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Life-Cycle Greenhouse Gas Emissions of Electricity Generation and Storage Technologies and Common Residential, Commercial, Industrial, and Agricultural Building Technologies

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Life-Cycle Greenhouse Gas Emissions of Electricity Generation and Storage Technologies and Common Residential, Commercial, Industrial, and Agricultural Building Technologies

– Report Prepared for the California Public Utilities Commission –

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Abstract

We have conducted a study to review and synthesize the current state of data availability for cradle-to-grave life-cycle emissions from major building technologies and electricity generation and storage technologies as specific to California as could be found. Results from 280 building technologies (120 unique) were organized across 9 categories and 27 subcategories. Many of the technologies in the list are common building materials, appliances, and process equipment used in the construction and operation of agricultural, residential, commercial, and industrial buildings. Target electricity generation technologies covered the GHG emissions from natural gas, solar, wind, geothermal, biomass and storage technologies for the California context. The search for relevant environmental impact data was in the form of Environmental Product Declarations (EPD) (if available), peer-reviewed journal articles, and publicly available reports from government and industry for each technology. In general, the "Building Materials" category in the building technologies area and "Wind Turbines" in the electricity generation and storage area have the most current and relevant data for California. However, we have identified several data gaps in our survey of the remaining categories. Due to lack of relevant data for California in building systems, there is an urgent need for policy makers and industry stakeholders to replicate policies such as AB 2446 to expand the coverage of availability of EPDs for products. Similarly, to achieve the SB 350 (Clean Energy and Pollution Reduction Act) goals and to support the state's efforts to reduce GHG emissions by 80% below 1990 levels by the year 2050, we need to account for embodied emissions together with the other important life-cycle stages of renewable energy sources.

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1. Introduction

1.1. Background

The building sector is responsible for approximately 40% of global anthropogenic greenhouse gas (GHG) emissions, with a majority of emissions attributable to electricity and natural gas use for building operations. Efforts to reduce operational GHG emissions in buildings are focused on two broad strategies. The first strategy focuses on switching from fossil fuel sources to electricity generated from renewable sources. The second strategy prioritizes increasing the energy efficiency of building materials, technologies, and appliances so that the building's overall energy consumption is less.

1.1.1. Electricity Generation and Storage Technologies

California has established targets for achieving emission reductions in electricity generation. According to SB 350 (Clean Energy and Pollution Reduction Act), by 2030, 50% of the electricity procurement in the state must come from renewable sources[1]. The law supports the state's efforts to reduce GHG emissions 80% below 1990 levels by the year 2050. In achieving the goals of this law, the state will need to account for any embodied emissions associated with the life-cycle stages of renewable sources.

1.1.2. Technologies and Products in Buildings for Energy Efficiency

It is important to explore the whole life-cycle impacts of the materials, technologies, and appliances utilized in making buildings more energy efficient and in electrifying building operations. Understanding both the operational and embodied environmental impacts from common and prevalent building technologies allows for improved control of impacts by regulatory agencies such as the California Public Utilities Commission.

There is increasing interest in ensuring that buildings are built with materials with low GHG emission footprints. A new California law, AB 2446, mandates that commonly used building materials for both commercial and residential projects meet a 40% reduction in net GHG emissions no later than 2035[2]. AB 2446 builds upon a prior California regulation (AB 262) enacted in 2017 called the Buy Clean California Act, which requires contractors for publicly funded contracts greater than $1,000,000 to only use concrete-reinforcing steel, structural steel, flat glass, and insulation with embodied GHG emission footprints lower than an established maximum[3]. There is interest in also ensuring that technologies/systems used within buildings have low manufacturing and operating GHG footprints and that design choices about which materials and technologies are selected will lead to an overall more energy efficient building.

To ensure that decisions about materials and technologies in buildings yield the lowest environmental footprint possible, it is crucial to quantify the relative comparison of embodied and operational emissions by technology. An estimation of embodied and operational emissions can inform understanding around future building changes, such as future electrical grid decarbonization implementation and in building energy efficient retrofits. Informed understanding can then influence future regulatory efforts. That is, there should be adequate and appropriate regulatory efforts to address the environmental impacts of all relevant technologies (e.g., building mechanical systems).

The accepted approach for identifying the environmental impacts of building materials and technologies is to consult environmental product declarations (EPDs). EPDs are standardized, third-party-verified documents which organize environmental impact data, including GHG emissions, according to each life-cycle stage of specific products[4]. Individual manufactures, as well as trade industry groups, are responsible for creating EPDs for a specific product. Regulations such as AB 2446 and the Buy Clean California Act require contractors to use EPDs as proof of a low GHG emission footprint for relevant products used in projects. It is important for regulatory agencies to understand the current scope of available EPDs so that any relevant gaps can be identified and lead to new directions for regulatory efforts. Once gaps can be filled with plentiful, relevant, and reliable data, more complex questions about buildings can definitively be addressed in the future, including:

- What is the significance of the differences between embodied and operational GHG emissions of various technologies?
- What is the significance of the differences in embodied/operational/total GHG emissions among various technologies?
- How do interventions/mitigation strategies of specific technologies change overall GHG emissions, particularly when accounting for building location and local climate conditions?

1.2. Overview of Research Scope

The research scope encompasses literature reviews and syntheses life-cycle GHG emission of electricity generation and storage technologies and energy efficiency devices and products for buildings. Detailed research scopes for each theme are provided in the following subsections.

1.2.1. Electricity Generation and Storage Technologies

The objective of this analysis is to review the literature and summarize what is known about the life-cycle greenhouse gas (GHG) emissions of electricity generation and storage technologies relevant to California.
We have answered these overarching questions:

1. What is the life cycle GHG emissions of electricity generation and storage technologies as best as we can establish based on current research?
2. If there is insufficient data currently available for any of the above resources, what data would we need to collect?
3. How can we collect such data?

Within the scope of the project, following target electricity and storage generation technologies have been evaluated:

- Natural gas
- Solar (utility scale and behind-the-meter)
- Wind (utility scale and behind-the-meter)
- Storage (utility scale and behind-the-meter)
- Geothermal
- Biomass

We have synthesized available information and data for all the relevant life-cycle stages of various electricity generation technologies and storage, and include them in the total life cycle GHG emissions:

- Construction of electric power plants (rooftop to power plant scale), including embedded energy and resulting GHG emissions due to manufacturing of power plant components (e.g., generators, turbines, buildings, PV cells, wind turbines, gas storage) and onsite construction activities for power plants (e.g., installing steel for natural gas power plant structure).
- Natural gas extraction, pipeline transportation, and storage.
- Extraction of materials used to manufacture devices such as solar panels, batteries, transmission, and distribution systems equipment.
- Growing, collection (e.g., orchard waste), and transportation of biomass to power plant.
- Transportation in the supply chain of power plant materials and components (e.g., iron ore to steel mill to solar thermal plant) and to get these components to the construction or customer site.
- Transportation of fuels to power plants.
- Operation of power plants (e.g., natural gas combustion).
- Maintenance, including related materials and construction activities (e.g., washing solar panels).
- Treatment of materials following the retirement (end of life) of the facility or equipment.
- Establishment of battery or other storage of electricity from renewable generation (wind and solar), including component manufacturing and construction of facilities.

1.2.2. Technologies and Products in Buildings for Energy Efficiency

A list of over 280 technologies, of which 120 are unique, was provided to us by the California Public Utilities Commission. Many of the technologies in the list are common building materials, appliances, and process equipment used in the construction and operation of agricultural, residential, commercial, and industrial buildings. The research team searched for relevant environmental impact data in the form of EPDs, peer-reviewed journal articles, and publicly available reports from government and industry for each technology. The objectives of this research were to:

1. Review and document a range, if possible, of embodied and operational GHG emissions for a wide-ranging list of residential, commercial, industrial, and agricultural building technologies. Contrast the range between operational and embodied carbon among the various technologies.
2. Survey existing EPD and other life-cycle inventory (LCI) data for each technology and sort by factors including geographic location, emission type (embodied, operational), and level of uncertainty of underlying data.
3. Identify gaps in existing EPD and other LCI data, in the context of the list of technologies.
4. Provide recommendations for regulatory agencies and private sector stakeholders to improve gaps in EPD/LCI data for these listed technologies.

2. Methods

2.1. Electricity Generation and Storage Technologies

We have conducted a *comprehensive literature review and* synthesis based on the most recent available sources (in terms of data and information) about the life cycle GHG emissions of electricity and storage technologies. As a first step, we searched for studies specific to California. Then, we have looked for publications specific to conditions and technologies operating in the United States, followed by technologies and systems from other countries.

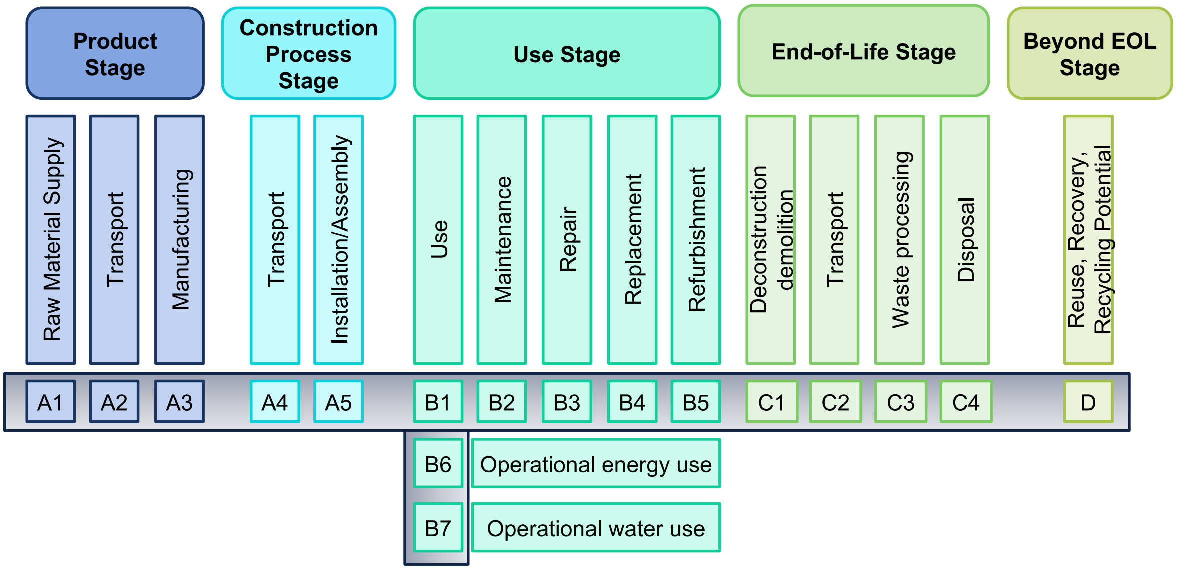
Following the literature analysis, we performed *gap analysis* to highlight what data we could find and what we could not and make recommendations as to what data we would need to collect in California in order to have the best life cycle GHG emissions estimates.

Our literature search has focused on *life-cycle assessment (LCA)* studies. LCA is the only internationally accepted systematic and documented methodology to quantify the direct and supply chain-inclusive energy and material inputs and environmental outputs of products, processes, and systems. It follows the ISO 14040 and 14044 standards, and all life-cycle stages are analyzed.

2.2. Technologies and Products in Buildings for Energy Efficiency

The primary methods in this research are very similar to those of a literature review. Using the named technologies and applicable key terms for each technology, we searched through EPD databases (such as EC3, a building materials database), journal article databases (including Web of Science, Google Scholar), and search engines (such as Google) to find data on the embodied and operational GHG emission values for each technology. We primarily used data that were recorded in English.

In order to harmonize all data sources according to a standard framework, we extracted information in the form of the EN Standard 15978 for life-cycle emissions (Figure 1) where emissions for each life-cycle stage are organized into life-cycle modules with alphanumeric codes. This is the common framework followed in most EPD documents and follows the "language" with which most government and private sector stakeholders are familiar.



"Model for Life Cycle Assessment (LCA) of buildings"[5].

Additional relevant information was extracted from each EPD/article/report including the technology's functional unit, service life, and data about the energy (source and location) used in manufacturing and/or operating the technology. Where appropriate, we noted ranges of values for specific technologies. For example, there are various types of wall insulation (blown, board, foam) and so a technology such as "Wall Insulation for Commercial Buildings" would have multiple entries to reflect the variations in type. Based on our survey of the existing data, we were able to then formulate recommendations for regulatory and private-sector stakeholders to motivate future directions for developing new EPDs and other relevant data.

We organized the list of technologies according to overarching categories. Some of the categories are then further organized into subcategories (see Figure 2). We started with a list of around 240 products and technologies. This was trimmed down to a smaller list as we removed duplicates of technologies in multiple climate zones. It should be noted that the values for technologies in the Commercial and Residential Building Technologies are duplicates.

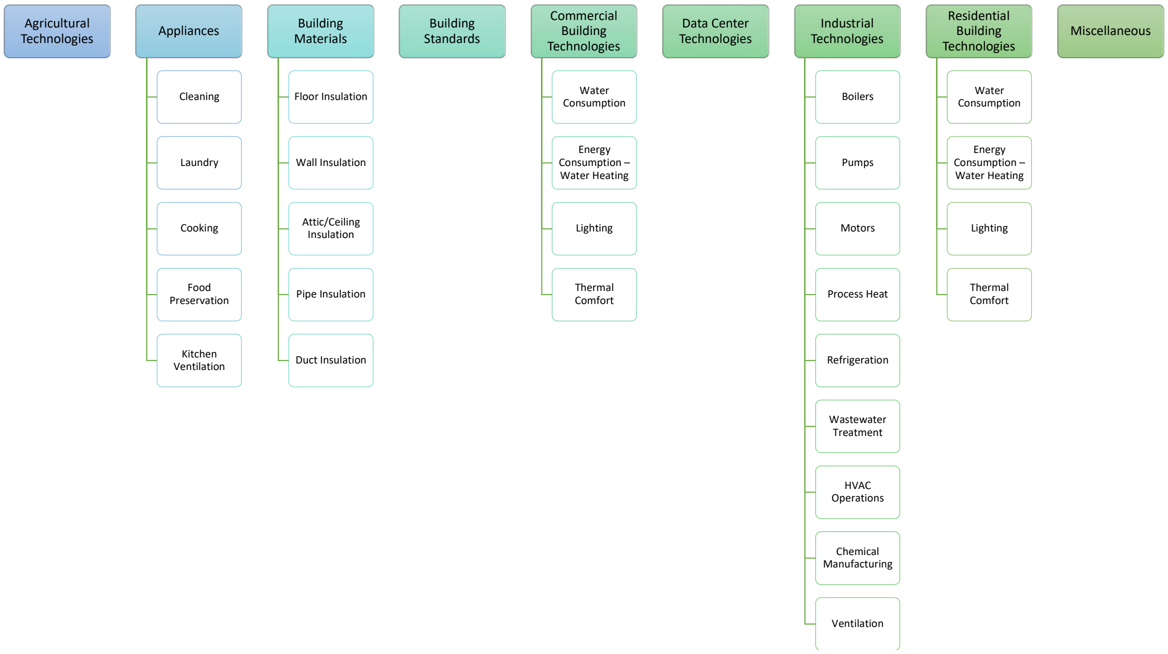


Figure 2. Overview of product categories and subcategories included in this report.

We only present results in a graphical manner if there are enough data points to present a range. We present embodied and operational GHG emission results for a technology in a box and whisker plot. Box and whisker plots are an effective visual representation of the spread and skewness of values, denoting minimum, maximum, and median values. We also present results for the number of EPDs/datapoints for each technology in each category. All other results are presented in-text in the Results section.

3. Results

3.1. Electricity Generation and Storage Technologies

Electricity generation mix in a region constitutes one of the main drivers in regional GHG emission intensity and in region-specific life cycle inventories (LCIs). However, despite its importance, the electricity industry is unique for LCA and policy analysis because while it is straightforward to measure electricity use, it is nearly impossible to track the electricity generated in a given power plant through the transmission and distribution system to a specific electricity consumer[6]. For this reason, it is common in LCA and carbon footprint applications to create and utilize emissions factors, or average amount of a pollutant per unit activity, for the use of grid electricity, such as g CO_2/kWh generated and/or stored.

Figure 3 provides an illustrative scope of targeted electricity generation and storage types and cradle-to-grave life cycle stages represented in the analysis, functional unit being per kWh of electricity.

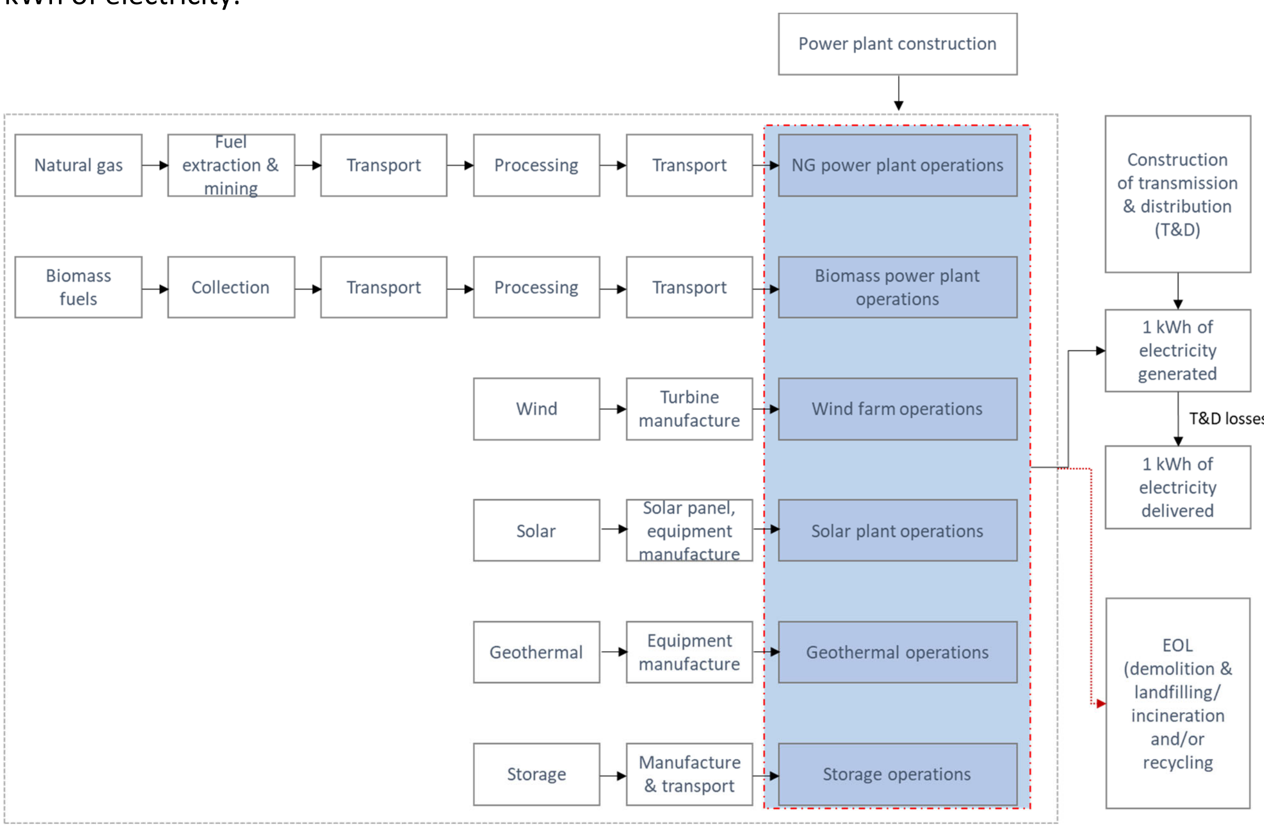


Figure 3. An illustrative scope of targeted electricity generation and storage types and cradle-to-grave life cycle stages represented in the analysis.

The following tables (Table 1-4) provide earlier data that would feasibly be used in estimating the direct and indirect GHG impacts from life-cycle phases preceding and pertaining to electricity generation.

