95E+01	3.84E+01	4.19E+01	3.93E+01	3.78E+01	3.32E+05	1.03E+01	1.24E+01	2.22E+01	1.04E+01	1.04E+01
WI	2.07E+01	3.78E+01	4.19E+01	3.87E+01	3.72E+01	3.32E+05	1.03E+01	1.24E+01	2.22E+01	1.04E+01	1.04E+01
WV	2.78E+01	3.91E+01	4.19E+01	3.87E+01	3.78E+01	3.32E+05	1.03E+01	1.24E+01	2.22E+01	1.04E+01	1.04E+01
WY	2.04E+01	3.68E+01	4.19E+01	3.87E+01	3.78E+01	3.32E+05	1.03E+01	1.24E+01	2.22E+01	1.04E+01	1.04E+01
U.S. Average	2.30E+01	3.82E+01	4.19E+01	3.84E+01	3.78E+01	3.32E+05	1.03E+01	1.24E+01	2.22E+01	1.04E+01	1.04E+01
Source	[260]	[258]	[260]	[260]	[260]	[258]	[259]	[261]	[221]	[221]	[221]

Table 9.6: 2009 State Fuel Heat Content Conversion Factors Used in Direct Energy Use Calculations Associated with Electric Power Generation (in units of MJ/kWh and calculated by multiplication of factors in Table 9.4 and Table 8.5)

State	Coal	Natural Gas	Residual (Heavy) Fuel Oil	Distillate (Light) Fuel Oil	Petcoke	Petroleum, Total	Nuclear	Hydro electric	Biomass	Geo thermal	Solar	Total
AK	1.17E+00	6.03E+00	5.94E-02	5.34E-01	0.00E+00	0.00E+00	2.03E+00	0.00E+00	0.00E+00	0.00E+00	1.09E-02	9.84E+00
AL	4.27E+00	1.71E+00	0.00E+00	7.49E-03	0.00E+00	3.06E+00	9.01E-01	3.61E-02	0.00E+00	0.00E+00	0.00E+00	9.99E+00
AR	4.79E+00	1.57E+00	8.96E-03	6.88E-03	0.00E+00	2.91E+00	7.51E-01	9.18E-03	0.00E+00	0.00E+00	0.00E+00	1.00E+01
AZ	3.80E+00	2.52E+00	0.00E+00	5.60E-03	0.00E+00	3.02E+00	5.91E-01	1.60E-02	0.00E+00	1.32E-03	2.75E-03	9.96E+00
CA	1.07E-01	4.28E+00	3.00E-04	3.48E-03	8.72E-02	1.71E+00	1.40E+00	3.99E-01	1.39E+00	3.30E-02	2.97E-01	9.71E+00
CO	7.10E+00	2.49E+00	0.00E+00	2.92E-03	0.00E+00	0.00E+00	3.84E-01	1.67E-02	0.00E+00	5.28E-03	6.52E-01	1.07E+01
CT	8.93E-01	2.42E+00	1.03E-01	9.78E-03	0.00E+00	5.89E+00	1.68E-01	4.56E-01	0.00E+00	0.00E+00	0.00E+00	9.95E+00
DC	0.00E+00	0.00E+00	0.00E+00	1.45E+01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.45E+01
DE	7.41E+00	2.45E+00	1.00E-01	1.44E-01	0.00E+00	0.00E+00	0.00E+00	3.49E-01	0.00E+00	0.00E+00	0.00E+00	1.05E+01
FL	2.72E+00	4.53E+00	2.96E-01	2.94E-02	1.42E-01	1.47E+00	9.84E-03	2.59E-01	0.00E+00	4.53E-04	0.00E+00	9.46E+00
GA	5.88E+00	1.21E+00	2.04E-04	8.96E-03	0.00E+00	2.72E+00	2.61E-01	3.28E-03	0.00E+00	0.00E+00	0.00E+00	1.01E+01
HI	1.61E+00	0.00E+00	6.38E+00	1.25E+00	0.00E+00	0.00E+00	1.05E-01	3.26E-01	3.38E-01	1.32E-03	2.38E-01	1.03E+01
IA	7.96E+00	2.05E-01	0.00E+00	1.51E-02	6.07E-03	9.96E-01	1.93E-01	3.05E-02	0.00E+00	0.00E+00	1.49E+00	1.09E+01
ID	0.00E+00	1.03E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	8.20E+00	1.21E-01	1.29E-01	0.00E+00	2.49E-01	9.73E+00
IL	5.19E+00	1.84E-01	3.43E-05	7.12E-03	0.00E+00	5.43E+00	7.24E-03	5.12E-02	0.00E+00	8.61E-07	1.52E-01	1.10E+01
IN	1.03E+01	3.35E-01	0.00E+00	1.30E-02	9.32E-04	0.00E+00	4.44E-02	2.71E-02	0.00E+00	0.00E+00	1.25E-01	1.09E+01
KS	8.01E+00	7.34E-01	1.23E-02	3.51E-02	4.61E-02	2.07E+00	2.82E-03	0.00E+00	0.00E+00	0.00E+00	6.40E-01	1.16E+01
KY	1.05E+01	1.00E-01	0.00E+00	1.91E-02	2.47E-01	0.00E+00	3.77E-01	9.31E-03	0.00E+00	0.00E+00	0.00E+00	1.12E+01
LA	2.99E+00	2.66E+00	4.45E-03	5.15E-03	1.88E-01	2.04E+00	1.40E-01	1.28E-02	0.00E+00	0.00E+00	0.00E+00	8.03E+00
MA	2.47E+00	4.21E+00	2.06E-01	3.99E-02	0.00E+00	1.53E+00	3.17E-01	5.66E-01	0.00E+00	1.15E-05	1.59E-03	9.34E+00
MD	5.91E+00	4.56E-01	4.30E-02	4.93E-02	0.00E+00	3.67E+00	4.44E-01	1.78E-01	0.00E+00	0.00E+00	0.00E+00	1.08E+01
ME	5.61E-02	2.49E+00	2.00E-01	4.54E-03	0.00E+00	0.00E+00	2.65E+00	1.95E+00	0.00E+00	0.00E+00	1.90E-01	7.54E+00
MI	7.18E+00	8.87E-01	8.43E-03	1.55E-02	1.37E-02	2.38E+00	1.40E-01	2.29E-01	0.00E+00	0.00E+00	3.09E-02	1.09E+01
MN	6.19E+00	4.81E-01	6.34E-04	1.41E-02	0.00E+00	2.61E+00	1.59E-01	4.20E-01	0.00E+00	0.00E+00	1.00E+00	1.09E+01
MO	8.97E+00	3.62E-01	0.00E+00	1.07E-02	4.93E-03	1.28E+00	2.12E-01	9.55E-03	0.00E+00	0.00E+00	5.89E-02	1.09E+01
MS	3.12E+00	4.03E+00	1.70E-03	2.92E-03	0.00E+00	2.49E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	9.65E+00

MT	6.74E+00	2.64E-02	0.00E+00	3.96E-03	3.12E-01	0.00E+00	3.66E+00	0.00E+00	0.00E+00	0.00E+00	3.20E-01	1.11E+01
NC	5.81E+00	3.58E-01	0.00E+00	2.51E-02	0.00E+00	3.81E+00	4.50E-01	9.80E-02	0.00E+00	4.02E-04	0.00E+00	1.05E+01
ND	1.01E+01	3.20E-05	0.00E+00	1.44E-02	0.00E+00	0.00E+00	4.44E-01	0.00E+00	0.00E+00	0.00E+00	9.14E-01	1.15E+01
NE	7.52E+00	1.03E-01	1.86E-04	7.99E-03	0.00E+00	3.06E+00	1.31E-01	1.86E-02	0.00E+00	0.00E+00	1.17E-01	1.10E+01
NH	1.62E+00	2.06E+00	9.45E-02	7.04E-03	0.00E+00	4.83E+00	8.58E-01	9.05E-01	0.00E+00	0.00E+00	3.23E-02	1.04E+01
NJ	9.97E-01	2.88E+00	8.11E-03	5.80E-03	0.00E+00	6.13E+00	5.34E-03	1.83E-01	0.00E+00	1.81E-03	3.53E-03	1.02E+01
NM	8.10E+00	1.92E+00	0.00E+00	1.27E-02	0.00E+00	0.00E+00	7.03E-02	1.33E-02	0.00E+00	0.00E+00	4.07E-01	1.05E+01
NV	2.25E+00	5.54E+00	0.00E+00	5.20E-03	0.00E+00	0.00E+00	6.72E-01	0.00E+00	9.60E-01	4.82E-02	0.00E+00	9.48E+00
NY	1.08E+00	2.97E+00	1.63E-01	3.41E-02	1.33E-02	3.60E+00	2.14E+00	2.50E-01	0.00E+00	0.00E+00	1.77E-01	1.04E+01
OH	9.32E+00	3.02E-01	0.00E+00	2.17E-02	7.78E-02	1.23E+00	3.99E-02	2.33E-02	0.00E+00	0.00E+00	1.08E-03	1.10E+01
OK	5.11E+00	4.13E+00	0.00E+00	1.91E-03	0.00E+00	0.00E+00	4.87E-01	0.00E+00	0.00E+00	0.00E+00	3.75E-01	1.01E+01
OR	5.81E-01	2.07E+00	0.00E+00	6.48E-04	0.00E+00	0.00E+00	6.00E+00	9.68E-02	0.00E+00	0.00E+00	6.38E-01	9.38E+00
PA	5.14E+00	1.04E+00	2.37E-02	1.65E-02	3.48E-03	3.89E+00	1.26E-01	1.37E-01	0.00E+00	1.69E-04	5.11E-02	1.04E+01
RI	0.00E+00	7.76E+00	0.00E+00	1.83E-02	0.00E+00	0.00E+00	6.34E-03	2.47E-01	0.00E+00	0.00E+00	0.00E+00	8.03E+00
SC	3.70E+00	8.13E-01	2.32E-03	1.10E-02	4.06E-02	5.75E+00	2.40E-01	8.96E-02	0.00E+00	0.00E+00	0.00E+00	1.06E+01
SD	4.55E+00	1.18E-01	0.00E+00	1.79E-02	0.00E+00	0.00E+00	5.57E+00	1.29E-02	0.00E+00	0.00E+00	5.36E-01	1.08E+01
TN	5.70E+00	5.00E-02	0.00E+00	2.61E-02	0.00E+00	3.73E+00	1.32E+00	3.97E-03	0.00E+00	0.00E+00	6.77E-03	1.08E+01
TX	3.95E+00	3.76E+00	0.00E+00	2.08E-03	3.87E-02	1.15E+00	2.67E-02	1.17E-02	0.00E+00	0.00E+00	5.26E-01	9.47E+00
UT	8.46E+00	1.25E+00	0.00E+00	8.84E-03	0.00E+00	0.00E+00	1.98E-01	2.67E-02	1.42E-01	0.00E+00	3.82E-02	1.01E+01
VA	0.00E+00	1.43E+00	7.09E-02	8.70E-02	0.00E+00	4.44E+00	2.18E-01	2.36E-01	0.00E+00	0.00E+00	1.72E-03	6.49E+00
VT	0.00E+00	9.62E-03	9.25E-04	2.51E-03	0.00E+00	8.12E+00	2.09E+00	8.26E-01	0.00E+00	0.00E+00	0.00E+00	1.11E+01
WA	8.44E-01	9.49E-01	0.00E+00	4.24E-03	0.00E+00	7.01E-01	7.19E+00	7.88E-02	0.00E+00	0.00E+00	3.57E-01	1.01E+01
WI	6.97E+00	7.32E-01	0.00E+00	9.63E-03	9.60E-02	2.33E+00	2.39E-01	1.72E-01	0.00E+00	0.00E+00	1.83E-01	1.07E+01
WV	1.04E+01	1.74E-02	0.00E+00	2.64E-02	0.00E+00	0.00E+00	2.39E-01	0.00E+00	0.00E+00	0.00E+00	1.09E-01	1.08E+01
WY	1.03E+01	2.44E-02	0.00E+00	1.22E-02	0.00E+00	0.00E+00	2.16E-01	0.00E+00	0.00E+00	0.00E+00	5.04E-01	1.10E+01
U.S. Average	4.94E+00	1.88E+00	4.89E-02	1.86E-02	3.50E-02	2.23E+00	7.13E-01	1.18E-01	8.42E-02	2.35E-03	1.95E-01	1.03E+01

Table 9.7: Direct LCI emission factors of GHG, NO_x, and SO_2 emissions associated with the States and the U.S. average electricity generation based on e-GRID [255]

U.S. States	**NOx (kg/kWh)**	**SO_2 (kg/kWh)**	**CO_2 (kg/kWh)**	**CH_4 (kg/kWh)**	**N_2O (kg/kWh)**
AK	1.59E-03	5.25E-04	5.11E-01	1.20E-05	3.17E-06
AL	3.36E-04	1.79E-03	4.72E-01	8.56E-06	7.18E-06
AR	5.64E-04	1.14E-03	5.05E-01	8.91E-06	7.89E-06
AZ	5.39E-04	2.95E-04	4.92E-01	7.02E-06	6.47E-06
CA	9.08E-05	6.39E-05	2.52E-01	1.41E-05	2.03E-06
CO	1.15E-03	8.64E-04	7.88E-01	9.85E-06	1.14E-05
CT	1.65E-04	1.71E-04	2.62E-01	2.81E-05	4.77E-06
DC	2.08E-03	8.42E-03	1.13E+00	4.84E-05	9.68E-06
DE	9.29E-04	3.26E-03	8.14E-01	1.19E-05	1.06E-05
FL	4.64E-04	9.95E-04	5.41E-01	1.78E-05	6.34E-06
GA	4.32E-04	1.95E-03	5.83E-01	8.68E-06	9.32E-06
HI	1.50E-03	2.23E-03	6.93E-01	4.25E-05	8.95E-06
IA	7.36E-04	1.70E-03	7.37E-01	8.39E-06	1.21E-05
ID	5.06E-05	7.68E-05	5.43E-02	4.86E-06	9.35E-07
IL	3.44E-04	1.12E-03	4.84E-01	5.54E-06	7.88E-06
IN	8.87E-04	3.25E-03	9.22E-01	1.08E-05	1.53E-05
KS	9.57E-04	1.00E-03	7.59E-01	8.75E-06	1.21E-05
KY	7.91E-04	2.53E-03	9.28E-01	1.07E-05	1.57E-05
LA	5.48E-04	8.59E-04	5.12E-01	1.02E-05	5.55E-06
MA	3.64E-04	9.34E-04	5.05E-01	3.34E-05	7.63E-06
MD	4.08E-04	4.23E-03	5.59E-01	1.39E-05	9.83E-06
ME	2.60E-04	2.86E-04	2.27E-01	6.75E-05	9.59E-06
MI	7.76E-04	2.54E-03	6.91E-01	1.38E-05	1.18E-05
MN	7.65E-04	9.60E-04	6.34E-01	2.19E-05	1.20E-05
MO	5.84E-04	2.60E-03	8.20E-01	9.26E-06	1.34E-05
MS	5.15E-04	7.96E-04	5.00E-01	9.46E-06	5.90E-06
MT	7.40E-04	1.17E-03	6.53E-01	7.75E-06	1.09E-05
NC	3.30E-04	8.94E-04	5.25E-01	8.03E-06	8.92E-06
ND	1.67E-03	3.48E-03	9.33E-01	1.01E-05	1.50E-05
NE	1.23E-03	1.99E-03	7.25E-01	8.08E-06	1.20E-05
NH	2.18E-04	1.57E-03	2.72E-01	3.25E-05	6.55E-06
NJ	1.46E-04	2.16E-04	2.49E-01	1.03E-05	2.62E-06
NM	1.53E-03	4.41E-04	8.26E-01	1.01E-05	1.24E-05
NV	3.74E-04	1.95E-04	4.81E-01	7.72E-06	3.92E-06
NY	1.92E-04	3.42E-04	2.64E-01	1.09E-05	2.79E-06
OH	6.73E-04	4.13E-03	8.08E-01	9.57E-06	1.34E-05
OK	9.46E-04	1.21E-03	6.78E-01	9.76E-06	8.28E-06
OR	1.42E-04	1.87E-04	1.65E-01	6.84E-06	1.69E-06
PA	5.02E-04	2.62E-03	5.17E-01	1.11E-05	8.45E-06

RI	7.69E-05	3.95E-06	4.06E-01	7.99E-06	8.06E-07
SC	2.28E-04	9.58E-04	3.74E-01	6.56E-06	6.08E-06
SD	1.40E-03	1.35E-03	4.15E-01	4.69E-06	6.81E-06
TN	3.35E-04	1.25E-03	4.86E-01	6.17E-06	8.32E-06
TX	3.73E-04	1.04E-03	5.64E-01	8.10E-06	6.36E-06
UT	1.33E-03	5.20E-04	8.41E-01	1.01E-05	1.34E-05
VA	4.18E-04	1.27E-03	4.51E-01	1.69E-05	7.74E-06
VT	4.61E-05	4.58E-06	9.85E-04	2.41E-05	3.22E-06
WA	1.14E-04	4.16E-05	1.30E-01	4.71E-06	1.94E-06
WI	5.48E-04	1.70E-03	6.87E-01	1.11E-05	1.13E-05
WV	4.79E-04	2.28E-03	9.12E-01	1.02E-05	1.53E-05
WY	1.37E-03	1.53E-03	9.60E-01	1.07E-05	1.59E-05
US Average	5.09E-04	1.40E-03	5.52E-01	1.09E-05	8.20E-06

Table 9.8: Direct LCI Data for Electricity Grid Mix for US Average and States (per kWh of electricity)

	Energy	H_2O	SW	GWP	Sb	As	Be	Cd	CO_2	CO	Cr	Co	Cu	CH_2O	Pb	Mn	Hg	CH_4	Ni	NO_X	N_2O	NMVOC	PM_{10}	PMt	Se	SO_2	VOC	Zn
	MJ	kg	kg	kg	kg	kg	kg	kg	kg	kg	kg	kg	kg	kg	kg	kg	kg	kg	kg	kg	kg	kg	kg	kg	kg	kg	kg	kg
US	1.03E+01	4.35E+01	6.79E-02	5.78E-01	1.17E-09	2.69E-08	3.30E-09	1.51E-08	5.75E-01	1.16E-03	4.30E-06	4.04E-08	3.24E-09	1.25E-06	6.10E-08	4.11E-08	2.19E-08	1.14E-05	6.05E-07	6.06E-04	8.91E-06	6.70E-05	2.58E-05	7.57E-04	7.41E-06	1.51E-03	1.17E-05	3.67E-07
AK	9.86E+00	3.28E+01	4.51E-02	6.34E-01	2.48E-10	2.63E-04	8.20E-10	7.77E-09	6.33E-01	2.63E-04	3.14E-07	3.76E-08	9.23E-10	2.60E-06	1.69E-08	2.40E-08	3.90E-09	1.19E-05	5.18E-07	2.51E-03	3.10E-06	6.05E-05	4.37E-05	2.24E-04	5.39E-07	5.54E-04	1.81E-05	3.47E-08
AL	1.00E+01	4.57E+01	5.81E-02	4.87E-01	1.02E-09	6.61E-06	2.90E-09	1.29E-08	4.83E-01	1.72E-03	6.61E-06	3.50E-08	2.87E-09	1.17E-06	7.48E-08	3.60E-08	2.83E-08	1.03E-05	6.22E-07	3.67E-04	9.79E-06	6.14E-05	2.36E-05	6.64E-04	1.14E-05	1.99E-03	1.06E-05	5.64E-07
AR	1.01E+01	4.61E+01	6.54E-02	5.33E-01	1.15E-09	3.92E-08	3.30E-09	1.42E-08	5.30E-01	2.19E-03	8.57E-06	3.92E-08	3.21E-09	1.08E-06	9.25E-08	4.03E-08	3.54E-08	1.15E-05	7.36E-07	6.45E-04	9.44E-06	6.88E-05	2.33E-05	7.45E-04	1.47E-05	1.31E-03	1.05E-05	7.29E-07
AZ	9.97E+00	4.36E+01	5.29E-02	4.80E-01	9.34E-10	2.61E-09	2.45E-09	1.22E-08	4.78E-01	2.31E-04	4.60E-07	3.16E-08	2.61E-09	1.55E-06	2.65E-08	3.25E-08	8.10E-09	7.19E-06	3.71E-07	5.50E-04	7.06E-06	5.25E-05	2.80E-05	6.05E-04	8.30E-07	2.94E-04	1.25E-05	4.26E-08
CA	9.73E+00	2.94E+01	2.33E-03	2.91E-01	2.64E-11	2.48E-06	6.35E-10	4.21E-09	2.90E-01	2.42E-03	9.38E-06	1.56E-09	4.50E-10	2.48E-06	7.26E-08	2.69E-09	3.09E-08	1.35E-05	3.47E-07	4.06E-04	1.92E-06	1.93E-05	3.58E-05	4.23E-05	1.60E-05	1.44E-05	1.48E-05	8.06E-07
CO	1.07E+01	3.91E+01	9.30E-02	7.75E-01	1.65E-09	4.28E-08	4.29E-09	2.01E-08	7.71E-01	2.35E-04	3.82E-07	5.55E-08	4.47E-09	1.51E-06	4.28E-08	5.67E-08	1.26E-08	1.04E-05	6.35E-07	1.07E-03	1.21E-05	8.73E-05	3.20E-05	1.06E-03	7.33E-07	8.54E-04	1.49E-05	3.41E-08
CT	9.95E+00	4.32E+01	1.48E-02	2.60E-01	2.07E-10	8.75E-09	8.35E-10	4.19E-09	2.58E-01	1.92E-03	7.53E-06	8.41E-09	7.83E-10	1.45E-06	6.27E-08	8.75E-09	2.59E-08	2.70E-05	3.59E-07	2.08E-04	5.28E-06	2.28E-05	2.26E-05	1.48E-04	1.29E-05	5.97E-05	9.48E-06	6.45E-07
DC	1.45E+01	3.99E+01	0.00E+00	1.01E+00	0.00E+00	4.50E-09	1.11E-09	1.59E-08	1.01E+00	2.16E-04	3.37E-08	2.40E-07	0.00E+00	1.32E-06	6.02E-08	1.20E-07	4.50E-09	5.42E-05	3.37E-06	3.66E-03	1.09E-05	4.45E-04	4.30E-05	5.53E-04	2.72E-08	8.00E-03	8.64E-06	0.00E+00

DE	FL	GA	HI	IA	ID	IL	IN	KS	KY	LA
1.05E+01	9.46E+00	1.01E+01	1.03E+01	1.09E+01	9.81E+00	1.10E+01	1.09E+01	1.16E+01	1.12E+01	8.03E+00
3.74E+01	3.17E+01	4.70E+01	3.80E+01	4.38E+01	4.91E+01	5.39E+01	4.84E+01	4.77E+01	4.98E+01	3.37E+01
9.50E-02	4.59E-02	8.02E-02	2.42E-01	1.07E-01	5.75E-03	6.88E-02	1.38E-01	1.02E-01	1.38E-01	3.78E-02
8.60E-01	5.30E-01	6.02E-01	7.91E-01	8.33E-01	7.87E-02	5.13E-01	9.57E-01	7.80E-01	9.56E-01	5.87E-01
1.55E-09	6.53E-10	1.42E-09	3.59E-10	1.90E-09	1.66E-11	1.22E-09	2.45E-09	1.82E-09	2.44E-09	6.68E-10
2.43E-05	5.15E-07	1.39E-03	1.59E-05	9.65E-05	8.85E-06	7.80E-04	1.58E-06	2.96E-03	1.17E-05	6.92E-07
4.37E-09	2.32E-09	3.94E-09	1.65E-09	4.96E-09	4.65E-10	3.21E-09	6.36E-09	4.77E-09	6.92E-09	2.57E-09
1.99E-08	1.23E-08	1.71E-08	1.17E-08	2.17E-08	9.90E-10	1.40E-08	2.79E-08	2.12E-08	3.03E-08	1.26E-08
8.56E-01	5.27E-01	5.98E-01	7.87E-01	8.29E-01	7.82E-02	5.11E-01	9.52E-01	7.76E-01	9.51E-01	5.85E-01
2.12E-03	1.67E-03	1.77E-03	2.17E-03	3.48E-04	2.82E-03	3.45E-04	3.29E-04	1.07E-04	4.32E-04	2.11E-03
8.07E-06	6.17E-06	6.83E-06	8.02E-06	1.04E-06	1.13E-05	1.16E-06	8.54E-07	3.80E-08	1.29E-06	8.06E-06
6.20E-08	2.55E-08	4.93E-08	1.02E-07	6.40E-08	1.07E-09	4.12E-08	8.24E-08	6.12E-08	8.23E-08	2.31E-08
4.30E-09	2.05E-09	3.88E-09	1.03E-09	5.00E-09	2.29E-10	3.23E-09	6.44E-09	4.80E-09	6.43E-09	2.08E-09
1.60E-06	2.56E-06	9.67E-07	6.66E-07	4.36E-07	5.64E-07	3.18E-07	5.76E-07	5.75E-07	4.73E-07	2.28E-06
1.01E-07	6.41E-08	8.60E-08	9.20E-08	5.31E-08	8.59E-08	3.79E-08	6.48E-08	4.38E-08	6.80E-08	7.78E-08
5.88E-08	2.53E-08	4.99E-08	5.79E-08	6.49E-08	1.70E-09	4.19E-08	8.36E-08	6.22E-08	8.36E-08	2.44E-08
3.67E-08	2.49E-08	3.16E-08	3.01E-08	1.60E-08	3.64E-08	1.19E-08	1.91E-08	1.24E-08	2.05E-08	3.09E-08
1.11E-05	1.86E-05	9.02E-06	4.68E-05	9.52E-06	6.12E-06	5.86E-06	1.08E-05	9.10E-06	1.11E-05	1.05E-05
1.00E-06	5.15E-07	7.91E-07	1.67E-06	7.52E-07	4.03E-07	5.01E-07	9.51E-07	6.87E-07	9.73E-07	5.46E-07
1.20E-03	5.31E-04	5.74E-04	2.04E-03	8.70E-04	1.54E-04	4.02E-04	9.51E-04	9.82E-04	8.15E-04	7.60E-04
1.17E-05	7.33E-06	1.05E-05	9.58E-06	1.34E-05	1.13E-06	8.27E-06	1.55E-05	1.29E-05	1.61E-05	5.30E-06
1.03E-04	4.85E-05	8.21E-05	7.98E-05	9.65E-05	1.32E-05	6.27E-05	1.24E-04	9.21E-05	1.24E-04	4.90E-05
3.47E-05	4.18E-05	2.35E-05	3.93E-05	1.85E-05	8.85E-06	1.25E-05	2.41E-05	1.99E-05	2.26E-05	3.71E-05
1.02E-03	4.39E-04	9.18E-04	3.02E-04	1.21E-03	2.74E-05	7.80E-04	1.56E-03	1.16E-03	1.56E-03	4.47E-04
1.39E-05	1.06E-05	1.18E-05	1.37E-05	1.88E-06	1.93E-05	2.05E-06	1.58E-06	1.55E-07	2.33E-06	1.38E-05
3.24E-03	1.01E-03	2.29E-03	2.02E-03	1.78E-03	3.53E-04	1.23E-03	3.29E-03	1.00E-03	2.56E-03	1.07E-03
1.55E-05	1.81E-05	1.09E-05	1.86E-05	9.43E-06	3.46E-06	6.30E-06	1.22E-05	9.98E-06	1.17E-05	1.59E-05
6.88E-07	5.32E-07	5.80E-07	6.80E-07	8.57E-08	9.62E-07	9.68E-08	6.88E-08	9.84E-10	1.06E-07	6.92E-07

