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Development of the Supply Chain Optimization and Planning for the Environment (SCOPE) Tool - Applied to Solar Energy

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Development of the Supply Chain Optimization and Planning for the Environment (SCOPE) Tool - Applied to Solar Energy

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Abstract—**A supply-chain decision tool is outlined that will assess the life-cycle greenhouse gases and energy demand of solar energy technology using a hybrid LCA structure. Energy and greenhouse gas metrics appropriate for the climate change mitigation goals of solar energy are discussed. Applying this methodology to SolFocus Inc. concentrator systems, preliminary results indicate that the energy payback time of SolFocus Panels can vary from 0.6 to 5 years depending on manufacturing locations. The greenhouse gas payback time, a new metric for energy technologies, varies from 1.1 to 64 years depending on the same factors indicating that greenhouse gas metrics are more sensitive to installation and supply chain decisions than energy metrics.**

Index Terms—**Operations Research, Decision Support Systems, Solar Energy, Greenhouse Gas Emissions.**

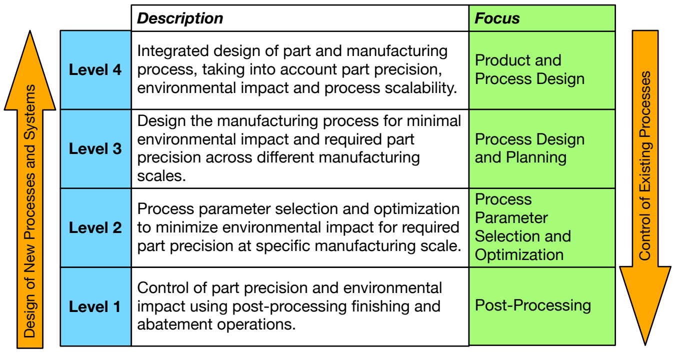
I. INTRODUCTION

Renewable energy systems are being developed to satisfy three main goals: (1) provide reasonably priced energy (2) mitigate climate change (3) provide energy independence. This paper presents the The Supply Chain Optimization and Planning for the Environment (SCOPE) tool designed to enable comprehensive LCA and ensure these goals are met. The life-cycle environmental impact of energy supply can be reduced through research on materials, product design, manufacturing, and the supply chain; however, the supply chain viewpoint is taken by SCOPE because environmental tradeoffs at this level are generally not considered in new energy development. The supply chain is defined as the set of suppliers required for a complete and successful final product, and the interconnecting network of these suppliers around the globe.

The supply chain has been found to impact up to 25% of manufacturing costs [6], and preliminary studies indicate that environmental impacts may be similarly distributed. An initial assessment of SolFocus Inc. concentrator photovoltaic systems found transportation to be 10-20% of the lifecycle energy demand when panel transportation to installation and glass transportation to assembly were included [21]. Additionally, supply chain tradeoffs have been demonstrated in a U.S. based study by Reich-Weiser et al. where greenhouse gas tradeoffs between manufacturing an automobile local to a customer versus manufacturing elsewhere and sending the vehicle by truck were investigated. The study found that the decision to minimize greenhouse gas emissions depends both on the electricity mix at the customer and transportation distances [15].

Environmental supply chain considerations can and should be incorporated early in the design process to ensure the greatest possible reduction in impact. Figure 1 shows 4 levels of design and manufacturing flexibility [19]. The SCOPE tool primarily operates at Levels 2 and 3, although it could be applied in level 4 to establish design for manufacturability tradeoffs based on potential supplier locations. At the highest level of flexibility, level 4, the product concept is just being developed; product specifications are in formation and design decisions are made for functionality and manufacturability. In Level 3, a product design has been set, however materials and manufacturing processes are still under consideration to minimize costs and environmental impact. In Level 2, the specific types of manufacturing to be used are determined, however adjustments to process parameters and the supply chain are made. In Level 1, there is no product or process design flexibility, and after-process abatement techniques are required to reduce environmental impact. Operating at Level 1 is risky because of the unpredictable costs of abatement and cleanup.