Table 1. GHG emission factors, excl. combustion (g CO_2e/kWh) – Source: [7]

Coal	Natural gas	Nuclear[1]	Wind	Solar[2] (PV)	Concentrating Solar Power[3]	Hydro	Biomass	Other biomass	Oil	Geo-thermal
<20	72	15	13	43	28	21	52	52	44	22

Table 2. GHG emission factors, material (cradle-to-gate, from mining to power plant) and power plant infrastructure (g CO_2e/kWh) – Source: [8]

	Coal	Natural gas	Nuclear (LWR)	Wind	Solar (PV)	Hydro	Biomass	Other biomass	Oil	Geo-thermal (EGS)
Material	21	38	142	-	-				44.2	-
Infrastructure	0.8	0.42	0.44	6.79	59.68	2.12	0.80			20.41

Table 3. GHG emission factors (g CO_2e/kWh), life cycle – Source: [9]

Coal	Natural gas	Nuclear	Wind	Solar	Hydro	Biomass	Other biomass	Oil	Geo-thermal
1,059	696	17	31	64	55	56	56	957	28

Table 4. GHG emission factors (g CO2e/kWh), life cycle – Source: [10]

PV Solar		Concentrated Solar Panel		Geothermal		Reservoir Hydro		River Hydro		Ocean Hydro		Wind	
Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max
5	217	7	89	6	76	-	165	3	12	2	23	2	81

The following sections describe each of the targeted electricity generation and storage technologies in further detail.

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[1] Light-water reactor (including pressurized water and boiling water) only.

[2] Thin film and crystalline silicon

[3] Tower and trough

3.1.1. Natural gas

3.1.1.1. Electricity Generation from Natural Gas

The cradle-to-gate analysis of the U.S natural gas from DOE-NETL[11] covered all construction and operation activities necessary to extract natural gas from the earth as well as intermediate gathering, processing, and transport steps. The analysis ended with the delivery of natural gas to large-scale utility and industrial users and small-scale commercial and residential users. The cradle-to-gate GHG emissions from the United States (U.S.) natural gas supply chain were estimated as 19.9 g CO_2e per MJ (71.6 g CO_2e/kWh) with a 95% mean confidence interval of 13.1 to 28.7 g CO_2e/MJ or 47.2 to 103.3 g CO_2e/kWh. The top contributors to CO_2 and CH_4 emissions were attributed to combustion exhaust and other venting from compressor systems. Compressor systems are prevalent in most supply chain stages, so compressor emissions are key emission drivers for life cycle emissions. Emission rates were found to be highly variable across the entire supply chain[11].

Figure 4 provides a systematic and comprehensive review of LCA literature of electricity generated from conventionally produced natural gas. Figure 4 was produced on the basis of data adapted from O'Donoughue et al[12]. It demonstrates estimates of GHG emissions emitted in the life cycle of electricity generation from natural gas-fired combustion turbine (NGCT) and combined-cycle (NGCC) systems. The smaller set of LCAs of natural gas plants with carbon capture and storage (NGCC-CSS) were also collected.

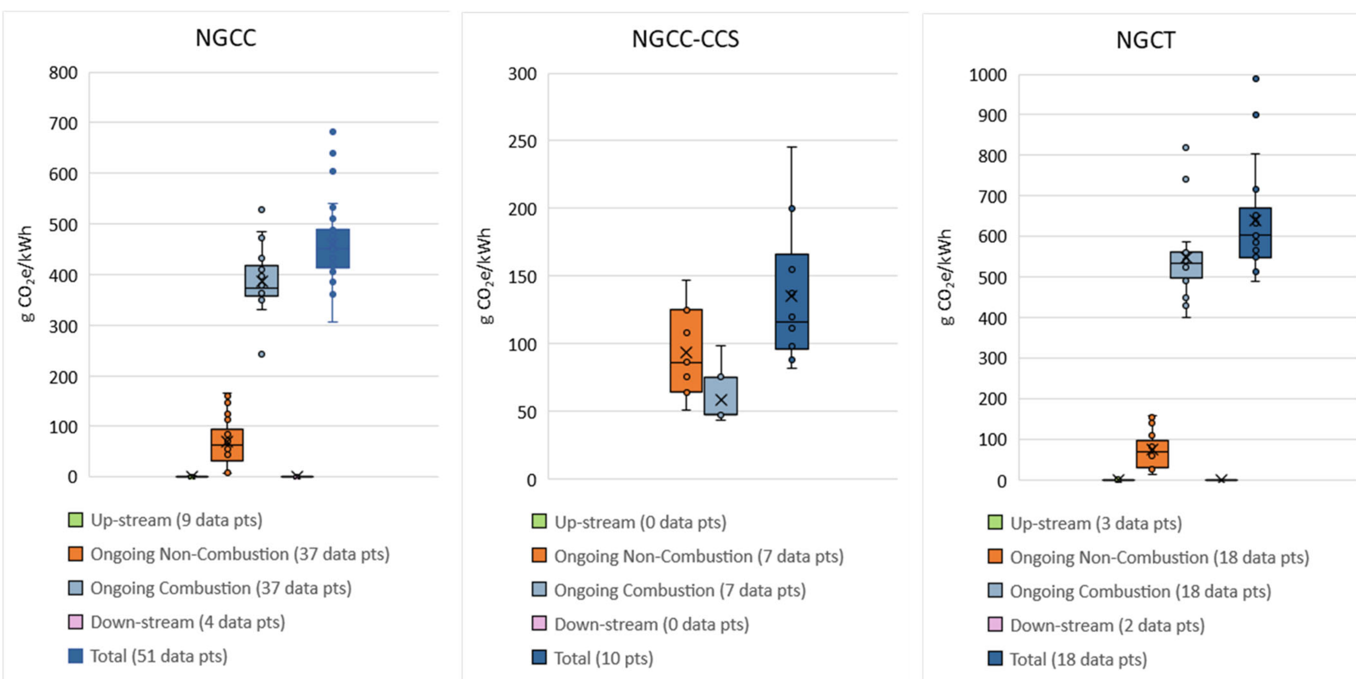


Figure 4. Cradle-to-grave life cycle GHG emissions from various natural gas power plants based on literature review adapted from O'Donoughue et al[12]. Note: NGCC - natural gas combined cycle; NGCC-CCS - natural gas combined cycle with carbon capture and storage; NGCT - natural gas combustion turbine.

3.1.2. Electricity Generation from Solar Power

Solar energy in California falls into two categories: solar thermal and solar photovoltaic (PV). The California Energy Commission (CEC) licenses solar thermal plants above 50 MW and promotes solar PV installation through the Renewables Portfolio Standard, with building efficiency standards, and as a partner in the California Solar Initiative[13].

3.1.2.1. Utility-Scale Solar Thermal Plants

Solar thermal power plants usually have a large field or array of collectors that supply heat to a turbine and generator. Several solar thermal power facilities in the United States have two or more solar power plants with separate arrays and generators. Solar thermal power systems may also have a thermal energy storage system component that allows the solar collector system to heat an energy storage system during the day, and the heat from the storage system is used to produce electricity in the evening or during cloudy weather. Solar thermal power plants may also be hybrid systems that use other fuels (usually natural gas) to supplement energy from the sun during periods of low solar radiation (EIA - https://www.eia.gov/energyexplained/solar/solar-thermal-power-plants.php).

The system boundary of the LCA accounts for the cradle-to-grave energy and material flows for solar thermal power/electric generation systems. The boundaries include five life cycle stages, beginning with the raw material extraction, and then moving to the intermediate steps of raw material transport, energy conversion, and electricity transmission and distribution, and ending with the electricity delivery to the consumer. In contrast to fossil energy and some forms of renewable energy conversion, solar thermal power does not incur any environmental burdens for the acquisition and transport of primary fuel. Thus, the equipment manufacture, construction, and installation requirements of solar thermal power plants dominate the life cycle greenhouse gas (GHG) emissions for solar thermal power.

In the DOE/NETL 2012 analysis, GHG emissions for solar thermal power from a U.S. 250 MW net power plant were calculated as *44.6 g CO_2e/kWh*[14]. The majority of GHG emissions are from CO_2 at 82.9 percent, with the remainder split between CH_4, N_2O, and SF_6 at 5.4 percent, 4.4 percent, and 7.3 percent, respectively. Solar collector construction accounts for 46.3 percent of the life cycle GHG emissions for solar thermal power, while plant operation accounts for 40.7 percent. The construction of the plant and the trunkline contribute a combined 5.7 percent, while transmission and distribution (T&D) account for 7.3 percent. The GHG emissions from direct land use change are an additional 4.4 g CO_2e/kWh. In the analysis, there was no indirect land use change since no agricultural land was displaced by the solar thermal facility modeled. Therefore, the land use GHG emissions from solar thermal power increase the total cradle-to-grave GHG emissions from *44.6 to 49.0 g CO_2e/kWh*.

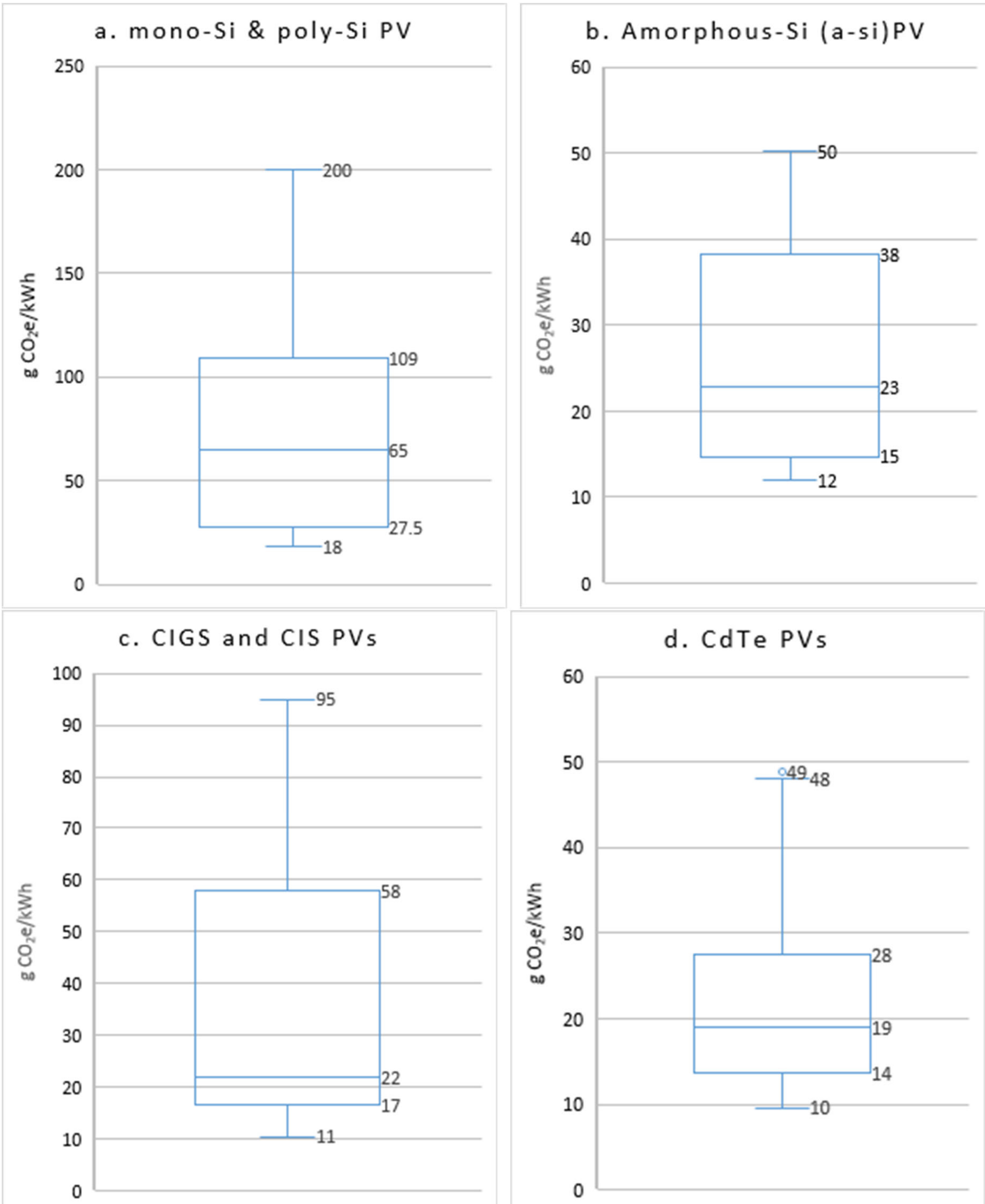
A dry-cooled, 106 MW net power tower concentrating solar power plant facility located near Tucson, AZ was evaluated by Whitaker et al[15]. The power plant uses a mixture of mined nitrate salts as the heat transfer fluid and storage medium, a two-tank thermal energy storage system designed for six hours of full load-equivalent storage and receives auxiliary power from the local electric grid. A thermocline-based storage system, synthetically derived salts, and natural gas auxiliary power are evaluated as design alternatives. Over its life cycle, the reference plant was estimated to have *GHG emissions of 37 g CO_2e/kWh, consume 1.4 L/kWh of water and 0.49 MJ/kWh of energy*[15].

Following Figure 5 provides a summary of data for the CO_2e/kWh for utility scale as well as rooftop solar power systems worldwide, including Canada, Chile, China, Germany, Italy, Japan, Singapore, Spain, and the United States (Arizona and California).

Figure 5. Life cycle GHG emissions of various utility-scale and rooftop solar power systems based on literature and manufacturer EPDs[12,16–38].

3.1.2.2. Thin-film solar technologies

Figure 6 (a-e) provides GHG emission factor datasets for commercial and emerging thin-film solar technologies based on life cycle assessment (LCA) studies and EPDs (if available) found in the literature.



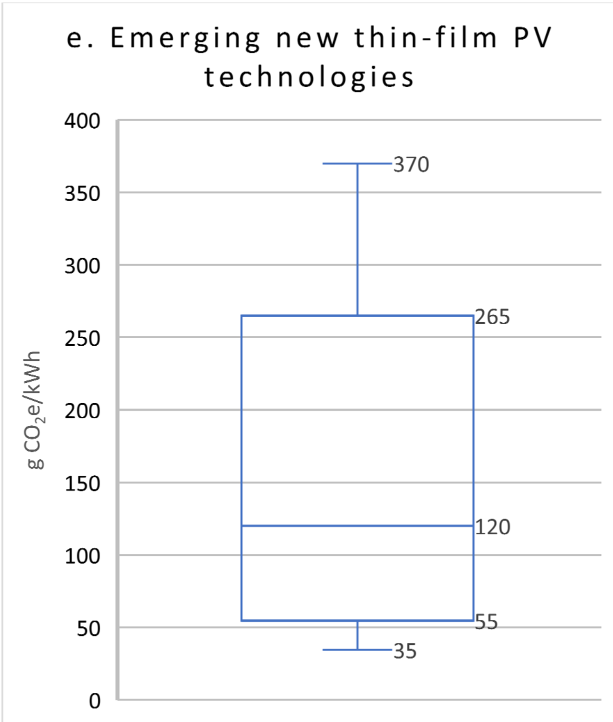


Figure 6. Commercial and emerging thin film PV technologies a. Mono-Si and poly-Si PV cells based on 17 data points[16,17,21,23,34,36] b. Amorphous-Si PV cells based on 7 data points[17,19,20,29,35,38] c. Copper indium gallium diselenide (CIGS) and copper indium selenium (CIS)) based on 9 data points[18,18,20,28,37] d. Cadmium telluride (CdTe) PV cells base on 13 data points[17–20,24,27,28,33] e. emerging thin-film solar technologies (GaAs/Si, GaInP/ GaAs nanowire solar modules, Perovskite PV) based on 9 data points[19,22,26,36]

Figure 7 shows CO_2e emission factors over the life cycle of commercial thin-film photovoltaics (PVs), that is, amorphous silicon (a-Si), cadmium telluride (CdTe), and copper indium gallium diselenide (CIGS) based on NREL's Kim et al.'s harmonization study[39]. It covers a literature analysis of 109 studies (initially) and harmonized the estimates of emissions by aligning the assumptions, parameters, and system boundaries. After their initial screening, 91 studies passed this initial screening-based criteria for completeness of reporting, validity of analysis methods, and modern relevance of the PV system studied. The resulting estimates for carbon footprints were 20, 14, and 26 g CO_2e/kWh, respectively, for a-Si, CdTe, and CIGS, for ground-mount application under southwestern United States (US-SW) irradiation of 2,400 kilowatt-hours per square meter per year (kWh/m^2/yr), a performance ratio of 0.8, and a lifetime of 30 years. Harmonization for the rooftop PV systems with a performance ratio of 0.75 and the same irradiation resulted in carbon footprint estimates of 21, 14, and 27 g CO_2e/kWh, respectively, for the three technologies.

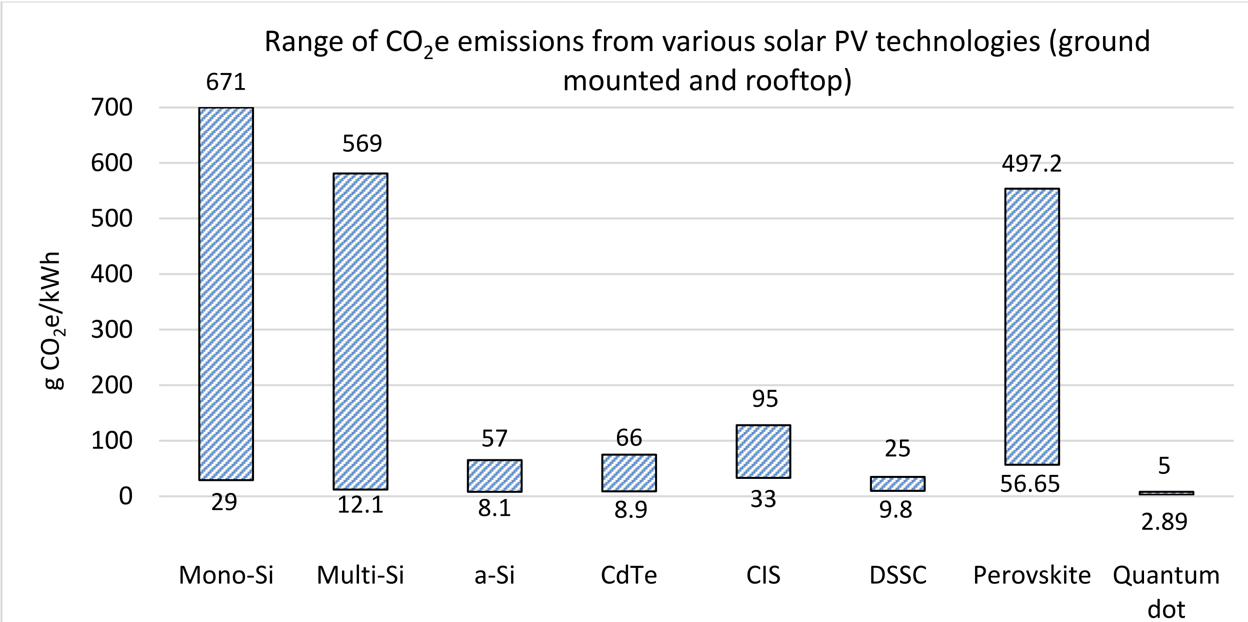


Figure 7. Life cycle GHG emissions of solar photovoltaic electricity generation technologies (Source: NREL website: https://www.nrel.gov/analysis/life-cycle-assessment.html)

3.1.3. Wind power systems

Dolan and Heath have performed a systematic review and harmonization of LCA literature of utility-scale wind power systems to determine the causes of and, where possible, reduce variability in estimates of life cycle GHG emissions[40]. Published estimates ranged from 1.7 to 81 g CO_2e/kWh, with median and interquartile range (IQR) both at 12 g CO_2e/kWh. After adjusting the published estimates to use consistent gross system boundaries and values for several important system parameters, the total range was reduced by 47% to 3.0 to 45 g CO_2e/kWh and the IQR was reduced by 14% to 10 g CO_2e/kWh, while the median remained relatively constant (11 g CO_2e/kWh). Estimates from EU-based studies for onshore wind farms consisting of multi-megawatt turbines were in the range of 5–16 g CO_2e/kWh[41]. More recently, Dammeier et al. quantified the GHG footprint of 26,821 wind farms located across the globe, combining turbine-specific technological parameters, LCI data, and location- and temporal-specific meteorological information[42]. These wind farms represent 79% of the 651 global wind (GW) capacity installed in 2019. Results indicate a median GHG footprint for global wind electricity of 10 g CO_2e/kWh, *ranging from 4 to 56 g CO_2e/kWh* (2.5th and 97.5th percentiles). Differences in the GHG footprint of wind farms are mainly explained by spatial variability in wind speed, followed by whether the wind farm is located onshore or offshore, the turbine diameter, and the number of turbines in a wind farm. (Figure 8)