NE	ND	NC	MT	MS	MO	MN	MI	ME	MD	MA
1.10E+01	1.15E+01	1.06E+01	1.11E+01	9.65E+00	1.09E+01	1.09E+01	1.09E+01	7.57E+00	1.08E+01	9.34E+00
5.28E+01	4.69E+01	5.23E+01	5.06E+01	3.59E+01	5.04E+01	4.48E+01	4.92E+01	2.50E+01	5.18E+01	3.27E+01
1.02E-01	1.29E-01	8.17E-02	8.88E-02	3.95E-02	1.20E-01	8.29E-02	9.83E-02	1.13E-02	8.33E-02	4.13E-02
7.06E-01	9.59E-01	5.51E-01	6.61E-01	4.85E-01	8.50E-01	6.46E-01	7.31E-01	2.94E-01	5.90E-01	5.08E-01
1.81E-09	2.28E-09	1.45E-09	1.54E-09	7.01E-10	2.14E-09	1.47E-09	1.74E-09	1.16E-11	1.45E-09	6.10E-10
0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
4.70E-09	5.91E-09	3.93E-09	4.50E-09	2.17E-09	5.55E-09	4.18E-09	4.81E-09	2.60E-09	3.91E-09	1.98E-09
2.06E-08	2.59E-08	1.67E-08	1.97E-08	1.06E-08	2.45E-08	1.71E-08	2.05E-08	3.61E-09	1.68E-08	1.01E-08
7.03E-01	9.54E-01	5.48E-01	6.57E-01	4.82E-01	8.46E-01	6.42E-01	7.27E-01	2.88E-01	5.86E-01	5.05E-01
2.42E-04	1.44E-04	1.29E-03	3.62E-04	2.36E-03	1.84E-04	2.51E-03	1.84E-03	1.69E-02	1.04E-03	2.54E-03
6.40E-07	1.52E-07	4.97E-06	1.13E-06	9.07E-06	3.09E-07	9.96E-06	7.14E-06	6.89E-05	3.93E-06	9.73E-06
6.09E-08	7.68E-08	4.94E-08	5.17E-08	2.41E-08	7.18E-08	5.01E-08	5.92E-08	6.03E-09	5.02E-08	2.38E-08
4.76E-09	5.98E-09	3.87E-09	4.05E-09	2.18E-09	5.62E-09	4.00E-09	4.68E-09	1.00E-09	3.88E-09	1.98E-09
3.59E-07	4.03E-07	4.40E-07	2.83E-07	2.26E-06	5.47E-07	5.02E-07	6.79E-07	2.04E-06	4.43E-07	2.53E-06
4.79E-08	5.55E-08	7.22E-08	4.52E-08	8.62E-08	5.33E-08	1.10E-07	9.56E-08	5.22E-07	6.46E-08	8.99E-08
6.18E-08	7.79E-08	5.01E-08	5.26E-08	2.55E-08	7.29E-08	5.12E-08	6.03E-08	8.06E-09	5.06E-08	2.39E-08
1.42E-08	1.57E-08	2.56E-08	1.39E-08	3.43E-08	1.53E-08	4.18E-08	3.46E-08	2.21E-07	2.24E-08	3.60E-08
7.52E-06	1.09E-05	8.57E-06	9.13E-06	9.96E-06	9.39E-06	1.94E-05	1.29E-05	8.88E-05	1.50E-05	2.94E-05
7.03E-07	8.65E-07	7.26E-07	6.24E-07	5.86E-07	8.14E-07	9.05E-07	9.10E-07	2.46E-06	7.01E-07	6.13E-07
1.30E-03	1.73E-03	3.74E-04	7.69E-04	5.64E-04	5.84E-04	9.37E-04	9.02E-04	7.58E-04	5.35E-04	4.28E-04
1.07E-05	1.63E-05	9.54E-06	1.25E-05	7.16E-06	1.34E-05	1.25E-05	1.09E-05	1.28E-05	1.05E-05	7.44E-06
9.13E-05	1.15E-04	7.86E-05	7.80E-05	5.13E-05	1.08E-04	8.40E-05	9.55E-05	7.13E-05	7.86E-05	5.00E-05
1.68E-05	2.05E-05	1.60E-05	1.40E-05	3.70E-05	2.16E-05	1.73E-05	2.14E-05	3.46E-05	1.62E-05	4.12E-05
1.15E-03	1.45E-03	9.28E-04	9.83E-04	4.68E-04	1.36E-03	9.47E-04	1.12E-03	7.59E-05	9.32E-04	4.15E-04
1.19E-06	3.74E-07	8.58E-06	2.01E-06	1.56E-05	6.34E-07	1.71E-05	1.23E-05	1.18E-04	6.79E-06	1.67E-05
2.06E-03	3.53E-03	1.07E-03	8.53E-04	9.32E-04	2.67E-03	1.23E-03	2.85E-03	2.01E-03	4.50E-03	8.58E-04
8.65E-06	1.06E-05	7.83E-06	7.33E-06	1.59E-05	1.10E-05	8.28E-06	1.03E-05	1.26E-05	7.95E-06	1.76E-05
5.14E-08	8.91E-09	4.20E-07	9.33E-08	7.78E-07	2.31E-08	8.45E-07	6.05E-07	5.86E-06	3.32E-07	8.35E-07

SC	RI	PA	OR	OK	OH	NY	NV	NM	NJ	NH
1.06E+01	8.03E+00	1.04E+01	9.44E+00	1.01E+01	1.10E+01	1.05E+01	9.48E+00	1.05E+01	1.02E+01	1.04E+01
5.22E+01	1.77E+01	4.91E+01	4.19E+01	3.43E+01	5.04E+01	4.30E+01	2.75E+01	4.19E+01	4.39E+01	4.38E+01
5.13E-02	7.58E-06	7.21E-02	1.19E-02	6.75E-02	1.24E-01	2.09E-02	3.00E-02	1.09E-01	1.32E-02	2.48E-02
3.83E-01	4.14E-01	5.34E-01	1.67E-01	6.95E-01	8.50E-01	2.88E-01	4.87E-01	8.48E-01	2.62E-01	2.76E-01
9.07E-10	0.00E+00	1.27E-09	1.49E-10	1.20E-09	2.20E-09	2.52E-10	5.27E-10	1.93E-09	2.17E-10	3.77E-10
0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
2.66E-09	2.72E-10	3.41E-09	5.62E-10	3.15E-09	5.95E-09	9.05E-10	1.40E-09	5.03E-09	7.55E-10	1.64E-09
1.14E-08	5.25E-09	1.52E-08	3.24E-09	1.60E-08	2.61E-08	4.93E-09	9.59E-09	2.31E-08	4.33E-09	5.97E-09
3.81E-01	4.13E-01	5.31E-01	1.66E-01	6.93E-01	8.46E-01	2.86E-01	4.85E-01	8.44E-01	2.60E-01	2.73E-01
1.39E-03	1.65E-03	8.80E-04	1.17E-03	4.05E-04	4.65E-04	1.35E-03	1.94E-04	2.15E-04	1.22E-03	4.34E-03
5.42E-06	5.82E-06	3.23E-06	4.39E-06	9.81E-07	1.45E-06	5.12E-06	2.28E-08	3.04E-07	4.66E-06	1.74E-05
3.10E-08	1.16E-09	4.32E-08	5.28E-09	4.03E-08	7.44E-08	1.10E-08	1.80E-08	6.52E-08	8.29E-09	1.44E-08
2.49E-09	5.56E-10	3.42E-09	5.81E-10	3.38E-09	5.81E-09	8.76E-10	1.73E-09	5.19E-09	7.89E-10	1.31E-09
5.97E-07	4.37E-06	8.20E-07	1.30E-06	2.27E-06	5.41E-07	1.46E-06	3.16E-06	1.31E-06	1.53E-06	1.26E-06
6.28E-08	4.63E-08	5.50E-08	3.73E-08	3.69E-08	6.35E-08	4.59E-08	1.43E-08	4.89E-08	4.12E-08	1.41E-07
3.17E-08	2.51E-09	4.39E-08	5.93E-09	4.17E-08	7.54E-08	1.07E-08	1.93E-08	6.65E-08	8.72E-09	1.52E-08
2.36E-08	1.99E-08	1.90E-08	1.54E-08	1.17E-08	1.94E-08	1.85E-08	4.43E-09	1.42E-08	1.68E-08	5.87E-08
7.27E-06	8.17E-06	1.08E-05	7.85E-06	9.80E-06	9.83E-06	1.21E-05	8.43E-06	9.98E-06	1.08E-05	2.82E-05
5.36E-07	2.21E-07	5.97E-07	2.12E-07	4.87E-07	8.86E-07	3.09E-07	2.06E-07	7.41E-07	2.57E-07	7.67E-07
2.42E-04	3.71E-04	5.48E-04	2.22E-04	9.68E-04	8.10E-04	3.31E-04	4.42E-04	1.54E-03	2.25E-04	2.72E-04
7.01E-06	8.30E-07	9.07E-06	2.28E-06	8.26E-06	1.38E-05	3.85E-06	4.54E-06	1.24E-05	3.93E-06	6.46E-06
5.23E-05	2.27E-05	6.90E-05	1.62E-05	6.83E-05	1.13E-04	2.39E-05	3.80E-05	1.01E-04	2.14E-05	3.94E-05
1.47E-05	6.22E-05	2.01E-05	1.96E-05	3.98E-05	2.20E-05	2.33E-05	4.80E-05	3.11E-05	2.35E-05	2.17E-05
5.85E-04	3.64E-05	8.13E-04	1.10E-04	7.76E-04	1.40E-03	1.77E-04	3.57E-04	1.24E-03	1.53E-04	2.62E-04
9.33E-06	9.95E-06	5.60E-06	7.51E-06	1.73E-06	2.60E-06	8.78E-06	5.75E-08	6.14E-07	7.98E-06	2.99E-05
1.05E-03	2.01E-05	2.66E-03	2.10E-04	1.22E-03	4.59E-03	4.42E-04	1.91E-04	4.41E-04	1.91E-04	1.52E-03
6.82E-06	2.58E-05	9.46E-06	8.25E-06	1.77E-05	1.12E-05	9.89E-06	2.06E-05	1.48E-05	9.89E-06	8.97E-06
4.61E-07	5.11E-07	2.75E-07	3.77E-07	8.89E-08	1.20E-07	4.40E-07	1.24E-08	2.61E-08	4.01E-07	1.49E-06

SD	1.09E+01	5.17E+01	6.14E-02	4.31E-01	1.03E-09	0.00E+00	2.69E-09	1.18E-08	4.28E-01	1.31E-04	2.40E-07	3.49E-08	2.72E-09	2.26E-07	2.65E-08	3.54E-08	7.69E-09	6.72E-06	4.00E-07	1.37E-03	8.69E-06	5.24E-05	9.93E-06	6.62E-04	4.61E-07	1.36E-03	5.13E-06	1.87E-08
TN	1.08E+01	5.47E+01	7.82E-02	5.49E-01	1.38E-09	0.00E+00	3.69E-09	1.57E-08	5.45E-01	9.28E-04	3.52E-06	4.69E-08	3.65E-09	2.67E-07	5.94E-08	4.75E-08	2.05E-08	8.06E-06	6.47E-07	3.76E-04	1.06E-05	7.30E-05	1.30E-05	8.81E-04	6.09E-06	1.57E-03	6.56E-06	2.97E-07
TX	9.47E+00	3.29E+01	5.19E-02	6.14E-01	9.23E-10	0.00E+00	2.54E-09	1.34E-08	6.11E-01	3.65E-04	8.63E-07	3.12E-08	2.67E-09	2.29E-06	2.96E-08	3.24E-08	9.51E-09	8.63E-06	3.83E-07	5.01E-04	6.73E-06	5.49E-05	3.83E-05	6.03E-04	1.52E-06	1.05E-03	1.69E-05	7.96E-08
UT	1.01E+01	4.57E+01	1.21E-01	8.43E-01	2.15E-09	0.00E+00	5.58E-09	2.52E-08	8.39E-01	2.29E-04	3.86E-07	7.24E-08	5.72E-09	1.04E-06	5.44E-08	7.37E-08	1.58E-08	1.06E-05	8.24E-07	1.57E-03	1.39E-05	1.10E-04	2.86E-05	1.37E-03	7.66E-07	6.80E-04	1.39E-05	3.15E-08
VA	6.49E+00	4.80E+01	5.67E-02	5.19E-01	9.62E-10	0.00E+00	2.90E-09	1.22E-08	5.16E-01	2.70E-03	1.07E-05	3.55E-08	2.73E-09	9.63E-07	1.05E-07	3.53E-08	4.10E-08	1.63E-05	7.75E-07	5.62E-04	8.81E-06	6.45E-05	2.10E-05	6.31E-04	1.84E-05	1.68E-03	9.31E-06	9.11E-07
VT	1.11E+01	5.63E+01	1.24E-03	3.03E-03	0.00E+00	0.00E+00	6.52E-10	2.27E-10	9.04E-04	4.34E-03	1.77E-05	7.25E-10	1.93E-10	4.17E-09	1.34E-07	1.42E-09	5.68E-08	3.42E-05	6.21E-07	8.61E-05	4.56E-06	1.62E-05	1.29E-06	1.46E-05	3.04E-05	5.22E-06	3.62E-08	1.51E-06
WA	1.02E+01	5.02E+01	1.48E-02	1.30E-01	1.89E-10	0.00E+00	6.55E-10	2.80E-09	1.29E-01	1.13E-03	4.37E-06	6.67E-09	6.00E-10	5.46E-07	3.77E-08	7.05E-09	1.54E-08	4.47E-06	2.26E-07	1.75E-04	1.97E-06	1.55E-05	9.24E-06	1.31E-04	7.48E-06	1.21E-04	3.97E-06	3.73E-07
WI	1.07E+01	4.76E+01	9.23E-02	7.42E-01	1.64E-09	0.00E+00	4.78E-09	2.05E-08	7.38E-01	1.73E-03	6.69E-06	5.55E-08	4.42E-09	6.97E-07	8.97E-08	5.66E-08	3.25E-08	1.22E-05	8.56E-07	8.09E-04	1.21E-05	8.98E-05	2.09E-05	1.05E-03	1.15E-05	2.33E-03	1.01E-05	5.67E-07
WV	1.08E+01	5.07E+01	1.43E-01	9.36E-01	2.53E-09	0.00E+00	6.56E-09	2.88E-08	9.31E-01	1.31E-04	4.87E-08	8.56E-08	6.65E-09	4.54E-07	6.08E-08	8.67E-08	1.71E-08	1.02E-05	9.60E-07	4.90E-04	1.51E-05	1.28E-04	2.29E-05	1.61E-03	2.10E-07	2.36E-03	1.18E-05	-2.85E-10
WY	1.10E+01	4.81E+01	1.35E-01	9.76E-01	2.40E-09	0.00E+00	6.22E-09	2.73E-08	9.71E-01	1.26E-04	4.97E-08	8.08E-08	6.30E-09	4.69E-07	5.76E-08	8.20E-08	1.62E-08	1.16E-05	9.06E-07	1.43E-03	1.72E-05	1.21E-04	2.22E-05	1.53E-03	2.05E-07	1.65E-03	1.14E-05	1.82E-10

Notes: H_2O: water consumption; SW: solid waste; GWP: global warming potential; PMt: particulate matter, total; CH_2O: formaldehyde

Table 9.9: Total (Direct and Supply-Chain) LCI Data for Electricity Grid Mix for US Average and States (per kWh of electricity)

	Energy	H_2O	SW	GWP	Sb	As	Be	Cd	CO_2	CO	Cr	Co	Cu	CH_2O	Pb	Mn	Hg	CH_4	Ni	NO_x	N_2O	NMVOC	PM_{10}	PM_t	Se	SO_2	VOC	Zn
	MJ	kg	kg	kg	kg	kg	kg	kg	kg	kg	kg	kg	kg	kg	kg	kg	kg	kg	kg	kg	kg	kg	kg	kg	kg	kg	kg	kg
US	1.30E+01	7.44E+01	6.80E-02	7.00E-01	1.17E-09	2.69E-08	3.30E-09	1.51E-08	6.99E-01	1.27E-03	4.30E-06	4.04E-08	3.24E-09	1.25E-06	6.10E-08	4.11E-08	2.19E-08	3.16E-03	6.05E-07	1.02E-03	9.79E-06	5.43E-04	2.58E-05	1.31E-03	7.41E-06	1.75E-03	1.18E-05	3.67E-07
Mix1	CALCULATED based on USER SELECTED ELECTRICITY GRID MIX PERCENTAGES																											
Mi#2	CALCULATED based on USER SELECTED ELECTRICITY GRID MIX PERCENTAGES																											
Mix3	CALCULATED based on USER SELECTED ELECTRICITY GRID MIX PERCENTAGES																											
AK	1.03E+01	3.44E+01	4.53E-02	7.74E-01	2.48E-10	2.63E-04	8.20E-10	7.77E-09	7.68E-01	4.31E-04	3.14E-07	3.76E-08	9.23E-10	2.60E-06	1.69E-08	2.40E-08	5.07E-07	6.38E-04	5.18E-07	3.14E-03	3.61E-06	6.87E-04	4.37E-05	3.73E-04	5.39E-07	7.52E-04	1.82E-05	3.47E-08
AL	1.34E+01	8.69E+01	5.81E-02	5.98E-01	1.02E-09	6.61E-06	2.90E-09	1.29E-08	5.96E-01	1.82E-03	6.61E-06	3.50E-08	2.87E-09	1.17E-06	7.48E-08	3.60E-08	4.22E-04	1.03E-05	6.22E-07	7.53E-04	1.07E-05	4.84E-04	2.36E-05	1.15E-03	1.14E-05	2.20E-03	1.06E-05	5.64E-07
AR	1.33E+01	8.77E+01	6.55E-02	6.47E-01	1.15E-09	3.92E-08	3.30E-09	1.42E-08	6.45E-01	2.29E-03	8.57E-06	3.92E-08	3.21E-09	1.08E-06	9.25E-08	4.03E-08	3.54E-08	5.55E-04	7.36E-07	1.03E-03	1.04E-05	5.10E-04	2.33E-05	1.29E-03	1.47E-05	1.53E-03	1.05E-05	7.29E-07
AZ	1.33E+01	7.84E+01	5.30E-02	6.02E-01	9.34E-10	2.61E-09	2.45E-09	1.22E-08	6.01E-01	3.53E-04	4.60E-07	3.16E-08	2.61E-09	1.55E-06	2.65E-08	3.25E-08	4.46E-04	7.19E-06	3.71E-07	1.00E-03	7.81E-06	5.03E-04	2.80E-05	1.05E-03	8.30E-07	4.93E-04	1.25E-05	4.26E-08

CA	1.31E+01	6.76E+01	2.50E-03	4.12E-01	2.64E-11	2.48E-06	6.35E-10	4.21E-09	4.07E-01	2.60E-03	9.38E-06	1.56E-09	4.50E-10	2.48E-06	7.26E-08	2.69E-09	3.09E-08	1.76E-04	3.47E-07	9.67E-04	2.79E-06	3.73E-04	3.58E-05	7.84E-05	1.60E-05	1.77E-04	1.48E-05	8.06E-07
CO	1.11E+01	4.23E+01	9.30E-02	9.32E-01	1.65E-09	4.28E-08	4.29E-09	2.01E-08	9.32E-01	3.75E-04	3.82E-07	5.55E-08	4.47E-09	1.51E-06	4.28E-08	5.67E-08	3.01E-04	1.04E-05	6.35E-07	1.59E-03	1.30E-05	7.08E-04	3.20E-05	1.83E-03	7.33E-07	1.16E-03	1.49E-05	3.41E-08
CT	1.61E+01	1.15E+02	1.49E-02	3.43E-01	2.07E-10	8.75E-09	8.35E-10	4.19E-09	3.40E-01	2.02E-03	7.53E-06	8.41E-09	7.83E-10	1.45E-06	6.27E-08	8.75E-09	3.04E-08	2.70E-05	3.59E-07	5.78E-04	6.09E-06	2.94E-04	2.26E-05	2.63E-04	1.29E-05	1.59E-04	9.48E-06	6.45E-07
DC	1.53E+01	4.13E+01	0.00E+00	1.14E+00	0.00E+00	4.50E-09	1.11E-09	1.59E-08	1.08E+00	2.16E-04	3.37E-08	2.40E-07	0.00E+00	1.32E-06	6.02E-08	1.20E-07	4.50E-09	5.42E-05	3.37E-06	4.18E-03	1.09E-05	1.69E-03	4.30E-05	6.45E-04	2.72E-08	8.72E-03	8.64E-06	0.00E+00
DE	1.09E+01	4.78E+01	9.51E-02	1.02E+00	1.55E-09	2.43E-05	4.37E-09	1.99E-08	1.02E+00	2.25E-03	8.07E-06	6.20E-08	4.30E-09	1.60E-06	1.01E-07	5.88E-08	3.67E-08	1.11E-05	1.00E-06	1.74E-03	1.28E-05	7.75E-04	3.47E-05	1.75E-03	1.39E-05	3.56E-03	1.55E-05	6.88E-07
FL	1.14E+01	5.53E+01	4.61E-02	6.82E-01	6.53E-10	5.15E-07	2.32E-09	1.23E-08	6.79E-01	1.84E-03	6.17E-06	2.55E-08	2.05E-09	2.56E-06	6.41E-08	2.53E-08	2.49E-08	1.86E-05	5.15E-07	1.17E-03	8.24E-06	6.05E-04	4.18E-05	7.61E-04	1.06E-05	1.19E-03	1.81E-05	5.32E-07
GA	1.32E+01	8.52E+01	8.02E-02	7.26E-01	1.42E-09	1.39E-03	3.94E-09	1.71E-08	7.25E-01	1.87E-03	6.83E-06	4.93E-08	3.88E-09	9.67E-07	8.60E-08	4.99E-08	3.16E-08	9.02E-06	7.91E-07	9.61E-04	1.15E-05	5.80E-04	2.35E-05	1.59E-03	1.18E-05	2.55E-03	1.09E-05	5.80E-07
HI	1.13E+01	4.97E+01	2.42E-01	8.88E-01	3.59E-10	1.59E-05	1.65E-09	1.17E-08	8.83E-01	2.19E-03	8.02E-06	1.02E-07	1.03E-09	6.66E-07	9.20E-08	5.79E-08	3.01E-08	4.68E-05	1.67E-06	2.36E-03	9.99E-06	1.22E-03	3.93E-05	5.39E-04	1.37E-05	2.46E-03	1.86E-05	6.80E-07
IA	1.23E+01	5.84E+01	1.07E-01	9.60E-01	1.90E-09	9.65E-05	4.96E-09	2.17E-08	9.59E-01	4.32E-04	1.04E-06	6.40E-08	5.00E-09	4.36E-07	5.31E-08	6.49E-08	1.60E-08	9.52E-06	7.52E-07	1.19E-03	1.43E-05	6.34E-04	1.85E-05	2.09E-03	1.88E-06	2.10E-03	9.44E-06	8.57E-08
ID	1.01E+01	6.11E+01	5.87E-03	1.12E-01	1.66E-11	8.85E-06	4.65E-10	9.90E-10	1.07E-01	2.91E-03	1.13E-05	1.07E-09	2.29E-10	5.64E-07	8.59E-08	1.70E-09	3.64E-08	6.12E-06	4.03E-07	2.90E-04	1.62E-06	9.82E-05	8.85E-06	5.59E-05	1.93E-05	3.84E-04	3.68E-06	9.62E-07

MN	MI	ME	MD	MA	LA	KY	KS	IN	IL
1.39E+01	1.37E+01	7.86E+00	1.48E+01	1.13E+01	1.05E+01	1.18E+01	1.41E+01	1.14E+01	1.67E+01
8.48E+01	8.44E+01	9.19E+01	9.74E+01	6.02E+01	6.50E+01	5.45E+01	7.29E+01	5.28E+01	1.16E+02
8.29E-02	9.83E-02	1.15E-02	8.34E-02	4.15E-02	3.80E-02	1.38E-01	1.02E-01	1.38E-01	6.88E-02
7.55E-01	8.59E-01	4.00E-01	6.93E-01	6.57E-01	7.27E-01	1.11E+00	9.07E-01	1.12E+00	5.99E-01
1.47E-09	1.74E-09	1.16E-11	1.45E-09	6.10E-10	6.68E-10	2.44E-09	1.82E-09	2.45E-09	1.22E-09
0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	6.92E-07	1.17E-05	2.96E-03	1.58E-06	7.80E-04
4.18E-09	4.81E-09	2.60E-09	3.91E-09	1.98E-09	2.57E-09	6.92E-09	4.77E-09	6.36E-09	3.21E-09
1.71E-08	2.05E-08	3.61E-09	1.68E-08	1.01E-08	1.26E-08	3.03E-08	2.12E-08	2.79E-08	1.40E-08
7.52E-01	8.58E-01	3.88E-01	6.92E-01	6.54E-01	7.25E-01	1.11E+00	9.07E-01	1.12E+00	5.99E-01
2.59E-03	1.93E-03	1.71E-02	1.11E-03	2.71E-03	2.27E-03	5.27E-04	1.92E-04	4.28E-04	3.97E-04
9.96E-06	7.14E-06	6.89E-05	3.93E-06	9.73E-06	8.06E-06	1.29E-06	3.80E-08	8.54E-07	1.16E-06
5.01E-08	5.92E-08	6.03E-09	5.02E-08	2.38E-08	2.31E-08	8.23E-08	6.12E-08	8.24E-08	4.12E-08
4.00E-09	4.68E-09	1.00E-09	3.88E-09	1.98E-09	2.08E-09	6.43E-09	4.80E-09	6.44E-09	3.23E-09
5.02E-07	6.79E-07	2.04E-06	4.43E-07	2.53E-06	2.28E-06	4.73E-07	5.75E-07	5.76E-07	3.18E-07
1.10E-07	9.56E-08	5.22E-07	6.46E-08	8.99E-08	7.78E-08	6.80E-08	4.38E-08	6.48E-08	3.79E-08
5.12E-08	6.03E-08	8.06E-09	5.06E-08	2.39E-08	2.44E-08	8.36E-08	6.22E-08	8.36E-08	4.19E-08
4.18E-08	3.46E-08	2.21E-07	2.24E-08	3.60E-08	3.09E-08	2.05E-08	1.24E-08	1.91E-08	1.19E-08
1.94E-05	1.29E-05	8.88E-05	1.50E-05	2.94E-05	1.05E-05	1.11E-05	9.10E-06	1.08E-05	5.86E-06
9.05E-07	9.10E-07	2.46E-06	7.01E-07	6.13E-07	5.46E-07	9.73E-07	6.87E-07	9.51E-07	5.01E-07
1.23E-03	1.26E-03	1.25E-03	8.16E-04	1.06E-03	1.34E-03	1.19E-03	1.32E-03	1.35E-03	6.36E-04
1.36E-05	1.20E-05	1.52E-05	1.14E-05	8.43E-06	6.25E-06	1.71E-05	1.37E-05	1.65E-05	9.06E-06
5.27E-04	6.30E-04	4.06E-04	5.15E-04	5.85E-04	5.35E-04	8.00E-04	6.28E-04	8.15E-04	4.17E-04
1.73E-05	2.14E-05	3.46E-05	1.62E-05	4.12E-05	3.71E-05	2.26E-05	1.99E-05	2.41E-05	1.25E-05
1.64E-03	1.93E-03	1.07E-04	1.61E-03	7.18E-04	7.73E-04	2.69E-03	2.01E-03	2.69E-03	1.36E-03
1.71E-05	1.23E-05	1.18E-04	6.79E-06	1.67E-05	1.38E-05	2.33E-06	1.55E-07	1.58E-06	2.05E-06
1.50E-03	3.16E-03	2.09E-03	4.77E-03	1.03E-03	1.25E-03	2.96E-03	1.32E-03	3.69E-03	1.45E-03
8.29E-06	1.03E-05	1.27E-05	7.96E-06	1.76E-05	1.59E-05	1.17E-05	9.98E-06	1.22E-05	6.30E-06
8.45E-07	6.05E-07	5.86E-06	3.32E-07	8.35E-07	6.92E-07	1.06E-07	9.84E-10	6.88E-08	9.68E-08