This work is novel in its approach to LCA and supply chain decision making for solar energy generation. Previous solar energy assessments, while thorough in their exe-



	Description	Focus
Level 4	Integrated design of part and manufacturing process, taking into account part precision, environmental impact and process scalability.	Product and Process Design
Level 3	Design the manufacturing process for minimal environmental impact and required part precision across different manufacturing scales.	Process Design and Planning
Level 2	Process parameter selection and optimization to minimize environmental impact for required part precision at specific manufacturing scale.	Process Parameter Selection and Optimization
Level 1	Control of part precision and environmental impact using post-processing finishing and abatement operations.	Post-Processing

Fig. 1. 4 Levels of Decision Making Flexibility [19].

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cution, have not focused on the climate change mitigation potential of a re-organized supply chain or installation location variables. In 2006, Fthenakis et al. conducted an energy and GHG based review of fossil fuels, various silicon technologies, and CdTe technology [9]. Alsema, additionally, reviewed the GHG emissions and energy demands of fossil fuels, nuclear, biomass, wind, multicrystalline silicon, and CdTe technologies [4]. Most recently, Fthenakis et al. conducted an updated review of Silicon and CdTe photovoltaic technology investigating the life-cycle energy use, greenhouse gas emissions, SO2 emissions, NOx emissions, and heavy metal emissions as compared with fossil fuels, nuclear, and hydro electricity generation [10]. Peharz et al. investigated the energy payback time of the FLATCON fresnel concentrator solar technology in 2005 [14], one of only a few analyses of concentrator technology.

The SCOPE tool is designed to expand upon previous solar LCA in the following ways:

1. Electricity mix and resource differences throughout the supply chain: Components along the supply chain do not generally come from a single location. In today's global economy, parts may originate from all over the globe, such as China, India, the U.S.A, and elsewhere. A single company producing a single solar technology could alter their GHG and energy footprint by relocating supplier and manufacturing sites. This is already well known in economic assessment, where manufacturing location decisions are influenced by economic decisions such as labor costs, energy costs, local regulations, resource availability, flexibility, and lead times.
2. Transportation: Previous analyses of energy have not always included the emissions and energy demand of transportation; as previously discussed by Zhang et al. [21]. Exceptions to this include an assessment of solar concentrator systems by Peharz et al. that included the final leg of transportation from assembly to installation [14] and a 2008 assessment of an italian wind farm by Ardente et al. that included transportation throughout the life-cycle [5].
3. Electricity distribution and circularity: When determining the electricity that is offset by a new solar installation the circularity or distribution losses of electricity supply have not been considered. Demand for electricity requires extra production to account for electricity that is lost in transport to consumers (distribution losses) or internally demanded by the energy sector (circularity).

The SCOPE tool is in preliminary development stages, however the basic tool architecture and underlying hybrid LCA methodology are presented here. Energy and greenhouse gas metrics are outlined as used by the tool to assess alternatives. Finally, a case study of preliminary results for SolFocus Inc. is presented to establish the feasibility, applicability, and usefulness of SCOPE.

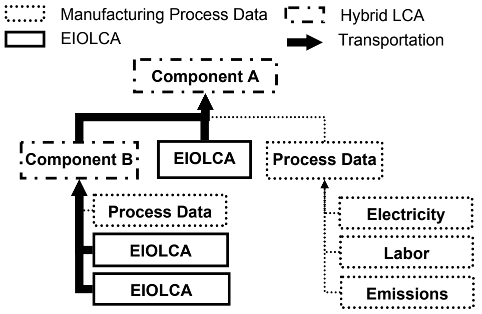

Fig. 2. Basic Data Structure for Hybrid LCA.