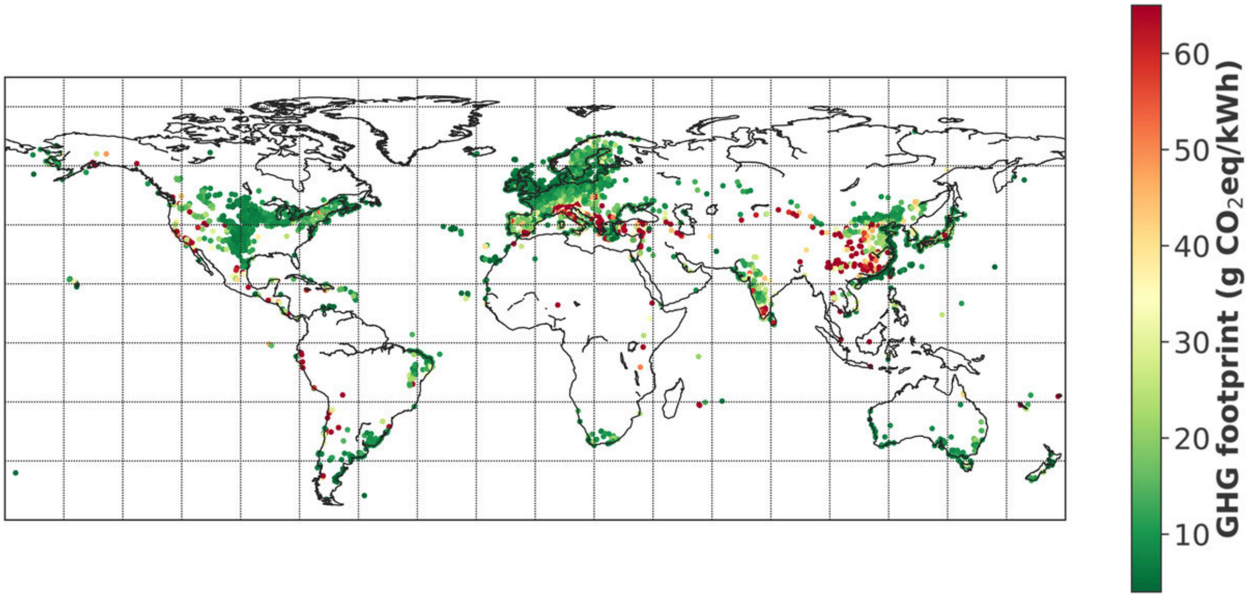
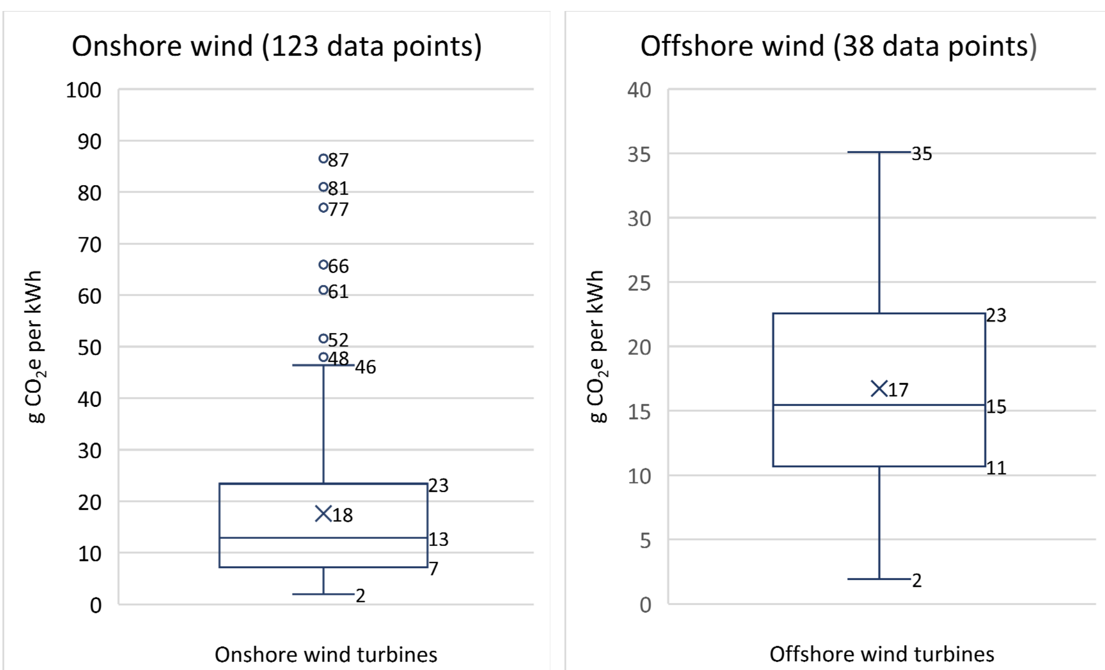


Figure 8. Greenhouse gas footprints of the individual wind farms in g CO_2eq/kWh of the global wind farm fleet[42].

The representative cradle-to-grave system boundary in reviewed LCAs and EPDs often include wind turbines with foundations, internal electrical connections, and cabling and a high-voltage transformer for connection to the electricity grid. In addition, the analysis includes installation, operation and maintenance, and decommissioning. The literature review provides a range of GHG emissions from 2 to 86.5 *g CO_2e/kWh* for onshore, offshore, and unspecified wind turbines (Figure 9).



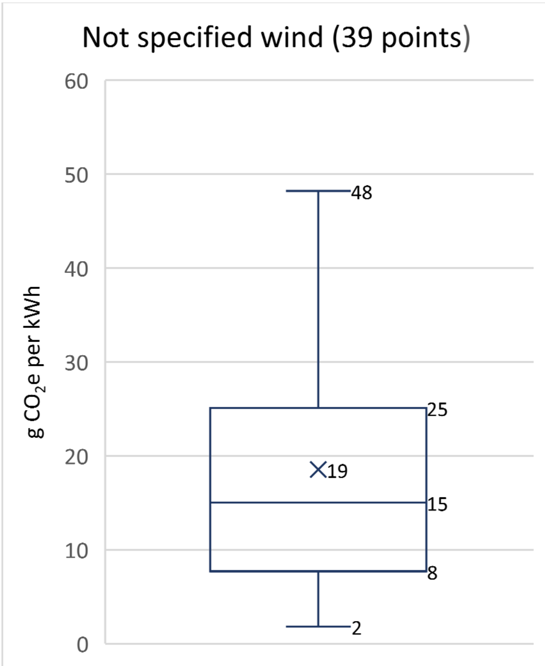


Figure 9. *The box the 25th to 75th percentile, and the whisker the 2.5th to 97.5th percentile. Underlying data for the results from 99 articles and reports from the literature review*[25,40–70].

Detailed life-cycle GHG emissions by cradle-to-gate stages for utility scale (onshore and offshore) wind power systems are demonstrated in Figure 10. Estimates of life cycle GHG emissions are in the range of 5.8-29.5 g CO_2e/kWh.

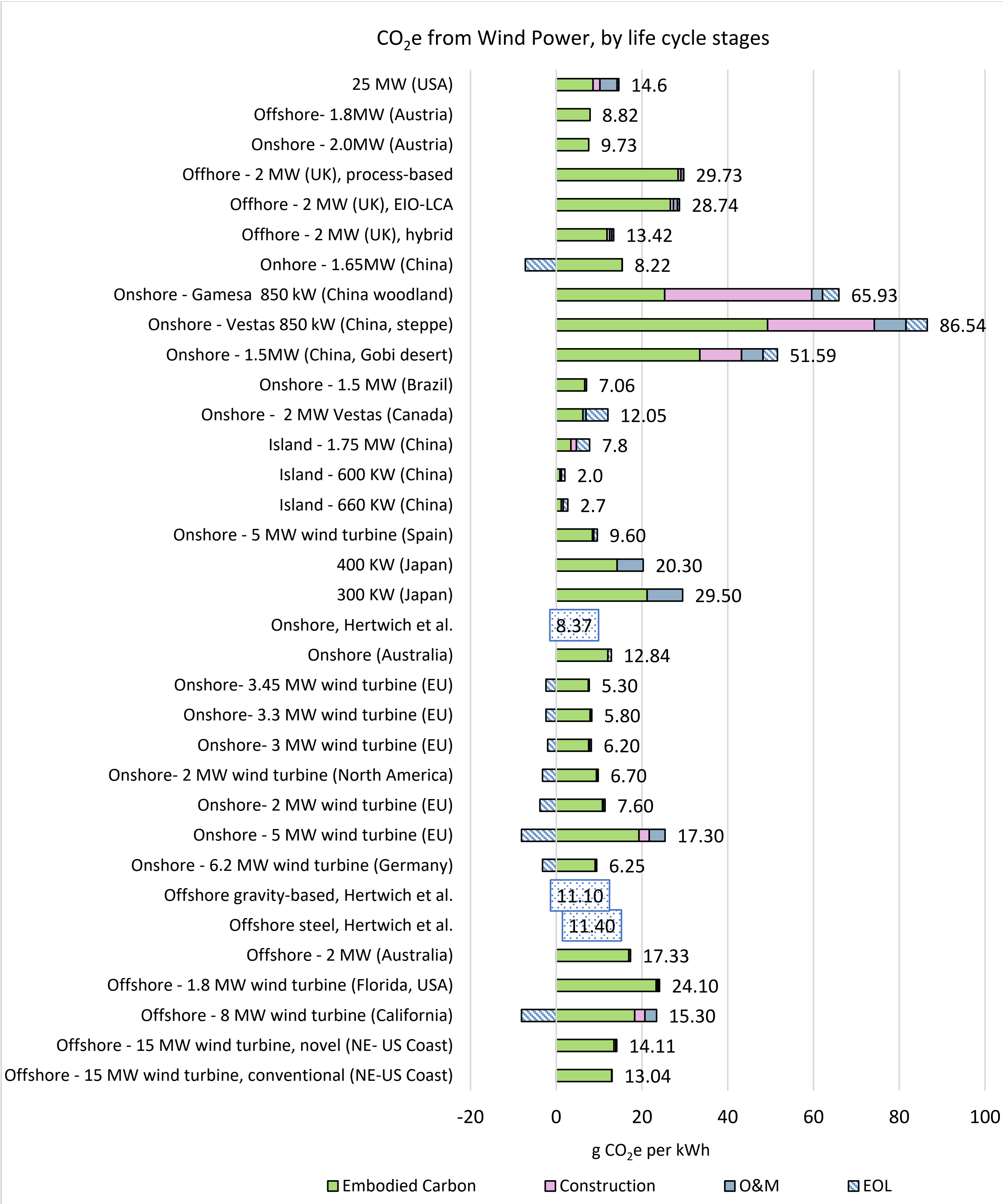


Figure 10. Life-cycle GHG emissions of various wind power systems based on literature and manufacturer EPDs[25,40–70].

3.1.4. Geothermal

With its abundance and reliability, geothermal energy presents opportunities for reducing the world's dependence on fossil fuels for power and heat generation. In addition, because geothermal power plants have been shown, in almost all cases, to have lower greenhouse gas (GHG) emissions than fossil fuel-fired power plants[71], they could also help mitigate climate change impacts. However, estimates for the environmental impacts of geothermal power plants vary considerably. In some cases, the estimates of GHGs emitted per kilowatt-hour of geothermal electricity are five to ten times larger than the median values reported for wind and solar technologies (https://www.nrel.gov/docs/fy17osti/68474.pdf). Technologies used in geothermal sourced electricity generation are:

1. EGS binary: EGSs used in the operation of binary cycle power plants,
2. HT binary: HT resources used in binary cycle plants,
3. HT flash: high-temperature HT resources that are vaporized and used in flash steam plants,
4. Dry steam: steam that directly drives a turbine, and
5. Hybrid systems: the combination or two or more electricity generation technologies (e.g., geothermal, and solar).
   (https://www.nrel.gov/docs/fy17osti/68474.pdf)

Geothermal energy is a source of renewable energy in California. The Geysers, the world's largest geothermal field, is in Sonoma, Lake, and Mendocino counties. Other major geothermal locations include the Salton Sea area in Imperial County, the Coso Hot Springs area in Inyo County, and the Mammoth Lakes area in Mono County.
GHG emissions disaggregated by phase of the life cycle (i.e., total, construction, operation, and end of life) for three geothermal electricity generation technologies: enhanced geothermal systems (EGS) binary, hydrothermal (HT) flash, and HT binary are shown in Figure 11[50,71–76].

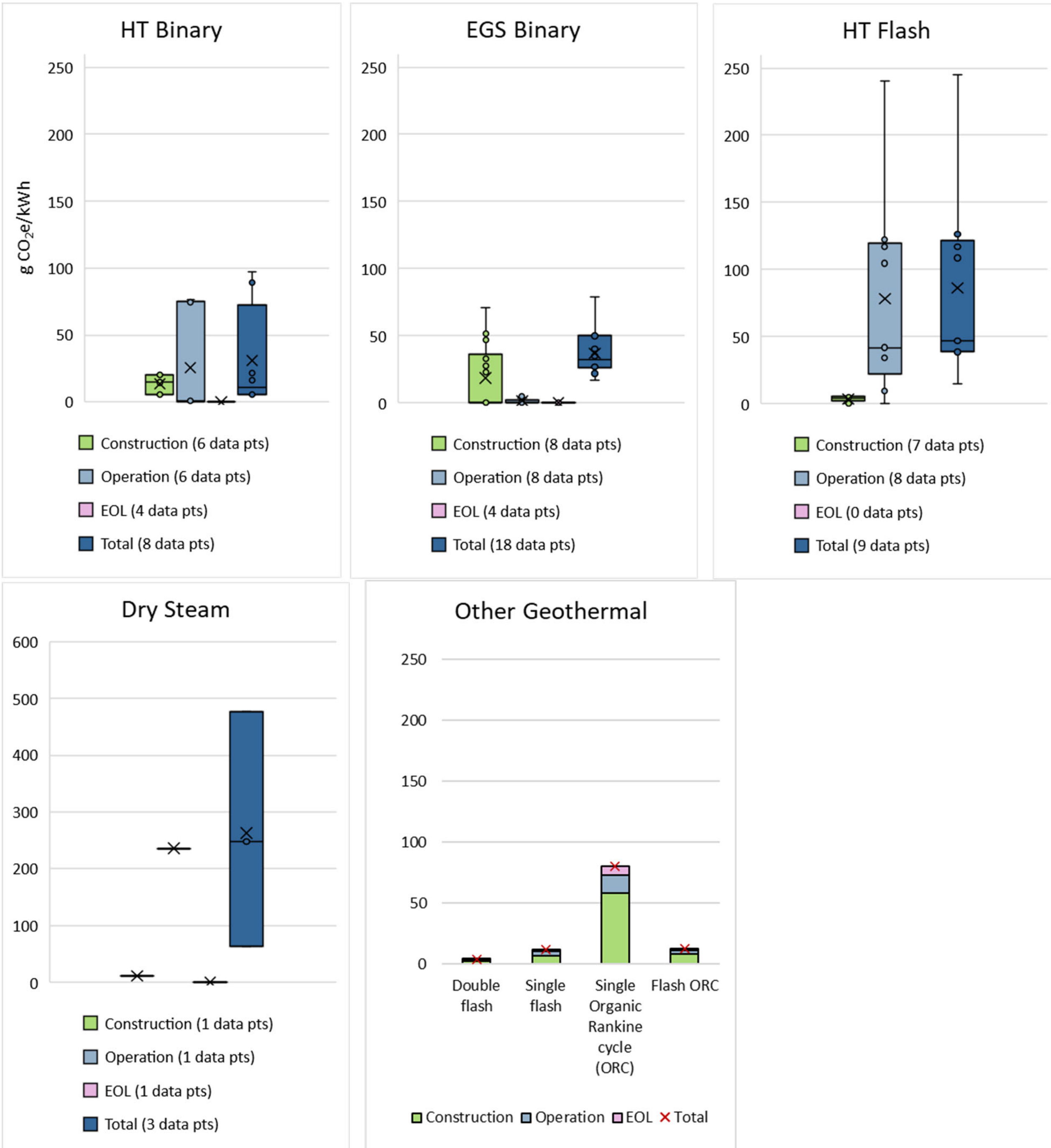


Figure 11. Lifecycle GHG emissions of geothermal power generation[50,71–76].

3.1.5. Biomass (Biopower)

Biomass electricity is drawn from combusting or decomposing organic matter. Biomass plants power homes and businesses with electricity from waste matter that would have been released into the atmosphere, added fuel to forest fires, or burdened landfills. In Gao et al., electricity generated from biomass was mainly powered by the direct combustion and gasification of forestry and agricultural residues, burning of garbage, and burning of landfill gas[25]. The biomass power generation system was analyzed with an installed capacity of 25 MW and an annual power generation time of 6000 h, resulting in an efficiency of 26%. In this analysis, the straw consumption was 1.4 kg/kWh with an acquisition radius of approximately 20 km and a power plant lifetime of 30 years. Figure 12 summarizes the cradle-to-gate GHG emissions from the studied biomass power plant located in China.

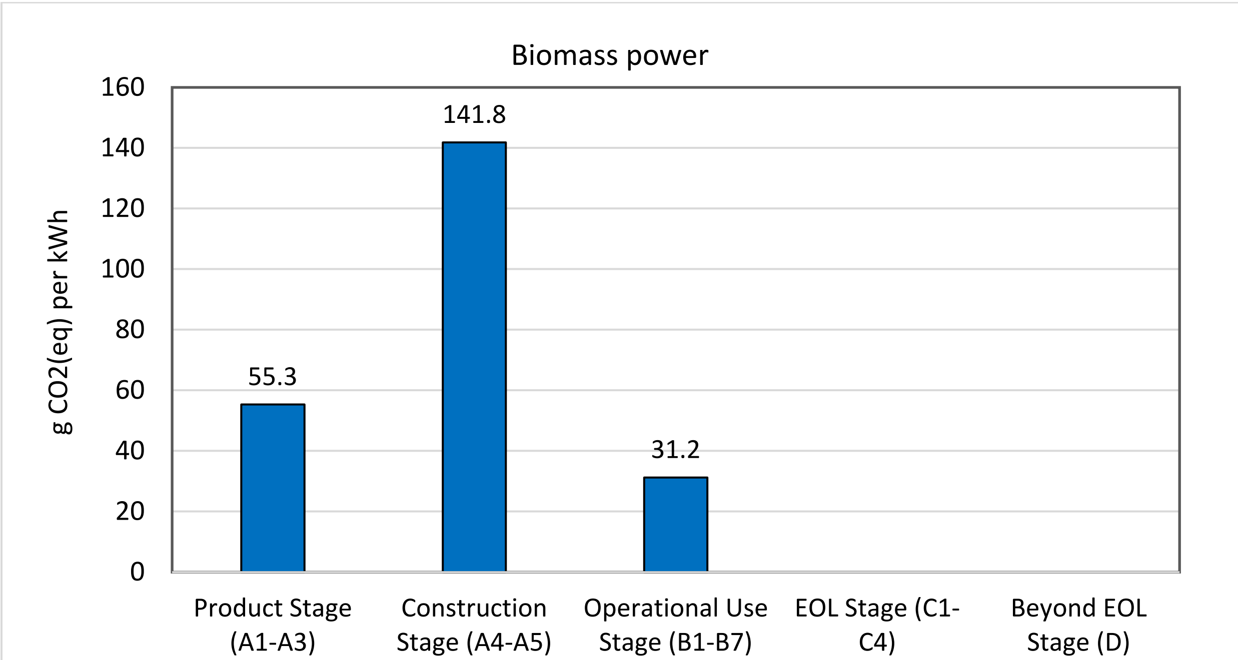


Figure 12. Life-cycle GHG emissions of biomass power generation[25]

Kadiyala et al. study has analyzed life cycle GHG emissions from the use of different biomass feedstock categories (agriculture residues, dedicated energy crops, forestry, industry, parks and gardens, wastes) independently on biomass-only (biomass as a standalone fuel) and cofiring (biomass used in combination with coal) electricity generation systems[30]. The statistical evaluation of the life cycle GHG emissions (gCO_2e/kWh) for biomass electricity generation systems was based on the review of 19 life cycle assessment studies (representing 66 biomass cases). The mean life cycle GHG emissions resulting from the use of agriculture residues (N = 4), dedicated energy crops (N = 19), forestry (N = 6), industry (N = 4), and wastes (N = 2) in biomass-only electricity generation systems were estimated as 291.25 gCO_2e/kWh, 208.41 gCO_2e/kWh, 43 gCO_2e/kWh, 45.93 gCO_2e/kWh, and 1,731.36 gCO_2e/kWh, respectively. Forestry and industry (avoiding the impacts of biomass production and emissions from waste management) contribute the least amount of GHGs, irrespective of the biomass electricity generation system. One may note the degree of variation in GHG emissions was less between LCA studies based on forestry, followed by industry, dedicated energy crops, agriculture residues, and wastes. The median quartile statistic (Q2) showed a consistent pattern to that observed in the mean life cycle GHG emissions pattern, with forestry being the minimum, followed by industry, dedicated energy crops, agriculture residues, and wastes (Figure 13).