MO	MS	MT	NC	ND	NE	NH	NJ	NM	NV
1.27E+01	1.25E+01	1.15E+01	1.47E+01	1.20E+01	1.44E+01	1.55E+01	1.66E+01	1.10E+01	1.09E+01
6.76E+01	7.32E+01	5.40E+01	1.00E+02	5.03E+01	8.91E+01	1.14E+02	1.15E+02	4.53E+01	3.60E+01
1.20E-01	3.96E-02	8.88E-02	8.18E-02	1.29E-01	1.02E-01	2.49E-02	1.33E-02	1.09E-01	3.02E-02
9.91E-01	6.26E-01	7.60E-01	6.54E-01	1.10E+00	8.24E-01	3.60E-01	3.48E-01	1.01E+00	6.58E-01
2.14E-09	7.01E-10	1.54E-09	1.45E-09	2.28E-09	1.81E-09	3.77E-10	2.17E-10	1.93E-09	5.27E-10
0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
5.55E-09	2.17E-09	4.50E-09	3.93E-09	5.91E-09	4.70E-09	1.64E-09	7.55E-10	5.03E-09	1.40E-09
2.45E-08	1.06E-08	1.97E-08	1.67E-08	2.59E-08	2.06E-08	5.97E-09	4.33E-09	2.31E-08	9.59E-09
9.92E-01	6.23E-01	7.58E-01	6.53E-01	1.10E+00	8.24E-01	3.56E-01	3.46E-01	1.01E+00	6.56E-01
2.74E-04	2.51E-03	4.46E-04	1.36E-03	2.35E-04	3.12E-04	4.43E-03	1.32E-03	3.47E-04	4.14E-04
3.09E-07	9.07E-06	1.13E-06	4.97E-06	1.52E-07	6.40E-07	1.74E-05	4.66E-06	3.04E-07	2.28E-08
7.18E-08	2.41E-08	5.17E-08	4.94E-08	7.68E-08	6.09E-08	1.44E-08	8.29E-09	6.52E-08	1.80E-08
5.62E-09	2.18E-09	4.05E-09	3.87E-09	5.98E-09	4.76E-09	1.31E-09	7.89E-10	5.19E-09	1.73E-09
5.47E-07	2.26E-06	2.83E-07	4.40E-07	4.03E-07	3.59E-07	1.26E-06	1.53E-06	1.31E-06	3.16E-06
5.33E-08	8.62E-08	4.52E-08	7.22E-08	5.55E-08	4.79E-08	1.41E-07	4.12E-08	4.89E-08	1.43E-08
7.29E-08	2.55E-08	5.26E-08	5.01E-08	7.79E-08	6.18E-08	1.52E-08	8.72E-09	6.65E-08	1.93E-08
1.53E-08	3.43E-08	1.39E-08	2.56E-08	1.57E-08	1.42E-08	5.87E-08	1.68E-08	1.42E-08	4.43E-09
9.39E-06	9.96E-06	9.13E-06	8.57E-06	1.09E-05	7.52E-06	2.82E-05	1.08E-05	9.98E-06	8.43E-06
8.14E-07	5.86E-07	6.24E-07	7.26E-07	8.65E-07	7.03E-07	7.67E-07	2.57E-07	7.41E-07	2.06E-07
9.49E-04	1.15E-03	1.01E-03	6.54E-04	2.07E-03	1.59E-03	6.21E-04	6.13E-04	2.04E-03	1.19E-03
1.43E-05	8.17E-06	1.32E-05	1.05E-05	1.72E-05	1.16E-05	7.55E-06	4.67E-06	1.34E-05	5.31E-06
7.18E-04	5.43E-04	5.02E-04	5.08E-04	7.41E-04	5.96E-04	3.27E-04	2.99E-04	7.67E-04	6.07E-04
2.16E-05	3.70E-05	1.40E-05	1.60E-05	2.05E-05	1.68E-05	2.17E-05	2.35E-05	3.11E-05	4.80E-05
2.35E-03	8.10E-04	1.70E-03	1.61E-03	2.51E-03	2.00E-03	4.55E-04	2.73E-04	2.14E-03	6.22E-04
6.34E-07	1.56E-05	2.01E-06	8.58E-06	3.74E-07	1.19E-06	2.99E-05	7.98E-06	6.14E-07	5.75E-08
3.02E-03	1.11E-03	1.11E-03	1.33E-03	3.90E-03	2.37E-03	1.64E-03	2.93E-04	7.82E-04	4.12E-04
1.10E-05	1.59E-05	7.43E-06	7.85E-06	1.06E-05	8.66E-06	8.99E-06	9.89E-06	1.48E-05	2.06E-05
2.31E-08	7.78E-07	9.33E-08	4.20E-07	8.91E-09	5.14E-08	1.49E-06	4.01E-07	2.61E-08	1.24E-08

NY	OH	OK	OR	PA	RI	SC	SD	TN	TX
1.43E+01	1.27E+01	1.06E+01	9.69E+00	1.47E+01	8.48E+00	1.67E+01	1.12E+01	1.49E+01	1.10E+01
8.78E+01	6.83E+01	3.76E+01	4.68E+01	9.62E+01	2.47E+01	1.21E+02	5.35E+01	1.00E+02	4.82E+01
2.10E-02	1.24E-01	6.77E-02	1.20E-02	7.21E-02	2.70E-04	5.13E-02	6.15E-02	7.82E-02	5.21E-02
3.73E-01	9.94E-01	8.61E-01	2.38E-01	6.44E-01	6.07E-01	4.65E-01	5.02E-01	6.40E-01	7.67E-01
2.52E-10	2.20E-09	1.20E-09	1.49E-10	1.27E-09	0.00E+00	9.07E-10	1.03E-09	1.38E-09	9.23E-10
0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
9.05E-10	5.95E-09	3.15E-09	5.62E-10	3.41E-09	2.72E-10	2.66E-09	2.69E-09	3.69E-09	2.54E-09
4.93E-09	2.61E-08	1.60E-08	3.24E-09	1.52E-08	5.25E-09	1.14E-08	1.18E-08	1.57E-08	1.34E-08
3.70E-01	9.95E-01	8.60E-01	2.34E-01	6.43E-01	6.04E-01	4.64E-01	4.99E-01	6.39E-01	7.66E-01
1.46E-03	5.55E-04	5.79E-04	1.30E-03	9.64E-04	1.92E-03	1.45E-03	2.12E-04	9.90E-04	5.31E-04
5.12E-06	1.45E-06	9.81E-07	4.39E-06	3.23E-06	5.82E-06	5.42E-06	2.40E-07	3.52E-06	8.63E-07
1.10E-08	7.44E-08	4.03E-08	5.28E-09	4.32E-08	1.16E-09	3.10E-08	3.49E-08	4.69E-08	3.12E-08
8.76E-10	5.81E-09	3.38E-09	5.81E-10	3.42E-09	5.56E-10	2.49E-09	2.72E-09	3.65E-09	2.67E-09
1.46E-06	5.41E-07	2.27E-06	1.30E-06	8.20E-07	4.37E-06	5.97E-07	2.26E-07	2.67E-07	2.29E-06
4.59E-08	6.35E-08	3.69E-08	3.73E-08	5.50E-08	4.63E-08	6.28E-08	2.65E-08	5.94E-08	2.96E-08
1.07E-08	7.54E-08	4.17E-08	5.93E-09	4.39E-08	2.51E-09	3.17E-08	3.54E-08	4.75E-08	3.24E-08
1.85E-08	1.94E-08	1.17E-08	1.54E-08	1.90E-08	1.99E-08	2.36E-08	7.69E-09	2.05E-08	9.51E-09
1.21E-05	9.83E-06	9.80E-06	7.85E-06	1.08E-05	8.17E-06	7.27E-06	6.72E-06	8.06E-06	8.63E-06
3.09E-07	8.86E-07	4.87E-07	2.12E-07	5.97E-07	2.21E-07	5.36E-07	4.00E-07	6.47E-07	3.83E-07
7.00E-04	1.18E-03	1.59E-03	5.27E-04	8.90E-04	1.32E-03	5.05E-04	1.55E-03	6.11E-04	1.11E-03
4.51E-06	1.48E-05	9.12E-06	2.73E-06	9.95E-06	1.71E-06	7.87E-06	9.17E-06	1.14E-05	7.54E-06
3.17E-04	7.40E-04	6.81E-04	2.34E-04	5.07E-04	6.31E-04	3.68E-04	3.43E-04	4.59E-04	6.03E-04
2.33E-05	2.20E-05	3.98E-05	1.96E-05	2.01E-05	6.22E-05	1.47E-05	9.93E-06	1.30E-05	3.83E-05
3.15E-04	2.43E-03	1.34E-03	2.00E-04	1.41E-03	6.29E-05	1.02E-03	1.15E-03	1.53E-03	1.05E-03
8.78E-06	2.60E-06	1.73E-06	7.51E-06	5.60E-06	9.95E-06	9.33E-06	4.61E-07	6.09E-06	1.52E-06
5.45E-04	4.95E-03	1.47E-03	2.72E-04	2.90E-03	1.28E-04	1.24E-03	1.53E-03	1.81E-03	1.26E-03
9.94E-06	1.12E-05	1.77E-05	8.41E-06	9.47E-06	2.58E-05	6.83E-06	5.27E-06	6.60E-06	1.69E-05
4.40E-07	1.20E-07	8.89E-08	3.77E-07	2.75E-07	5.11E-07	4.61E-07	1.87E-08	2.97E-07	7.96E-08

UT	1.08E+01	5.04E+01	1.21E-01	1.01E+00	2.15E-09	0.00E+00	5.58E-09	2.52E-08	1.01E+00	3.50E-04	3.86E-07	7.24E-08	5.72E-09	1.04E-06	5.44E-08	7.37E-08	1.58E-08	1.06E-05	8.24E-07	2.04E-03	1.49E-05	7.91E-04	2.86E-05	2.37E-03	7.66E-07	1.06E-03	1.39E-05	3.15E-08
VA	1.12E+01	1.08E+02	5.68E-02	6.21E-01	9.62E-10	0.00E+00	2.90E-09	1.22E-08	6.18E-01	2.79E-03	1.07E-05	3.55E-08	2.73E-09	9.63E-07	1.05E-07	3.53E-08	4.10E-08	1.63E-05	7.75E-07	9.09E-04	9.85E-06	4.62E-04	2.10E-05	1.09E-03	1.84E-05	1.88E-03	9.32E-06	9.11E-07
VT	1.93E+01	1.61E+02	1.29E-03	1.60E-02	0.00E+00	0.00E+00	6.52E-10	2.27E-10	1.10E-02	4.35E-03	1.77E-05	7.25E-10	1.93E-10	4.17E-09	1.34E-07	1.42E-09	5.68E-08	3.42E-05	6.21E-07	1.39E-04	5.47E-06	2.74E-05	1.29E-06	3.31E-05	3.04E-05	4.50E-05	9.24E-08	1.51E-06
WA	1.11E+01	6.24E+01	1.49E-02	1.71E-01	1.89E-10	0.00E+00	6.55E-10	2.80E-09	1.67E-01	1.22E-03	4.37E-06	6.67E-09	6.00E-10	5.46E-07	3.77E-08	7.05E-09	1.54E-08	4.47E-06	2.26E-07	3.26E-04	2.33E-06	1.40E-04	9.24E-06	2.37E-04	7.48E-06	1.74E-04	4.16E-06	3.73E-07
WI	1.35E+01	8.18E+01	9.23E-02	8.65E-01	1.64E-09	0.00E+00	4.78E-09	2.05E-08	8.64E-01	1.82E-03	6.69E-06	5.55E-08	4.42E-09	6.97E-07	8.97E-08	5.66E-08	3.25E-08	1.22E-05	8.56E-07	1.16E-03	1.31E-05	5.99E-04	2.09E-05	1.82E-03	1.15E-05	2.62E-03	1.01E-05	5.67E-07
WV	1.14E+01	5.44E+01	1.43E-01	1.09E+00	2.53E-09	0.00E+00	6.56E-09	2.88E-08	1.10E+00	2.25E-04	4.87E-08	8.56E-08	6.65E-09	4.54E-07	6.08E-08	8.67E-08	1.71E-08	1.02E-05	9.60E-07	8.75E-04	1.62E-05	8.25E-04	2.29E-05	2.79E-03	2.10E-07	2.78E-03	1.18E-05	-2.85E-10
WY	1.16E+01	5.16E+01	1.35E-01	1.13E+00	2.40E-09	0.00E+00	6.22E-09	2.73E-08	1.13E+00	2.21E-04	4.97E-08	8.08E-08	6.30E-09	4.69E-07	5.76E-08	8.20E-08	1.62E-08	1.16E-05	9.06E-07	1.81E-03	1.81E-05	7.86E-04	2.22E-05	2.64E-03	2.05E-07	2.05E-03	1.15E-05	1.82E-10

Notes: H_2O: water consumption; SW: solid waste; GWP: global warming potential; PMt: particulate matter, total

Table 9.10: Surface water (SW) and ground water (GW) withdrawals by state and by industrial and mining water use, 2005, in million gallons per day, adapted from USGS [87]

	Industrial Self-Supplied Water Withdrawals				**Public-Supply Water Withdrawals for Industrial Use**				**Mining Water Withdrawals**			
State	**GW**	**SW**	**GW, %**	**SW, %**	**GW**	**SW**	**GW, %**	**SW, %**	**GW**	**SW**	**GW, %**	**SW, %**
AK	4.14E+00	4.02E+00	51%	49%	2.59E+01	4.99E+01	34%	66%	1.14E+02	8.31E+01	58%	42%
AL	2.76E+01	5.23E+02	5%	95%	2.77E+02	5.24E+02	35%	65%	1.96E+01	8.26E+00	70%	30%
AR	6.58E+01	1.13E+02	37%	63%	1.38E+02	2.66E+02	34%	66%	2.40E-01	1.05E+00	19%	81%
AZ	2.24E+01	0.00E+00	100%	0%	5.67E+02	6.02E+02	49%	51%	9.42E+01	9.05E+00	91%	9%
CA	6.23E+01	9.90E+00	86%	14%	1.28E+03	5.71E+03	18%	82%	2.90E+02	1.89E+01	94%	6%
CO	3.61E+00	1.39E+02	3%	97%	1.02E+02	7.62E+02	12%	88%	1.98E+01	1.63E+00	92%	8%
CT	7.02E+00	6.06E+01	10%	90%	7.61E+01	4.04E+02	16%	84%	6.70E-01	2.73E+00	20%	80%
DC	0.00E+00	0.00E+00	0%	0%	0.00E+00	0.00E+00	0%	0%	0.00E+00	0.00E+00	0%	0%
DE	1.16E+01	2.97E+01	28%	72%	5.12E+01	4.50E+01	53%	47%	8.00E-01	7.60E-01	51%	49%
FL	1.81E+02	6.25E+01	74%	26%	2.20E+03	3.39E+02	87%	13%	1.38E+02	5.69E+01	71%	29%
GA	2.40E+02	2.91E+02	45%	55%	2.54E+02	9.26E+02	22%	78%	4.89E+01	4.70E-01	99%	1%
HI	2.92E+01	0.00E+00	100%	0%	2.49E+02	1.14E+01	96%	4%	1.42E+00	4.40E-01	76%	24%
IA	1.77E+02	1.23E+01	94%	6%	3.12E+02	8.60E+01	78%	22%	3.23E+00	4.42E+01	7%	93%
ID	4.11E+01	2.21E+01	65%	35%	2.20E+02	2.67E+01	89%	11%	2.16E+00	2.20E+01	9%	91%
IL	1.28E+02	2.36E+02	35%	65%	4.06E+02	1.30E+03	24%	76%	4.10E+01	7.12E+01	37%	63%
IN	8.69E+01	2.11E+03	4%	96%	3.56E+02	3.20E+02	53%	47%	4.70E+00	9.55E+01	5%	95%
KS	3.55E+01	6.34E+00	85%	15%	1.60E+02	2.42E+02	40%	60%	1.01E+01	4.64E+00	69%	31%
KY	4.81E+01	1.38E+02	26%	74%	6.90E+01	4.89E+02	12%	88%	7.89E+00	2.87E+01	22%	78%
LA	2.65E+02	2.84E+03	9%	91%	3.54E+02	3.65E+02	49%	51%	1.57E+02	2.08E+01	88%	12%
MA	1.56E+01	9.67E+01	14%	86%	2.03E+02	5.90E+02	26%	74%	2.96E+00	7.77E+00	28%	72%
MD	1.42E+01	4.55E+01	24%	76%	9.59E+01	5.85E+02	14%	86%	9.05E+00	4.17E+00	68%	32%
ME	8.61E+00	1.61E+02	5%	95%	2.74E+01	6.85E+01	29%	71%	1.50E+00	5.26E+00	22%	78%
MI	8.91E+01	5.40E+02	14%	86%	2.60E+02	8.83E+02	23%	77%	1.41E+01	8.14E+01	15%	85%
MN	6.55E+01	7.30E+01	47%	53%	3.72E+02	1.65E+02	69%	31%	8.05E+00	4.18E+02	2%	98%
MO	3.74E+01	4.36E+01	46%	54%	2.43E+02	5.88E+02	29%	71%	2.29E+01	1.18E+01	66%	34%
MS	7.69E+01	1.20E+02	39%	61%	3.30E+02	3.95E+01	89%	11%	1.13E+01	6.10E-01	95%	5%

MT	3.74E+01	2.96E+01	56%	44%	6.73E+01	7.48E+01	47%	53%	6.32E+00	3.42E+01	16%	84%
NC	1.71E+02	2.23E+02	43%	57%	1.56E+02	7.65E+02	17%	83%	3.50E+01	1.10E+01	76%	24%
ND	5.00E+00	9.70E+00	34%	66%	3.19E+01	3.52E+01	48%	52%	5.26E+00	4.00E-01	93%	7%
NE	1.13E+01	1.00E-02	100%	0%	2.36E+02	9.42E+01	71%	29%	1.70E-01	1.02E+01	2%	98%
NH	5.65E+00	3.59E+01	14%	86%	3.72E+01	6.26E+01	37%	63%	2.00E-02	3.74E+00	1%	99%
NJ	4.62E+01	3.98E+01	54%	46%	4.10E+02	5.48E+02	43%	57%	9.10E-01	3.74E+01	2%	98%
NM	1.15E+01	1.72E+00	87%	13%	2.49E+02	3.73E+01	87%	13%	5.74E+01	1.29E+00	98%	2%
NV	7.00E-01	5.20E+00	12%	88%	1.35E+02	5.41E+02	20%	80%	9.91E+01	0.00E+00	100%	0%
NY	1.61E+02	1.40E+02	53%	47%	5.03E+02	2.03E+03	20%	80%	7.36E+00	2.63E+01	22%	78%
OH	1.49E+02	5.54E+02	21%	79%	4.88E+02	9.47E+02	34%	66%	1.12E+02	6.17E+01	64%	36%
OK	8.04E+00	1.60E+01	33%	67%	1.14E+02	5.32E+02	18%	82%	1.91E+02	1.67E+00	99%	1%
OR	8.95E+00	1.64E+02	5%	95%	8.09E+01	4.49E+02	15%	85%	1.39E+01	2.09E+00	87%	13%
PA	6.61E+01	7.04E+02	9%	91%	2.10E+02	1.21E+03	15%	85%	8.49E+01	1.08E+01	89%	11%
RI	5.00E-01	0.00E+00	100%	0%	1.62E+01	1.03E+02	14%	86%	5.90E-01	1.12E+00	35%	65%
SC	3.24E+01	3.86E+02	8%	92%	1.51E+02	4.96E+02	23%	77%	8.56E+00	5.00E-01	94%	6%
SD	4.31E+00	1.00E-01	98%	2%	6.59E+01	3.46E+01	66%	34%	4.55E+00	5.93E+00	43%	57%
TN	4.56E+01	7.38E+02	6%	94%	3.32E+02	5.81E+02	36%	64%	1.04E+01	1.14E+01	48%	52%
TX	1.87E+02	1.06E+03	15%	85%	1.21E+03	3.07E+03	28%	72%	5.75E+02	6.42E+01	90%	10%
UT	2.06E+01	1.47E+01	58%	42%	3.48E+02	2.59E+02	57%	43%	3.74E+01	1.29E+02	22%	78%
VA	1.81E+00	6.14E+00	23%	77%	1.38E+01	3.20E+01	30%	70%	2.40E-01	3.55E+00	6%	94%
VT	1.06E+02	4.21E+02	20%	80%	8.38E+01	8.98E+02	9%	91%	2.47E+00	2.73E+01	8%	92%
WA	1.07E+02	3.46E+02	24%	76%	5.39E+02	4.51E+02	54%	46%	2.24E+01	4.14E+00	84%	16%
WI	5.44E+01	9.11E+02	6%	94%	3.72E+01	1.52E+02	20%	80%	5.22E+00	9.44E+00	36%	64%
WV	7.09E+01	4.00E+02	15%	85%	3.05E+02	2.47E+02	55%	45%	1.76E+01	1.49E+01	54%	46%
WY	4.12E+00	1.92E+00	68%	32%	4.98E+01	4.65E+01	52%	48%	2.15E+02	1.35E+01	94%	6%
U.S. average	**6.00E+01**	**2.72E+02**	**18%**	**82%**	**2.84E+02**	**5.70E+02**	**33%**	**67%**	**4.97E+01**	**2.91E+01**	**63%**	**37%**

9.2 Appendix B: Building Materials and Components Information

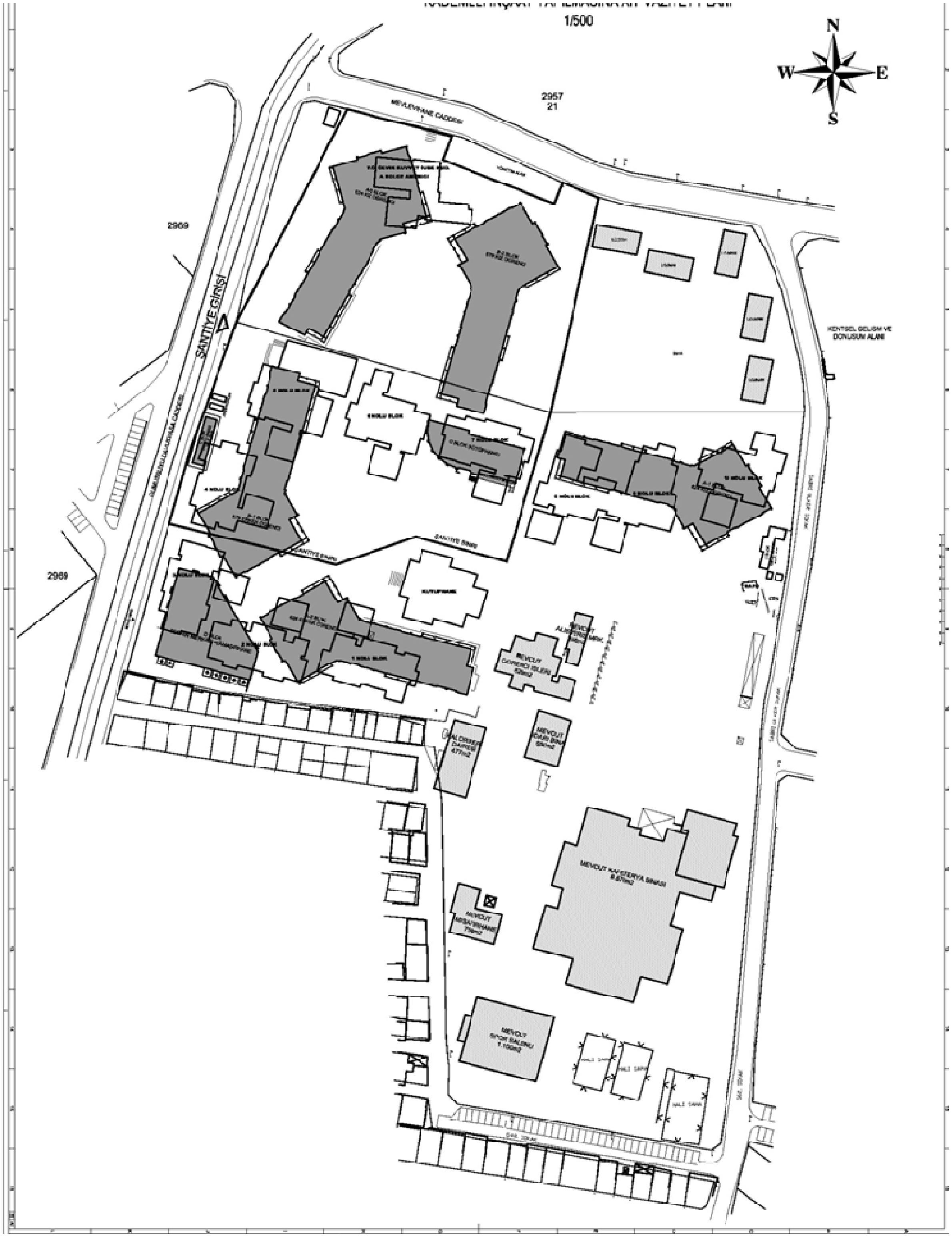

Figure 9.1: Site layout for the dormitory building in Istanbul

Table 9.11: Building materials characteristics and data sources

Item No.	Building material	Unit	Weight (kg) per unit of material	Notes	Source
1	Aluminum_profile for window frame with heat insulation, external	m^2	39.6	Frame only	Kellenberger et al. (2007) EcoInvent v2.0
2,3	Aluminum_profile for door frames, with and without heat insulation, external and internal	m^2	10.8	Aluminum frame only (with 2mm thickness) x 2 sheets + insulation	Turkish Standards TS-EN 10305-5, TS-914 EN ISO 1461 and project technical specifications
4,5	Aluminum_sheets for suspended ceiling, 30x30 and 60x60, in sheet form	m^2	4.5		SAS International (2013). Trucell- Aluminum Open Cell Ceiling. http://www.sasint.co.uk/trucell.php Accessed on February 16, 2013
6	Aluminum_sheets for façade covering (sandwiched wall)	m^2	4.9		Institut Bauen und Umwelt e.V. [IBU] (2013). Decken-Wandpaneel glatt, Metawell GmbH. http://bau-umwelt.de/download/CY1d5b419X13c2eba8bc6Xedd/EPD_MWL_2013121_D.pdf Accessed on February 23, 2013
7	Aluminum_ fixed sun breakers	m^2	1.4		MetalScreen® S.p.A. (2013) Sun breakers http://www.metalscreen.it/Portals/0/schede/EN/Doghe/Rivestimenti%20esterni%20Inglese.pdf Accessed on February 12, 2013
8	Hollow bricks (horizontal perforated bricks) with 8.5 cm wall thickness, based on TS 4563 Standards	piece	1.9	25 pieces per m^2 of wall area; 326 pieces per m^3, dimensions (cm): 19x19x8.5, wall thickness of 8.5 cm	Kilsan Tugla, Asmolen (2013). Horizontal Perforated Bricks http://www.kilsan.com/eng/urun_oz_eng1.php Accessed on February 17, 2013
9	Hollow bricks (horizontal perforated bricks) with 13.5 cm wall thickness	piece	2.8	25 pieces per m^2 of wall area; 205 pieces per m^3, dimensions (cm): 19x19x13.5, wall thickness of 13.5 cm	Kilsan Tugla, Asmolen (2013). Horizontal Perforated Bricks http://www.kilsan.com/eng/urun_oz_eng1.php Accessed on February 17, 2013
10	Hollow bricks (horizontal perforated bricks) with 19 cm wall thickness	piece	1.9	52 pieces per m^2 of wall area; 326 pieces per m^3, dimensions (cm): 19x19x8.5, wall thickness of 19 cm	Kilsan Tugla, Asmolen (2013). Horizontal Perforated Bricks http://www.kilsan.com/eng/urun_oz_eng1.php Accessed on February 17, 2013
11	Hollow bricks (horizontal perforated bricks) with 29 cm wall thickness	piece	5.0	35 pieces per m^2 of wall area, dimensions (cm): 29x19x13.5, wall thickness of 29 cm	Tekdemir Blok Tugla-Kiremit (2013). Products (in Turkish only) http://www.tuglaci.com.tr/urunlr.html Accessed on February 17, 2013
12	Ceramic_floor tiles	m^2	17.0	Major constituents are kaolin, clay, granite and feldspar	Institut Bauen und Umwelt e.V. [IBU] (2012). Ceramic Floor Tiles. Kaleseramik Çanakkale Kalebodur Ceramic Ind. Inc. http://bau-umwelt.de/download/CY6523e6cX1385b2f8dfeXY3c9/EPD_KSK_2012311_E_.pdf Accessed on February 18, 2013