II. SCOPE LCA Methodology & Structure

SCOPE is designed as a hybrid LCA tool, as suggested by Hendrickson et al. [11]. The basic structure of this methodology is illustrated in Figure 2, where process data (such as manufacturing electricity use) is combined with sector level economic input-output life-cycle assessment data (EIOLCA) from Carnegie Mellon University [3]. SCOPE allows users to construct a hybrid assessment through inputs on EIOLCA sector, cost, and processing data. Included in this analysis are the following life-cycle aspects: materials, manufacturing, manufacturing yield, shipping yield, component transportation, final transportation, local energy efficiency, component replacement, overhead, and maintenance; end of life is not yet incorporated.

When EIOLCA data is used in SCOPE, the user's choice of manufacturing location approximately adjusts the U.S. based EIOLCA data to be relevant to different supplier locations. This is done by scaling the contribution of "power generation" in EIOLCA from a U.S. value to the local electricity mix using data on the electricity conversion efficiency (MJ/kWh) and greenhouse gas emissions (GHG/kWh) including circularity and distribution differences. Note the assumption here that all other sectors and their interdependencies in EIOLCA are constant between locations. Equation 1 translates a U.S. based EIOLCA $GHG/\$$ value to a $GHG/\$$ value in Country "A" where GHG_{PG} are the GHG emissions of power generation as given in EIOLCA and $(\frac{GHG}{kWh})_A$ are the greenhouse gas emissions per kWh produced in country A.

$$\begin{aligned}(\frac{GHG}{\$})_A = {} & (\frac{GHG_{total} - GHG_{PG}}{\$})_{US} \\ & + (\frac{GHG_{PG}}{\$})_{US}(\frac{(\frac{GHG}{kWh})_A}{(\frac{GHG}{kWh})_{US}})\end{aligned} \tag{1}$$

The bottom level of a hybrid analysis are EIOLCA and processing inputs. The user of SCOPE, therefore determines how many levels there are to the supply chain based on data availability. For example the user can choose a "manufacturing input" or a "purchasing" input to any given component. A purchasing input will require information on EIOLCA sector, cost, weight, and potential

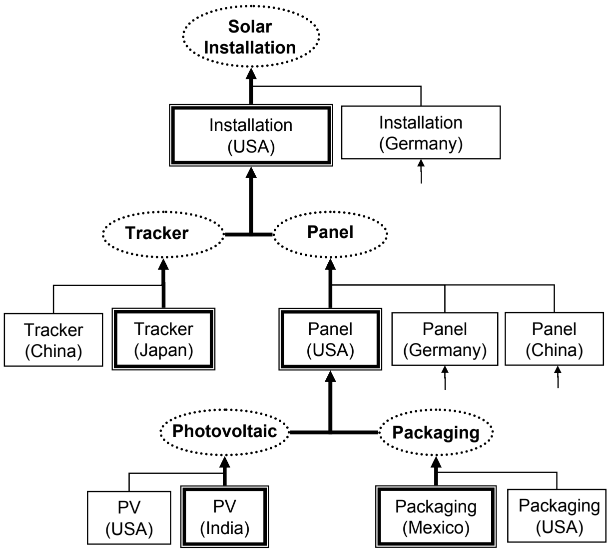

Fig. 3. Mockup of choices for producing a solar panel - the double outline boxes indicate one possible supply chain.

locations. A manufacturing input will require processing data and information on additional components required, adding additional levels to the supply chain. Data availability, time constraints, and more will effect the levels of supply chain included by the user. When using SCOPE, the user should also consider how appropriate EIOLCA data is for any given input. EIOLCA data is an aggregate value for a sector, and is currently based on 1997 information [3]. It is not necessarily appropriate for emerging processes and new materials; for these, the user is encouraged to seek out specific processing data.

An important aspect of SCOPE is its ability to assess alternate supply chains based on potential supplier locations. Figure 3 illustrates this for a solar panel, where each component of the solar panel can be obtained from 2 or 3 different suppliers. By choosing between alternatives, a supply chain that will optimize one or more of the metrics can be obtained. Optimization to find the "best" supply chain is not discussed here, but is the topic of future work on SCOPE. The current tool allows the user to manually find an optimal scenario by adjusting supply chain factors.