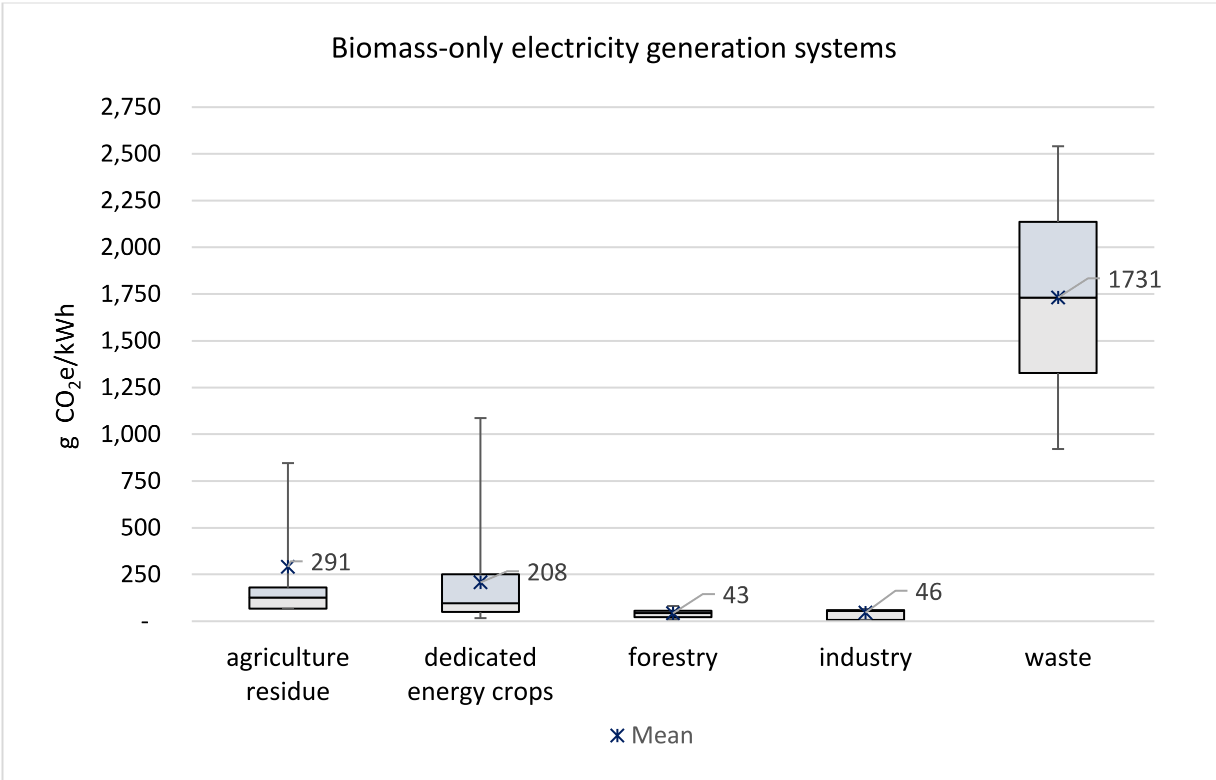


Figure 13. GHG emission (gCO_2e/kWh) statistics from biomass-only electricity generation systems[30].

3.1.6. Storage Systems (utility and beyond-the-meter scale)

Energy storage technologies that are currently viable for large, multi-MW applications are listed as follows:

1. Pumped hydropower storage (PHS) is a proven technology installed worldwide.
2. Compressed air energy storage (CAES) is a hybrid storage/generation system that requires natural gas fuel.
3. Advanced battery energy storage systems (BESS), such as flow-cell batteries, are currently being installed in several locations. Among the most suitable for large applications are the Vanadium-Redox Battery (VRB) and the Polysulphide Battery (PSB.)

Figure 14 shows the GHG emission factors estimated for utility-scale storage systems on the basis of data from Mostert et al[77].

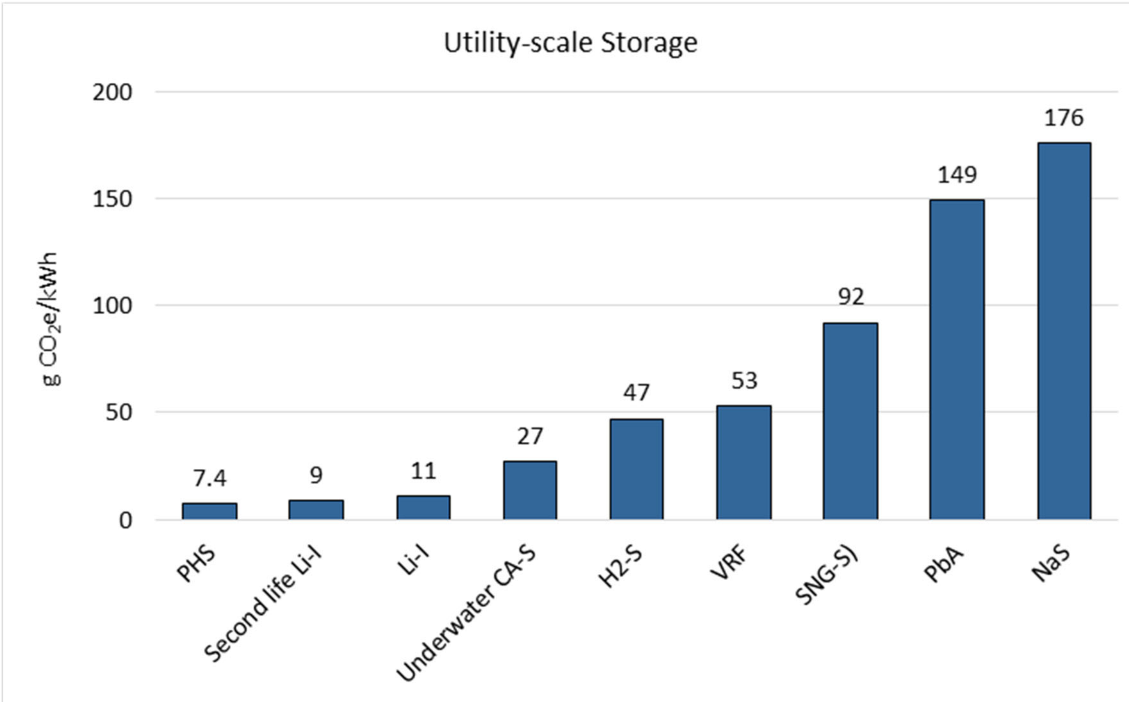


Figure 14. the GHG emission factors estimated for utility-scale storage systems[77]. Note: Li-l-B: lithium-ion battery, NaS: Sodium-sulfur battery, PbA: Lead-acid battery, SL-Li-I: Second-life battery, SNG-S: power-to-gas synthetic natural gas storage, VRF: Vanadium redox flow battery

3.1.6.1. Lithium-ion Technologies:

Utility-scale lithium-ion batteries have recently entered the energy scene. Albeit much smaller than most pumped hydropower plants, they can also provide the required balancing and ancillary services. Cathode chemistries include lithium iron phosphate (LFP), lithium cobalt oxide (LCO), manganese spinel oxide (LMO), and composite oxides (NCM and NCA) (including nickel (N), cobalt (C), aluminum (A) or manganese (M)), Lithium salt of titanium oxide (lithium titanate; LTO-type); Lithium vanadium oxide or Li3VO4 (LVO); Combination of LFP and LTO. Figure 15 was created based on LCA studies on Li-ion batteries or battery production from 2000 to 2016[78].

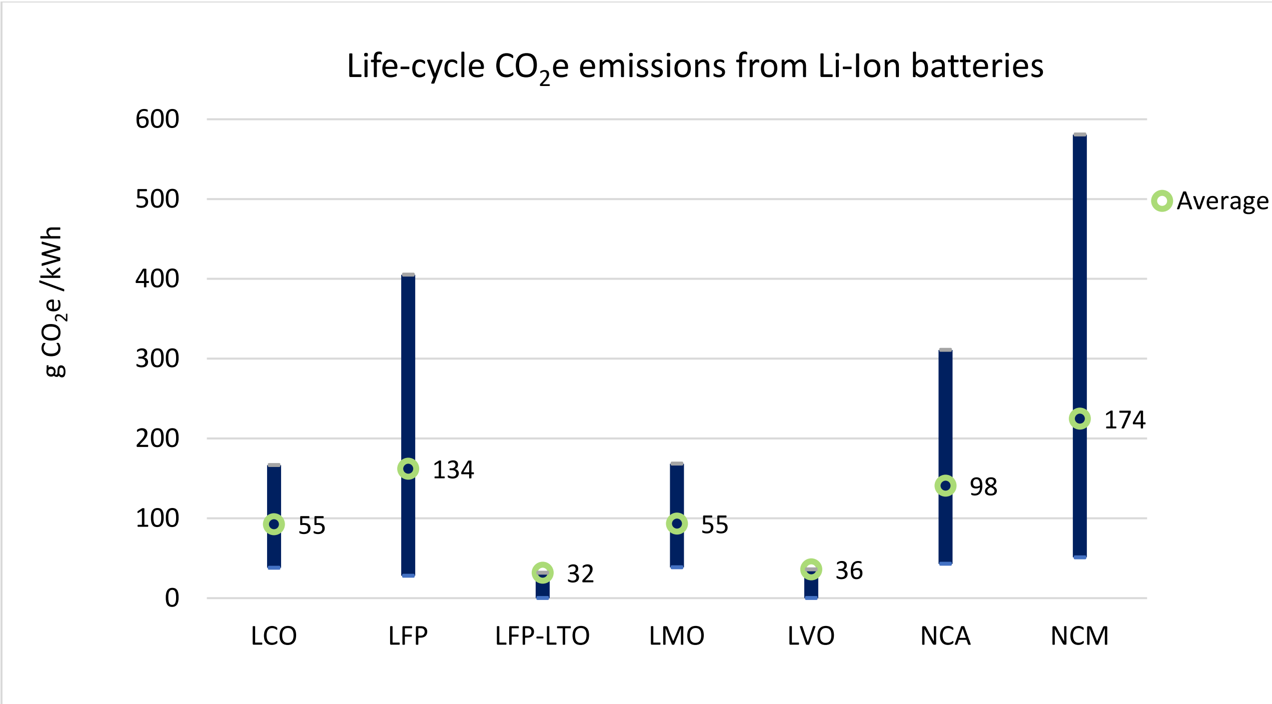


Figure 15. Life cycle GHG emissions of lithium-ion batteries

3.1.7. Summary and Key Sources of variability between LCA studies of electric power technologies

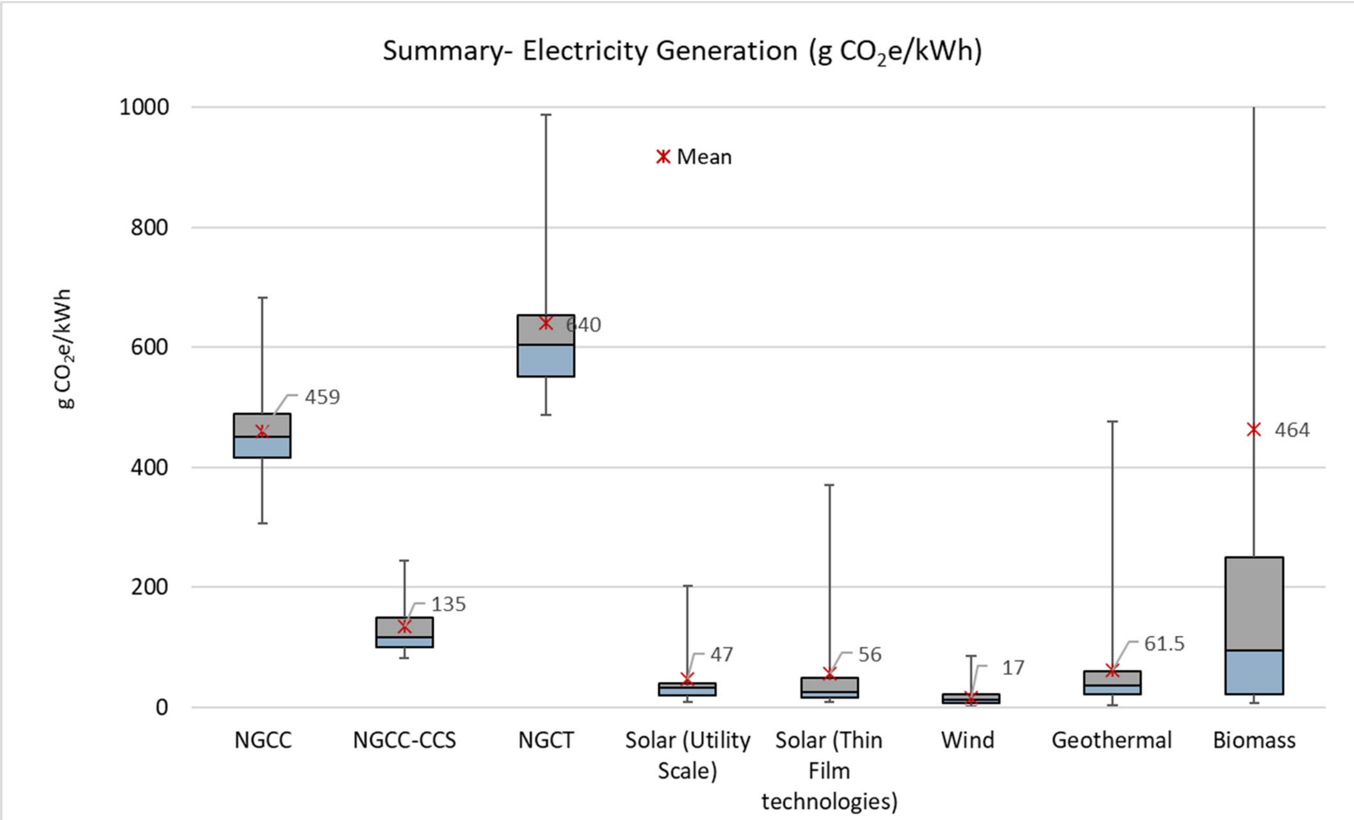


Figure 16. Variability in GHG emission factors calculated for targeted electricity generation technologies.

Table 5. Summary of major assumptions that account for variability between data sources from LCA studies and EPDs.

Electric power technology	Major assumptions that account for variability between life-cycle assessment studies
Biomass (bioenergy)	Reference use of biomass feedstock, biomass growth and transport, impacts avoided through biomass combustion, land use change, capacity factor, combustion efficiency
Geothermal	Quality of geothermal resource, conversion efficiency, capacity factor
Natural gas–fired combustion	Capacity factor, combustion efficiency, fuel carbon content, fuel-cycle system boundaries
Solar power	Technology vintage and conversion efficiency, operating lifetime, capacity factor, quality of solar resource, manufacturing, and end-of-life system boundaries
Wind turbines	Operating lifetime, quality of wind resource, conversion efficiency, capacity

Electric power technology	Major assumptions that account for variability between life-cycle assessment studies
	factor
Energy storage	Regional resource quality, system flexibility, and demand patterns, manufacturing and EOL system boundaries

3.2. Technologies and Products in Buildings for Energy Efficiency

The technologies are presented in alphabetical order. All source data for technologies are included in the accompanying spreadsheet.

3.2.1. Agricultural Technologies

The technologies in the Agricultural Technologies category are shown in Table 6. There are no EPDs or datapoints specific to the agricultural industry or agricultural buildings. There are limited EPDs for industrial or commercial-scale pumps. The products for which data were found are bolded. Using a European EPD from 2012 for a process pump, the embodied carbon impact from raw materials procurement and manufacturing is around 37 kg CO_2 (eq) per kW of pump power; the operational impact is over 160,000 kg CO_2 (eq) per kW of pump power[79].

Table 6. Products includes in the Agricultural Technologies category.

Category	Products
Agricultural technologies	• **Agricultural Pump – Irrigation** • Agricultural Pump – Process Optimization • Agricultural Pump Retrofit - Irrigation • Greenhouse Envelope • Greenhouse HVAC Efficiency Upgrades • Dairy Ventilation Efficiency Upgrades

3.2.2. Appliances

The technologies in the Appliances category are listed under their respective subcategories in Table 7. Only limited EPD information is available for most commercial and residential appliances. As identified in Table 7, there are major gaps in information for cooking and food preservation. Figure 17 outlines the number of distinct EPDs/datapoints for each product.

Table 7. Products included in Appliances category.

Subcategory	Products

Subcategory	Products
Cleaning	• Commercial Dishwashers
	• **Residential Dishwashers**
	• **Pre-Rinse Spray Valve**
Laundry	• Commercial Process Laundry
	• **Clothes Dryers (Natural Gas)**
	• **Clothes Dryers (Electric)**
	• **Residential Clothes Washers (Electric)**
Cooking	• Electric Combination Ovens
	• Electric Convection Ovens
	• Electric Fryers
	• Electric Griddles
	• Electric Steamers
	• Electric Cooking
	• Gas Combination Ovens
	• Gas Convention Ovens
	• Gas Conveyor Ovens
	• **Gas Fryers**
	• Gas Griddles
	• **Gas Rack Ovens**
	• Gas Steamers
	• Gas Broilers
	• **Residential Induction Cooktop**
	• **Residential Gas Cooktop**
Food Preservation	• Commercial Refrigeration – Compressor Retrofit
	• Commercial Refrigeration – Anti Sweat Heat Controls
	• Commercial Refrigeration – Display Case Lighting Retrofit
	• Commercial Refrigeration – Walk-In Motors
	• Commercial Refrigeration – Display Case Motors
	• Commercial Refrigeration – Display Case Replacement
	• Commercial Refrigeration – Floating Head Pressure Controls
	• **Commercial Refrigeration – Add Doors to Open Display Cases**
	• **Refrigerators**
Kitchen ventilation	• **Demand Controlled Ventilation Exhaust Hood**

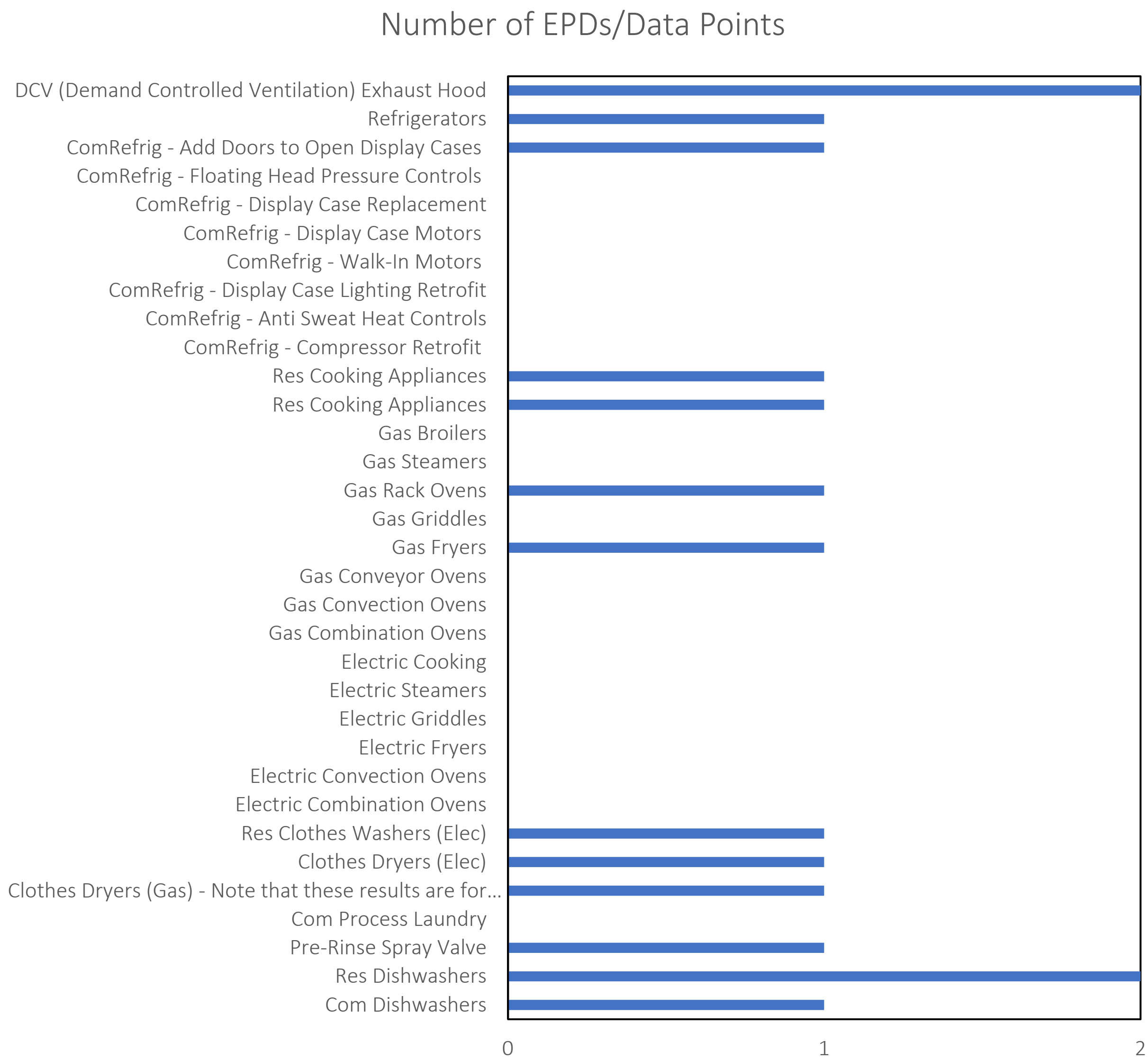


Figure 17. Number of distinct EPDs/data points for each appliance.