13	Ceramic_wall cladding tiles	m^2	14.0	Major constituents are kaolin, clay, granite and feldspar	Institut Bauen und Umwelt e.V. [IBU] (2012). Ceramic Wall Tiles. Kaleseramik Çanakkale Kalebodur Ceramic Industries Inc. http://bau-umwelt.de/download/CY6523e6cX1385b2f8dfeXY3c0/EPD_KSK_2012111_E.pdf Accessed on February 18, 2013
14, 15, 16	Concrete_structural C25, C30, C35			Table 9.12	GreenConcrete LCA Tool (2013)
17, 18, 19, 20	Concrete_non-structural, w/o reinforcement: Doses of 150, 200, 400, 500			Table 9.13	GreenConcrete LCA Tool (2013)
21	Elevator	piece	630.0		Kone (2012). Kone Ecospace Environmental Product Declaration. http://www.kone.com/countries/en_US/sustainability/Documents/KONE-EcoSpace-Environmental-Product-Declaration-sf2882.pdf Accessed on March 28, 2013
22	Glass_partition wall, modular internal, whole flat	m^2	33.5	Weight per area varies: 25-42 kg/m^2	A.E. Yapi Sanayi Tic. Ltd. Sti. (2013) Straehle 3400 (Vertical Frameless Partitions). http://www.aemimarlik.com/product-detail/6/Straehle-3400 Accessed on February 19, 2013
23,24	90 min fire resistant glazed partition wall	m^2	28.7	Product weight (for 3 m^2 size panel): 86 kg. Components (%) in one m^2 of the system (excluding production waste and packaging): Safety glass: 85.5%; anodized aluminum profiles: 10.6%; steel components: 2.8%; copper components: 0.3%; zinc die-cast components: 0.3%; plastics components: 0.3%	Institut Bauen und Umwelt e.V. [IBU] (2012).VARITRANS Partition System Fullwall Element. DORMA Hüppe Raumtrennsysteme GmbH + Co. KG http://bau-umwelt.de/download/C4f62b935X13caac028f1XY2bd0/EPD_DHR_2012111_E.pdf Accessed on February 24, 2013
25	Gypsum_board panels with fire and moisture resistance, 2 x 12.5 mm wall thickness	m^2	9.0	Weight of one panel per area (two sandwich panels with rockwool in between with t= 75 mm) (kg/m^2): 9-10; thickness of gypsum board (mm): 12.5; thickness of rockwool: (mm): 50; width of gypsum board (m): 1.2; length of gypsum board (m): varies between 2.5-3.0	Knauf A.S. (2013). Alcipan http://www.knauf.com.tr/alcipan.asp?t=1&subs=0#x1 Accessed on February 19, 2013
26	Gypsum_board suspended ceiling (60x60) with fire and water resistance	m^2	6.0	Weight of one panel per area (kg/m^2): 6-7; thickness of gypsum board (mm): 9.5; width of gypsum board (m): 0.6; length of gypsum board (m): 0.6	Knauf A.S. (2013). Alcipan http://www.knauf.com.tr/alcipan.asp?t=2&subs=0#x2 Accessed on February 19, 2013

27	Cement fibre boards	m^2	24.0	Thickness (mm):16 ; width (m): 1.25; length (m): 2.8, unit weight (kg/m^3): 1,600	Tepe Betopan (2013). http://www.betopan.com.tr/bmalzeme.aspx Accessed on March 1, 2013 and LCI from Bau-Umwelt website: http://bau-umwelt.de/download/C4f37a652X1365375f564X6f35/EPD_CEM_2012111_E.pdf Accessed on March 01, 2013
28, 29, 30, 31	XPS_Extruded polystyrene foam for heat and fire insulation	m^2	2.1	Ethyl benzene polymer, max 90%. CAS #: 9003-53-6. Unit weight (kg/m^3), as specified in the technical documents: 30; thickness as specified in the technical documents (mm): 70	Audenaert et al. (2012); Izocam Ticaret ve Sanayi A.S. (2013). İzocam Foamboard Extruded Polystyrene (XPS) http://www.izocam.com.tr/izocam/media/urun-brosurleri/yalitim-malzemeleri/ekstrude-polistren-xps/msds-xps_turkce.pdf Accessed on February 21, 2013
32,33, 34, 35, 36	FPO (Flexible Polyolefin) membrane for water insulation.	m^2	0.2	Assume Sarnafi l® TU 111: for moderate climate and conditions. Thickness, min. (mm), as specified in the technical documents: 1.2; unit weight (kg/m^3): 150	Sika Supply Center AG (2008). Environmental Impact Study: Sarnafi l® TU www.sika.com Accessed on February 21, 2013
37,38	Polypropylene membrane for water insulation.	m^2	4.5	Thickness, min. (mm), average: 11; varies between 7-15 mm	Istanbul Technical (2013). Product Range for insulation materials. www.tradekey.com/brochure/32622-867179-4/yem-ist-eng.pdf Accessed on February 22, 2013
39a	Rock wool insulation for gypsum partition walls	m^2	15.0	Thickness, min. (mm), average: 50 ; unit weight (kg/m^3): 300 based on technical specifications	Izocam Ticaret ve Sanayi A.S. (2013). http://www.izocam.com.tr/izocam/media/urun-brosurleri/yalitim-malzemeleri/tasyunu_genel.pdf?ext=.pdf and http://malzeme.sermimar.net/tasyunu-ve-mantolama-metrekare-agirligi
39b	Rock wool insulation (60x60) for suspended ceilings	m^2	4.5	Thickness, min. (mm), average: 15 ; unit weight (kg/m^3): 300 based on technical specifications	Izocam Ticaret ve Sanayi A.S. (2013). http://www.izocam.com.tr/izocam/media/urun-brosurleri/yalitim-malzemeleri/tasyunu_genel.pdf?ext=.pdf and http://malzeme.sermimar.net/tasyunu-ve-mantolama-metrekare-agirligi
40	Laminated wood parquet flooring	m^2	6.5	Three-layered with polished surface and glued to the ground, similar to the multi-layered parquet flooring described in Nebel et al. (2006). Thickness, min. (mm), average: 15; width x length (m), min: 0.13 x 2	Nebel et al. (2006); Institut Bauen und Umwelt e.V. [IBU] (2012). EGGER Laminate Flooring. EGGER Retail Products GmbH & Co. KG http://bau-umwelt.de/download/CY3969297eX137a7270bd8XY3536/EPD_EHW_2008211_E.pdf Accessed on February 22, 2013

41	Laminated exterior facade cladding (HPL compact type) and internal wall cladding	m^2	16.8	Thickness, (mm), average: 12 ; unit weight (kg/m^3): 1,400	Technical specifications and Institut Bauen und Umwelt e.V. [IBU] (2012) Decorative High-Pressure Laminates (HPL). International Committee of the Decorative Laminates Industry (ICDLI). http://bau-umwelt.de/download/CY6523e6cX138558f4de4X3275/EPD_ICDLI_2012111_E.pdf Accessed on February 23, 2013. http://turkeybuilding.com/Urunler/wooden-facade-claddings-130459.html
42	Laminated wooden door, indoor	m^2	27.6	Unit weight (kg/m^3): 600; dimensions (m): 0.8 x 2	Zabalza Bribián et al. (2011)
43	American panel wooden door (100x220), indoor	piece	32.0	Weight of door (kg/piece) varies between 30-33 kg	Institut Bauen und Umwelt e.V. [IBU] http://bau-umwelt.de/download/C69eabf0eX135c8458dc6XY7e8f/EPD_EHW_2008311_E.pdf
44	Automatic revolving (or sliding) door	piece	336.8	Diameter 240cm, h=240cm (aluminum facade is not included)	Institut Bauen und Umwelt e.V. [IBU] http://bau-umwelt.de
45	Colored marble sill, parapet and capping - assume same density as marble tiles	m^2	80.6	Unit weight (kg/m^3), similar to marble products defined in Traverso et al. (2010): 2,685; width x length x thickness (mm): 300 x L X 30	Turkish Ministry of Public Works and Settlement cost estimation procedures (see http://www.birimfiyat.com/BF001.php?Ak=G1&D1=BAYINDIRLIK&Anh=7&kayno=04.410/1A Accessed on February 18, 2013)
46	Colored marble floor covering		67.1	Unit weight (kg/m^3), similar to marble products defined in Traverso et al. (2010): 2,685; width x length x thickness (mm): 600 x 300 x 25	Traverso et al. (2010)
47, 48	Colored marble stair covering	meter	20.1	Width x length x thickness (mm): 300 x L x 25	Turkish Ministry of Public Works and Settlement cost estimation procedures (see http://www.birimfiyat.com/BF001.php?Ak=G1&D1=BAYINDIRLIK&Anh=7&kayno=04.410/1A Accessed on February 18, 2013). Also RS Means specifies a stair cover thickness of 2.225. cm (7/8")
49	Lime washing	m^2	0.2	Lime/water ratio: 20/80; 3 coats are required on the basis of specifications, 20 liters cover an average of 70 m^2 per coat which is about 11.23 kg of solid quicklime per 70 m^2	http://www.lime.org/BLG/Mold.pdf
50	Paint, water-based, plastic paint, interior	m^2	0.2	Chemical structure: acrylic copolymer emulsion; unit weight (kg/m^3): 1,620; solid matter ratio: 72-75%; 2 coats are applied and 10 kg of paint can cover 10-12 m^2	http://www.kardelenboya.com.tr/en/products/water-based-interior-paint/kardelen-plastic/

51	Paint, water-based semi-matt plastic paint, interior	m2	0.2	Chemical structure: acrylic copolymer emulsion; unit weight (kg/m3): 1,100; with 3 coats of application	http://www.filliboya.com.tr/Upload/ProductOrjinal/637/ALP%C4%B0NA%20STYLE%20%C4%B0NC%C4%B0%20TEKNIK%20BULTEN%20TR.pdf Accessed on February 21, 2013
52	Paint, silicone-based grained paint for exterior façade	m^2	1.2	Unit weight (kg/m^3): 1,780; solid matter ratio: 74-76%; one coat application	http://www.kardelenboya.com.tr/en/products/water-based-exterior-paint/kardelen-silicone-based-textured-paint/ Accessed on February 22, 2013
53	Paint, silicone-based decorative paint for interiors	m^2	0.2	Unit weight (kg/m^3): 1,250; solid matter ratio: 35-40%; 2 coats of application	http://www.kardelenboya.com.tr/en/products/water-based-interior-paint/karsilan-silicone-based-matte-silk/ Accessed on February 23, 2013
54	Paint, Fasarit (water, silicone-based) spray paint for outer surfaces	m^2	1.4	2 coats of application; 0.6-0.8 kg per area, for the case study assume 0.7 kg/m^2	http://www.fasarit.com.tr/pdf/silikon.pdf Accessed on February 23, 2013
55	Anti-mold paint	m^2	0.2	Water emulsion; 3 coats of application; 55 - 80 ml/m2 per coat; 202.5 ml/m^2; unit weight: 1,100 kg/m^3	http://www.filliboya.com.tr/Upload/ProductOrjinal/657/INDEKO-W%20TEKNIK%20BULTEN%20TR.pdf Accessed on February 23, 2013
56	Plaster on outer façade (lime-based), two coats on exterior masonary walls	m^2	8.3	The product is "3-coat Portland cement-based stucco over masonary. The total thickness varies between 1.5-2 cm. 25 kg bucket covers about 6 m^2	ATHENA (2001)
57	Plaster on inner surfaces (gypsum-based)	m^2	6.3	For a 1.5 cm wall thickness; 2 coats of application, 25 kg for 8 m2 of wall area	European Commission - DG Joint Research Centre - Institute for Environment and Sustainability (2002). Gypsum plaster (CaSO4 alpha hemihydrates). http://lca.jrc.ec.europa.eu/lcainfohub/dataset2.vm?id=177 Accessed on February 24, 2013
58	Carpet (polyamide)	m^2	5.0	Weight per area varies: 4.8 - 5.1 kg/m^2	Samur Halıları Sanayi ve Ticaret A.Ş. (2013). Polyamide Carpet Products. http://samur.com.tr/karo/ Accessed on February 18, 2013
59	PVC floor tiles	m^2	1.4		Jönsson et al. (1997)
60a, 60b	Structural steel, rebars and mesh	kg		Already in mass units; based on EU and non-EU manufacturer's average data, representing BSt 500 steel bars, corresponding to DIN 488 or TS 708 standards	Institut Bauen und Umwelt e.V. [IBU] (2012) http://www.bauforumstahl.de/upload/documents/nachhaltigkeit/new_LCA_comparison_single_storey_buildings_2012.pdf Accessed on February 22, 2013
61	Structural steel, hot-rolled, mix of EAF (100% scrap) and BOF (35% scrap), represents Turkish steel industry	kg		Mix of EAF (100% scrap) and BOF (35% scrap) (represents Turkish industry)	Institut Bauen und Umwelt e.V. [IBU] (2010) http://bau-umwelt.de/download/C19f8156eX12e04597580XY2aa2/EPD_BFS_2010111_E.pdfAccess: February 21, 2013

62a, 62b	Steel, hot-dip galvanized with zinc alloy	kg		Light gauge steel profiles from hot-dip galvanized steel are used in construction industry as well as many other applications: roofing (roofing sheets, roof tiles), cladding (Trapezoidal sheets, sandwich panels, wall cassettes), interior trim (trapezoidal sheets, sandwich panels, wall cassettes),etc.	Institut Bauen und Umwelt e.V. [IBU] (2012) Akkon Steel, Istanbul. http://bau-umwelt.de/download/CY78cdb686X1374a76ec3aXY30a7/EPD_AKK_2012111_E.pdf Accessed on February 15, 2013
63	Stainless steel	kg		Electric furnace and argon–oxygen decarburization (AOD). Pig iron (94% Fe), chromites ore (27.0% Cr, 17.4% Fe); laterite ore (2.4% Ni, 13.4% Fe)	Norgate et al. (2007)
64	Steel, galvanized (for doors)	piece	40.0	90 min. fire resistant door and subframe galvanized steel (110x220)	Knight et al. (2005)
65	Natural stone (andasite and granite)	m^2	82.4	Facade cladding, granite cut panels; unit weight: 2,750 kg/m^3; length x width x thickness (m): 0.5 x 0.5 x 0.03; weight of one plate (kg): 21	EcoInvent v2.0
66a, 66b	Terrazzo tiles for interior and exterior surfaces	m^2	24.2	Raw materials: 1.5 kg marble dust and 0.23 kg marble chips per 0.09 m^2; 3.8 L epoxy resin per 0.8 m^2 (8.5 ft^2); and, depending on customer, from 1 % to 15 % pigment content. Marble dust and chips (77%), epoxy resin (22%), pigment (1%) by mass; unit weight (kg/m^3) from specifications: 2,550	BEES v4.0; http://www.dovetailinc.org/files/DovetailFloors0809.pdf; http://www.ntma.com/epoxy2.htm
67	Soft plywood for formwork	m^2	4.8	Where concrete surface is covered; second-class wood; unit weight (kg/m^3), for plywood boards: 456-533; for the case study: 500 kg/m^3; For 1 cm (3/8") thickness, weight per area (kg/m^2):	ATHENA (2008)
68	Steel formwork	m^2	12.2	Where concrete surface is not covered	
69	Copper conductor, wire	m	0.45	Copper wire is drawn from copper rod and is used in various applications, including power transmission and generation lines, building wiring, telecommunication and electrical and electronic products.	EPA WARM Version12 (2012) [370]

Table 9.12: Structural concrete mix designs and characteristics

Concrete Type	Strength (MPa)	Water (kg/m^3)	CEM I (kg/m^3)	Fine aggregates (kg/m^3)	Coarse aggregates (kg/m^3)	Super plasticizers (kg/m^3)	Unit weight (kg/m^3)	Air (%)	Water /cement
C16	16	170	215	1027	804	1.51	2,218	1.8	0.79
C20	20	160	250	1006	821	2.50	2,240	1.8	0.64
C25	25	175	300	924	817	3.60	2,220	1.8	0.58
C30	30	165	325	926	819	4.88	2,240	1.8	0.51
C35	35	169	366	867	831	6.22	2,239	1.8	0.46
Sources: GreenConcrete LCA Tool and Concrete Manufacturer's Mix designs, technical specifications									

Table 9.13: Non-structural (plain) concrete mix designs and characteristics

	150 Dose plain concrete (protective concrete)	250 Dose plain concrete (protective concrete)	400 dose leveling concrete, screed (Technical Specifications)	500 dose leveling concrete, screed (Technical Specifications)
Thickness (cm)	10	10	2.5	2.5
Portland cement (kg/m^3)	150	250	400	500
Fine aggregates (kg/m^3)	1,600	1,600	1,600	1,600
Water (kg/m^3)	130	130	260	260
Total (kg/m^3)	1,880	1,980	2,260	2,360
Note: The bulk density of aggregates in normal-weight concrete varies between 1,200-1,760 kg /m^3 (ACI Education Bulletin E1-07 Aggregates for Concrete). Based on Mehta and Monteiro (2006), natural mineral aggregates such as sand and gravel, have a bulk density of 1,520 and 1,680 kg /m^3				

Table 9.14: Building materials LCI factors (data sources are given in Table 9.15)

					Air emission factors (kg/unit of material or component)											
Item #	**Material type**	**Function**	**Unit**	**Primary Energy (MJ/unit)**	**CO_2**	**CO**	**Pb**	**CH_4**	**NO_x**	**N_2O**	**PM**	**SO_2**	**VOC**	**Solid Waste (kg)**	**Liquid Waste (kg)**

1	Aluminum	Window frame, external	kg	1.91E+02											
2	Aluminum	Door frame, internal	kg	2.18E+02											
3	Aluminum	Door frame, external	kg	1.91E+02											
4, 5	Aluminum	Suspended ceiling	kg	3.13E+02											
6	Aluminum	Façade cladding	m^2	4.28E+02											
7	Aluminum	Fixed sun brakers	kg	3.13E+02											
8, 9, 10, 11	Brick, hollow clay	Horizontal perforated bricks	kg	4.36E+00	2.02E-01	4.53E-05			3.31E-04		1.41E-05	2.00E-03	2.31E-05	2.30E-03	9.70E-03
12	Ceramic	Floor covering (tiles)	m^2	1.92E+02										2.33E-02	

13	Ceramic	Wall surface cladding (tiles)	m^2	1.70E+02											
14	Concrete	C25 structural concrete, retaining walls	m^3	2.12E+03	4.07E+02	1.75E-01	5.90E-06	2.65E+01	2.07E+00	7.26E-01	1.06E+03	9.62E-01	3.64E-03	7.81E+00	
15	Concrete	C30 structural concrete, foundation	m^3	2.21E+03	4.31E+02	1.81E-01	6.39E-06	2.62E+01	2.20E+00	7.18E-01	1.07E+03	1.03E+00	4.18E-03	8.43E+00	
16	Concrete	C35 structural concrete, beams, columns, slabs	m^3	2.41E+03	4.77E+02	1.88E-01	7.20E-06	2.75E+01	2.42E+00	7.52E-01	1.08E+03	1.14E+00	4.90E-03	9.49E+00	
17	Concrete	150 dose lean concrete, protective	m^3	1.32E+03	2.46E+02	1.28E-01	3.71E-06	1.91E+01	1.29E+00	5.21E-01	3.42E-01	5.59E-01	1.32E-03	4.36E+00	
18	Concrete	250 dose lean concrete, protective	m^3	1.78E+03	3.65E+02	1.50E-01	6.16E-06	2.17E+01	3.65E+02	5.93E-01	5.14E-01	8.50E-01	2.08E-03	7.10E+00	
19	Concrete	400 dose leveling concrete, screed	m^2	1.00E+03	8.25E+01	3.13E-02	1.35E-06	2.37E+01	2.22E-01	6.45E-01	1.76E-01	1.83E-01	8.06E-05	6.39E-01	
20	Concrete	500 dose leveling concrete, screed	m^2	1.01E+03	8.55E+01	3.18E-02	1.68E-06	2.37E+01	2.37E-01	6.47E-01	2.19E-01	1.90E-01	9.97E-05	7.07E-01	

21	Equipment	Elevator	piece	1.15E+05											
22	Glass	Partition wall, modular internal, whole flat glass	kg	1.55E+01											
23	Glass	4mm heat control coated (low-E) glass	kg	1.60E+01											
22, 23	Glass	Window, 4mm heat control coated (low-E) glass + 16mm air space + 4mm flat glass	kg	3.15E+01											
24	Glass	Partition wall, glass 90 min fire resistant, with automatic fire resistant glazed doors	m^2	1.53E+03										1.33E+02	
25, 26	Gypsum	Board panels, partition wall, internal and suspended ceiling	m^2	4.60E+01	2.55E+00	4.03E-03		2.74E-04	1.14E-02			7.88E-03	1.32E-03	2.17E+00	
27	Cement fibre board + gypsum board	Wall cladding, external	m^2												
28, 29, 30, 31	Extruded polystyrene foam (XPS)	Heat insulation	kg	9.07E+01								1.76E-02			

32, 33, 34, 35, 36	Flexible Polyolefin (FPO) membrane	Water insulation	kg	3.20E+00											
37, 38	Polypropylene (PP) membrane	Vapor and water insulation	kg	3.09E+00	1.67E+00	6.10E-03	1.99E-09		3.29E-03	4.82E-13	5.94E-04	3.78E-03	5.68E-05	1.34E-03	
39a, 39b	Rockwool	Heat insulation	kg	1.67E+01	8.05E-01	1.09E-04	5.31E-08		1.22E-03		1.16E-04	2.60E-03	1.16E-04		
40	Laminated wood	Floor covering (parquet)	m^2	9.17E+02										1.52E+01	
42	Laminated wood	Laminate covered wooden door	kg	1.272E+01										3.53E-01	
41, 42	Compact laminate	Exterior façade and internal wall surface claddings	m^2	1.24E+03										4.82E+01	
43	Wood	American panel, hard wood door (MDF, HDF)	kg	2.832E+01											
44	Other, Equipment	Automatic revolving (or sliding) door	piece	2.049E+04											

45, 46, 47, 48	Marble	Floor covering tiles	kg	6.60E-01	1.17E-01	1.28E-04			2.09E-04		2.07E-04	2.85E-04	3.17E-05		
49	Lime washing	Ceiling covering	kg	6.25E+00	7.68E-01						5.63E-05	1.50E-04			
50, 51, 52, 53, 54, 55	Paint (water-based or latex)	Wall covering (paint)	per amount that covers 20 m^2	1.07E+02	5.06E+00	5.13E-03			1.88E-02	7.25E-04	5.24E-03	3.29E-02	1.35E-01	4.70E+00	
56	Plaster on outer façade (lime-based)	Façade surface covering (plaster)	m^2	1.77E+01	2.65E+00	1.14E-03		5.35E-05	1.05E-02		6.34E-03	4.05E-04	2.06E-04	6.24E-02	
57	Plaster on interior surfaces (gypsum-based)	Wall covering (plaster)	kg	3.59E+00	2.30E-01	3.87E-05	7.76E-09	4.68E-04	2.02E-04	4.41E-06	1.21E-06	1.55E-04	1.26E+00	2.21E-01	
58	Polyamide	Floor covering (carpet)	m^2	1.65E+02	6.72E+00	8.07E-03			5.35E-02	2.01E-04	8.19E-02	3.16E-03	1.55E-02	1.71E+00	5.61E-02
59	PVC	Floor covering (tiles)	m^2	1.02E+02	4.56E+00	6.77E-03	5.01E-07	0.00E+00	6.52E-03	5.01E-04	1.93E-02	6.02E-03		1.02E+00	

60a, 60b	Steel, reinforcing bars and mesh	Structural steel	kg	1.34E+01											
	Steel, EAF and hot-rolled with 100% scrap (Best Tech)	Structural steel	kg	1.31E+01										1.49E+00	
	Steel, blast furnace (from iron ore, 64% Fe) and Basic oxygen furnace	Structural steel	tonne	2.30E+04										2.40E+03	
61	Steel, hot-rolled	Structural steel	tonne	2.01E+04										4.52E+03	
62a, 62b	Steel, hot-dip galvanized with zinc alloy	Non-structural metal work, stair handrails, door /window frames, metal sections, sheets, plates	tonne	3.86E+04										8.70E+01	
63	Stainless steel	Non-structural metal work, guardrails, gutters	tonne	7.50E+04										6.40E+03	
	Stainless steel, bath smelting	Non-structural metal work, guardrails	tonne	5.60E+04											
64	Steel, galvanized (for doors)	Door and subframe system - 90 min. fire resistant	kg	5.43E+01	3.375E+00			1.468E-01		2.500E-03				5.58E-01	

65	Natural stone (andasite and granite)	Façade cladding, polished stone	kg	9.78E+00	6.91E-01	8.54E-04	1.05E-09	2.84E-03	1.95E-03	7.29E-04	7.46E-03	1.48E-03	1.84E-04		3.73E+00
66a, 66b	Terrazzo tiles	Floor covering (tiles)	m^2	3.87E+01											
67	Soft plywood	Formwork	m^2	1.944E+02											
68	Steel formwork	Formwork	m^2	4.712E+02											
69	Copper conductors, wires	Electrical	tonne	1.425E+05											

Table 9.15: Building materials LCIA factors (per building material or component units)

Item #	**Material type**	**Unit**	**GHG (kg CO_2-eq)**	**Acidification (kg SO4-eq) or (kg SO2-eq)**	**Eutrophication (kg PO4-eq)**	**Photochemical oxidant formation potential (POCP) (kg ethylene or ethene-eq.)**	**Source**	**Region**	**Included processes and description**
1	Aluminum	kg	3.08E+00				[324]	EU, Spain	Section bar rolling for steel bars and fittings, extrusion for aluminum parts, extrusion of HDPE plastic, surface treatment with powder coating, transportation, and disposal of plastic cuttings. For aluminum, embodied energy

									varies: 166 - 312.7 MJ/kg [371]. Extruded, powder coated aluminum: 218 MJ/kg [325].
2	Aluminum	kg	9.21E+00				[325]	EU, New Zealand	69.8% from aluminum, 9.5% from glass fiber r/f plastic, 8.0% from section bar extrusion, and 7.65% from powder coating. All others constitute 5.1% of total GHGs
3	Aluminum	kg	3.08E+00				[324]	EU, Spain	
4, 5	Aluminum	kg	1.18E+01	9.48E-02			[112]	Greece	
6	Aluminum	m^2	2.51E+01	1.03E-01	1.03E-01	2,94E-01	[372]	EU	Based on a similar system called Metawell panels from [IBU] website
7	Aluminum	kg	1.18E+01				[112]	Greece	
8, 9, 10, 11	Brick, hollow clay	kg	2.21E-01	2.23E-03	3.00E-05		[336]	Greece	Diesel: 11.5%; Electricity: 2.4%; Pet-coke:86.1%
12	Ceramic	m^2	1.11E+01	2.38E-02	8.42E-03	2.35E-01	[330]	Turkey, EU	Pretreatment before production such as slurry preparation and production of granules by spray drying. Production covers forming, drying, glazing, firing and packaging. Transport is only relevant for delivery of raw materials to the plant and forklift usage within the factory.
13	Ceramic	m^2	9.74E+00	2.14E-02	7.17E-03		[331]	Turkey, EU	Same as item #12
14	Concrete	m^3	4.14E+02				[316]		Green Concrete LCA tool
15	Concrete	m^3	4.39E+02						Green Concrete LCA tool
16	Concrete	m^3	4.85E+02						Green Concrete LCA tool
17	Concrete	m^3	2.50E+02						Gro-beton or lean concrete is unreinforced concrete with a smaller ratio of cement to aggregate than structural concrete. It is used for not structural duties.
18	Concrete	m^3	3.70E+02						Green Concrete LCA tool
19	Concrete	m^2	8.64E+01						Green Concrete LCA tool
20	Concrete	m^2	8.94E+01						Green Concrete LCA tool
21	Equipment (elevator)	piece	7.07E+03				[373]	EU	About 10% of total primary energy use and 12% of total GWP is from raw materials and component manufacturing. Cradle-to-grave