III. METRICS

The use of appropriate metrics for determining tradeoffs is a critical part of decision making. There are many potentially competing environmental indicators that could be used to assess the environmental impact of a solar system, including eutrophication, toxic releases, acidification, and particulate emissions. All of these are important, however greenhouse gas metrics are considered here as relevant to solar energy's goal of mitigating climate change and energy metrics are included as measures of efficiency. GHG emissions are expressed in terms of their 100-year global warming potential in CO_{2eq}.

Energy payback time (EPBT) is one of the most common metrics used to describe solar technologies. EPBT indicates the number of years a technology must produce electricity, thus offsetting the use of primary energy from another electricity source, to offset the total energy required over its lifetime (E_{LCA}) (equation 2). EPBT calculations utilize a conversion factor to translate electricity produced by the system to the amount of primary energy offset ($E_{AnnualOffset}$) based on the local electricity mix and distribution system efficiencies (η_{elec}). The electricity output by the system is here called $Elec_{useful}$ because it only includes useful electricity leaving the system; electricity consumption by peripherals, wiring losses, and conversion efficiency from DC to AC should already be accounted for.

$$EPBT[years] = \frac{E_{LCA}}{E_{AnnualOffset}} = \frac{E_{LCA} * \eta_{elec}}{Elec_{AnnualUseful}} \quad (2)$$

EPBT is a useful metric of basic efficiency; however it does not acknowledge differences in lifetime. For example, two technologies' with a EPBT of 5 years are not equivalent if one lasts 10 years and the other 20 years. For this reason, researchers have suggested the Energy Return on Investment metric, calculated as the lifetime divided by the EPBT [13] [17] (equation 3). EROI indicates how many MJ of primary energy are saved from consumption for every MJ of primary energy consumed.

$$EROI[\frac{E_{saved}}{E_{consumed}}] = \frac{Lifetime}{EPBT} \quad (3)$$

Also used in previous comparisons of energy technology is the GHG/kWh metric [4] [9]. This is calculated as the LCA determined greenhouse gas emissions divided by the total kWh output by the system. Unlike EPBT and EROI, the drawback of this metric is that it does not account for installation differences. EPBT and EROI incorporate the conversion efficiency of electricity at the location site, and therefore encourage installations to replace electricity where conversion is least efficient.

Following the example set by EPBT and EROI, the greenhouse gas payback time (GPBT) (equation 4) and greenhouse gas return on investment (GROI) (equation 5) are utilized by SCOPE. Similar to EROI, GROI indicates the GHG emissions prevented for every unit of GHG emitted encouraging the fastest route to reducing energy related greenhouse gas emissions [16].

$$GPBT[years] = \frac{GHG_{LCA} * \eta_{GHG}}{Elec_{AnnualUseful}} \quad (4)$$

$$GROI[\frac{GHG_{saved}}{GHG_{emitted}}] = \frac{Lifetime}{GPBT} \quad (5)$$

Note that these metrics assume a 0% discount rate on emissions and energy consumption over time. This means that a kg of GHG emissions emitted ten years from now is equivalent to a kg of emissions today. This assumption favors technologies like solar that have the majority of their emissions upfront, during production, and is something to be aware of when comparing technologies with these metrics.

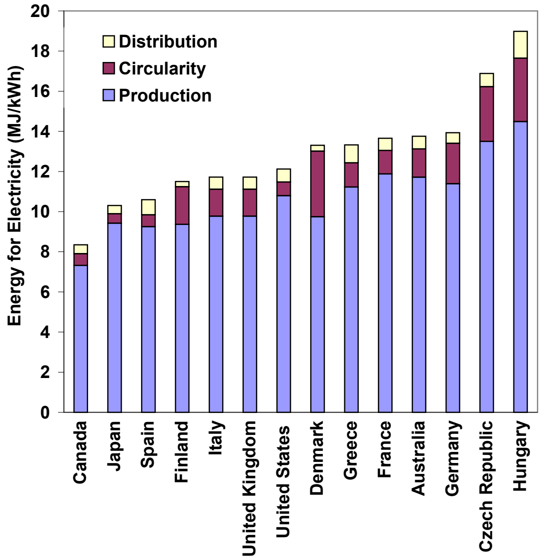

Fig. 4. Primary energy demand for a kWh of electricity in countries with available data.