3.2.2.1. Cleaning

Similar to previous subcategories, there are limited datapoints in the "Cleaning" subcategory. While there are no datapoints for commercial dishwashers, there are a few datapoints for residential dishwashers in U.S. case studies. The life-cycle GHG and embodied GHG values for faucet aerators are shown in Figures 18 and 19, respectively.

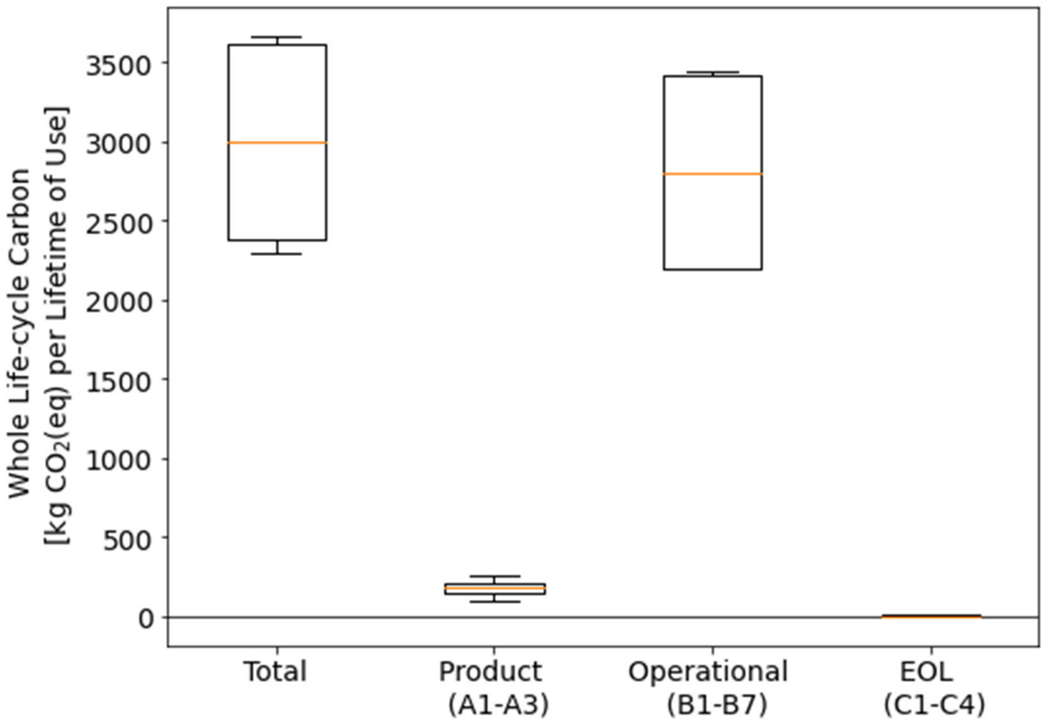


Figure 18. Life-cycle GHG emissions, in units of kg CO_2 (eq) per lifetime of use, for residential dishwashers.

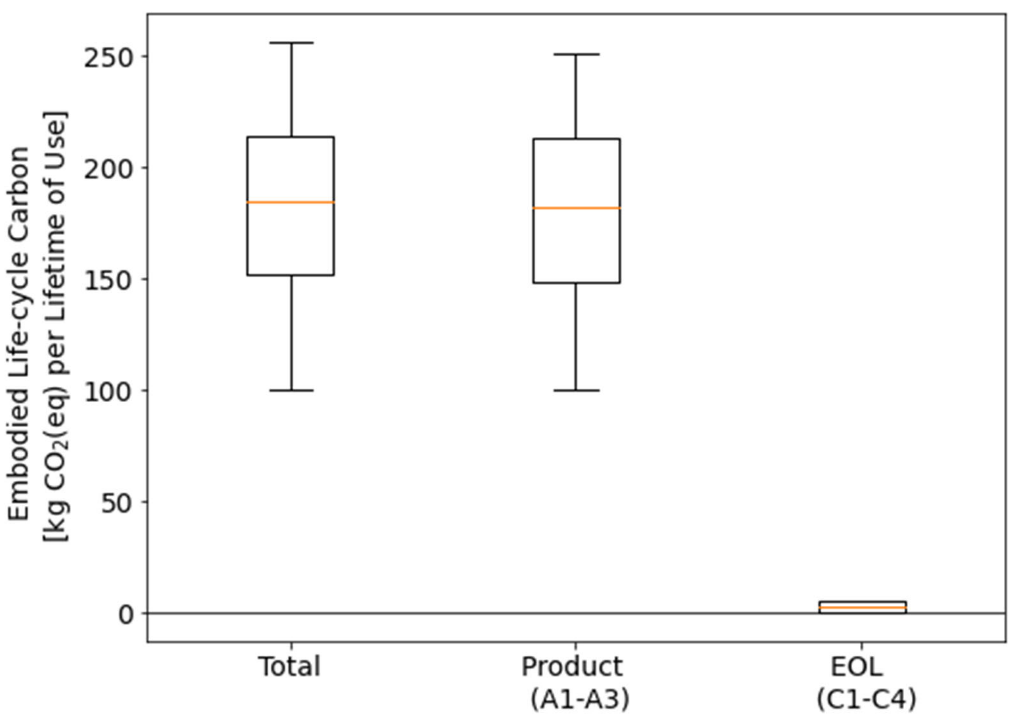


Figure 19. Embodied GHG values, in units of kg CO2 (eq) per lifetime of use, for residential dishwashers.

A Michigan study found that for a residential dishwasher that washes 215 loads per year for 10 years, the embodied carbon footprint is between 100 and 200 kg CO_2 (eq) and the operational impact is approximately 2200 kg CO_2 (eq)[80]. Another U.S. study examined the total life-cycle carbon emissions between similarly sized stainless steel and plastic tub dishwashers. The stainless-steel tub version has an A1-A3 emissions footprint of 250 kg CO_2 (eq) for a dishwasher that washes 215 loads per year for 10 years, and the plastic tub's footprint is 160 kg CO_2 (eq) for a dishwasher that washes 215 loads per year for 10 years[80].

One European EPD for a pre-rinse spray valve indicates an embodied footprint of around 6 kg CO2 (eq) per unit[81].

3.2.2.2. Laundry

An Australian natural gas-powered clothes dryer has an embodied carbon footprint of 0.05 kg CO_2 (eq) per 1 kg of dried clothes. While information about use is not specified, a European electric clothes dryer has an A1-A3 footprint of 210 kg CO_2 (eq)[82]. A European electric clothes washer has an A1-A3 footprint of 360 kg CO_2 (eq) per unit[83].

3.2.2.3. Cooking

There are limited data for technologies included in the "Cooking" subcategory. A stovetop deep fryer manufactured in Brazil has an embodied carbon footprint of over 8 kg CO_2 (eq) per fryer[84]. One gas oven used in "the baking of a food, considering the Italian context and a lifetime of 10 years" has an embodied carbon emission footprint of 210 kg CO_2 (eq); the operational footprint is as low as 200 kg CO_2 (eq) and as high as 450 kg CO_2 (eq)[85]. An Italian research study for two types of cook tops (induction and gas) have estimated embodied carbon footprints of 100 and 60 kg CO_2 (eq) per 20 years of cooking[86].

3.2.2.4. Food Preservation

Two European refrigerators from different studies and operating conditions have embodied carbon footprints of between 60 and 300 kg CO_2 (eq) per refrigerator[87].

3.2.2.5. Kitchen Ventilation

A European EPD for a demand ventilation-controlled exhaust hood for cooking has an embodied carbon footprint of around 35 kg CO_2 (eq) per 25 years of service, which is significantly greater than its operational emissions of 3 kg CO_2 (eq) per lifetime of use[88].

3.2.3. Building Materials

The technologies in the Building Materials category are provided in Table 3.

Table 8. Products included in Building Materials category.

Category	Products
Building Materials	• **Floor insulation** • **Wall and ceiling insulation** • **Duct insulation** • **Piping insulation**

Results for the products listed in Table 8 are depicted in Figures 20 through 23. For the results that include a range of values, the Product Stage (A1-A3) is the most emissions-intensive stage of the product's life-cycle. Of the insulation types used in floor applications (Figure 20), extruded polystyrene (XPS) has the higher product emissions intensity. Among the different wall and ceiling insulation types, foamed-in-place insulation has the highest embodied carbon emission intensity (Figure 21).

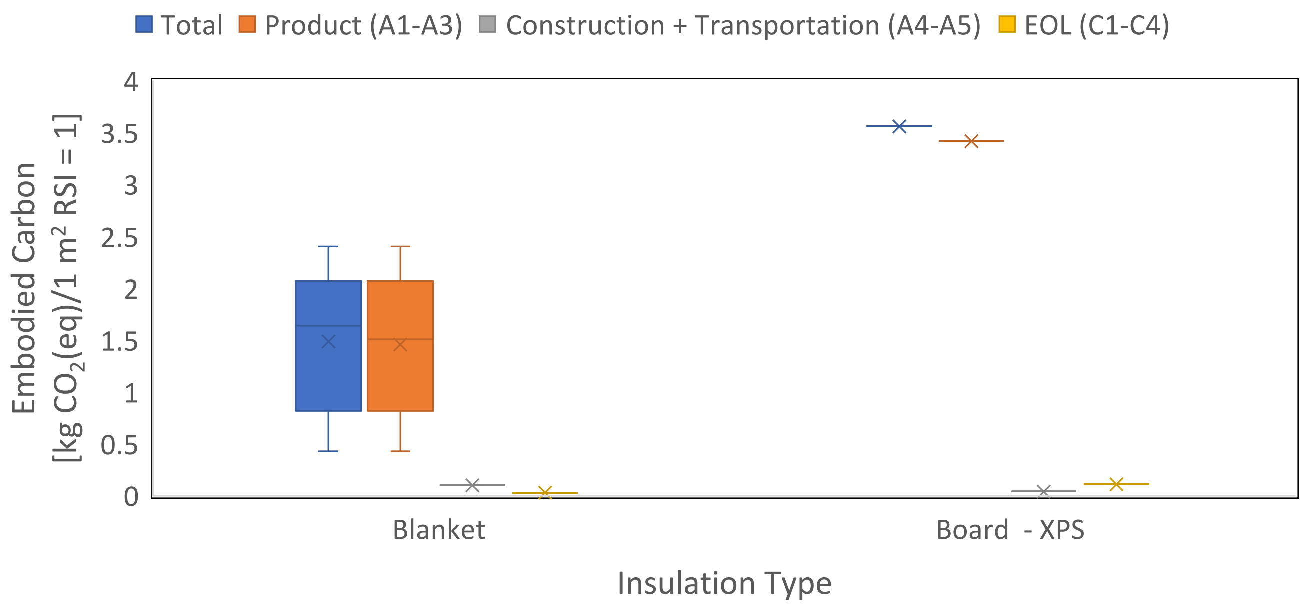


Figure 20. Range of embodied GHG values, in units of kg CO_2 (eq) per functional unit (1 m^2 of insulation at an RSI =1), by floor insulation type and life-cycle stage. All EPDs for this product are sourced in the United States/North America. The embodied carbon footprint of foamed-in-place insulation is approximately 5 times greater than board insulation and is approximately 5 times and almost 25 times greater than blown insulation in wall and ceiling applications.

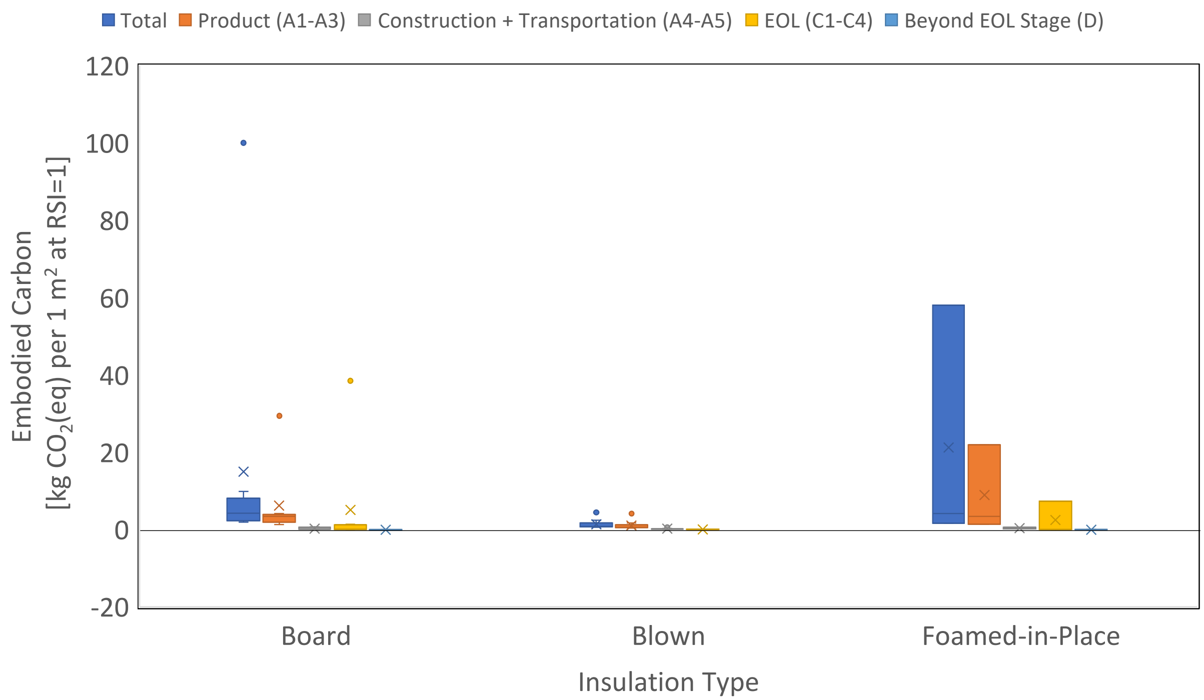


Figure 21. Range of embodied GHG values, in units of kg CO_2 (eq) per functional unit (1 m^2 of insulation at an RSI =1), by insulation type and life-cycle stage. Applies for commercial and residential wall and ceiling insulation. All EPDs for this product are sourced in the United States/North America.

There is a larger spread in embodied carbon intensity for HVAC duct insulation manufactured in North America than compared to Europe (Figure 22); the average carbon intensity for just the Product Stage (A1-A3) for North American insulation is around 1.3 times greater than European insulation. There is a greater spread in values for European-manufactured piping insulation, but the carbon intensity of North American piping insulation is over 1.5 times greater than the same type manufactured in Europe (Figure 23).

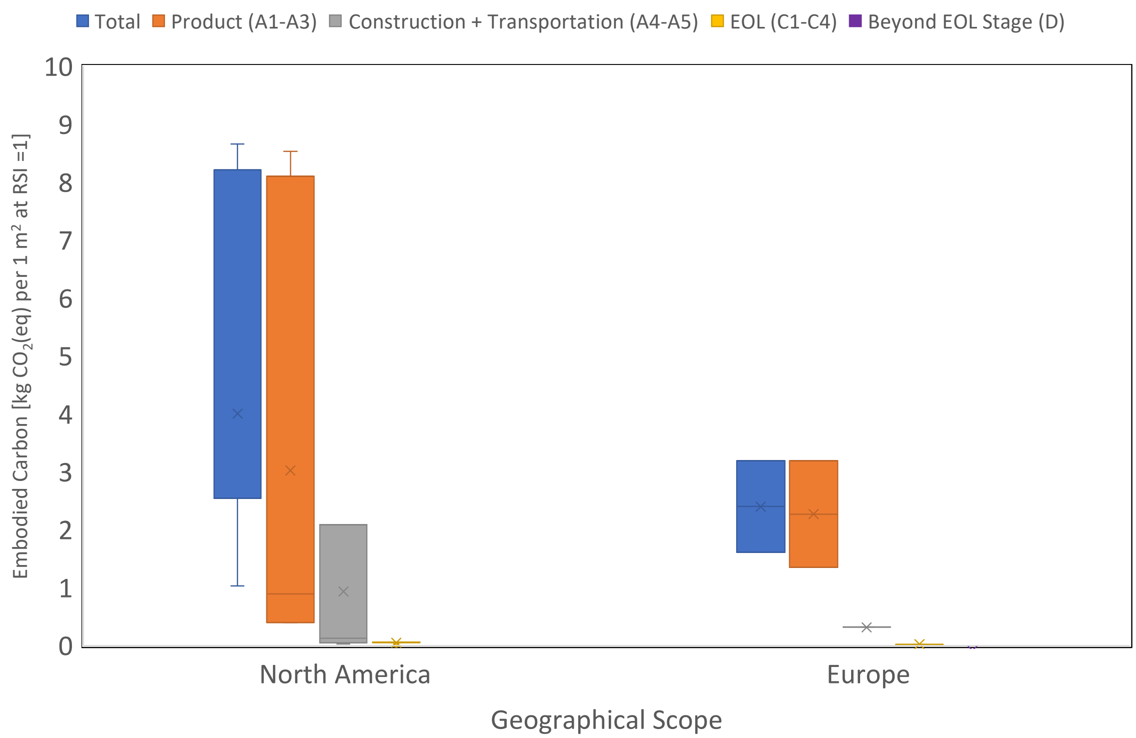


Figure 22. Range of embodied GHG values, in units of kg CO_2 (eq) per functional unit (1 m^2 of insulation at an RSI =1), for HVAC duct insulation by geographical scope and life-cycle stage.

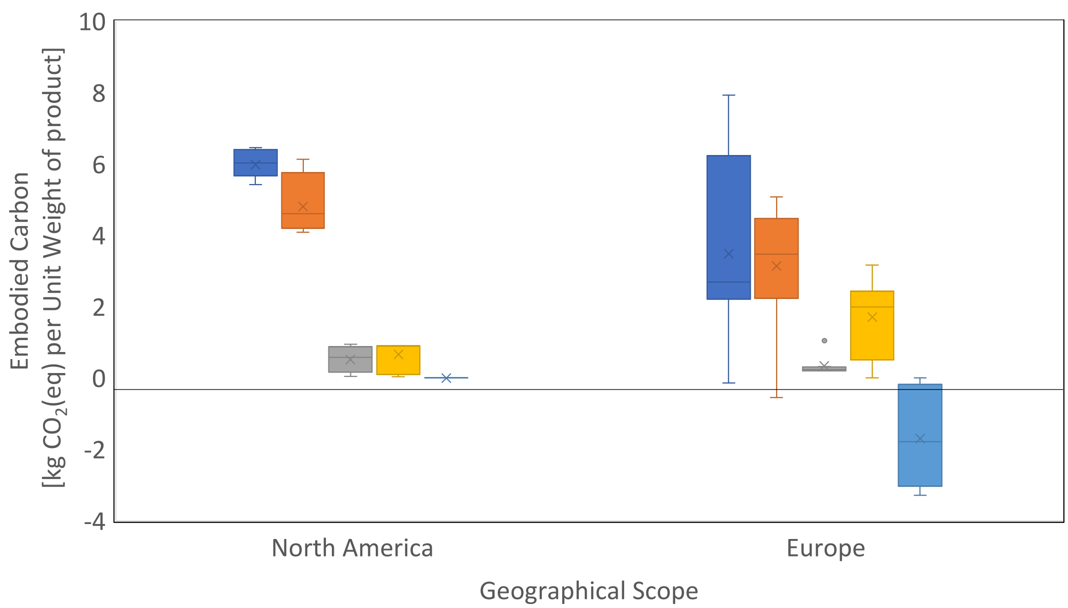


Figure 23. Range of embodied GHG values, in units of kg CO_2 (eq) per unit weight of product, for pipe insulation by geographical scope and life-cycle stage.