22	Glass	kg	1.14E+00				[62, 70]	EU	Silica sand and soda are the major raw material input for glass manufacturing. Thermal energy for glass melting process is from EcoInvent [70]. The reference [62] estimates 15,511 MJ/tonne of flat glass. 57% from natural gas: 4.56 MJ; 38% from heavy fuel oil: 0.0738 kg oil; %5 from electricity: 0.111 kWh.
23	Glass	kg	1.18E+00				[62, 70]	EU	See above
22, 23	Glass	kg	2.31E+00				[34, 70]	EU	See above
24	Glass	m^2	6.68E+01	5.19E-01	5.55E-02	3.43E-02	[374]	EU	Similar to the DORMA Hüppe full wall system described in Bau-Umwelt link. Glass thickness varies between 10-12 mm. Single-pane safety glass partition system comprised of independently moving individual elements (including doors, manual or fully automatic operation)
25, 26	Gypsum	m^2	2.56E+00				Athena (1997)	Canada	Extraction of gypsum raw materials, crushing, calcination of gypsum to stucco, milling, drying, gypsum board production, paper manufacturing, and transportation. LCI for the 1/2" (12.5 cm) regular gypsum board with fire resistance (Type X). Dry weight: 8.1854 kg/m^2 and wet weight: 12.4370 kg/m^2
27	Cement fibre board + gypsum board	m^2					[375]	EU	See the source for further details
28, 29, 30, 31	Extruded polystyrene foam (XPS)	kg	1.91E+00				[70, 112]	Greece	For, GHG emission calculations HFC-134a, HFC-152a, styrene, etc. are included.
32, 33, 34, 35, 36	Flexible Polyolefin (FPO) membrane	kg	1.50E-01				[101]	UK	Based on Sarnafi l® TU 111 eco-profile Sika Supply Center AG (www.sika.com)
37, 38	Polypropylene (PP) membrane	kg	1.67E+00				[101, 163]	EU	Unit weight: 950 kg/m3 and primary energy use: 3,700 MJ/tonne
39a, 39b	Rockwool	kg	8.05E-01				[70, 376]	EU	The energy use is for the packed product. For unpacked rock wool: 15.2 MJ/kg. Range of data: 13-22.12 MJ/kg based on EcoInvent v2.0 Part XIV, Chapter 4.3.3 Table 4.11

40	Laminated wood	m^2	1.27E+01	2.23E-01	3.39E-02	4.90E-01	[300, 377]	Germany	Forest management, sawmilling, manufacturing, laying and surface finishing, refurbishment and end-of-life and transportation when appropriate. EOL scenario is the thermal utilization of the floor coverings. The energy gained during EOL is accounted for by system expansion (avoided burden approach).
42	Laminated wood	kg	(1.39E-01)	9.09E-04	1.93E-04	9.75E-05	[62, 70]	EU	Primary energy demand for laminated board shaped wood
41, 42	Compact laminate	m^2	3.74E+01	1.69E-01	2.93E-02	1.68E-02	[378]	EU	More than 60 % of the HPL consists of paper, and the remaining 30 to 40 % consists of cured phenol formaldehyde resin for core layers and melamine formaldehyde resin for the surface layer. The result is a homogeneous, non porous material with a density ≥ 1350 kg/m³
43	Wood	kg	(7.01E-01)	2.44E-03	6.82E-04	6.03E-04	[306, 375]	EU	Medium and high density Fiberboard with thicknesses between 6 and 40 mm with an average density of 720 kg/ m³ for MDF and 900 kg/m³ for HDF.
45, 46, 47, 48	Marble	kg	1.17E-01	4.43E-04	2.72E-05	1.71E-05	[335]	Italy	Assume same density for all marble elements, with a unit weight of 2,685 kg/m^3 as defined in [335].
49	Lime washing	kg	7.68E-01				[45]	US	NREL LCI database for quicklime, at plant. This module shows limestone mining and lime production as 2 separate unit processes, and also shows it as 1 cradle-to-gate process. Lime is manufactured by calcining in a rotary kiln.
50, 51, 52, 53, 54, 55	Paint (water-based or latex)	20 m^2	5.27E+00				[379]	EU	Water borne, styrene acrylic emulsion. Functional unit is the amount of paint that is needed to cover a $20m^2$ area to 98% opacity. Paint type LCI included in dissertation is the paint with water constitutes the solvent medium. And styrene-acrylate is the binder.

56	Plaster on outer façade (lime-based)	m^2	2.65E+00				Athena (2001)	Canada	LCI numbers are from ATHENA and designed for exterior stucco finishes, which are produced on "site", using as their inputs cement, hydraulic lime, and sand. The product is "3-coat Portland-cement based stucco over masonary. The LCI numbers are for a 1.5 cm wall thickness.
57	Plaster on interior surfaces (gypsum-based)	kg	2.42E-01				[380]	EU	CaSO4 alpha hemihydrates http://lca.jrc.ec.europa.eu/lcainfohub/dataset2.vm?id=177
58	Polyamide	m^2	6.77E+00	4.01E-02	7.02E-03	8.52E-03	[301]	EU	Functional unit was defined originally as 1.995 m^2
59	PVC	m^2	4.76E+00	8.52E-02	1.00E-03		[301]	EU	Extraction and processing of raw materials, product manufacturing, use, and waste disposal and processing.
60a, 60b	Steel, reinforcing bars and mesh	kg	8.70E-01	1.64E-03	1.39E-04	2.74E-04	[381]	EU	Based on EU and non-EU manufacturers' average data. Representing BSt 500 steel bars, corresponding to DIN 488 or TS 708 standards.
	Steel, EAF and hot-rolled with 100% scrap (Best Tech)	kg	6.70E-01	4.06E-03	2.33E-04	2.87E-04	[332]	EU	The LCA comprises raw material and energy consumption, raw material transports and the actual production phase of structural steel. Base material: 100% from metal scrap and EAF.
	Steel, BF and BOF	tonne	2.30E+03	2.00E+01			[382]	World average, Australia	Cradle-to-gate. Integrated route: Blast Furnace (BF) (from iron ore, 64% Fe) and Basic Oxygen Furnace (BOF)
61	Steel, hot-rolled	tonne	1.68E+03	3.47E-01	2.89E-01	7.55E-01	[381]	EU	The LCA comprises raw material and energy consumption, raw material transports and the actual production phase of structural steel. It covers steel products rolled out to structural sections, merchant bars and heavy plates, intended for bolting, welding or connecting. The Electric Arc Furnace type dominates the production phase in terms of primary energy input with a contribution ~75% while less than 25% is from BOF in Turkey (see OECD 2012 report). More than 70% of base material is metal scrap. Therefore, the data is representative of Turkish iron and steel industry.
62a, 62b	Steel, hot-dip galvanized with zinc alloy	tonne	2.62E+03	3.87E+01		2.13E+00	[333]	EU, Turkey	Raw materials extraction, transportation, and manufacturing stages. Turkey has a very active scrap market and produced nearly 90% of the steel from recycled steel in 2008. Steel products exported to the EU as well as used in the local market.

									Therefore, European recycling rate of 70% for steel is used in modeling end of life. Light gauge steel profiles manufactured from cold-formed galvanized steel sheets in thickness from 0.6 mm to 3.0mm at a single site by Akkon Steel Structure System Co. in Turkey. Profiles vary in thickness depending on the project requirements so averaged profile thickness of 1.5mm is used based on the production figures.
63	Stainless steel	tonne	6.80E+03	5.10E+01			[382]	World average, Australia	Electric furnace and argon–oxygen decarburization (AOD). Pig iron (94% Fe), chromate ore (27.0% Cr, 17.4% Fe); laterite ore (2.4% Ni, 13.4% Fe)
	Stainless steel, bath smelting	tonne	5.00E+03	4.00E+01	1.24E+01		[382]	World average, Australia	Cradle-to-gate. Bath smelting technology is more advanced compared to EF and AOD (see above) and takes place in a single reactor where ore and coal are both charged into the same melt or bath (hence the name “bath smelting”).
64	Steel, galvanized (for doors)	kg	3.53E+00				[383]	US	Cradle-to-gate.
65	Natural stone (andasite and granite)	kg	7.28E-01				[70]	Adjusted to Turkish grid mix	Granite mining, sawing, and cooling, polishing, transports within the mine, storage, infrastructure (machines).
66a, 66b	Terrazzo tiles	m^2	2.67E+00				[384]	US	Based on BEES model. Generic product. Extraction, processing, transportation, installation, and disposal
44	Other, Equipment (motorized door system)	piece	1.29E+03	8.38E+00	6.17E-01		[307]	EU	Raw materials extraction, transportation, and manufacturing stages.
67	Soft plywood	m^2	1.28E+00	2.03E-02			Athena (2008)	Canada	http://www.athenasmi.org/wp-content/uploads/2012/01/CIPEC_Canadian_Plywood_LCA_Final_Report.pdfAccessed on March 28, 2013
68	Steel formwork	m^2	3.22E+01						Same as item #62
69	Copper conductors, wires	tonne	8.080E+03				[370]	US	Assumed 100% virgin materials

9.3 Appendix C: Heavy-duty Truck and Construction Equipment Pool Database

Table 9.16: Projected Class Specific BSFCs by HDDV Model Year, in units of lb/bhp-hour **[309, 310]**

Model Year	2B	3	4	5	6	7	8A	8B
1988	0.544	0.532	0.493	0.460	0.435	0.399	0.400	0.377
1989	0.539	0.526	0.491	0.460	0.433	0.398	0.399	0.375
1990	0.533	0.521	0.489	0.459	0.431	0.397	0.397	0.372
1991	0.528	0.515	0.487	0.459	0.429	0.396	0.396	0.370
1992	0.523	0.509	0.485	0.458	0.427	0.395	0.395	0.368
1993	0.518	0.504	0.483	0.458	0.425	0.394	0.394	0.366
1994	0.512	0.498	0.481	0.458	0.423	0.393	0.392	0.364
1995	0.507	0.493	0.479	0.457	0.422	0.392	0.391	0.361
1996	0.502	0.487	0.477	0.457	0.420	0.391	0.390	0.359
1997	0.497	0.482	0.475	0.457	0.418	0.391	0.389	0.357
1998	0.492	0.477	0.474	0.456	0.416	0.390	0.388	0.355
1999	0.487	0.471	0.472	0.456	0.415	0.389	0.386	0.353
2000	0.483	0.466	0.470	0.455	0.413	0.388	0.385	0.351
2001	0.478	0.461	0.468	0.455	0.411	0.387	0.384	0.349
2002	0.473	0.456	0.466	0.455	0.409	0.386	0.383	0.347
2003	0.468	0.451	0.465	0.454	0.408	0.385	0.382	0.345
2004+	0.464	0.446	0.463	0.454	0.406	0.385	0.381	0.343

Table 9.17: Projected Fuel Economies by HDDV Weight Class and Model Year, in units mpg **[309, 310]**

Model Year	2B	3	4	5	6	7	8A	8B
1988	12	11	10	9	8	7	6	6
1989	12	11	10	9	8	7	6	6
1990	12	11	10	9	8	7	6	6
1991	12	11	10	9	8	7	6	6
1992	12	11	10	10	8	7	6	6
1993	13	11	10	10	9	7	6	6
1994	13	11	10	10	9	8	6	6
1995	13	12	10	10	9	8	6	6
1996	13	12	10	10	9	8	7	6
1997	13	12	10	10	9	8	7	6
1998	13	12	10	10	9	8	7	6
1999	13	12	10	10	9	8	7	7
2000	14	12	10	10	9	8	7	7
2001	14	12	11	10	9	8	7	7
2002	14	12	11	10	9	8	7	7
2003	14	13	11	10	9	8	7	7
2004+	14	13	11	11	9	8	7	7

Table 9.18: Conversion factors in bhp-hr/mi = Fuel Density (lb/gal) / [BSFC (lb/bhp-hr) x Fuel Economy (mpg)] [309, 310]

Model Year	**2B**	**3**	**4**	**5**	**6**	**7**	**8A**	**8B**
1988	1.103	1.253	1.496	1.676	1.979	2.392	2.925	3.368
1989	1.101	1.252	1.491	1.662	1.974	2.394	2.907	3.336
1990	1.099	1.251	1.486	1.649	1.969	2.396	2.890	3.305
1991	1.097	1.250	1.481	1.636	1.964	2.398	2.873	3.275
1992	1.095	1.250	1.476	1.623	1.960	2.400	2.856	3.246
1993	1.094	1.250	1.472	1.610	1.955	2.403	2.840	3.217
1994	1.093	1.250	1.467	1.597	1.951	2.405	2.824	3.189
1995	1.091	1.250	1.463	1.585	1.947	2.407	2.808	3.162
1996	1.090	1.250	1.458	1.573	1.942	2.409	2.793	3.135
1997	1.089	1.250	1.454	1.561	1.938	2.411	2.778	3.109
1998	1.088	1.251	1.450	1.549	1.934	2.413	2.763	3.083
1999	1.087	1.251	1.446	1.538	1.930	2.415	2.748	3.058
2000	1.087	1.252	1.441	1.527	1.927	2.417	2.734	3.034
2001	1.086	1.253	1.437	1.516	1.923	2.419	2.719	3.010
2002	1.086	1.254	1.434	1.505	1.919	2.421	2.706	2.987
2003	1.086	1.255	1.430	1.494	1.915	2.423	2.692	2.964
2004+	1.085	1.256	1.426	1.483	1.912	2.425	2.678	2.941

Table 9.19: HC Emission Factors for HDDV (raw data from MOBILE 6.1)

	HC Emission Factors - Zero Mile (new engine) Level (g/bhp-hr) based on MOBILE6.1 data								**HC Emission Factors - Deterioration rate (g/bhp-hr per 10,000 miles) based on MOBILE6.1 data**							
Model Year	**2B**	**3**	**4**	**5**	**6**	**7**	**8A**	**8B**	**2B**	**3**	**4**	**5**	**6**	**7**	**8A**	**8B**
1988	0.640	0.640	0.640	0.640	0.660	0.660	0.470	0.470	0.002	0.002	0.002	0.002	0.002	0.002	0.001	0.001
1989	0.640	0.640	0.640	0.640	0.660	0.660	0.470	0.470	0.002	0.002	0.002	0.002	0.002	0.002	0.001	0.001
1990	0.520	0.520	0.520	0.520	0.520	0.520	0.520	0.520	0.001	0.001	0.001	0.001	0.001	0.001	0.000	0.000
1991	0.470	0.470	0.470	0.470	0.400	0.400	0.300	0.300	0.001	0.001	0.001	0.001	0.001	0.001	0.000	0.000
1992	0.470	0.470	0.470	0.470	0.400	0.400	0.300	0.300	0.001	0.001	0.001	0.001	0.001	0.001	0.000	0.000
1993	0.470	0.470	0.470	0.470	0.400	0.400	0.300	0.300	0.001	0.001	0.001	0.001	0.001	0.001	0.000	0.000
1994	0.260	0.260	0.260	0.260	0.310	0.310	0.220	0.220	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001
1995	0.260	0.260	0.260	0.260	0.310	0.310	0.220	0.220	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001
1996	0.260	0.260	0.260	0.260	0.310	0.310	0.220	0.220	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001
1997	0.260	0.260	0.260	0.260	0.310	0.310	0.220	0.220	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001
1998	0.260	0.260	0.260	0.260	0.310	0.310	0.220	0.220	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001
1999	0.260	0.260	0.260	0.260	0.310	0.310	0.220	0.220	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001
2000	0.260	0.260	0.260	0.260	0.310	0.310	0.220	0.220	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001
2001	0.260	0.260	0.260	0.260	0.310	0.310	0.220	0.220	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001
2002	0.260	0.260	0.260	0.260	0.310	0.310	0.220	0.220	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001
2003	0.260	0.260	0.260	0.260	0.310	0.310	0.220	0.220	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001
2004+	0.140	0.140	0.140	0.140	0.170	0.170	0.170	0.170	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001

Table 9.20: Adjusted HC Emission Factors for HDDV (calculated by multiplication of Table 9.18 and Table 9.19)

	HC Emission Factors - Zero Mile (new engine) Level (g/miles)								**HC Emission Factors - Deterioration rate (g/miles) per 10,000 miles**							
Model Year	**2B**	**3**	**4**	**5**	**6**	**7**	**8A**	**8B**	**2B**	**3**	**4**	**5**	**6**	**7**	**8A**	**8B**
1988	0.706	0.802	0.957	1.073	1.306	1.579	1.375	1.583	0.002	0.003	0.003	0.003	0.004	0.005	0.003	0.003
1989	0.704	0.801	0.954	1.064	1.303	1.580	1.366	1.568	0.002	0.003	0.003	0.003	0.004	0.005	0.003	0.003
1990	0.571	0.651	0.773	0.857	1.024	1.246	1.503	1.719	0.001	0.001	0.001	0.002	0.002	0.002	0.000	0.000
1991	0.516	0.588	0.696	0.769	0.786	0.959	0.862	0.983	0.001	0.001	0.001	0.002	0.002	0.002	0.000	0.000
1992	0.515	0.587	0.694	0.763	0.784	0.960	0.857	0.974	0.001	0.001	0.001	0.002	0.002	0.002	0.000	0.000
1993	0.514	0.587	0.692	0.757	0.782	0.961	0.852	0.965	0.001	0.001	0.001	0.002	0.002	0.002	0.000	0.000

1994	0.284	0.325	0.381	0.415	0.605	0.745	0.621	0.702	0.001	0.001	0.001	0.002	0.002	0.002	0.003	0.003
1995	0.284	0.325	0.380	0.412	0.603	0.746	0.618	0.696	0.001	0.001	0.001	0.002	0.002	0.002	0.003	0.003
1996	0.283	0.325	0.379	0.409	0.602	0.747	0.614	0.690	0.001	0.001	0.001	0.002	0.002	0.002	0.003	0.003
1997	0.283	0.325	0.378	0.406	0.601	0.747	0.611	0.684	0.001	0.001	0.001	0.002	0.002	0.002	0.003	0.003
1998	0.283	0.325	0.377	0.403	0.600	0.748	0.608	0.678	0.001	0.001	0.001	0.002	0.002	0.002	0.003	0.003
1999	0.283	0.325	0.376	0.400	0.598	0.749	0.605	0.673	0.001	0.001	0.001	0.002	0.002	0.002	0.003	0.003
2000	0.283	0.325	0.375	0.397	0.597	0.749	0.601	0.667	0.001	0.001	0.001	0.002	0.002	0.002	0.003	0.003
2001	0.282	0.326	0.374	0.394	0.596	0.750	0.598	0.662	0.001	0.001	0.001	0.002	0.002	0.002	0.003	0.003
2002	0.282	0.326	0.373	0.391	0.595	0.751	0.595	0.657	0.001	0.001	0.001	0.002	0.002	0.002	0.003	0.003
2003	0.282	0.326	0.372	0.388	0.594	0.751	0.592	0.652	0.001	0.001	0.001	0.001	0.002	0.002	0.003	0.003
2004+	0.152	0.176	0.200	0.208	0.325	0.412	0.455	0.500	0.001	0.001	0.001	0.001	0.002	0.002	0.003	0.003

Table 9.21: CO Emission Factors for HDDV (raw data from MOBILE 6.1)

	CO Emission Factors - Zero Mile Level (g/bhp-hr) based on MOBILE6.1 data								**CO Emission Factors - Deterioration rate (g/bhp-hr/10,000 miles) based on MOBILE6.1 data**							
Model Year	**2B**	**3**	**4**	**5**	**6**	**7**	**8A**	**8B**	**2B**	**3**	**4**	**5**	**6**	**7**	**8A**	**8B**
1988	1.21	1.21	1.21	1.21	1.70	1.70	1.34	1.34	0.022	0.022	0.022	0.022	0.018	0.018	0.008	0.008
1989	1.21	1.21	1.21	1.21	1.70	1.70	1.34	1.34	0.022	0.022	0.022	0.022	0.018	0.018	0.008	0.008
1990	1.81	1.81	1.81	1.81	1.81	1.81	1.81	1.81	0.012	0.012	0.012	0.012	0.007	0.007	0.005	0.005
1991	0.40	0.40	0.40	0.40	1.26	1.26	1.82	1.82	0.004	0.004	0.004	0.004	0.010	0.010	0.003	0.003
1992	0.40	0.40	0.40	0.40	1.26	1.26	1.82	1.82	0.004	0.004	0.004	0.004	0.010	0.010	0.003	0.003
1993	0.40	0.40	0.40	0.40	1.26	1.26	1.82	1.82	0.004	0.004	0.004	0.004	0.010	0.010	0.003	0.003
1994	1.19	1.19	1.19	1.19	0.85	0.85	1.07	1.07	0.003	0.003	0.003	0.003	0.009	0.009	0.004	0.004
1995	1.19	1.19	1.19	1.19	0.85	0.85	1.07	1.07	0.003	0.003	0.003	0.003	0.009	0.009	0.004	0.004
1996	1.19	1.19	1.19	1.19	0.85	0.85	1.07	1.07	0.003	0.003	0.003	0.003	0.009	0.009	0.004	0.004
1997	1.19	1.19	1.19	1.19	0.85	0.85	1.07	1.07	0.003	0.003	0.003	0.003	0.009	0.009	0.004	0.004
1998	1.19	1.19	1.19	1.19	0.85	0.85	1.07	1.07	0.003	0.003	0.003	0.003	0.009	0.009	0.004	0.004
1999	1.19	1.19	1.19	1.19	0.85	0.85	1.07	1.07	0.003	0.003	0.003	0.003	0.009	0.009	0.004	0.004
2000	1.19	1.19	1.19	1.19	0.85	0.85	1.07	1.07	0.003	0.003	0.003	0.003	0.009	0.009	0.004	0.004
2001	1.19	1.19	1.19	1.19	0.85	0.85	1.07	1.07	0.003	0.003	0.003	0.003	0.009	0.009	0.004	0.004
2002	1.19	1.19	1.19	1.19	0.85	0.85	1.07	1.07	0.003	0.003	0.003	0.003	0.009	0.009	0.004	0.004
2003	1.19	1.19	1.19	1.19	0.85	0.85	1.07	1.07	0.003	0.003	0.003	0.003	0.009	0.009	0.004	0.004
2004+	1.19	1.19	1.19	1.19	0.85	0.85	1.07	1.07	0.003	0.003	0.003	0.003	0.009	0.009	0.004	0.004

Table 9.22: Adjusted CO Emission Factors for HDDV (calculated by multiplication of Table 9.18 and Table 9.21)

	CO Emission Factors - Zero Mile (new engine) Level (g/miles)								**CO Emission Factors - Deterioration rate (g/miles) per 10,000 miles**							
Model Year	**2B**	**3**	**4**	**5**	**6**	**7**	**8A**	**8B**	**2B**	**3**	**4**	**5**	**6**	**7**	**8A**	**8B**
1988	1.334	1.516	1.810	2.028	3.364	4.066	3.919	4.513	0.024	0.028	0.033	0.037	0.036	0.043	0.023	0.027
1989	1.332	1.515	1.804	2.012	3.356	4.070	3.896	4.470	0.024	0.028	0.033	0.037	0.036	0.043	0.023	0.027
1990	1.989	2.264	2.690	2.985	3.564	4.337	5.231	5.982	0.013	0.015	0.018	0.020	0.014	0.017	0.014	0.017
1991	0.439	0.500	0.592	0.654	2.475	3.022	5.229	5.961	0.004	0.005	0.006	0.007	0.020	0.024	0.009	0.010
1992	0.438	0.500	0.591	0.649	2.469	3.025	5.199	5.907	0.004	0.005	0.006	0.006	0.020	0.024	0.009	0.010
1993	0.438	0.500	0.589	0.644	2.464	3.027	5.169	5.855	0.004	0.005	0.006	0.006	0.020	0.024	0.009	0.010
1994	1.300	1.487	1.746	1.901	1.658	2.044	3.022	3.412	0.003	0.004	0.004	0.005	0.018	0.022	0.011	0.013
1995	1.299	1.487	1.741	1.886	1.655	2.046	3.005	3.383	0.003	0.004	0.004	0.005	0.018	0.022	0.011	0.013
1996	1.297	1.487	1.735	1.872	1.651	2.048	2.988	3.354	0.003	0.004	0.004	0.005	0.017	0.022	0.011	0.013
1997	1.296	1.488	1.730	1.858	1.648	2.049	2.972	3.326	0.003	0.004	0.004	0.005	0.017	0.022	0.011	0.012
1998	1.295	1.488	1.725	1.844	1.644	2.051	2.956	3.299	0.003	0.004	0.004	0.005	0.017	0.022	0.011	0.012
1999	1.294	1.489	1.720	1.830	1.641	2.053	2.940	3.272	0.003	0.004	0.004	0.005	0.017	0.022	0.011	0.012
2000	1.293	1.490	1.715	1.817	1.638	2.055	2.925	3.246	0.003	0.004	0.004	0.005	0.017	0.022	0.011	0.012
2001	1.293	1.491	1.711	1.803	1.634	2.056	2.910	3.221	0.003	0.004	0.004	0.005	0.017	0.022	0.011	0.012
2002	1.292	1.492	1.706	1.791	1.631	2.058	2.895	3.196	0.003	0.004	0.004	0.005	0.017	0.022	0.011	0.012
2003	1.292	1.494	1.701	1.778	1.628	2.060	2.880	3.171	0.003	0.004	0.004	0.004	0.017	0.022	0.011	0.012
2004+	1.292	1.495	1.697	1.765	1.625	2.062	2.866	3.147	0.003	0.004	0.004	0.004	0.017	0.022	0.011	0.012

Table 9.23: NO_x Emission Factors for HDDV (raw data from MOBILE 6.1)

	NO_x Emission Factors - Zero Mile Level (g/bhp-hr) based on MOBILE6.1data								**NO_x Emission Factors - Deterioration rate (g/bhp-hr/10,000 miles) based on MOBILE6.1 data**							
Model Year	**2B**	**3**	**4**	**5**	**6**	**7**	**8A**	**8B**	**2B**	**3**	**4**	**5**	**6**	**7**	**8A**	**8B**
1988	4.34	4.34	4.34	4.34	6.43	6.43	6.28	6.28	0.002	0.002	0.002	0.002	0.009	0.009	0.010	0.010
1989	4.34	4.34	4.34	4.34	6.43	6.43	6.28	6.28	0.002	0.002	0.002	0.002	0.009	0.009	0.010	0.010
1990	4.85	4.85	4.85	4.85	4.85	4.85	4.85	4.85	0.011	0.011	0.011	0.011	0.006	0.006	0.004	0.004
1991	4.38	4.38	4.38	4.38	4.53	4.53	4.56	4.56	0.003	0.003	0.003	0.003	0.007	0.007	0.004	0.004
1992	4.38	4.38	4.38	4.38	4.53	4.53	4.56	4.56	0.003	0.003	0.003	0.003	0.007	0.007	0.004	0.004
1993	4.38	4.38	4.38	4.38	4.53	4.53	4.56	4.56	0.003	0.003	0.003	0.003	0.007	0.007	0.004	0.004
1994	4.08	4.08	4.08	4.08	4.61	4.61	4.61	4.61	0.001	0.001	0.001	0.001	0.001	0.001	0.003	0.003