3.2.4. Building Standards

The elements in the Building Standards category are provided in Table 9. More context is needed to further define applicable and relevant technologies for each element. There is no relevant information available for these elements.

Table 9. Products includes in the Building Standards category.

Category	Products
Building standards	• Room Air Conditioning • Commercial Building Standards • Residential Whole Building Retrofit • Residential Building Standards

3.2.5. Commercial (and Residential) Building Technologies

The technologies in the Commercial Building Technologies category are listed under their respective subcategories in Table 10. For several of the products in Table 10, no EPDs are available. The products for which data were found are bolded.

Table 10. Products included in Commercial Building Technologies category.

Subcategory	Products
Water consumption	• **Showerheads** • **Faucet Aerators**
Energy Consumption – Water Heating	• **Electric water heaters** • **Gas-fired water heaters** • **Drain Water Heat Recovery System (Gas and Electric)** • Commercial Water Heating Controls
Lighting	• LED Reflector Lamps • LED Specialty Lamps • **LED General Service Lamps (Indoor, Outdoor)** • **Lighting Controls** • Lighting Upgrades (Interior, Exterior) • Power Strips • Screw-In Lamps • **LED High and Low Bay Lights** • LED Fixtures • Energy Efficient Lighting
Thermal Comfort	• Quality HVAC Installation • Packaged Terminal Air Conditioner Controls • **Ductless Mini Split Heat Pump** • **Packaged Rooftop Air Conditioning Unit** • **Packaged Rooftop Heat Pump Unit** • HVAC Pump Variable Frequency Drive (VFD)

Subcategory	Products
	• **Split System AC** • **Split System Heat Pump** • **HVAC Boiler** • **HVAC Heat Recovery/Energy Recovery Ventilator (ERV)** • **DOAS (Dedicated Outdoor Air System)** • **Manual Thermostat** • HVAC Motor - Shaded Pole • **Commercial Furnace** • **HVAC System Integrated Furnace and AC** • **Chiller** • Ceiling Fans • Boiler Controls • Economizers • HVAC Fan with VFD • HVAC Fan with no VFD • Demand Controlled Ventilation • Energy Management System for HVAC System

3.2.5.1. Water Consumption

The life-cycle GHG and embodied GHG values for showerheads are shown in Figures 24 and 25, respectively. The life-cycle GHG and embodied GHG values for faucet aerators are shown in Figures 26 and 27, respectively. When excluding emissions from operation, the Product Stage (A1-A3) is the most emissions-intensive stage for both showerheads and faucet aerators.

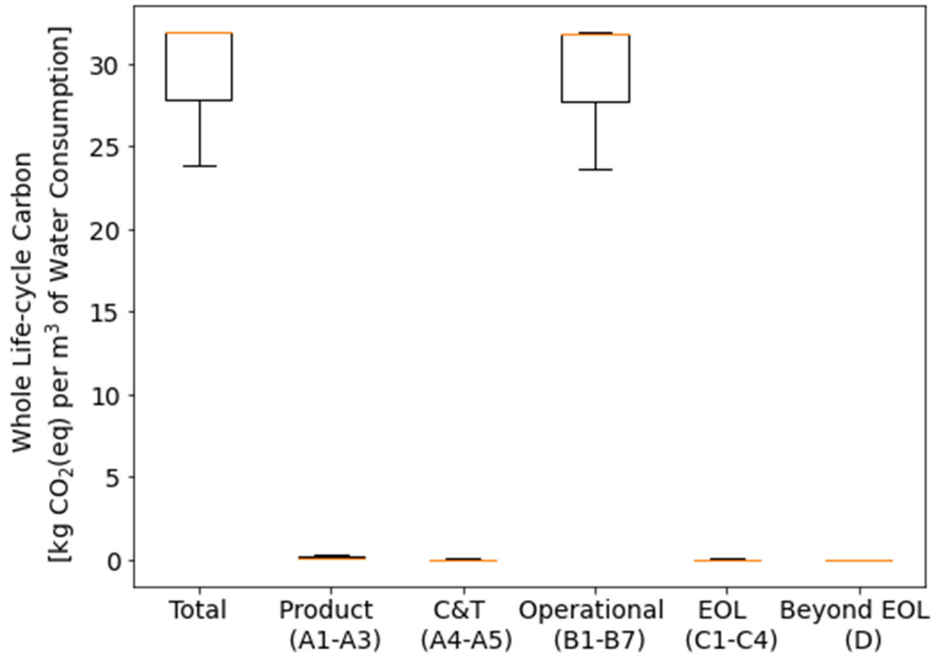


Figure 24. Life-cycle GHG emissions, in units of kg CO_2 (eq) per m^3 of water consumption, for commercial and residential showerheads.

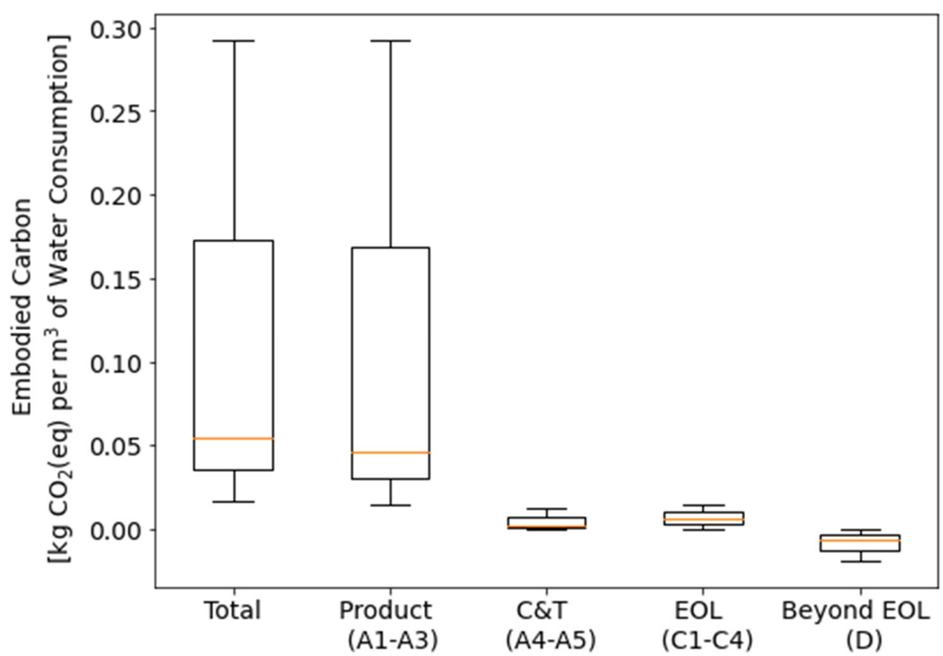


Figure 25. Embodied GHG values, in units of kg CO_2 (eq) per m^3 of water consumption, for commercial and residential showerheads.

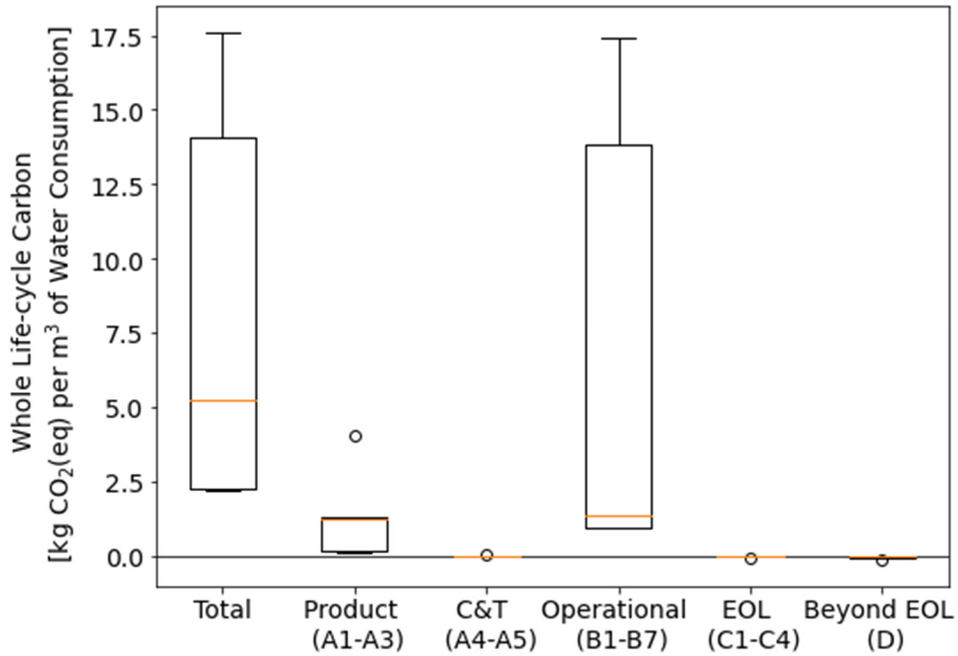


Figure 26. Life-cycle GHG emissions, in units of kg CO_2 (eq) per m^3 of water consumption, for commercial and residential faucet aerators.

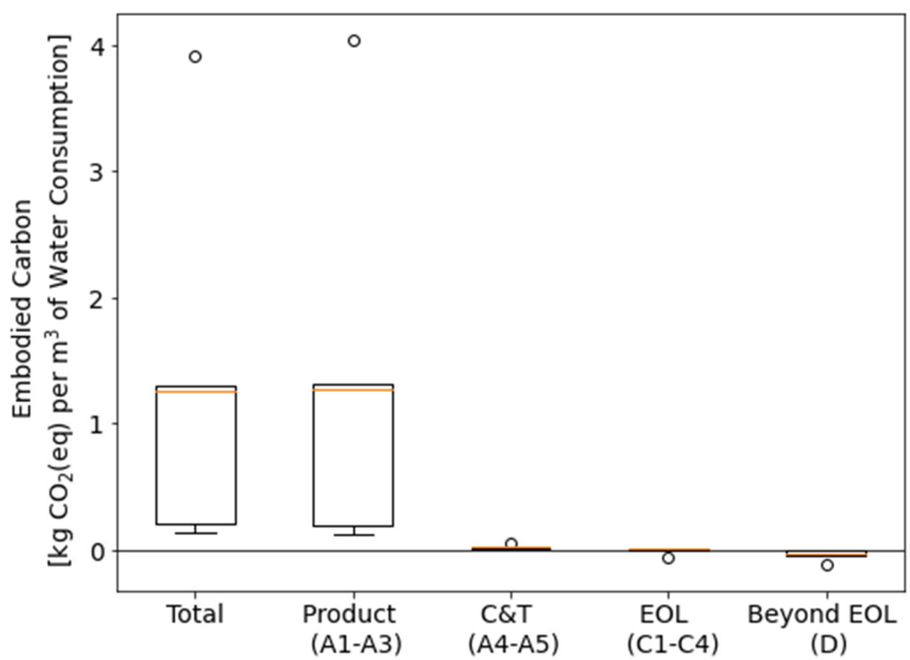


Figure 27. Embodied GHG values, in units of kg CO_2 (eq) per m^3 of water consumption, for commercial and residential faucet aerators.

3.2.5.2. Energy Consumption – Water

The embodied carbon values for various types of water heaters are depicted in Figure 28. There is little variation between GHG emissions from the product stage for each of the water heater types. While not depicted, operational emissions from a gas-fired water heater would be greater than an electric-powered water heater that consumed electricity sources from renewable generation.

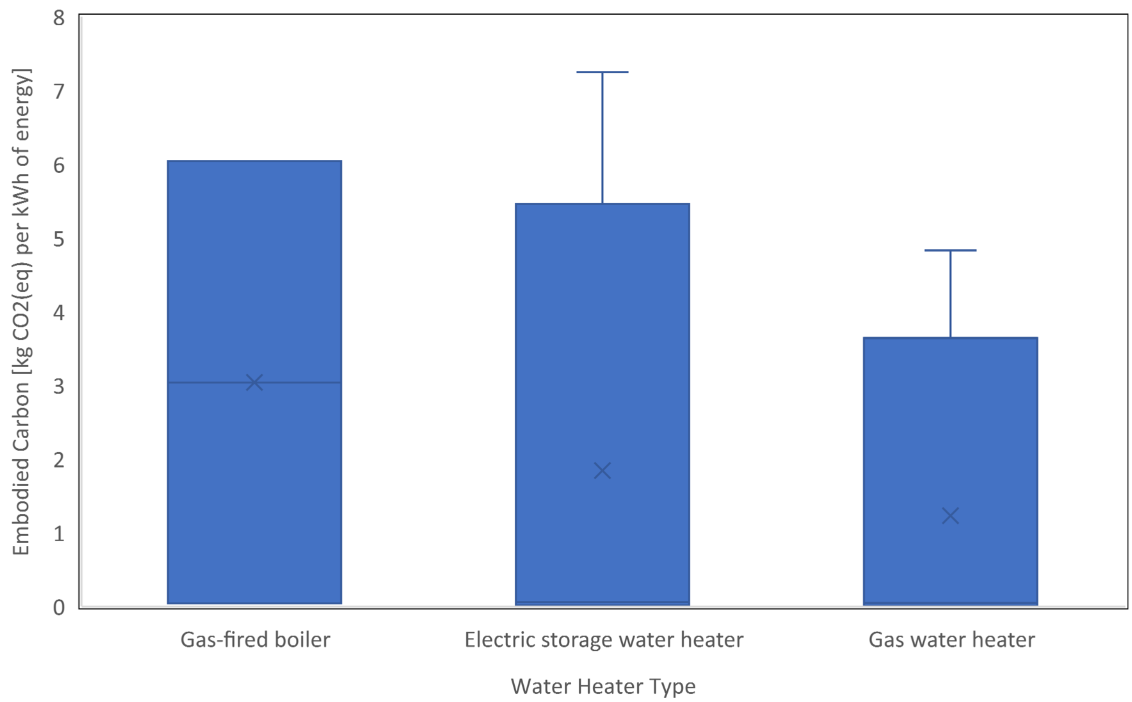


Figure 28. Embodied GHG values, in units of kg CO_2 (eq) per kWh of energy needed to heat water, for various water heater types.

Two examples of embodied carbon values for drain water heat recovery systems were found, both in applications in the United Kingdom. A shower waste heat recovery heat exchanger for a U.K. sports facility, with a service life of 50 years, has an embodied carbon footprint of around 60 kg CO_2 (eq)[89]. A heat recovery system retrofitted to a commercial kitchen has an embodied carbon footprint of approximately 30 kg CO_2 (eq) for every 1 kWh of water heating delivered through heat recovery.[90]

No information could be found on the embodied or operational carbon impacts from water heating controls.

3.2.5.3. Lighting

Of the technologies listed in the Lighting subcategory, we were able to document datapoints for lamps considered “General Service” and “High and Low Bay”. More context is needed to define the other lamp types; nevertheless, we were unable to find distinct EPDs and emissions inventory information that contained key words matching the other lamp types. The only EPDs/emission inventory data applicable for outdoor lamps are for road/street lighting; we assume that streetlamp EPDs are a suitable proxy for outdoor lighting.

The whole life-cycle carbon and embodied carbon values for various indoor “general service” lamps are shown in Figures 29 and 30, respectively. As shown in Figure 29, operational emissions dominate the total life-cycle emission footprint for the indoor lamp types. Among the different indoor lamp types, the recessed lamp has the highest median Product Stage (A1-A3) footprint. According to the datapoints for each lamp type, recessed indoor lighting has a Product Stage embodied carbon footprint over 4, 8, and 3 times higher than linear, surface, and pendant lighting, respectively.

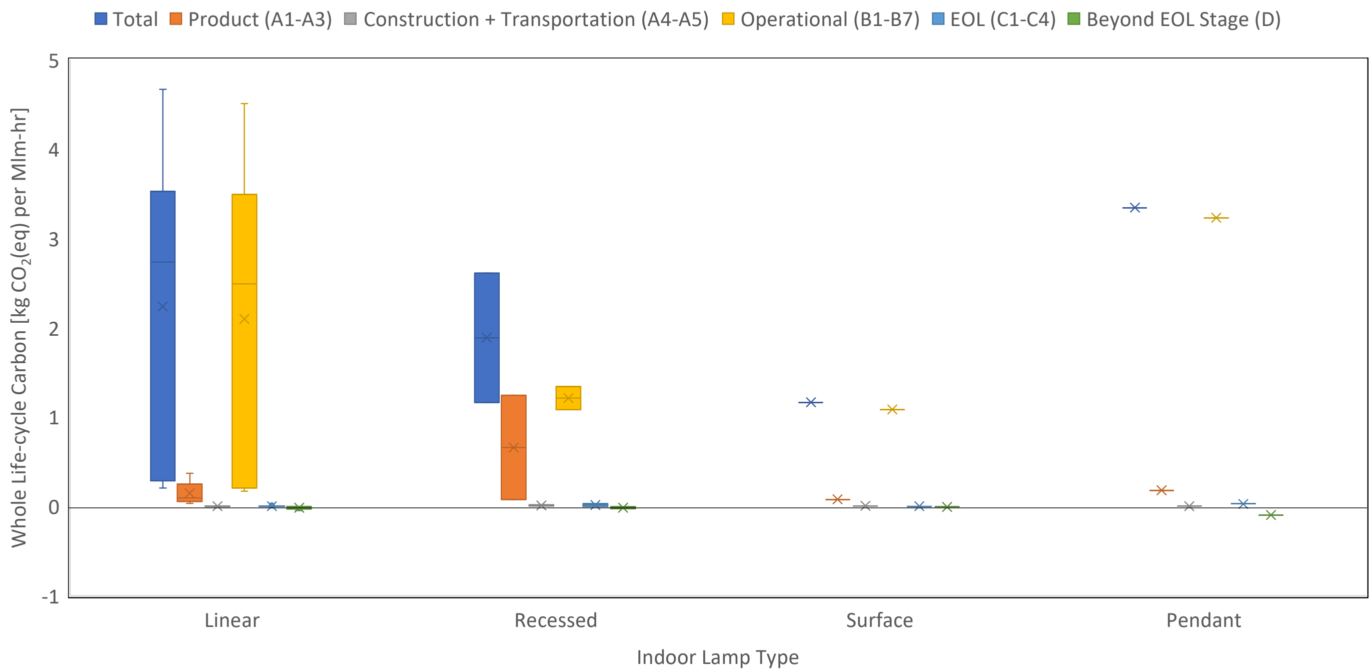


Figure 29. Life-cycle GHG emissions, in units of kg CO_2 (eq) mega lumen-hour, for various indoor lamp types.

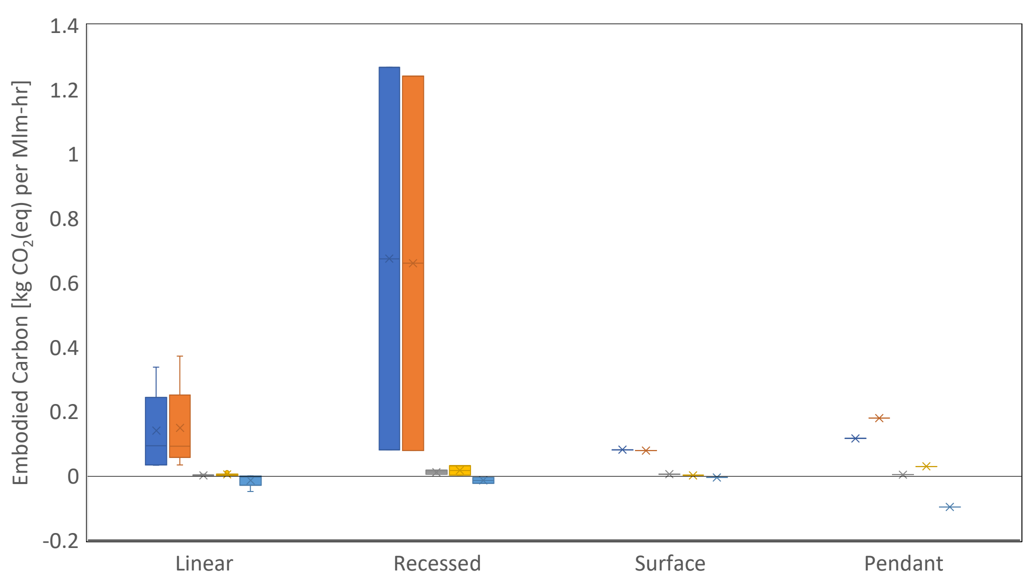


Figure 30. Embodied GHG values, in units of kg CO_2 (eq) mega lumen-hour, for various indoor lamp types.