1995	4.08	4.08	4.08	4.08	4.61	4.61	4.61	4.61	0.001	0.001	0.001	0.001	0.001	0.001	0.003	0.003
1996	4.08	4.08	4.08	4.08	4.61	4.61	4.61	4.61	0.001	0.001	0.001	0.001	0.001	0.001	0.003	0.003
1997	4.08	4.08	4.08	4.08	4.61	4.61	4.61	4.61	0.001	0.001	0.001	0.001	0.001	0.001	0.003	0.003
1998	3.26	3.26	3.26	3.26	3.69	3.69	3.68	3.68	0.001	0.001	0.001	0.001	0.001	0.001	0.003	0.003
1999	3.26	3.26	3.26	3.26	3.69	3.69	3.68	3.68	0.001	0.001	0.001	0.001	0.001	0.001	0.003	0.003
2000	3.26	3.26	3.26	3.26	3.69	3.69	3.68	3.68	0.001	0.001	0.001	0.001	0.001	0.001	0.003	0.003
2001	3.26	3.26	3.26	3.26	3.69	3.69	3.68	3.68	0.001	0.001	0.001	0.001	0.001	0.001	0.003	0.003
2002	3.26	3.26	3.26	3.26	3.69	3.69	3.68	3.68	0.001	0.001	0.001	0.001	0.001	0.001	0.003	0.003
2003	3.26	3.26	3.26	3.26	3.69	3.69	3.68	3.68	0.001	0.001	0.001	0.001	0.001	0.001	0.003	0.003
2004+	1.99	1.99	1.99	1.99	2.10	2.10	2.11	2.11	0.001	0.001	0.001	0.001	0.001	0.001	0.003	0.003

Table 9.24: Adjusted NO$_x$ Emission Factors for HDDV (calculated by multiplication of Table 9.18 and Table 9.23)

	NO$_x$ Emission Factors - Zero Mile Level (g/miles)								**NO$_x$ Emission Factors - Deterioration rate(g/miles) per 10,000 miles**							
Model Year	**2B**	**3**	**4**	**5**	**6**	**7**	**8A**	**8B**	**2B**	**3**	**4**	**5**	**6**	**7**	**8A**	**8B**
1988	4.786	5.437	6.492	7.275	12.723	15.380	18.368	21.148	0.002	0.003	0.003	0.003	0.018	0.022	0.029	0.034
1989	4.777	5.433	6.471	7.215	12.692	15.394	18.257	20.950	0.002	0.003	0.003	0.003	0.018	0.022	0.029	0.033
1990	5.329	6.068	7.207	7.997	9.550	11.622	14.016	16.030	0.012	0.014	0.016	0.018	0.012	0.014	0.012	0.013
1991	4.805	5.477	6.487	7.164	8.899	10.865	13.101	14.934	0.003	0.004	0.004	0.005	0.014	0.017	0.011	0.013
1992	4.798	5.475	6.467	7.107	8.878	10.874	13.025	14.800	0.003	0.004	0.004	0.005	0.014	0.017	0.011	0.013
1993	4.791	5.474	6.446	7.051	8.858	10.884	12.951	14.670	0.003	0.004	0.004	0.005	0.014	0.017	0.011	0.013
1994	4.458	5.098	5.986	6.517	8.994	11.086	13.019	14.701	0.001	0.001	0.001	0.002	0.002	0.002	0.008	0.010
1995	4.452	5.098	5.968	6.467	8.974	11.095	12.946	14.575	0.001	0.001	0.001	0.002	0.002	0.002	0.008	0.009
1996	4.448	5.099	5.950	6.417	8.955	11.105	12.875	14.452	0.001	0.001	0.001	0.002	0.002	0.002	0.008	0.009
1997	4.444	5.100	5.932	6.369	8.936	11.114	12.805	14.332	0.001	0.001	0.001	0.002	0.002	0.002	0.008	0.009
1998	3.548	4.077	4.726	5.051	7.138	8.904	10.167	11.347	0.001	0.001	0.001	0.002	0.002	0.002	0.008	0.009
1999	3.545	4.079	4.713	5.013	7.123	8.912	10.113	11.255	0.001	0.001	0.001	0.002	0.002	0.002	0.008	0.009
2000	3.543	4.081	4.699	4.977	7.109	8.919	10.060	11.165	0.001	0.001	0.001	0.002	0.002	0.002	0.008	0.009
2001	3.541	4.084	4.686	4.941	7.095	8.927	10.008	11.077	0.001	0.001	0.001	0.002	0.002	0.002	0.008	0.009
2002	3.540	4.088	4.673	4.905	7.081	8.934	9.956	10.991	0.001	0.001	0.001	0.002	0.002	0.002	0.008	0.009
2003	3.539	4.092	4.661	4.870	7.068	8.942	9.906	10.907	0.001	0.001	0.001	0.001	0.002	0.002	0.008	0.009
2004+	2.160	2.500	2.837	2.952	4.015	5.093	5.651	6.206	0.001	0.001	0.001	0.001	0.002	0.002	0.008	0.009

Table 9.25: PM Emission Factors for HDDV (raw data from MOBILE 6.1 [312])

	PM Emission Factors (g/bhp-hr)							
Model Year	**2B**	**3**	**4**	**5**	**6**	**7**	**8A**	**8B**
1988	0.60	0.60	0.60	0.60	0.60	0.60	0.60	0.60
1989	0.60	0.60	0.60	0.60	0.60	0.60	0.60	0.60
1990	0.60	0.60	0.60	0.60	0.60	0.60	0.60	0.60
1991	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25
1992	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25
1993	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25
1994	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10
1995	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10
1996	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10
1997	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10
1998	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10
1999	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10
2000	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10
2001	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10
2002	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10
2003	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10
2004+	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10
2005	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10
2006	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10
2007+	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01

Table 9.26: Adjusted PM Emission Factors for HDDV (calculated by multiplication of Table 9.18 and Table 9.25)

	PM Emission Factors (g/miles)							
Model Year	**2B**	**3**	**4**	**5**	**6**	**7**	**8A**	**8B**
1988	0.662	0.752	0.898	1.006	1.187	1.435	1.755	2.021
1989	0.660	0.751	0.895	0.997	1.184	1.436	1.744	2.002
1990	0.659	0.751	0.892	0.989	1.181	1.438	1.734	1.983
1991	0.274	0.313	0.370	0.409	0.491	0.600	0.718	0.819
1992	0.274	0.312	0.369	0.406	0.490	0.600	0.714	0.811
1993	0.273	0.312	0.368	0.402	0.489	0.601	0.710	0.804
1994	0.109	0.125	0.147	0.160	0.195	0.240	0.282	0.319
1995	0.109	0.125	0.146	0.158	0.195	0.241	0.281	0.316
1996	0.109	0.125	0.146	0.157	0.194	0.241	0.279	0.313
1997	0.109	0.125	0.145	0.156	0.194	0.241	0.278	0.311
1998	0.109	0.125	0.145	0.155	0.193	0.241	0.276	0.308
1999	0.109	0.125	0.145	0.154	0.193	0.242	0.275	0.306
2000	0.109	0.125	0.144	0.153	0.193	0.242	0.273	0.303
2001	0.109	0.125	0.144	0.152	0.192	0.242	0.272	0.301
2002	0.109	0.125	0.143	0.150	0.192	0.242	0.271	0.299
2003	0.109	0.126	0.143	0.149	0.192	0.242	0.269	0.296
2004+	0.109	0.126	0.143	0.148	0.191	0.243	0.268	0.294
2005	0.109	0.126	0.143	0.148	0.191	0.243	0.268	0.294
2006	0.109	0.126	0.143	0.148	0.191	0.243	0.268	0.294
2007+	0.109	0.126	0.143	0.148	0.191	0.243	0.268	0.294

Table 9.27: Adjusted SO_2 Emission Factors for HDDVs*

Sulfur content (ppm)	**SO_2 Emission Factors (g/mi) for diesel fuels**								
	Model Year	**2B**	**3**	**4**	**5**	**6**	**7**	**8A**	**8B**
15	1988	0.016	0.018	0.020	0.021	0.023	0.026	0.032	0.035
15	1989	0.016	0.018	0.020	0.021	0.023	0.026	0.032	0.034
15	1990	0.016	0.018	0.020	0.021	0.023	0.026	0.031	0.033
15	1991	0.016	0.018	0.020	0.020	0.023	0.026	0.031	0.033
15	1992	0.016	0.017	0.019	0.020	0.023	0.026	0.031	0.032
15	1993	0.015	0.017	0.019	0.020	0.023	0.026	0.030	0.032
15	1994	0.015	0.017	0.019	0.020	0.022	0.026	0.030	0.032
15	1995	0.015	0.017	0.019	0.020	0.022	0.026	0.030	0.031
15	1996	0.015	0.017	0.019	0.020	0.022	0.026	0.030	0.031
15	1997	0.015	0.016	0.019	0.019	0.022	0.026	0.029	0.030
15	1998	0.015	0.016	0.019	0.019	0.022	0.026	0.029	0.030
15	1999	0.014	0.016	0.019	0.019	0.022	0.026	0.029	0.029
15	2000	0.014	0.016	0.018	0.019	0.022	0.026	0.029	0.029
15	2001	0.014	0.016	0.018	0.019	0.022	0.025	0.028	0.029
15	2002	0.014	0.016	0.018	0.019	0.021	0.025	0.028	0.028
15	2003	0.014	0.015	0.018	0.018	0.021	0.025	0.028	0.028
15	2004+	0.014	0.015	0.018	0.018	0.021	0.025	0.028	0.027
500	1988	0.544	0.605	0.669	0.699	0.780	0.866	1.061	1.151
500	1989	0.538	0.598	0.664	0.693	0.775	0.864	1.051	1.134
500	1990	0.532	0.591	0.659	0.687	0.770	0.863	1.042	1.116
500	1991	0.525	0.584	0.654	0.681	0.764	0.862	1.032	1.100
500	1992	0.519	0.577	0.649	0.675	0.759	0.861	1.023	1.083
500	1993	0.514	0.571	0.645	0.669	0.754	0.859	1.014	1.067
500	1994	0.508	0.565	0.640	0.663	0.749	0.858	1.005	1.052
500	1995	0.502	0.558	0.636	0.657	0.745	0.857	0.996	1.036
500	1996	0.497	0.552	0.631	0.652	0.740	0.856	0.988	1.022
500	1997	0.491	0.546	0.627	0.647	0.735	0.854	0.980	1.007
500	1998	0.486	0.541	0.623	0.641	0.731	0.853	0.971	0.993
500	1999	0.481	0.535	0.619	0.636	0.726	0.852	0.963	0.979
500	2000	0.476	0.529	0.615	0.631	0.722	0.851	0.955	0.966
500	2001	0.471	0.524	0.611	0.626	0.717	0.850	0.948	0.953
500	2002	0.466	0.518	0.607	0.621	0.713	0.848	0.940	0.940
500	2003	0.461	0.513	0.603	0.616	0.709	0.847	0.933	0.927
500	2004+	0.457	0.508	0.599	0.611	0.704	0.846	0.925	0.915

* Calculated based on the methodology which assumes that 98 percent of the fuel sulfur is converted to gaseous SO_2 emissions and remaining 2 percent is converted to sulfate emissions. The gaseous SO_2 emission is a function of user input fuel sulfur level and the vehicle fuel economies [385].

Table 9.28: Construction Equipment Pool Database

Brand	Model	Net Power (hp) or (watts)	Bucket or mixer drum capacity (m^3) or crane capacity (mt)	Power Source	Truck GCWR or equipment weight (EWe) (kg)	Concrete Pump Output (m3/hr)	Source
Hydraulic Excavator (Backhoe)							
Caterpillar	311D LRR	80	0.4	diesel	12,480		http://www.cat.com/equipment/hydraulic-excavators/small-hydraulic-excavators Accessed on March 20, 2013.
Caterpillar	312D/ 312DL	90	0.5	diesel	12,918		
Caterpillar	315DL	115	0.6	diesel	17,449		
Caterpillar	319DL/ 319DLN	125	0.8	diesel	19,480		
Caterpillar	320DL	148	1.0	diesel	20,330		
Caterpillar	324E	194	1.1	diesel	29,479		
Caterpillar	328D LCR	204	1.2	diesel	34,700		
Caterpillar	336DL	268	1.6	diesel	35,668		
Caterpillar	336EL	300	1.7	diesel	36,567		
Caterpillar	345DL	380	1.8	diesel	45,377		
Caterpillar	365CL	404	2.7	diesel	65,966		
Caterpillar	374DL	476	3.8	diesel	71,132		
Caterpillar	385C L	513	4.6	diesel	84,985		
Caterpillar	390L	523	6.0	diesel	86,190		
Wheel Loader (Assume 25 mph, min speed)							
Caterpillar	904H	52	0.6	diesel	4,491		http://www.cat.com/equipment/wheel-loaders/compact-wheel-loaders# Accessed on March 20, 2013.
Caterpillar	906H	70	0.9	diesel	5,630		
Caterpillar	908H	79	1.1	diesel	6,465		
Caterpillar	914G	95	1.4	diesel	7,950		
Komatsu	WA150-5	96	1.5	diesel	7,425		http://www.komatsu.com/ce/products/wheel_loaders.html
Komatsu	WA180-3	110	1.7	diesel	8,700		

Komatsu	WA200-6	126	2.0	diesel	9,630		Accessed on March 20, 2013.
Caterpillar	924H	128	2.1	diesel	11,632		http://xml.catmms.com/servlet/ImageServlet?imageId=C332527
Komatsu	WA250PZ-6	138	2.2	diesel	12,690		http://www.komatsu.com/ce/products/wheel_loaders.html Accessed on March 20, 2013.
Komatsu	WA250-5	135	2.3	diesel	10,620		
Komatsu	WA320-3	163	2.7	diesel	13,700		
Caterpillar	930H	149	2.8	diesel	13,029		http://www.cat.com/equipment/wheel-loaders/midsize-wheel-loaders Accessed on March 20, 2013.
Caterpillar	938H	180	3.0	diesel	15,055		
Komatsu	WA380-3	187	3.2	diesel	16,480		http://www.komatsu.com/ce/products/wheel_loaders.html Accessed on March 20, 2013.
Caterpillar	950H	197	3.3	diesel	18,341		http://www.cat.com/equipment/wheel-loaders/midsize-wheel-loaders Accessed on March 20, 2013.
Caterpillar	962H	211	3.5	diesel	19,368		
Komatsu	WA430-5	217	3.7	diesel	18,350		http://www.komatsu.com/ce/products/wheel_loaders.html
Caterpillar	966H	262	3.8	diesel	23,702		http://www.cat.com/equipment/wheel-loaders/midsize-wheel-loaders
Caterpillar	972H	287	4.0	diesel	25,152		
Komatsu	WA470-5	261	4.2	diesel	21,600		http://www.komatsu.com/ce/products/wheel_loaders.html
Komatsu	WA480-6	299	4.6	diesel	25,005		
Concrete mixer truck							
Generic		285	9.2	diesel			RS Means 2013
International	Paystar 5600i	330	8.0	diesel			http://www.mixertrucks.com/uploadedfiles/IH00MTM105FVTX.pdf

Peterbilt	357 6x6	305	8.0	diesel			http://www.mixertrucks.com/uploadedfiles/PT00MT_FV_FL.pdf
Volvo	WG64F	335	8.0	diesel			http://www.rockanddirt.com/trucks-for-sale/VOLVO/WG64F/invnum=8409798
Terex	FD3000	425	8.0	diesel	29,937		http://www.terex.com/
Generic		250	6.1	diesel			RS Means 2013
Terex	Rear discharge	565	6.9	diesel			http://www.terex.com/
Air compressor							
Sullair portable	1600H	540		diesel	7,416		http://www.sullair.com/
Sullair portable	425	140		diesel	2,014		
Sullair portable	130	61		diesel	966		
Concrete pump							
Putzmeister	VS 60HP truck-mounted	131		diesel	8,733	46	http://www.putzmeisteramerica.com/pdfs/CP2626-6_US.pdf
Putzmeister	VS 50 truck-mounted	100		diesel	8,733	41	
Putzmeister	VS 70 truck-mounted	100		diesel	8,733	57	
Putzmeister	CP 2116H truck-mounted	250		diesel	9,460	160	http://www.putzmeisteramerica.com/pdfs/CP_3136-1_US.pdf
Putzmeister	CP 2112L truck-mounted	250		diesel	9,460	109	
Putzmeister	CP 1409H truck-mounted	250		diesel	9,460	90	
Schwing	SP8000-2018-7 stationary	590		diesel	9,979	94	http://www.schwing.com/01_cpumps/linepumps/pdf/SP4800-8800_Brochure.pdf
Schwing	SP8000-2020-7 stationary	590		diesel	9,979	116	
Schwing	SP4800-2018-5 stationary	443		diesel	8,000	66	
Schwing	SP4800-2020-5 stationary	443		diesel	8,000	81	
Crane, truck mounted							
Grove-Manitowoc	TM500E-2	300	40	diesel	25,912		http://www.manitowoccra

Grove -Manitowoc	TMS 700E	450	50	diesel	39,657		nes.com/MCG_GRO/Products/EN/Range_TM.asp
Grove -Manitowoc	TMS 800E	450	73	diesel	41,817		
Grove -Manitowoc	TMS 9000E	450	100	diesel	40,811		
Cutting torch							
(Arc gouging) Arcair	Extreme	9,600		electricity			Guggemos 2003
(AHPA 120A) Thermal Dynamics	PakMaster 150XL	24,960		electricity			Guggemos 2003
Forklift							
Gradall	544D10-55	125	4.54	diesel	15,227		http://www.goldcoasthilift.com/equipment_pdf_library/Gradall_544D10-55_Telehandler_Product_Brochure.pdf
Gradall	534D10-45	115	4.54	diesel	11,476		http://www.goldcoasthilift.com/equipment_pdf_library/Gradall_534D10_Telehandler_Product_Brochure.pdf
Caterpillar	TL1255	135	5.44	diesel	16,057		http://xml.catmms.com/servlet/ImageServlet?imageId=C477524
Generator							
Dewalt	DG4300	8		gasoline	75		Guggemos 2003
Dewalt	DG6000	11		gasoline	84		Guggemos 2003
Multiquip	GA-3.6 HZ	8		gasoline	75		Guggemos 2003
Multiquip	GA-6HZR	11		gasoline	90		Guggemos 2003
Power saw, concrete							
Circular Saw		1,350		electricity			Guggemos 2003
Circular Saw		1,150		electricity			Guggemos 2003
Circular Saw	7-1/4"	900		electricity			Guggemos 2003
Circular Saw	8-1/4"	1,400		electricity			Guggemos 2003
Circular Saw		1,100		electricity			Guggemos 2003
Target	14" Quickie	1,800		electricity	12		Guggemos 2003

Makita	5740NB	1,260		electricity	4		Guggemos 2003
Generic	Saws, band, table saw	3		gasoline			RS Means 2013 (4 hours daily)
Rebar bender							
Multiquip	MB-25A	1,500		electricity	150		http://www.multiquip.com/multiquip/pdfs/product-brochures/Rebar_low_res_0711.pdf
Diamond Northern	DBD-32X	1,400		electricity	180		http://www.diamondnorthern.com/dbd-32x-rebar-bender/
Diamond Northern	DBD-25X	1,400		electricity	86		http://www.diamondnorthern.com/dbd-25x-rebar-bender/
Rebar cutter							
Diamond Northern	DC-20WH	1,200		electricity	12		http://www.diamondnorthern.com/dc-20wh-rebar-cutter/
Diamond Northern	DC-32WH	2,100		electricity	36		http://www.diamondnorthern.com/dc-32wh-rebar-cutter/
Diamond Northern	DC-25X	1,200		electricity	22		http://www.diamondnorthern.com/rebar-cutter-dc-25x/
Multiquip	HBC-19B	1,330		electricity	18		http://www.multiquip.com/multiquip/pdfs/product-brochures/Rebar_low_res_0711.pdf
Multiquip	HBC-25B	1,430		electricity	30		http://www.multiquip.com/multiquip/pdfs/product-brochures/Rebar_low_res_0711.pdf
Multiquip	BC-25	1,400		electricity	58		http://www.pcesas.com/pdfs/MQ_Bender_Cutter.pdf
Shear Stud Welder							
Stud Welding Assoc.	CD-512	2,200		electricity	25		Guggemos 2003
Stud Welding Assoc.	CD-312	2,200		electricity	21		Guggemos 2003
Steel Grinder							
Gallmeyer & Livingston		3,729		electricity	2,495		Guggemos 2003

Koyo		55,927		electricity			Guggemos 2003
Steel Plate Cutter							
(AHPA 300A) ESAB		36,000		electricity	599		Guggemos 2003
(AHPA 150A) ESAB		33,000		electricity	343		Guggemos 2003
Steel Press							
Bertsch	550 ton	3,729		electricity			Guggemos 2003
Chicago D&K	412DSP	55,927		electricity			Guggemos 2003
Steel Punch Equipment							
Kling	Ironworker #44	3,729		electricity			Guggemos 2003
Union Boring Mill	BFT-90/3-2 3	11,185		electricity	8,618		Guggemos 2003
Steel Spray (Paint) Equipment							
Speeflo	HydraM2000			electricity			Guggemos 2003
Speeflo	PT12000GHD	6,711		electricity			Guggemos 2003
Graco	HydraMax350	11		electricity			Guggemos 2003
Titan	1140i	1,193		electricity			Guggemos 2003
Vibrator							
Oztec	1.2 oz.	1,080		electricity			Guggemos 2003
Oztec	1.8 oz.	1,800		electricity			Guggemos 2003
Oztec	2.4 oz.	2,040		electricity			Guggemos 2003
Oztec	3.2 oz.	2,280		electricity			Guggemos 2003
Generic		1,491		electricity			RS Means 2013
Generic		2,237		electricity			RS Means 2013
Oztec	GV-5	5		gasoline			Guggemos 2003
Oztec	GV-5H	5.5		gasoline			Guggemos 2003
Generic		5		gasoline			RS Means 2013
Generic		8		gasoline			
Welder							

(SMAW, GMAW, FCAW) - Miller heavy duty	Gold Star 302	9,600		electricity	160		Guggemos 2003
(SMAW) - Maxstar	300 DX	7,500		electricity	39		Guggemos 2003
(SMAW, FCAW) - Invision	456MP	17,100		electricity	54		Guggemos 2003
(SMAW, GMAW, FCAW) - Invision	354MP	9,600		electricity	34		Guggemos 2003
Welder	140A	4,000		electricity			

Table 9.29: BSFC and emission factors data for diesel-engine powered non-road construction equipment [146]

	BSFC (Brake Specific Fuel Consumption) (lb/hp-hr)												
Engine Power	**0-11**	**>11-16**	**>16-25**	**>25-50**	**>50-75**	**>75-100**	**>100-175**	**>175-300**	**>300-600**	**>600-750**	**>750**	**> 750-1200**	**>1200**
Model Year	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**
pre-1988	0.408	0.408	0.408	0.408	0.408	0.408	0.367	0.367	0.367	0.367	0.367	0.367	0.367
1988	0.408	0.408	0.408	0.408	0.408	0.408	0.367	0.367	0.367	0.367	0.367	0.367	0.367
1989	0.408	0.408	0.408	0.408	0.408	0.408	0.367	0.367	0.367	0.367	0.367	0.367	0.367
1990	0.408	0.408	0.408	0.408	0.408	0.408	0.367	0.367	0.367	0.367	0.367	0.367	0.367
1991	0.408	0.408	0.408	0.408	0.408	0.408	0.367	0.367	0.367	0.367	0.367	0.367	0.367
1992	0.408	0.408	0.408	0.408	0.408	0.408	0.367	0.367	0.367	0.367	0.367	0.367	0.367
1993	0.408	0.408	0.408	0.408	0.408	0.408	0.367	0.367	0.367	0.367	0.367	0.367	0.367
1994	0.408	0.408	0.408	0.408	0.408	0.408	0.367	0.367	0.367	0.367	0.367	0.367	0.367
1995	0.408	0.408	0.408	0.408	0.408	0.408	0.367	0.367	0.367	0.367	0.367	0.367	0.367
1996	0.408	0.408	0.408	0.408	0.408	0.408	0.367	0.367	0.367	0.367	0.367	0.367	0.367
1997	0.408	0.408	0.408	0.408	0.408	0.408	0.367	0.367	0.367	0.367	0.367	0.367	0.367
1998	0.408	0.408	0.408	0.408	0.408	0.408	0.367	0.367	0.367	0.367	0.367	0.367	0.367
1999	0.408	0.408	0.408	0.408	0.408	0.408	0.367	0.367	0.367	0.367	0.367	0.367	0.367
2000	0.408	0.408	0.408	0.408	0.408	0.408	0.367	0.367	0.367	0.367	0.367	0.367	0.367
2001	0.408	0.408	0.408	0.408	0.408	0.408	0.367	0.367	0.367	0.367	0.367	0.367	0.367
2002	0.408	0.408	0.408	0.408	0.408	0.408	0.367	0.367	0.367	0.367	0.367	0.367	0.367
2003	0.408	0.408	0.408	0.408	0.408	0.408	0.367	0.367	0.367	0.367	0.367	0.367	0.367
2004	0.408	0.408	0.408	0.408	0.408	0.408	0.367	0.367	0.367	0.367	0.367	0.367	0.367
2005	0.408	0.408	0.408	0.408	0.408	0.408	0.367	0.367	0.367	0.367	0.367	0.367	0.367
2006	0.408	0.408	0.408	0.408	0.408	0.408	0.367	0.367	0.367	0.367	0.367	0.367	0.367
2007	0.408	0.408	0.408	0.408	0.408	0.408	0.367	0.367	0.367	0.367	0.367	0.367	0.367
2008	0.408	0.408	0.408	0.408	0.408	0.408	0.367	0.367	0.367	0.367	0.367	0.367	0.367
2009	0.408	0.408	0.408	0.408	0.408	0.408	0.367	0.367	0.367	0.367	0.367	0.367	0.367
2010	0.408	0.408	0.408	0.408	0.408	0.408	0.367	0.367	0.367	0.367	0.367	0.367	0.367
2011	0.408	0.408	0.408	0.408	0.408	0.408	0.367	0.367	0.367	0.367	0.367	0.367	0.367
2012	0.408	0.408	0.408	0.408	0.408	0.408	0.367	0.367	0.367	0.367	0.367	0.367	0.367
2013+	0.408	0.408	0.408	0.408	0.408	0.408	0.367	0.367	0.367	0.367	0.367	0.367	0.367
	HC (g/hp-hr)												
Engine Power	**0-11**	**>11-16**	**>16-25**	**>25-50**	**>50-75**	**>75-100**	**>100-175**	**>175-300**	**>300-600**	**>600-750**	**>750**	**>750-1200**	**>1200**
Model Year	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**Generators**	
pre-1988	1.5000	1.7000	1.7000	1.8000									
1988	1.5000	1.7000	1.7000	1.8000	0.9900	0.9900	0.6800	0.6800	0.6800	0.6800	0.6800	0.6800	0.6800
1989	1.5000	1.7000	1.7000	1.8000	0.9900	0.9900	0.6800	0.6800	0.6800	0.6800	0.6800	0.6800	0.6800

1990	1.5000	1.7000	1.7000	1.8000	0.9900	0.9900	0.6800	0.6800	0.6800	0.6800	0.6800	0.6800	0.6800
1991	1.5000	1.7000	1.7000	1.8000	0.9900	0.9900	0.6800	0.6800	0.6800	0.6800	0.6800	0.6800	0.6800
1992	1.5000	1.7000	1.7000	1.8000	0.9900	0.9900	0.6800	0.6800	0.6800	0.6800	0.6800	0.6800	0.6800
1993	1.5000	1.7000	1.7000	1.8000	0.9900	0.9900	0.6800	0.6800	0.6800	0.6800	0.6800	0.6800	0.6800
1994	1.5000	1.7000	1.7000	1.8000	0.9900	0.9900	0.6800	0.6800	0.6800	0.6800	0.6800	0.6800	0.6800
1995	1.5000	1.7000	1.7000	1.8000	0.9900	0.9900	0.6800	0.6800	0.6800	0.6800	0.6800	0.6800	0.6800
1996	1.5000	1.7000	1.7000	1.8000	0.9900	0.9900	0.6800	0.3085	0.2025	0.1473	0.6800	0.6800	0.6800
1997	1.5000	1.7000	1.7000	1.8000	0.9900	0.9900	0.3384	0.3085	0.2025	0.1473	0.6800	0.6800	0.6800
1998	1.5000	1.7000	1.7000	1.8000	0.9900	0.5213	0.3384	0.3085	0.2025	0.1473	0.6800	0.6800	0.6800
1999	1.5000	1.7000	1.7000	1.8000	0.9900	0.5213	0.3384	0.3085	0.2025	0.1473	0.6800	0.6800	0.6800
2000	0.7628	0.4380	0.4380	0.2789	0.5213	0.5213	0.3384	0.3085	0.2025	0.1473	0.2861	0.2861	0.2861
2001	0.7628	0.4380	0.4380	0.2789	0.5213	0.5213	0.3384	0.3085	0.1669	0.1473	0.2861	0.2861	0.2861
2002	0.7628	0.4380	0.4380	0.2789	0.5213	0.5213	0.3384	0.3085	0.1669	0.1669	0.2861	0.2861	0.2861
2003	0.7628	0.4380	0.4380	0.2789	0.5213	0.5213	0.3384	0.3085	0.1669	0.1669	0.2861	0.2861	0.2861
2004	0.7628	0.4380	0.4380	0.2789	0.5213	0.3672	0.3384	0.3085	0.1669	0.1669	0.2861	0.2861	0.2861
2005	0.5508	0.4380	0.4380	0.2789	0.3672	0.3672	0.3384	0.3085	0.1669	0.1669	0.2861	0.2861	0.2861
2006	0.5508	0.4380	0.4380	0.2789	0.3672	0.3672	0.3384	0.1836	0.1669	0.1669	0.1669	0.1669	0.1669
2007	0.5508	0.4380	0.4380	0.2789	0.3672	0.3672	0.1836	0.1836	0.1669	0.1669	0.1669	0.1669	0.1669
2008	0.5508	0.4380	0.4380	0.2789	0.1836	0.1836	0.1836	0.1836	0.1669	0.1669	0.1669	0.1669	0.1669
2009	0.5508	0.4380	0.4380	0.2789	0.1836	0.1836	0.1836	0.1836	0.1669	0.1669	0.1669	0.1669	0.1669
2010	0.5508	0.4380	0.4380	0.2789	0.1836	0.1836	0.1836	0.1836	0.1669	0.1669	0.1669	0.1669	0.1669
2011	0.5508	0.4380	0.4380	0.2789	0.1836	0.1836	0.1836	0.1314	0.1314	0.1314	0.2815	0.2815	0.2815
2012	0.5508	0.4380	0.4380	0.2789	0.1836	0.1314	0.1314	0.1314	0.1314	0.1314	0.2815	0.2815	0.2815
2013+	0.5508	0.4380	0.4380	0.1314	0.1314	0.1314	0.1314	0.1314	0.1314	0.1314	0.2815	0.2815	0.2815
	CO (g/hp-hr)												
	0-11	**>11-16**	**>16-25**	**>25-50**	**>50-75**	**>75-100**	**>100-175**	**>175-300**	**>300-600**	**>600-750**	**>750**	**>750-1200**	**>1200**
Model Year	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**Generators**	
pre-1988	5.0000	5.0000	5.0000	5.0000									
1988	5.0000	5.0000	5.0000	5.0000	3.4900	3.4900	2.7000	2.7000	2.7000	2.7000	2.7000	2.7000	2.7000
1989	5.0000	5.0000	5.0000	5.0000	3.4900	3.4900	2.7000	2.7000	2.7000	2.7000	2.7000	2.7000	2.7000
1990	5.0000	5.0000	5.0000	5.0000	3.4900	3.4900	2.7000	2.7000	2.7000	2.7000	2.7000	2.7000	2.7000
1991	5.0000	5.0000	5.0000	5.0000	3.4900	3.4900	2.7000	2.7000	2.7000	2.7000	2.7000	2.7000	2.7000
1992	5.0000	5.0000	5.0000	5.0000	3.4900	3.4900	2.7000	2.7000	2.7000	2.7000	2.7000	2.7000	2.7000
1993	5.0000	5.0000	5.0000	5.0000	3.4900	3.4900	2.7000	2.7000	2.7000	2.7000	2.7000	2.7000	2.7000
1994	5.0000	5.0000	5.0000	5.0000	3.4900	3.4900	2.7000	2.7000	2.7000	2.7000	2.7000	2.7000	2.7000
1995	5.0000	5.0000	5.0000	5.0000	3.4900	3.4900	2.7000	2.7000	2.7000	2.7000	2.7000	2.7000	2.7000
1996	5.0000	5.0000	5.0000	5.0000	3.4900	3.4900	2.7000	0.7475	1.3060	1.3272	2.7000	2.7000	2.7000
1997	5.0000	5.0000	5.0000	5.0000	3.4900	3.4900	0.8667	0.7475	1.3060	1.3272	2.7000	2.7000	2.7000
1998	5.0000	5.0000	5.0000	5.0000	3.4900	2.3655	0.8667	0.7475	1.3060	1.3272	2.7000	2.7000	2.7000
1999	5.0000	5.0000	5.0000	5.0000	3.4900	2.3655	0.8667	0.7475	1.3060	1.3272	2.7000	2.7000	2.7000
2000	4.1127	2.1610	2.1610	1.5323	2.3655	2.3655	0.8667	0.7475	1.3060	1.3272	0.7642	0.7642	0.7642

2001	4.1127	2.1610	2.1610	1.5323	2.3655	2.3655	0.8667	0.7475	0.8425	1.3272	0.7642	0.7642	0.7642
2002	4.1127	2.1610	2.1610	1.5323	2.3655	2.3655	0.8667	0.7475	0.8425	1.3272	0.7642	0.7642	0.7642
2003	4.1127	2.1610	2.1610	1.5323	2.3655	2.3655	0.8667	0.7475	0.8425	1.3272	0.7642	0.7642	0.7642
2004	4.1127	2.1610	2.1610	1.5323	2.3655	2.3655	0.8667	0.7475	0.8425	1.3272	0.7642	0.7642	0.7642
2005	4.1127	2.1610	2.1610	1.5323	2.3655	2.3655	0.8667	0.7475	0.8425	1.3272	0.7642	0.7642	0.7642
2006	4.1127	2.1610	2.1610	1.5323	2.3655	2.3655	0.8667	0.7475	0.8425	1.3272	0.7642	0.7642	0.7642
2007	4.1127	2.1610	2.1610	1.5323	2.3655	2.3655	0.8667	0.7475	0.8425	1.3272	0.7642	0.7642	0.7642
2008	4.1127	2.1610	2.1610	1.5323	2.3655	2.3655	0.8667	0.7475	0.8425	1.3272	0.7642	0.7642	0.7642
2009	4.1127	2.1610	2.1610	1.5323	2.3655	2.3655	0.8667	0.7475	0.8425	1.3272	0.7642	0.7642	0.7642
2010	4.1127	2.1610	2.1610	1.5323	2.3655	2.3655	0.8667	0.7475	0.8425	1.3272	0.7642	0.7642	0.7642
2011	4.1127	2.1610	2.1610	1.5323	2.3655	2.3655	0.8667	0.0750	0.0840	0.1330	0.7642	0.7642	0.7642
2012	4.1127	2.1610	2.1610	1.5323	2.3655	0.2370	0.0870	0.0750	0.0840	0.1330	0.7642	0.7642	0.7642
2013+	4.1127	2.1610	2.1610	0.1530	0.2370	0.2370	0.0870	0.0750	0.0840	0.1330	0.7642	0.7642	0.7642
	NO_x (g/hp-hr)												
	0-11	**>11-16**	**>16-25**	**>25-50**	**>50-75**	**>75-100**	**>100-175**	**>175-300**	**>300-600**	**>600-750**	**>750**	**>750-1200**	**>1200**
Model Year	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**Generators**	
pre-1988	10.0000	8.5000	8.5000	0.8000									
1988	10.0000	8.5000	8.5000	0.8000	6.9000	6.9000	8.3800	8.3800	8.3800	8.3800	8.3800	8.3800	8.3800
1989	10.0000	8.5000	8.5000	0.8000	6.9000	6.9000	8.3800	8.3800	8.3800	8.3800	8.3800	8.3800	8.3800
1990	10.0000	8.5000	8.5000	0.8000	6.9000	6.9000	8.3800	8.3800	8.3800	8.3800	8.3800	8.3800	8.3800
1991	10.0000	8.5000	8.5000	0.8000	6.9000	6.9000	8.3800	8.3800	8.3800	8.3800	8.3800	8.3800	8.3800
1992	10.0000	8.5000	8.5000	0.8000	6.9000	6.9000	8.3800	8.3800	8.3800	8.3800	8.3800	8.3800	8.3800
1993	10.0000	8.5000	8.5000	0.8000	6.9000	6.9000	8.3800	8.3800	8.3800	8.3800	8.3800	8.3800	8.3800
1994	10.0000	8.5000	8.5000	0.8000	6.9000	6.9000	8.3800	8.3800	8.3800	8.3800	8.3800	8.3800	8.3800
1995	10.0000	8.5000	8.5000	0.8000	6.9000	6.9000	8.3800	8.3800	8.3800	8.3800	8.3800	8.3800	8.3800
1996	10.0000	8.5000	8.5000	0.8000	6.9000	6.9000	8.3800	5.5720	6.0153	5.8215	8.3800	8.3800	8.3800
1997	10.0000	8.5000	8.5000	0.8000	6.9000	6.9000	5.6523	5.5720	6.0153	5.8215	8.3800	8.3800	8.3800
1998	10.0000	8.5000	8.5000	0.8000	6.9000	5.5988	5.6523	5.5720	6.0153	5.8215	8.3800	8.3800	8.3800
1999	10.0000	8.5000	8.5000	0.8000	6.9000	5.5988	5.6523	5.5720	6.0153	5.8215	8.3800	8.3800	8.3800
2000	5.2298	4.4399	4.4399	0.3389	5.5988	5.5988	5.6523	5.5720	6.0153	5.8215	6.1525	6.1525	6.1525
2001	5.2298	4.4399	4.4399	0.3389	5.5988	5.5988	5.6523	5.5720	4.3351	5.8215	6.1525	6.1525	6.1525
2002	5.2298	4.4399	4.4399	0.3389	5.5988	5.5988	5.6523	5.5720	4.3351	4.1000	6.1525	6.1525	6.1525
2003	5.2298	4.4399	4.4399	0.3389	5.5988	5.5988	4.1000	4.0000	4.3351	4.1000	6.1525	6.1525	6.1525
2004	5.2298	4.4399	4.4399	0.3389	5.5988	4.7000	4.1000	4.0000	4.3351	4.1000	6.1525	6.1525	6.1525
2005	4.3000	4.4399	4.4399	0.3389	4.7000	4.7000	4.1000	4.0000	4.3351	4.1000	6.1525	6.1525	6.1525
2006	4.3000	4.4399	4.4399	0.3389	4.7000	4.7000	4.1000	2.5000	2.5000	2.5000	4.1000	4.1000	4.1000
2007	4.3000	4.4399	4.4399	0.3389	4.7000	4.7000	2.5000	2.5000	2.5000	2.5000	4.1000	4.1000	4.1000
2008	4.3000	4.4399	4.4399	0.2000	3.0000	3.0000	2.5000	2.5000	2.5000	2.5000	4.1000	4.1000	4.1000
2009	4.3000	4.4399	4.4399	0.2000	3.0000	3.0000	2.5000	2.5000	2.5000	2.5000	4.1000	4.1000	4.1000
2010	4.3000	4.4399	4.4399	0.2000	3.0000	3.0000	2.5000	2.5000	2.5000	2.5000	4.1000	4.1000	4.1000
2011	4.3000	4.4399	4.4399	0.2000	3.0000	3.0000	2.5000	2.5000	2.5000	2.5000	2.3920	2.3920	2.3920

2012	4.3000	4.4399	4.4399	0.2000	3.0000	3.0000	2.5000	2.5000	2.5000	2.5000	2.3920	2.3920	2.3920
2013+	4.3000	4.4399	4.4399	0.0184	3.0000	3.0000	2.5000	2.5000	2.5000	2.5000	2.3920	2.3920	2.3920
	PM (g/hp-hr)												
	0-11	**>11-16**	**>16-25**	**>25-50**	**>50-75**	**>75-100**	**>100-175**	**>175-300**	**>300-600**	**>600-750**	**>750**	**>750-1200**	**>1200**
Model Year	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**Generators**	
pre-1988	1.0000	0.9000	0.9000	6.9000									
1988	1.0000	0.9000	0.9000	6.9000	0.7220	0.7220	0.4020	0.4020	0.4020	0.4020	0.4020	0.4020	0.4020
1989	1.0000	0.9000	0.9000	6.9000	0.7220	0.7220	0.4020	0.4020	0.4020	0.4020	0.4020	0.4020	0.4020
1990	1.0000	0.9000	0.9000	6.9000	0.7220	0.7220	0.4020	0.4020	0.4020	0.4020	0.4020	0.4020	0.4020
1991	1.0000	0.9000	0.9000	6.9000	0.7220	0.7220	0.4020	0.4020	0.4020	0.4020	0.4020	0.4020	0.4020
1992	1.0000	0.9000	0.9000	6.9000	0.7220	0.7220	0.4020	0.4020	0.4020	0.4020	0.4020	0.4020	0.4020
1993	1.0000	0.9000	0.9000	6.9000	0.7220	0.7220	0.4020	0.4020	0.4020	0.4020	0.4020	0.4020	0.4020
1994	1.0000	0.9000	0.9000	6.9000	0.7220	0.7220	0.4020	0.4020	0.4020	0.4020	0.4020	0.4020	0.4020
1995	1.0000	0.9000	0.9000	6.9000	0.7220	0.7220	0.4020	0.4020	0.4020	0.4020	0.4020	0.4020	0.4020
1996	1.0000	0.9000	0.9000	6.9000	0.7220	0.7220	0.4020	0.2521	0.2008	0.2201	0.4020	0.4020	0.4020
1997	1.0000	0.9000	0.9000	6.9000	0.7220	0.7220	0.2799	0.2521	0.2008	0.2201	0.4020	0.4020	0.4020
1998	1.0000	0.9000	0.9000	6.9000	0.7220	0.4730	0.2799	0.2521	0.2008	0.2201	0.4020	0.4020	0.4020
1999	1.0000	0.9000	0.9000	6.9000	0.7220	0.4730	0.2799	0.2521	0.2008	0.2201	0.4020	0.4020	0.4020
2000	0.4474	0.2665	0.2665	4.7279	0.4730	0.4730	0.2799	0.2521	0.2008	0.2201	0.1934	0.1934	0.1934
2001	0.4474	0.2665	0.2665	4.7279	0.4730	0.4730	0.2799	0.2521	0.1316	0.2201	0.1934	0.1934	0.1934
2002	0.4474	0.2665	0.2665	4.7279	0.4730	0.4730	0.2799	0.2521	0.1316	0.1316	0.1934	0.1934	0.1934
2003	0.4474	0.2665	0.2665	4.7279	0.4730	0.4730	0.1800	0.1316	0.1316	0.1316	0.1934	0.1934	0.1934
2004	0.4474	0.2665	0.2665	4.7279	0.4730	0.2400	0.1800	0.1316	0.1316	0.1316	0.1934	0.1934	0.1934
2005	0.5000	0.2665	0.2665	4.7279	0.2400	0.2400	0.1800	0.1316	0.1316	0.1316	0.1934	0.1934	0.1934
2006	0.5000	0.2665	0.2665	4.7279	0.2400	0.2400	0.1800	0.1500	0.1500	0.1500	0.1316	0.1316	0.1316
2007	0.5000	0.2665	0.2665	4.7279	0.2400	0.2400	0.2200	0.1500	0.1500	0.1500	0.1316	0.1316	0.1316
2008	0.2800	0.2800	0.2800	4.7279	0.2000	0.2000	0.2200	0.1500	0.1500	0.1500	0.1316	0.1316	0.1316
2009	0.2800	0.2800	0.2800	4.7279	0.2000	0.2000	0.2200	0.1500	0.1500	0.1500	0.1316	0.1316	0.1316
2010	0.2800	0.2800	0.2800	4.7279	0.2000	0.2000	0.2200	0.1500	0.1500	0.1500	0.1316	0.1316	0.1316
2011	0.2800	0.2800	0.2800	4.7279	0.2000	0.2000	0.2200	0.0092	0.0092	0.0092	0.0690	0.0690	0.0690
2012	0.2800	0.2800	0.2800	4.7279	0.2000	0.0092	0.0092	0.0092	0.0092	0.0092	0.0690	0.0690	0.0690
2013+	0.2800	0.2800	0.2800	3.0000	0.0184	0.0092	0.0092	0.0092	0.0092	0.0092	0.0690	0.0690	0.0690
	CO_2 (g/hp-hr)												
	0-11	**>11-16**	**>16-25**	**>25-50**	**>50-75**	**>75-100**	**>100-175**	**>175-300**	**>300-600**	**>600-750**	**>750**	**>750-1200**	**>1200**
Model Year	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**Generators**	
pre-1988	583.733	583.733	583.733	583.733									
1988	583.733	583.733	583.733	583.733	583.733	583.733	525.073	525.073	525.073	525.073	525.073	525.073	525.073
1989	583.733	583.733	583.733	583.733	583.733	583.733	525.073	525.073	525.073	525.073	525.073	525.073	525.073

1990	583.733	583.733	583.733	583.733	583.733	583.733	525.073	525.073	525.073	525.073	525.073	525.073	525.073
1991	583.733	583.733	583.733	583.733	583.733	583.733	525.073	525.073	525.073	525.073	525.073	525.073	525.073
1992	583.733	583.733	583.733	583.733	583.733	583.733	525.073	525.073	525.073	525.073	525.073	525.073	525.073
1993	583.733	583.733	583.733	583.733	583.733	583.733	525.073	525.073	525.073	525.073	525.073	525.073	525.073
1994	583.733	583.733	583.733	583.733	583.733	583.733	525.073	525.073	525.073	525.073	525.073	525.073	525.073
1995	583.733	583.733	583.733	583.733	583.733	583.733	525.073	525.073	525.073	525.073	525.073	525.073	525.073
1996	583.733	583.733	583.733	583.733	583.733	583.733	525.073	525.073	525.073	525.073	525.073	525.073	525.073
1997	583.733	583.733	583.733	583.733	583.733	583.733	525.073	525.073	525.073	525.073	525.073	525.073	525.073
1998	583.733	583.733	583.733	583.733	583.733	583.733	525.073	525.073	525.073	525.073	525.073	525.073	525.073
1999	583.733	583.733	583.733	583.733	583.733	583.733	525.073	525.073	525.073	525.073	525.073	525.073	525.073
2000	583.733	583.733	583.733	583.733	583.733	583.733	525.073	525.073	525.073	525.073	525.073	525.073	525.073
2001	583.733	583.733	583.733	583.733	583.733	583.733	525.073	525.073	525.073	525.073	525.073	525.073	525.073
2002	583.733	583.733	583.733	583.733	583.733	583.733	525.073	525.073	525.073	525.073	525.073	525.073	525.073
2003	583.733	583.733	583.733	583.733	583.733	583.733	525.073	525.073	525.073	525.073	525.073	525.073	525.073
2004	583.733	583.733	583.733	583.733	583.733	583.733	525.073	525.073	525.073	525.073	525.073	525.073	525.073
2005	583.733	583.733	583.733	583.733	583.733	583.733	525.073	525.073	525.073	525.073	525.073	525.073	525.073
2006	583.733	583.733	583.733	583.733	583.733	583.733	525.073	525.073	525.073	525.073	525.073	525.073	525.073
2007	583.733	583.733	583.733	583.733	583.733	583.733	525.073	525.073	525.073	525.073	525.073	525.073	525.073
2008	583.733	583.733	583.733	583.733	583.733	583.733	525.073	525.073	525.073	525.073	525.073	525.073	525.073
2009	583.733	583.733	583.733	583.733	583.733	583.733	525.073	525.073	525.073	525.073	525.073	525.073	525.073
2010	583.733	583.733	583.733	583.733	583.733	583.733	525.073	525.073	525.073	525.073	525.073	525.073	525.073
2011	583.733	583.733	583.733	583.733	583.733	583.733	525.073	525.073	525.073	525.073	525.073	525.073	525.073
2012	583.733	583.733	583.733	583.733	583.733	583.733	525.073	525.073	525.073	525.073	525.073	525.073	525.073
2013+	583.733	583.733	583.733	583.733	583.733	583.733	525.073	525.073	525.073	525.073	525.073	525.073	525.073
	SOx (g/hp-hr)												
	0-11	**>11-16**	**>16-25**	**>25-50**	**>50-75**	**>75-100**	**>100-175**	**>175-300**	**>300-600**	**>600-750**	**>750**	**>750-1200**	**>1200**
Model Year	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**Generators**	
pre-1988	1.184	1.183	1.183	1.182	1.194	1.194	1.074	1.074	1.074	1.074	1.074	1.074	1.074
1988	1.184	1.183	1.183	1.182	1.187	1.187	1.070	1.070	1.070	1.070	1.070	1.070	1.070
1989	1.184	1.183	1.183	1.182	1.187	1.187	1.070	1.070	1.070	1.070	1.070	1.070	1.070
1990	1.184	1.183	1.183	1.182	1.187	1.187	1.070	1.070	1.070	1.070	1.070	1.070	1.070
1991	1.184	1.183	1.183	1.182	1.187	1.187	1.070	1.070	1.070	1.070	1.070	1.070	1.070
1992	1.184	1.183	1.183	1.182	1.187	1.187	1.070	1.070	1.070	1.070	1.070	1.070	1.070
1993	1.184	1.183	1.183	1.182	1.187	1.187	1.070	1.070	1.070	1.070	1.070	1.070	1.070
1994	1.184	1.183	1.183	1.182	1.187	1.187	1.070	1.070	1.070	1.070	1.070	1.070	1.070
1995	1.184	1.183	1.183	1.182	1.187	1.187	1.070	1.070	1.070	1.070	1.070	1.070	1.070
1996	1.184	1.183	1.183	1.182	1.187	1.187	1.070	1.072	1.073	1.073	1.070	1.070	1.070
1997	1.184	1.183	1.183	1.182	1.187	1.187	1.072	1.072	1.073	1.073	1.070	1.070	1.070
1998	1.184	1.183	1.183	1.182	1.187	1.191	1.072	1.072	1.073	1.073	1.070	1.070	1.070
1999	1.184	1.183	1.183	1.182	1.187	1.191	1.072	1.072	1.073	1.073	1.070	1.070	1.070
2000	1.189	1.191	1.191	1.192	1.191	1.191	1.072	1.072	1.073	1.073	1.072	1.072	1.072

2001	1.189	1.191	1.191	1.192	1.191	1.191	1.072	1.072	1.073	1.073	1.072	1.072	1.072
2002	1.189	1.191	1.191	1.192	1.191	1.191	1.072	1.072	1.073	1.073	1.072	1.072	1.072
2003	1.189	1.191	1.191	1.192	1.191	1.191	1.072	1.072	1.073	1.073	1.072	1.072	1.072
2004	1.189	1.191	1.191	1.192	1.191	1.192	1.072	1.072	1.073	1.073	1.072	1.072	1.072
2005	1.190	1.191	1.191	1.192	1.192	1.192	1.072	1.072	1.073	1.073	1.072	1.072	1.072
2006	1.190	1.191	1.191	1.192	1.192	1.192	1.072	1.073	1.073	1.073	1.073	1.073	1.073
2007	1.190	1.191	1.191	1.192	1.192	1.192	1.073	1.073	1.073	1.073	1.073	1.073	1.073
2008	1.190	1.191	1.191	1.192	1.193	1.193	1.073	1.073	1.073	1.073	1.073	1.073	1.073
2009	1.190	1.191	1.191	1.192	1.193	1.193	1.073	1.073	1.073	1.073	1.073	1.073	1.073
2010	1.190	1.191	1.191	1.192	1.193	1.193	1.073	1.073	1.073	1.073	1.073	1.073	1.073
2011	1.190	1.191	1.191	1.192	1.193	1.193	1.073	1.073	1.073	1.073	1.072	1.072	1.072
2012	1.190	1.191	1.191	1.192	1.193	1.193	1.073	1.073	1.073	1.073	1.072	1.072	1.072
2013+	1.190	1.191	1.191	1.193	1.193	1.193	1.073	1.073	1.073	1.073	1.072	1.072	1.072

Table 9.30: BSFC, energy consumption and emission factors data for gasoline powered non-road construction equipment [151, 218]

Engine Power (hp)	**Model Year**	**BSFC (lb/hp-hr)**	**Energy (MJ/hp-hr)**	**HC (g/hp-hr)**	**CO (g/hp-hr)**	**NO_x (g/hp-hr)**	**PM (g/hp-hr)**	**CO_2 (g/hp-hr)**	**SO_x (g/hp-hr)**
All	All	0.363	7.778	9.67	199	5.16	0.327	493	0.268

Table 9.31: Energy consumption and emission factors for Turkish electricity grid mix, including upstream and direct impacts [316, 317]:

Energy Source (per kWh)	**Mix (%)**	**Energy (MJ)**	**GWP (kg CO2-eq)**	**CO_2 (kg)**	**CO (kg)**	**CH_4 (kg)**	**NO_x (kg)**	**N_2O (kg)**	**NMVOC (kg)**	**PM (kg)**	**SO_2 (kg)**
Natural gas	49	4.25E+00	2.42E-01	2.14E-01	1.39E-04	1.36E-03	3.87E-04	3.49E-07	1.81E-04	4.40E-05	1.56E-04
Hydro	19	2.22E-02	4.54E-03	2.75E-03	1.65E-05	1.40E-05	4.27E-06	3.09E-08	9.71E-07	4.63E-06	1.53E-05
Lignite coal	28	3.32E+00	3.18E-01	3.12E-01	3.43E-05	1.43E-03	**1.01E-03**	1.83E-07	6.97E-06	3.35E-04	**1.48E-03**
Residuel (Heavy) oil	3	3.82E-01	2.79E-02	2.65E-02	0.00E+00	7.72E-05	5.54E-05	3.41E-04	7.48E-07	3.20E-05	2.72E-04
Wind	1	2.81E-03	2.17E-04	1.99E-04	5.81E-07	7.59E-07	4.35E-07	3.60E-09	1.03E-07	3.03E-07	5.98E-07
Total	**100%**	**7.98E+00**	**5.86E-01**	**5.56E-01**	**1.57E-04**	**2.79E-03**	**1.28E-03**	**3.41E-04**	**1.83E-04**	**2.29E-04**	**1.06E-03**

Table 9.32: Other construction-related equipment use LCI data

Other Construction Equipment Use Impacts
Welding Impacts for PM_{10} and heavy metals are obtained from AP-42: Electric Arc Welding
Impacts are averages for each type of electric arc welding. All emission factors are measured in g/lb of electrode consumed.
SMAW = shielded metal arc welding

GMAW = gas metal arc welding

FCAW = flux cored arc welding

Model Type	**PM_{10} (g/lb)**	**Cr (g/lb)**	**Cr (VI) (g/lb)**	**Mn (g/lb)**	**Ni (g/lb)**
SMAW	9.155	0.193	0.292	0.930	0.119
GMAW	4.170	0.092	0.005	0.078	0.192
FCAW	9.284	0.177	0.064	0.442	0.029

Torch Cutting Impacts for PM and hazardous metals obtained from Kura, B., et al. (2000). Impacts are average values for each type of cutting.