We were able to identify three EPDs for high and low bay lighting, which is typically used in high ceiling commercial and industrial buildings (e.g., warehouses, gymnasiums). All three values have differing functional units, applications, reference service lives, and geographical locations. One high bay light manufactured in the United Kingdom with no provided reference service life has an embodied carbon footprint of almost 400 kg CO_2 (eq)[91]. Another bay light manufactured in the U.K. bay light, with a 40 year reference service life, has an embodied GHG footprint of around 220 kg CO_2 (eq)[92]. An Austrian manufactured bay light that has a 144 lumen per watt efficacy and a 20 year reference service life has an embodied GHG footprint of 60 kg CO2(eq) per unit[93].

There are no existing EPDs for outdoor lamps. We use an EPD for street lighting as a proxy for outdoor lamps. The Italian-based EPD notes that one piece of street lighting, which is designed to be operated for up to 40,000 hours, has an embodied carbon footprint of over 1200 kg CO_2 (eq).

We found one reported EPD for light switches. One light switch with a power consumption of 0.015 W used for 10 years has an embodied carbon footprint of 1.8 kg CO_2 (eq)[94].

3.2.5.4. Thermal Comfort

There are relatively limited EPD and emission inventory data for the technologies listed in the Thermal Comfort subcategory in Table 10. As shown in Figure 31, few datapoints are available for each technology; most commonly, we were able to identify one data source for technologies in this subcategory. Most of the data sources from this category come from peer-reviewed research and not from EPDs. More of the thermal comfort datapoints included in this study come from Europe rather than from the United States (Figure 32).

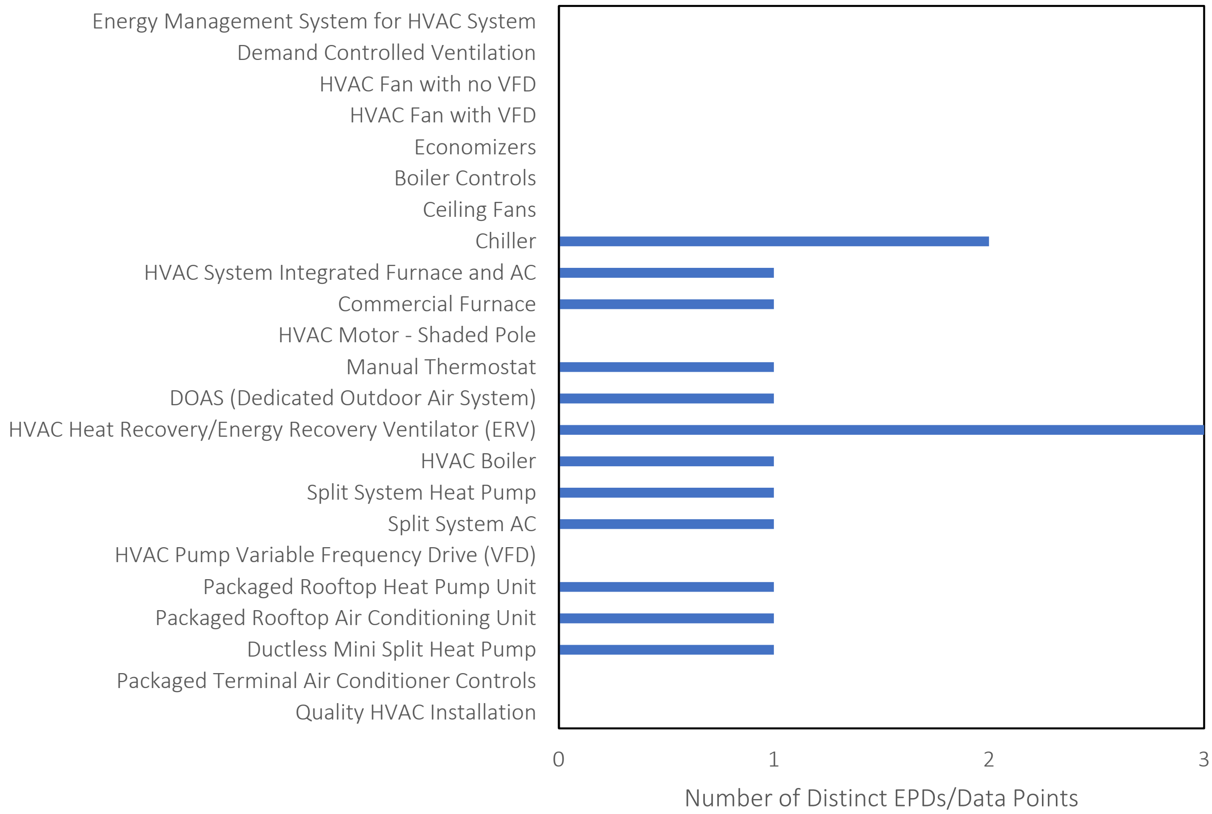


Figure 31. Number of distinct EPDs/data points for each thermal comfort technology.

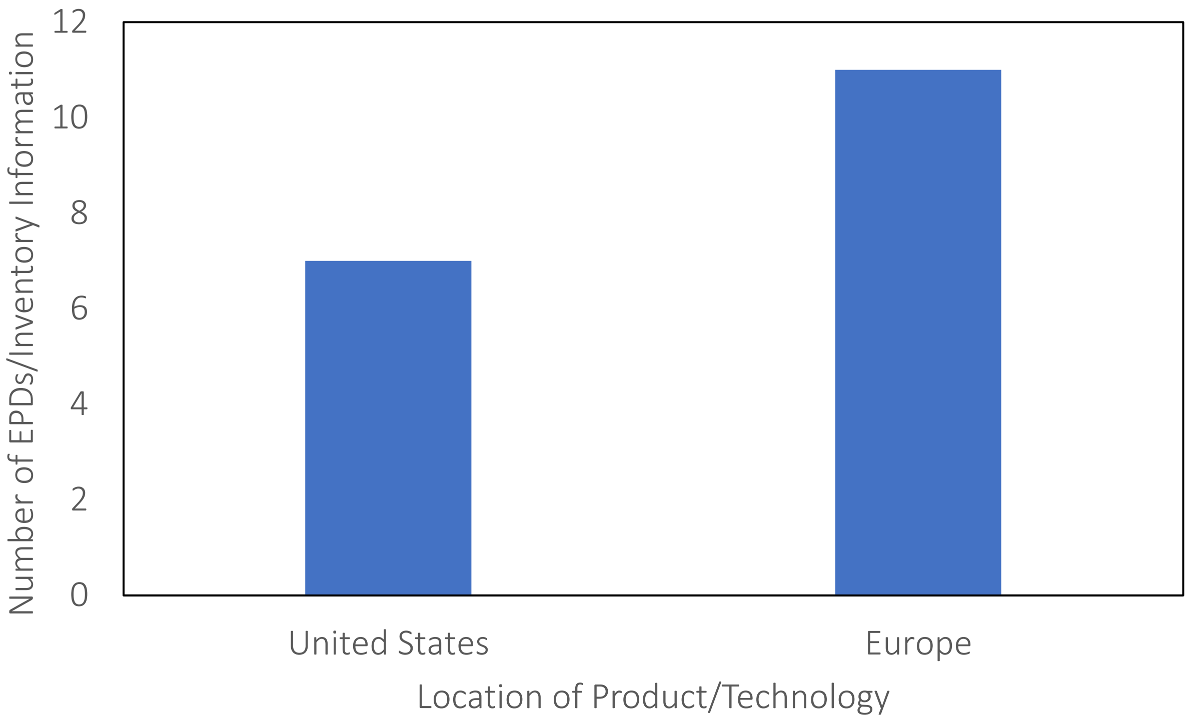


Figure 32. Breakdown for EPD/Inventory data by location for available technologies in the Commercial Thermal Comfort category.

Recent research from the Carbon Leadership Forum, a non-profit organization based out of the University of Washington, conducted a preliminary investigation of the embodied carbon impacts from Mechanical, Electrical, and Plumbing (MEP) systems in office buildings in the Pacific Northwest[95]. Embodied GHG values for packaged rooftop systems, in units of kg CO_2 (eq) per m^2 of conditioned space in a building, range from a low of 35 kg CO_2 (eq) per m^2 for a packaged rooftop air conditioner and furnace system to a high of 57 kg CO_2 (eq) per m^2 for a packaged rooftop heat pump.

The embodied GHG values for various configurations of dedicated outdoor air systems (DOAS) range from 40 kg CO_2 (eq) per m^2 of conditioned space for a DOAS with variable refrigerant flow to 120 kg CO_2 (eq) per m^2 of conditioned space for a DOAS with a water source heat pump.

A German study found that a mini-split ductless heat pump has an embodied carbon footprint of around 45 kg CO_2 (eq) per kWh of energy used in air conditioning[96].

A household scale split air conditioning system's A1-A3 GHG emissions were around 0.01 kg CO_2 (eq) per kWh of thermal energy[97].

The total embodied carbon impacts for different versions of a Finnish split system heat pump range from 2200 to 2700 kg CO2 (eq) per unit, with the majority of emissions attributable to the manufacturing stage (A1-A3)[98].

Another HVAC integrated system (split air conditioning and furnace) from a European study of a Swiss office building 22 kg CO_2 (eq) per m^2 of conditioned area[99], which is around the same order of magnitude as the University of Washington study on MEP systems.

A German EPD for a gas condensing boiler with a 20-year service life estimates the materials impact to be around 3,422 kg CO_2 (eq) per unit. Emissions savings from reusing the boiler amount to -1,358 kg CO_2 (eq) per unit. The EPD assumes that 95% of the boiler can be recycled[100].

There are four datapoints for HVAC systems coupled with heat recovery/energy recovery ventilators (ERV). A German EPD lists an A1-A3 GHG footprint of 370 kg CO_2 (eq) for a HVAC ERV system that has a 20-year service life[101]. This value is close to the materials impact of 280 kg CO_2 (eq) for an HVAC ERC system from an Irish EPD; the Irish EPD provides a construction impact (A4-A5) of over 700 kg CO_2 (eq)[102]. The University of Washington team also investigated the embodied carbon impacts of various DOASs equipped with ERV and estimated a range of 82 to 87 kg CO_2 (eq) per m^2 of conditioned space.[95]

Two EPDs for thermostats indicate an embodied carbon footprint of between 5 and 11 kg CO_2 (eq) per thermostat, each with a service life of 10 years[103,104].

A Master's thesis conducted on the life-cycle impacts of a residential furnace in the United States estimates the embodied impact at around 1,600 kg CO_2 (eq) per 20 years of service; the operational impact is around 100 times greater at 160,000 kg CO_2 (eq)[105].

Two recent EPDs for commercial-grade chillers manufactured in the United States delivering one ton of chilling capacity estimate embodied carbon impacts of between 40 and 140 kg CO_2 (eq).

3.2.6. Data Center Technologies

The technologies in the Data Center Technologies category are provided in Table 11. An industry LCA study on a server was conducted[106]. Per one piece of "general purpose rack server equipment" providing four years of computing service at a load ranging between 176 and 1,778 kWh per year, the embodied carbon footprint is 4,300 kg CO_2 (eq) and the operational carbon footprint is 6,700 kg CO_2 (eq).

Table 11. Products included in the Data Center Technologies category.

Category	Products
Data Center technologies	• Data Center Computer Room Air Conditioner upgrades • PC Power Management • Data Center Server Visualization • Data Center High Efficiency Uninterruptible Power Supply • Data Center Air Flow Management • **Servers**

3.2.7. Industrial Technologies

The technologies in the Industrial Technologies category are provided in Table 12. As with other categories within the entire technologies list, there are few EPD and emission inventory datapoints

Table 12. Products included in Industrial Technologies category.

Category	Products
Boilers	• Steam Boiler • Steam Boiler Controls
pumps	• Pump Variable Frequency Drive • Pump Upgrades • **Oil Pump**
motors	• **Motor Variable Frequency Drive**
process heat	• Process Heat • Process Heating Upgrades
refrigeration	• Refrigeration • Process Refrigeration
Wastewater treatment	• Wastewater Aerator • Energy Efficient Aerator
hvac operations	• Electronics Retro-commissioning – HVAC • Compressed Air
chemical manufacturing	• Chemical Manufacturing Advance Automation – Electric
ventilation	• **Electronics Low Pressure Drop - Electric**

3.2.7.1. Pumps

An EPD for an oil pump used in the oil and gas industry has an embodied carbon footprint of 30 kg CO_2 (eq) per kW of hydraulic power. Assuming a 20-year service life, the operational carbon footprint is 47,000 kg CO_2 (eq) per kW of hydraulic power[79].

3.2.7.2. Motors

A motor with a variable frequency drive used for 10 years in industrial pump applications and manufactured in Europe has an embodied carbon footprint of 1,800 kg CO_2 (eq) and an operational impact of over 82,000 kg CO_2 (eq)[107].

3.2.7.3. Ventilation

The product listed in the ventilation subcategory is a bag filter used in HVAC applications. A European EPD estimates an embodied carbon footprint of 12 kg CO_2 (eq) per bag filter, with an operational impact of 33 kg CO_2 (eq) per bag filter.

3.2.8. Miscellaneous

There is only one technology in the Miscellaneous category (Table 13). There are no EPDs or emission inventory datapoints for the listed technology.

Table 13. Products includes in the Agricultural Technologies category.

Category	Products
Miscellaneous	• Pool Cover

3.2.9. Comparison Between Embodied and Operational Emissions

An objective of this research has been to investigate and quantify the breakdown between embodied and operational GHG emissions for each relevant product and technology in the list. As illustrative examples, we present comparisons between embodied and operational emissions for a sample of technologies including lighting in commercial buildings and washing machines and clothes dryers in residential buildings. We do not present an estimation of each technology's embodied and operational GHG emissions for the following reasons:

(1) Operational emissions for some of the technologies cannot be estimated without additional information and context. Technologies in the "Building Materials" category, which only include various insulation types, only account for embodied emissions. One would need to assess how different thicknesses of insulation material would impact the energy use in a building to be able to quantify resulting operational emissions. Calculating operational emissions in example buildings is beyond the scope of this research project.

(2) For technologies that have both an embodied and operational footprint, results are often limited by the parameters and assumptions used in creating the technology's EPD or emissions inventory. For example, operational emissions could be calculated using a European electricity mix, whose carbon intensity would likely differ from the carbon intensity of a California-based electricity mix.

Figure 33 shows the breakdown between embodied and operational GHG emissions for various indoor lighting types. The embodied footprint includes all calculated emissions in life-cycle stages A1-A5, B1-B5, C, and D and the operational footprint accounts for emissions in stage B6. Across all indoor lighting types, the average embodied carbon footprint is 0.2 kg CO_2 (eq) per mega lumen-hour, while the average operational carbon footprint is 1.9 kg CO_2 (eq) per mega lumen-hour. In the lighting example, embodied, on average, represents 10% of total emissions and operational accounts for 90% of total life-cycle emissions. Note that the lighting EPDs included in Figure 33 are all European based.

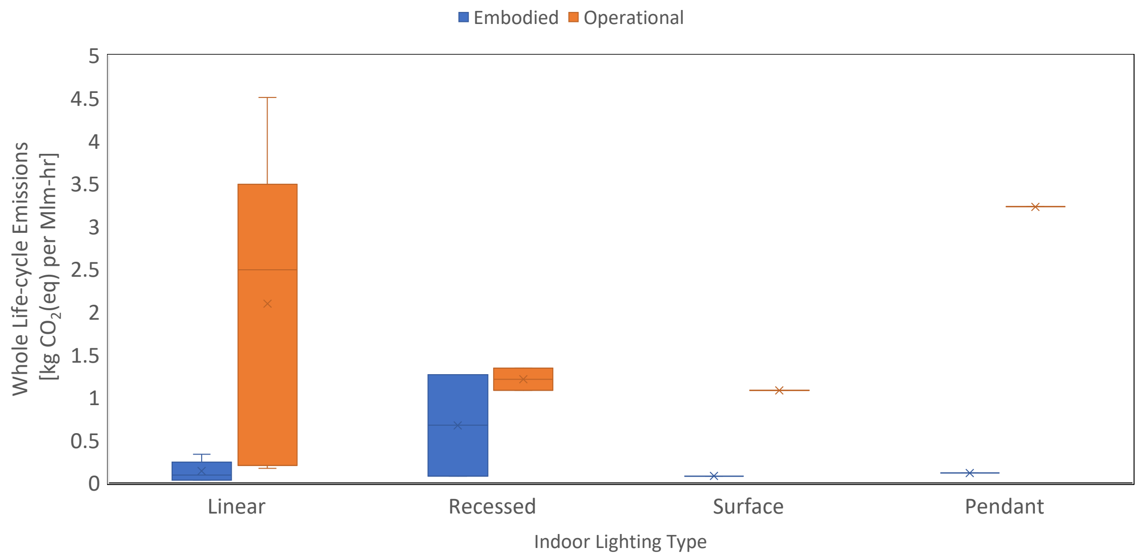


Figure 33. Breakdown between embodied and operational GHG emissions, units of kg CO_2 (eq) mega lumen-hour, for various indoor lighting types.

Figure 34 shows an example breakdown between embodied and operational GHG emissions for a residential dishwasher manufactured in North America. In the dishwasher example, embodied emissions represent 7% of the total and operational represents 93% of the total emissions.

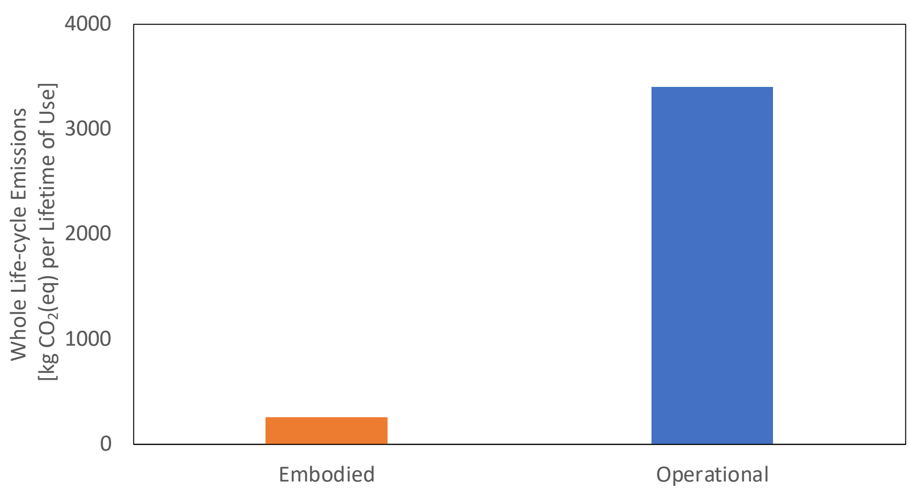


Figure 34. Embodied and operational GHG emissions, in units of kg CO_2(eq) per lifetime of use, for a residential dishwasher.

Figure 35 depicts another example breakdown between embodied and operational GHG emissions for a residential electric clothes dryer manufactured in Europe. In clothes dryer example embodied emissions represent 13% of the total and operational represents 87% of the total emissions.

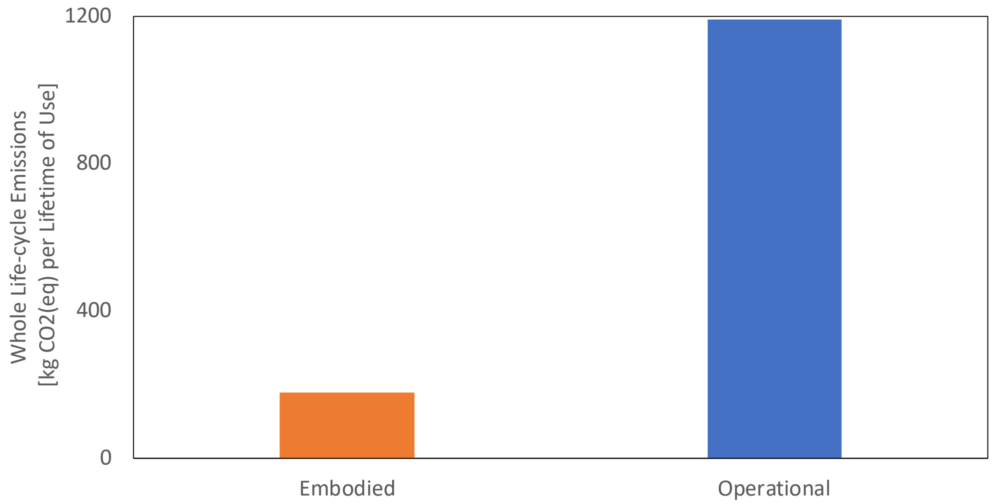


Figure 35. Embodied and operational GHG emissions, in units of kg CO_2 (eq) per lifetime of use, for a residential electric clothes dryer.

4. Discussion

4.1. Electricity Generation and Storage Technologies

The results of this report reflect the existing availability of cradle-to-grave, life-cycle GHG emissions from five types of electricity generation technologies (biomass, geothermal, natural gas, solar power, and wind turbine) and energy storage systems specific to the California context. Existing data were captured and sorted by factors such as geographic location, type of technology for generation and storage capacity, and lifetime. An overview of the extensive data coverage reveals key trends:

- The cradle-to-grave electricity generation from natural gas covers GHG emission factors from three major types of power plants, namely, NGCT, NGCC and NGCC with CCS. Emissions are grouped under four life-cycle stages, that are upstream, on-going non-combustion and combustion, and downstream. NGCC has the highest number of data points (N=51 from 42 different sources), followed by NGCT (N=18 from 7 different sources), and NGCC with CCCS (N=10 from 7 different sources) based on DOE-NETL harmonization study from 2014. The data was from peer-reviewed articles and reports from 1995 to 2012, covering geographically diverse power plants from Australia, China, EU, Japan, and Northern America (Canada and US). The mean and median emission factors for NGCT, NGCC, and NGCC with CCS plants are 640, 459,135, and 605, 450, 116 g CO_2e/kWh, respectively.
- The solar energy power falls into two major categories: utility scale and thin film solar PV technologies. In our analysis, we have used a total of 68 data points, 27 of which represent the utility scale and the rest (N=41 data points) represent various thin film solar PV technologies. Except for one EPD study from Acciona Energy Division -Chile, peer reviewed LCA studies and reports constitute the basis for the sources of data. Out of 10 studies, three are from US, one from Canada, one from Chile, one from China, one from Japan, and three are from EU-Germany, Italy, Sapin). The US plants were located in Arizona and California. The two Californian plants were 103 MW parabolic trough concentrating solar power with solar irradiation of 2,724 kWh/m^2/yr and varying capacity factors and efficiencies. These two plants emitted 26-28 g/CO_2e per kWh, considerably lower than the median at 33 g/CO_2e per kWh and the mean at 47 g/CO_2e per kWh. When available, cradle-to-grave emissions from solar power systems cover embodied, construction, O&M (energy conversion and maintenance-related), and EOL stages.
- Thin film solar PV technologies cover the first generation (Mono-Si: N=10 data and Poly-Si: N=7) from Canada, EU, Japan, and US (Arizona, Michigan and Ohio; second generation (Amorphous-Si: N=7, Copper indium gallium diselenide (CIGS) and copper

indium selenium (CIS): N=9, and Cadmium telluride (CdTe) PV cells: N=13) from China, EU, Japan, and US; and emerging (such as Perovskite PV, GaAs/Si, GaInP/ GaAs nanowire solar modules: N=9) technologies from Western EU and US (Ohio). Median GHG emissions for Mono- & Poly-Si, A-Si, CIGS & CIS, CdTe, and emerging technologies are 65, 23, 22, 19, and 120 g CO_2e /kWh, respectively. Corresponding mean values are: 75, 27, 36, 23, and 156 g CO_2e/kWh. The variation in carbon estimates result from differences in technology age, conversion efficiency (e.g., 6% for the first generation and 29% for the emerging technologies), operating life time (20-30 years), capacity factor, performance ratio (75-85%), quality of solar resource in terms of solar irradiation (e.g., considerably higher in Arizona compared to Michigan), manufacturing conditions, and end-of-life system boundaries as well as systems with or without batteries.

- The representative cradle-to-grave system boundary in reviewed LCAs and EPDs (e.g., Vestas and Gamesa for EU and US systems) often includes wind turbines with foundations, internal electrical connections, and cabling and a high-voltage transformer for connection to the electricity grid. In addition, the analysis includes installation, operation and maintenance, and decommissioning. The literature review provides a range of GHG emissions from 2 to 86.5 g CO_2e/kWh for onshore, offshore, and unspecified wind turbines. Based on 123 data points worldwide, both mean and median for carbon estimates from onshore wind turbines was calculated as 18 g CO_2e /kWh. Regarding the offshore wind turbines, we estimated the mean and median as 17 g CO_2e /kWh on the basis of 38 data points. The mean and median for the unspecified category was estimated as 19 g CO_2e /kWh using 39 data points. Differences in the GHG footprint of wind farms are mainly explained by spatial variability in wind speed, followed by whether the wind farm is located onshore or offshore, the turbine diameter, and the number of turbines in a wind farm.
- GHG emission estimates were disaggregated by major life-cycle stages (construction, operation, and end of life) for four major geothermal electricity generation technologies: dry steam, enhanced geothermal systems (EGS) binary, hydrothermal (HT) flash, and HT binary. In the same order, corresponding median values for each of these technologies are 248, 26, 44, and 11 g CO_2e /kWh. Differences in carbon emission factors mainly stem from variation in the quality of geothermal resources, conversion efficiency, and capacity factor.
- The statistical evaluation of the life-cycle GHG emissions (g CO_2e/kWh) for biomass electricity generation systems was based on the review of 19 life-cycle assessment studies (representing 66 biomass cases). The mean life-cycle GHG emissions resulting from the use of agriculture residues (N = 4), dedicated energy crops (N = 19), forestry (N = 6), industry (N = 4), and wastes (N = 2) in biomass-only electricity generation systems were estimated as 291, 208, 43, 46, and 1,731 g CO_2e/kWh, respectively. Forestry and industry (avoiding the impacts of biomass production and emissions from waste management) contribute the least amount of GHGs, irrespective of the biomass electricity generation system. Based on the analysis, we have found out that the degree of variation in GHG emissions was less between LCA studies based on forestry, followed by industry, dedicated energy crops, agriculture residues, and wastes.

- Our literature data for the utility-scale storage systems was based on one study from Mostert et al. (2018)[76]. In this study from Germany, eight different electrical energy storage (EES) technologies were analysed. The comparative life cycle assessment focused on the storage of electrical excess energy from a renewable energy power plant. The considered technologies were lead-acid, lithium-ion, sodium-sulphur, vanadium redox flow and stationery second-life batteries. We also added the pumped hydropower storage (PHS), which is a proven technology installed worldwide, to the comparisons. The results showed that the PHS (7.4 g CO_2/kWh) and second-life batteries (9 g CO_2/kWh) have had the lowest GHG emissions and material use, followed by the lithium-ion battery (11 g CO_2/kWh) and the underwater compressed air energy storage (27 g CO_2/kWh). Therefore, these four technologies were preferred options compared to the remaining five technologies according to the study. The production phase accounted for the highest share of GHG emissions and material use for nearly all technologies. The results of a sensitivity analysis showed that lifetime and storage capacity had a comparable high influence on the footprints. The GHG emissions and the material use of the power-to-gas technologies, the vanadium redox flow battery as well as the underwater compressed air energy storage declined strongly with increased storage capacity.
- Life-cycle GHG results from the utility-scale lithium-ion batteries are comparable to the EES technologies analyzed in this report. Albeit much smaller than most pumped hydropower plants, they can also provide the required balancing and ancillary services. In increasing order, estimated mean carbon impacts from combined LFP-LTO, LVO, LMO and LCO, NCA, LFP, and NCM are 32, 36, 55, 98, 134, and 174 g CO_2/kWh, respectively.

4.2. Technologies and Products in Buildings for Energy Efficiency

The results of this report represent a first pass effort to assess the current availability of embodied and operational carbon data for energy-related products and technologies used in commercial, residential, agricultural, and industrial buildings. A broad overview of the data coverage reveals key trends. Figures 36 and 37 show the total number of EPDs/datapoints for each category and subcategory, respectively, organized by geographic location.

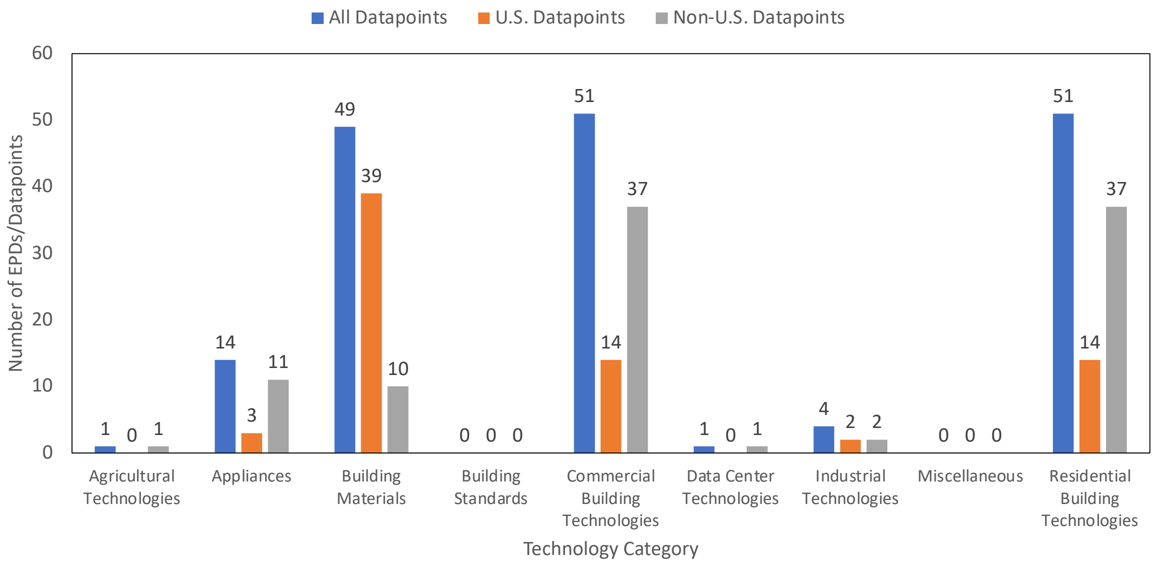


Figure 36. Coverage of building technology and product data by category.

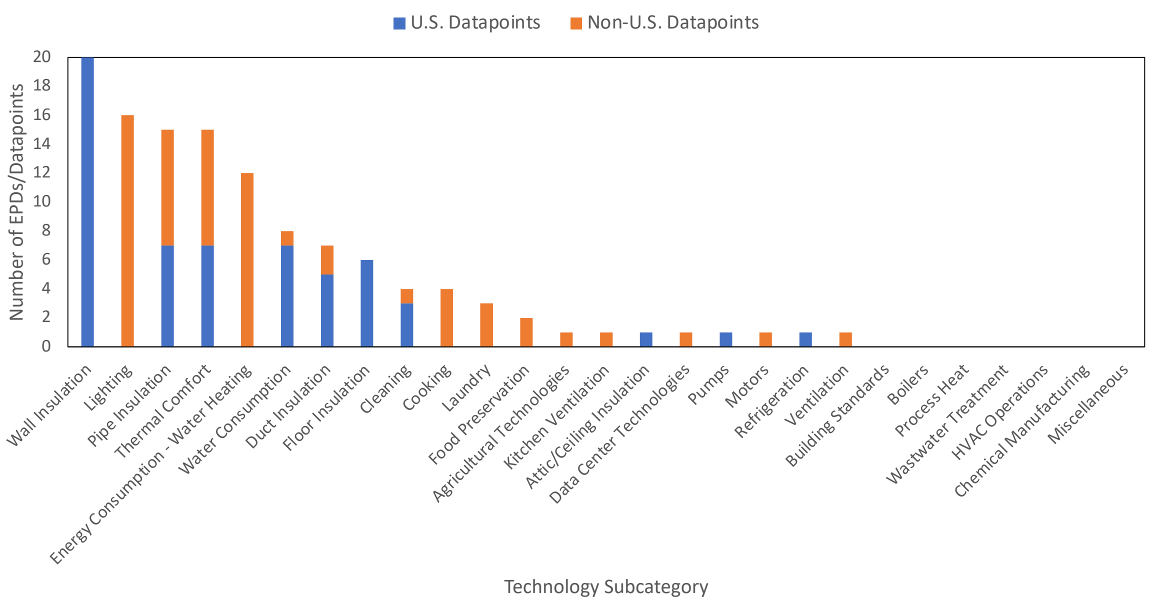


Figure 37. Ranking of subcategories by number of EPDs/datapoints by geographic category.

Of the nine categories of technologies, the Building Materials and Commercial and Residential Building Technologies categories have the most embodied and operational carbon datapoints. Note that we do not distinguish between the Commercial and Residential Building Technologies categories because: (1) they each have duplicates of the same technologies and (2) in many instances we use EPDs for residential technologies and proxies for commercial ones and vice versa. Additional key trends from our literature review of the technologies include:

- The category for which there are the most EPDs available is the Building Materials category, of which the subcategories include various types of insulation. There are significantly more EPDs from American manufactured insulation in this category than there are from non-U.S. manufacturers for most insulation types; there are slightly more EPDs for non-U.S. manufactured pipe insulation than for U.S.-made pipe insulation.
- The Commercial/Residential Building categories have the most EPDs/datapoints, with data for each subcategory mainly coming from a specific source. Data for the Water Consumption subcategory mainly come from EPDs produced in North America. The Energy Consumption-Water Heating subcategory is entirely populated from data found in peer-reviewed journal articles with non-U.S. case studies. Non-U.S. EPDs comprise all the datapoints for the Lighting subcategory. The data found in the Thermal Comfort subcategory are mainly derived from non-U.S. journal articles.
- There is limited embodied and operational carbon information available for the Agricultural Technologies, Data Center Technologies, and Industrial Technologies categories. The unavailability of information is due to a lack of context and definition for some of the technologies making it if difficult to find relevant datapoints. For example, there is no specification for "Dairy Ventilation Efficiency Upgrades" in the Agricultural Technologies category. Information is also unavailable simply because EPDs or studies that investigate the environmental impacts of the technologies do not exist.
- In the Appliances Category, there is limited environmental impact information and most of the embodied and operational carbon data pertains to non-U.S. case studies and EPDs.
- There is no available information for the Building Standards and Miscellaneous categories.
- Across all categories, information on various technology sizes, material components, manufacturing locations, and other specifications is so limited that overarching conclusions about the range of impacts for specific products is not justified at this time.

What needs to change to fill in the gaps in missing data for the building technologies? The most information, in terms of absolute number as well as variety in location of product manufacturing and design, is for the products in the Building Materials category. Recent regulations at both the state and federal level, such as California's AB 2446 and the Federal Buy Clean Initiative[2,108], necessitate the use of construction materials (e.g., concrete, steel, etc.) with low embodied carbon values. As a result of these regulations, there are now thousands of EPDs for varying concrete mixes, for example. Implementation of similar mandates for other building components, appliances, and products would likely result in more EPDs for those missing technologies. Another key issue that needs to be addressed is the lack of harmonization of functional units among the different product categories. We recommend that regulatory bodies of EPDs improve the standardization across products so that, as an example in the lighting category, there is one functional unit used for all lighting types.

Is there the possibility of determining the breakdown between embodied and operational GHG emissions in all products? The operational data we do have is often specific to the assumptions and data sources included in the EPDs or peer-reviewed research articles. This makes it difficult to provide a definitive estimation of whether embodied or operational emissions are the more dominant source of emissions. In all relevant example technologies in this report, the operational stage is the most emissions intensive. A limiting factor for the technologies where there are both embodied and operational carbon data is that the operational impacts are estimated with the carbon intensities of current electrical grids and fuel sources and do not account for future changes to grid or fuel carbon intensity. Again, we emphasize that a definitive assessment between operational and embodied emissions for technologies in California is not possible currently.

To date, most work aimed at establishing benchmarks between embodied and operational emissions largely focus on whole buildings, with a specific focus on comparing GHG emissions from building structural materials to emissions from operational use[109]. This report is the first large scale effort to establish benchmarks between embodied and operational emissions for building technologies that both consume and affect the energy consumption in buildings. Future research can further expand this effort by considering additional factors such as the rate of decarbonization for electrical grids, but multiple data gaps must be filled to provide more meaningful and comprehensive results than those presented in this report.

5. Conclusions

5.1. Electricity Generation and Storage Technologies

We have conducted a literature review of existing data for cradle-to-grave (if possible) and cradle-to-gate GHG emissions from target electricity generation and storage technologies for the California context. Based on the available data, we sorted the existing data by factors such as geographic location, type of technology, generation and storage capacity, lifetime, conversion efficiency, and quality of the energy source, depending on the type of the technology (provided in the accompanying Excel file). Our search focused mainly on the environmental data on EPDs, which tend to be the most current and detailed data available. If EPD data were not available, we consulted peer-reviewed journal articles, industry publications, and government reports for information on the carbon footprints of the electricity generation and storage technologies. In general, onshore and offshore wind turbines, followed by the solar power systems have the most current and relevant data for California. Results from the cradle-to-grave life cycle GHG emissions of five major electricity generation technologies in California show that wind (both offshore and onshore options) (17 g CO_2/kWh) is by far the best options to consider followed by solar at utility scale (47 g CO_2/kWh), solar thin film technologies (56 g CO_2/kWh), and geothermal (62 g CO_2/kWh). It is also important to note that the variability in wind turbine data is considerably low, followed by solar systems. The number of publicly available data for wind turbines and solar power systems is also larger and more current compared to other technologies. As source of data, EPDs (especially in EU and US context) are mostly common for wind turbines.

Future work regarding the data collection efforts specific to California can improve the results from this report. The biggest gap in the analysis was the lack of distinction between embodied, operational, and EOL stage GHG emissions when comparative LCAs were considered. California has established targets for achieving emission reductions in electricity generation. According to SB 350 (Clean Energy and Pollution Reduction Act), by 2030, 50% of the electricity procurement in the state must come from renewable sources. The law supports the state's efforts to reduce GHG emissions 80% below 1990 levels by the year 2050. In achieving the goals of this law, the state will need to account for any embodied emissions associated with the life-cycle stages of renewable sources.

Additionally, California-specific data was limited to only wind and solar power systems based on the available LCAs. Similar to the energy using devices and products in buildings, there is an urgent need for policy makers and industry stakeholders to replicate policies such as AB 2446 to expand the coverage of embodied impacts in electricity generation and storage technologies that require EPDs.

5.2. Technologies and Products in Buildings for Energy Efficiency

In this report, we define the current scope of embodied and operational carbon data for technologies used in residential, commercial, agricultural, and industrial buildings. We conducted a literature review and survey of existing data for a list of 120 technologies from nine categories. We primarily concentrated our search of environmental data on EPDs, which tend to be the most current and detailed data available. If EPD data were not available, we consulted peer-reviewed journal articles, industry publications, and government reports for information on the embodied and operational carbon footprints of the technologies. In general, there Building Materials category has the most current and relevant data for California. However, there are multiple data gaps within our survey for the remaining categories.

Of interest is whether the results of the report can be used to answer important questions around the embodied and operational carbon impacts of our buildings. Are the embodied GHG emissions from energy-efficient products greater than savings in operational carbon from switching to more efficient devices? Or from switching from natural gas-powered devices to electric devices? These key questions cannot currently be answered for the technologies in this report due to lack of relevant data for California. There is an urgent need for policy makers and industry stakeholders to replicate policies such as AB 2446 to expand the coverage of products that require EPDs.

Future work can improve the results from this report. We need to concretely define and explore differences in embodied and operational GHG differences between efficient and "retired" products. Ultimately, we need to explore the impact of the technologies in the context of entire buildings. The state should explore, to the extent possible, how decisions on these energy efficient devices and technologies impact embodied and operational emissions in prototypical residential, commercial, agricultural, and industrial buildings.

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