AHPA = Argon-Hydrogen Plasma Arc

oxy-MAPP = uses trademark liquefied acetylene compound

Model Type	**PM_{10} (g/lb)**	**Cr (VI) (g/lb)**	**Ni (g/lb)**
Arc gouging	24.740	3.41E-03	0.810
oxy-MAPP	8.940	1.09E-04	0.380
AHPA 600A	7.128	1.09E-04	0.250
AHPA 500A	2.270	5.68E-05	0.120
AHPA 360A	0.908	4.54E-06	0.040

Table 9.33: Upstream air emissions of natural gas, for EU and TR, 2005 (in kg/m^3) [315]

	CO_2-eq	**CO_2**	**CH_4**	**N_2O**	**SO_2-eq**	**SO_2**	**NO_x**	**PM**	**CO**	**NMVOC**
AT	5.26E-01	2.83E-01	1.04E-02	1.18E-05	1.14E-03	6.40E-05	1.54E-03	6.20E-05	9.77E-04	1.83E-04
BE	1.75E-01	1.17E-01	2.45E-03	4.67E-06	4.41E-04	8.12E-05	5.16E-04	2.11E-05	2.42E-04	2.30E-05
CZ	2.74E-01	1.71E-01	4.37E-03	7.01E-06	6.42E-04	3.29E-05	8.74E-04	3.37E-05	5.17E-04	7.09E-05
DE	3.38E-01	1.93E-01	6.21E-03	7.81E-06	7.30E-04	5.82E-05	9.60E-04	4.17E-05	6.12E-04	1.01E-04
DK	8.47E-02	3.73E-02	2.05E-03	1.26E-06	1.03E-04	1.84E-05	1.21E-04	1.15E-05	1.35E-04	6.13E-06
ES	4.36E-01	3.35E-01	4.20E-03	1.46E-05	1.42E-03	5.48E-05	1.96E-03	3.83E-05	1.05E-03	7.55E-05
FI	7.29E-01	3.88E-01	1.46E-02	1.62E-05	1.58E-03	8.85E-05	2.13E-03	8.54E-05	1.35E-03	2.60E-04
FR	3.47E-01	2.13E-01	5.74E-03	8.85E-06	7.75E-04	5.40E-05	1.03E-03	3.72E-05	5.73E-04	9.04E-05
GR	6.72E-01	3.69E-01	1.30E-02	1.55E-05	1.46E-03	9.04E-05	1.96E-03	7.58E-05	1.20E-03	2.24E-04
HU	4.62E-01	2.68E-01	8.30E-03	1.14E-05	1.09E-03	7.58E-05	1.45E-03	6.13E-05	8.90E-04	1.38E-04
IE	9.76E-02	5.14E-02	1.98E-03	1.92E-06	1.61E-04	1.95E-05	2.03E-04	1.26E-05	1.61E-04	1.23E-05
IT	3.86E-01	2.33E-01	6.52E-03	9.80E-06	8.49E-04	7.43E-05	1.11E-03	3.83E-05	5.89E-04	9.15E-05

NL	1.01E-01	5.68E-02	1.88E-03	2.26E-06	1.78E-04	1.72E-05	2.30E-04	1.19E-05	1.56E-04	8.81E-06
PL	7.63E-01	5.89E-01	7.25E-03	2.51E-05	1.75E-03	4.90E-04	1.79E-03	1.00E-04	9.42E-04	1.21E-04
PT	3.63E-01	2.65E-01	4.10E-03	1.15E-05	8.40E-04	1.03E-04	1.06E-03	2.22E-05	3.34E-04	2.49E-05
TR	**6.59E-01**	**3.95E-01**	**1.12E-02**	**1.79E-05**	**1.60E-03**	**1.28E-04**	**2.11E-03**	**8.04E-05**	**1.30E-03**	**1.93E-04**
UK	9.60E-02	4.75E-02	2.09E-03	1.72E-06	1.44E-04	2.11E-05	1.77E-04	1.30E-05	1.57E-04	9.96E-06
EU	4.26E-01	2.36E-01	8.13E-03	9.77E-06	9.25E-04	5.40E-05	1.25E-03	5.06E-05	7.86E-04	1.37E-04
NO	1.48E-01	9.66E-02	2.17E-03	3.75E-06	3.24E-04	1.76E-05	4.40E-04	1.88E-05	2.72E-04	2.99E-05
RU	6.81E-01	3.77E-01	1.30E-02	1.58E-05	1.54E-03	8.54E-05	2.08E-03	8.27E-05	1.31E-03	2.30E-04

Table 9.34: Air emissions data for heating systems using natural gas, limited to Mediterranean Environmental zone, 2005

	CO_2-eq	**CO_2**	**CH_4**	**N_2O**	**SO-eq**	**SO_2**	**NO_x**	**PM**	**CO**	**NMVOC**
(g/kWh), raw data [315]	2.99E+02	2.72E+02	1.17E+00	3.00E-03	2.40E-01	2.00E-02	3.10E-01	1.00E-02	2.00E-01	3.00E-02
(kg/m^3), calculated on the basis of HHV fuel data [316]	2.70E+00	2.44E+00	1.05E-02	2.70E-05	2.16E-03	1.80E-04	2.79E-03	9.00E-05	1.80E-03	2.70E-04

Table 9.35: Water heating system data used in the simulation for calculating both solar and total energy consumption (Prokon 2010)

Climate Data	
Location:	Istanbul
Total annual global radiation:	1,503.26 kWh
Latitude:	41.02 °
Longitude:	-28.97 °
Domestic Hot Water (DHW) Data	
Average Daily Consumption:	28 m^3
Desired Temperature:	60 °
System Components Data	
- Solar Collector Loop	
Manufacturer:	Viessmann
Type:	Vitosol 100-F
Number:	100
Total Gross Surface Area:	251.8 m^2
Total Active Solar Surface Area:	232.9 m^2
Tilt Angle:	30 °
Azimuth:	0 °
- DHW Standby Tank	
Manufacturer:	T*SOL Database
Type:	DHW Tank - 5000
Volume:	5 m^3
- Solar	
Manufacturer:	T*SOL Database
Type:	2 x DHW Tank - 5000
Volume:	2 x 5 m^3
- Auxiliary Heating	
Manufacturer:	T*SOL Database
Type:	Gas Boiler - 5000
Nominal Output:	1,000 kW

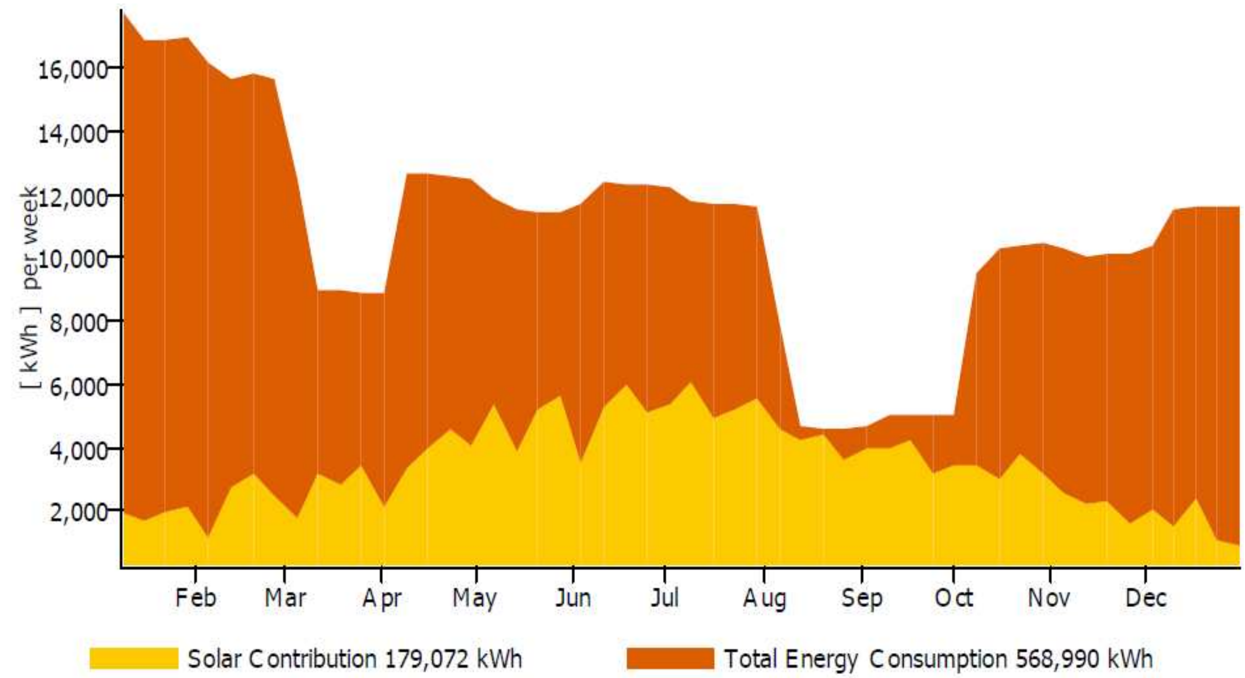

Figure 9.2: Total and solar energy consumption for hot water supply (Prokon 2010)

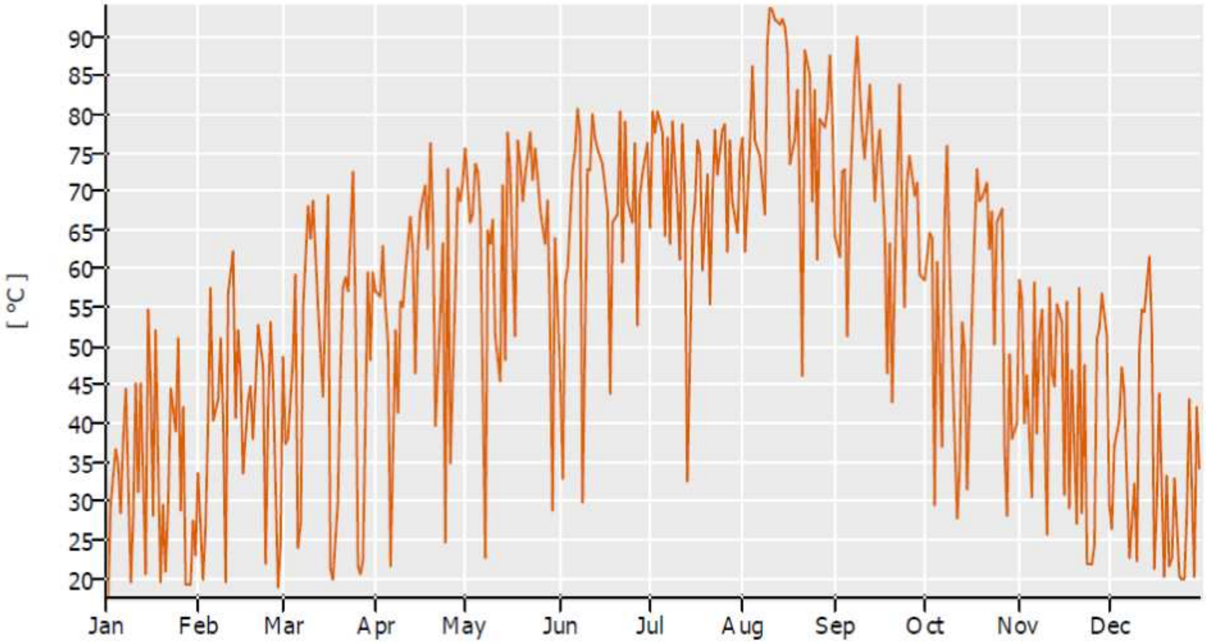

Figure 9.3: Daily maximum solar collector temperature used in T*SOL Pro 4.5 simulation calculations (Prokon 2010)

Table 9.36: Details of materials used in one solar thermal collector [320]

Absorbing collector		Water tank		Support		Other parts (packaging)	
Material	**Mass (kg)**	**Material**	**Mass (kg)**	**Material**	**Mass (kg)**	**Material**	**Mass (kg)**
Galvanized steel	33.9	Galvanized steel	49.6	Galvanized steel	27	Cardboard	3
Glass	10.5	Stainless steel	21	Stainless steel	0.5	LDPE (low density polyethylene)	0.8
Copper	8.2	Rigid PUR	4.8			HDPE (high density polyethylene)	0.87
Stainless steel	6.1	Thermal fluid	5.4			Copper	0.46
Rigid PUR (polyurethane) foam	4.2	Copper	3.8				
Aluminum	4	Epoxy dust	0.7				
Thermal fluid	0.9	Steel	0.4				
Epoxy dust	0.3	Welding rod	0.2				
Welding rod	0.1	Brass	0.1				
Brass	0.04	Magnesium	0.2				
Flexible PUR	0.01						
PVC	0.01						
Total	**68.2**		**86.2**		**27.5**		**5.1**

Table 9.37: Total upstream LCA energy use and emission factors for one solar thermal collector (dimensions: 2.005×1.165×0.91 m) with a total net surface of 2.13 m^2 [320]

Total embodied energy (MJ)	9,101.50
CO_2-eq (kg)	721.00
CO_2 (kg)	657.00
CO (kg)	4.50
SO_2 (kg)	3.60
CH_4 (kg)	2.20
NO_x (kg)	1.80
PM (kg)	0.60
NMCOV (kg)	0.30
N_2O (g)	24.30

Table 9.38: Pedigree matrix with data quality indicators, adapted from **[328]**

Indicator score	**1**	**2**	**3**	**4**	**5**
Reliability (independence of data supplier)	Verified data based on measurements	Verified data partly based on assumptions or non-verified data based on measurements	Non-verified data partly based on assumptions	Qualified estimate (e.g. by industrial expert or generally accepted industry average)	Non-qualified estimate
Completeness (representation)	Representative data from a sufficient sample of sites over an adequate period to even out normal fluctuations	Representative data from a smaller number of sites but from shorter period	Representative data from an adequate number of sites but from shorter periods	Representative data but from a smaller number of sites and shorter periods or incomplete data from an adequate number of sites and periods	Representativeness unknown or incomplete data from a smaller number of sites and/or from shorter periods
Temporal correlation (data age)	< 3 years of difference to year of study	< 6 years difference	< 10 years difference	< 15 years difference	Age of data unknown or > 15 years difference
Geographical correlation	Data from area under study	Average data from larger area in which the area under study is included, same country	Data from different area within same country, similar production conditions	Data from a different country, somewhat similar production conditions	Data from unknown area or area with very different production conditions
Technological correlation	Data from enterprises, processes, and materials under study	Data from processes and materials under study but from different enterprises	Data from processes and materials under study but from different technology	Data on related processes or materials but same technology	Data on related processes or materials but different technology

Table 9.39: LCI results of six cement manufacturing scenarios for Turkish pyroprocessing activity

	A	B	C	D	E	F
	Wet kiln	**Long dry kiln**	**Preheater kiln**	**Preheater/ precalciner kiln**	**Preheater/ precalciner kiln, blended cement (with fly ash)**	**Preheater/ precalciner kiln, blended cement (with slag)**
Total Energy (MJ)	6.91E+03	5.74E+03	4.11E+03	3.93E+03	2.98E+03	6.16E+02
Electricity (MJ)	4.81E+02	5.11E+02	5.11E+02	5.11E+02	3.70E+02	7.66E+01
Fuel (MJ)	6.43E+03	5.23E+03	3.59E+03	3.42E+03	2.61E+03	5.39E+02
Air emissions (kg)						
Total GWP (CO$_2$-eq)	1.67E+03	1.46E+03	1.17E+03	1.14E+03	4.89E+02	1.76E+02
GWP (electricity related)	3.52E+01	3.74E+01	3.74E+01	3.74E+01	2.71E+01	5.62E+00
GWP (fuel use related)	1.14E+03	9.27E+02	6.37E+02	6.07E+02	1.03E+02	9.56E+01
GWP (process related)	4.96E+02	4.96E+02	4.96E+02	4.96E+02	3.60E+02	7.44E+01
Total CO$_2$	1.65E+03	1.44E+03	1.16E+03	1.13E+03	4.81E+02	9.94E+01
CO$_2$ (electricity related)	3.34E+01	3.55E+01	3.55E+01	3.55E+01	2.57E+01	5.32E+00
CO$_2$ (fuel use related)	1.12E+03	9.13E+02	6.27E+02	5.97E+02	9.54E+01	1.97E+01
CO$_2$ (process related)	4.96E+02	4.96E+02	4.96E+02	4.96E+02	3.60E+02	7.44E+01
Total CO	4.60E-01	1.90E-01	1.34E-01	1.28E-01	9.68E-02	2.00E-02
CO (electricity related)	9.57E-03	1.02E-02	1.02E-02	1.02E-02	7.37E-03	1.53E-03
CO (fuel use related)	4.51E-01	1.79E-01	1.23E-01	1.17E-01	8.95E-02	1.85E-02
Total NOx	4.60E-01	8.82E+00	6.09E+00	5.80E+00	4.42E+00	9.14E-01
NOx (electricity related)	7.69E-02	8.17E-02	8.17E-02	8.17E-02	5.93E-02	1.23E-02
NOx (fuel use related)	3.83E-01	8.74E+00	6.01E+00	5.72E+00	4.36E+00	9.02E-01
Total PM	3.95E-01	4.44E-01	2.19E-01	2.20E-01	1.59E-01	3.28E-02
PM (electricity related)	1.36E-02	1.44E-02	1.44E-02	1.44E-02	1.05E-02	2.16E-03
PM (fuel use	1.01E-01	8.22E-02	5.65E-02	5.38E-02	4.10E-02	8.47E-03

related)						
PM (process related)	2.80E-01	3.47E-01	1.48E-01	1.52E-01	1.07E-01	2.22E-02
Total SO_2	5.30E+00	4.33E+00	3.00E+00	2.85E+00	1.26E+01	4.49E-01
SO_2 (electricity related)	6.18E-02	6.56E-02	6.56E-02	6.56E-02	4.76E-02	9.85E-03
SO_2 (fuel use related)	5.24E+00	4.26E+00	2.93E+00	2.79E+00	1.26E+01	4.40E-01
Total VOC (unspecified)	1.61E-02	1.31E-02	9.03E-03	8.59E-03	6.55E-03	1.35E-03
VOC (electricity related)						
VOC (fuel use related)	1.61E-02	1.31E-02	9.03E-03	8.59E-03	6.55E-03	1.35E-03

Table 9.40: LCI results of six cement manufacturing scenarios for U.S. pyroprocessing activity

	A	**B**	**C**	**D**	**E**	**F**
US cement kilns	**Wet kiln**	**Long dry kiln**	**Preheater kiln**	**Preheater/ precalciner kiln**	**Preheater/ precalciner kiln, blended cement (with fly ash)**	**Preheater/ precalciner kiln, blended cement (with slag)**
Total Energy (MJ)	6.80E+03	5.71E+03	4.17E+03	4.01E+03	2.90E+03	6.01E+02
Electricity (MJ)	7.29E+02	7.77E+02	7.77E+02	7.77E+02	5.64E+02	1.17E+02
Fuel (MJ)	6.07E+03	4.94E+03	3.39E+03	3.23E+03	2.34E+03	4.84E+02
Air emissions (kg)						
Total GWP (CO_2-eq)	1.51E+03	1.33E+03	1.08E+03	1.06E+03	7.66E+02	1.59E+02
GWP (electricity related)	3.56E+01	3.80E+01	3.80E+01	3.80E+01	2.75E+01	5.70E+00
GWP (fuel use related)	9.83E+02	8.00E+02	5.50E+02	5.23E+02	3.79E+02	7.85E+01
GWP (process related)	4.96E+02	4.96E+02	4.96E+02	4.96E+02	3.60E+02	7.44E+01
Total CO_2	1.49E+03	1.33E+03	1.07E+03	1.05E+03	7.58E+02	1.57E+02
CO_2 (electricity related)	3.43E+01	3.66E+01	3.66E+01	3.66E+01	2.65E+01	5.48E+00
CO_2 (fuel use related)	9.64E+02	8.01E+02	5.39E+02	5.13E+02	3.72E+02	7.69E+01
CO_2 (process related)	4.96E+02	4.96E+02	4.96E+02	4.96E+02	3.60E+02	7.44E+01

Total CO	1.80E-01	1.49E-01	1.07E-01	1.02E-01	7.42E-02	1.54E-02
CO (electricity related)	1.27E-02	1.35E-02	1.35E-02	1.35E-02	9.80E-03	2.03E-03
CO (fuel use related)	1.67E-01	1.36E-01	9.34E-02	8.88E-02	6.44E-02	1.33E-02
Total NOx	9.59E+00	7.82E+00	5.39E+00	5.13E+00	3.72E+00	7.70E-01
NOx (electricity related)	4.73E-02	5.05E-02	5.05E-02	5.05E-02	3.66E-02	7.58E-03
NOx (fuel use related)	9.55E+00	7.77E+00	5.34E+00	5.08E+00	3.68E+00	7.62E-01
Total PM	6.73E-01	7.14E-01	4.62E-01	4.61E-01	3.34E-01	6.91E-02
PM (electricity related)	1.86E-01	1.99E-01	1.99E-01	1.99E-01	1.44E-01	2.98E-02
PM (fuel use related)	2.07E-01	1.68E-01	1.16E-01	1.10E-01	7.97E-02	1.65E-02
PM (process related)	2.80E-01	3.47E-01	1.48E-01	1.52E-01	1.10E-01	2.28E-02
Total SO_2	4.83E+00	3.95E+00	2.75E+00	2.62E+00	1.90E+00	3.93E-01
SO_2 (electricity related)	9.55E-02	1.02E-01	1.02E-01	1.02E-01	7.39E-02	1.53E-02
SO_2 (fuel use related)	4.74E+00	3.85E+00	2.65E+00	2.52E+00	1.83E+00	3.78E-01
Total VOC (unspecified)	2.09E-02	1.71E-02	1.19E-02	1.13E-02	8.22E-03	1.70E-03
VOC (electricity related)	3.58E-04	3.82E-04	3.82E-04	3.82E-04	2.77E-04	5.72E-05
VOC (fuel use related)	2.06E-02	1.67E-02	1.15E-02	1.10E-02	7.94E-03	1.64E-03

9.4 Appendix D: Environmental Product Declarations (EPDs)

In recent years, the construction industry is moving toward using “green building materials” and “green building technologies” as a solution to the strict environmental and air quality regulations and requirements. It drives the construction industry towards better environmental performance.

EPDs are similar to nutrition labels on food packages and they disclose life-cycle environmental performance of products and services. EPDs rely on Life Cycle Assessment (LCA) to provide information on a number of environmental impacts of products over their life cycle. The information covers use of energy and resources and to what extent a product contributes to the greenhouse effect, acidification, eutrophication, destruction of the ozone layer, and smog formation. Additionally, EPDs give details about the technical properties which are required for assessing the performance of the building products in the buildings, such as durability, heat and sound insulation, or the influence on the quality of the indoor air. EPDs follow international standards and are internationally recognized.

Recently *“LEED v4-compliant EPD”*, that is, the newest version of the US Green Building Council’s LEED standard, gives credit to building projects using products that have Environmental Product Declarations (EPDs). LEEDv4-compliant EPDs summarize potential environmental impacts of products and materials for selected impact categories across the product life cycle. They are based on ISO 14025, the international standard for Type III environmental declarations [360]. As part of the ISO 14000 series of environmental management standards, the ISO 14020 series deals specifically with environmental labels and declarations. ISO 14021:1999 is the International Standard that deals with so-called self-declared claims. It states that “the overall goal of environmental labels and declarations is, through the communication of verifiable, accurate information that is not misleading, to encourage the demand for, and supply of, products which cause less stress on the environment, thereby stimulating the potential for market-driven, continual environmental improvement.” The first and second versions are defined as follows: The “classic” ecolabelling schemes, which award a mark or a logo based on the fulfillment of a set of criteria, were identified as Type I environmental labeling. Claims which were made by manufacturers and businesses, and could be seen as being “self-declared”, were identified as Type II self-declared environmental claims. In addition, the third type consisted of “a formalized set of environmental data describing the environmental aspects of a product. These declarations were identified as Type III environmental declarations”.[347]

Despite its benefits, LEED v4-compliant EPDs are found to have some shortcomings, such as they can leave out major impact categories, and report phantom impacts that do not reflect actual impacts in the real world. As a result, comparisons based on such EPDs can be misleading, and should be approached cautiously. Some environmental stakeholders have expressed skepticism. On the other hand, *“full Transparency EPDs”* provide a comprehensive look at the environmental and human health impacts associated with products or materials. They are derived through an iterative LCA process that narrows down the analysis to focus exclusively on relevant impact categories, and then uses site-specific environmental data to determine whether actual impacts are occurring [360].

In the United States, one concrete manufacturer conducted EPDs for 1,479 different concrete mixes produced at 8 different concrete plants in the San Francisco Bay Area. Central Concrete is known as the first U.S. manufacturer to produce EPDs at the *individual* product level. “This is in contrast to the EPDs that are developed for classes of products – an approach that diminishes the value of the EPD, because specific product performance characteristics are only matched to general environmental impacts within a category.” [386]

In Table 9.41, various concrete EPDs from the United States, Europe and Turkey are compared. The functional unit is 1 m^3 of concrete mixture that is ready to be delivered at concrete plant. Results vary significantly because of many factors, including data sources, LCA system boundary, variations in technology, and resources used.

Table 9.41: Comparison of EPDs of ready-mixed concrete for EU, US California and US average

Europe	**GWP (kg $CO_{2\text{-eq}}$)**	**AP (kg $SO_{2\text{-eq}}$)**	**EP kg $(PO_4)^{-3}_{\text{-eq}}$**	**POCP (kg ethene - eq)**	**Source**
C 20/25	1.91E+02	2.73E-01	4.35E-02	3.30E-02	Institut Bauen und Umwelt e.V. [359]
C 25/30	2.11E+02	2.97E-01	4.72E-02	3.61E-02	
C 30/37	2.32E+02	3.23E-01	5.13E-02	3.93E-02	
C 35/45	2.65E+02	3.64E-01	5.72E-02	4.42E-02	
C 45/55	3.13E+02	4.20E-01	6.46E-03	5.07E-02	
C 50/60	3.35E+02	4.51E-01	6.90E-02	5.40E-02	
United States, California					
C 14	2.57E+02	1.85E+00	9.74E-02	2.94E+01	Central Concrete [386]
C 17	2.62E+02	1.99E+00	9.91E-02	3.36E+01	
C 20	2.81E+02	2.16E+00	1.00E-01	3.63E+01	
C 25	3.01E+02	2.30E+00	1.04E-01	3.80E+01	
C 28	3.17E+02	2.40E+00	1.06E-01	3.87E+01	
C 30	3.48E+02	2.64E+00	1.09E-01	4.16E+01	
C 35	3.77E+02	2.86E+00	1.14E-01	4.47E+01	
C 38	3.96E+02	3.02E+00	1.17E-01	4.72E+01	
C 41	3.96E+02	3.02E+00	1.17E-01	4.72E+01	
C 45	3.95E+02	3.08E+00	1.18E-01	5.01E+01	
C 48	4.23E+02	3.27E+00	1.21E-01	5.21E+01	
C 52	4.32E+02	3.44E+00	1.29E-01	5.70E+01	
United States, average					
C 18	3.1E+02	1.1E+02	7.3E-02	2.1E+00	GreenConcrete LCA tool
C 30	4.3E+02	1.4E+02	9.8E-02	2.8E+00	
C 60	6.0E+02	2.0E+02	1.4E-01	3.8E+00	