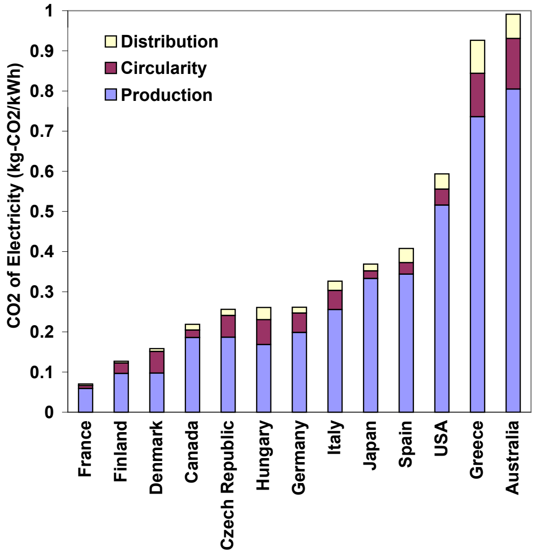

Fig. 5. Greenhouse gas emissions of a kWh of electricity in countries with available data.

IV. Database

SCOPE requires a database of location electricity data, EIOLCA data, and transportation data. The current database used to translate user inputs into metrics is described here.

A. Country Level Electricity Data:

Information on the MJ/kWh of primary energy and the GHG/kWh emissions of electricity generation in various locations are needed to determine η_{elec} and η_{GHG} for use in EPBT and GPBT calculations, to scale the power generation portion of EIOLCA data to local conditions, and to determine the energy or GHG emissions associated with processing electricity use. This data is currently stored in SCOPE as an average value for each country.

Primary energy to electricity conversion efficiency, distribution losses and circularity factors are accounted for in each location. It is noted that the electricity mix supply chain should also be considered, but these values are not yet known [16].

The MJ to kWh conversion data is obtained from energy balance charts provided by the International Energy Agency [1]. Data on distribution losses, electricity used by the electricity industry, and the total electricity production are used along with the total change in primary energy supply to obtain the results shown in Figure 4.

CO2 Emissions data for various electricity mixes is also obtained from the IEA [1], and was previously discussed by Reich-Weiser et al. [16]. Note that these results utilize IEA circularity data rather than economic input-output circularity data from the OECD [2] as was done previously [16]. Results are given in Figure 5, and CO2 emissions are shown rather than GHG emissions due to data limitations. Note the larger variation in CO2/kWh across countries than is seen for MJ/kWh.

B. U.S. EIOLCA Data:

US EIOLCA data (GHG/$ and Energy/$) from Carnegie Mellon [3] is utilized to determine the impact of components based on their production cost. Four datapoints from EIOLCA are stored for each sector of the economy, to be used as was described in equation 1: (1) GHG per dollar (2) energy per dollar (3) GHG of power generation (GHG_{PG}) per dollar (4) energy demand of power generation per dollar.

C. Transportation Data:

Transportation CO_2 emissions and energy use data come from transportation studies by Facanha et al. [8], Spielmann et al. [18], and Corbett et al. [7] as previously discussed by Reich-Weiser et al. [15]. A complete GHG assessment of transportation has not been completed, so the $CO2$ values are used for now. An average value for trucking, rail, international shipping, and air freight are utilized. Transportation values are based on the weight rather than the volume carried a distance; this assumes that the supplier is maximizing packing efficiency [15].

D. Labor Data:

Zhang et al. has suggested the incorporation of hourly environmental data on labor into life-cycle assessment to provide a fair comparison between manual and automated systems [20]. Zhang suggests quantifying the energy per worker-hour (for the industrial sector) by taking data on the total energy consumption of a society minus the industrial energy consumption all divided by the working population; this provides a reasonable estimate of the infrastructure and consumer needs for labor. The inclusion of labor in LCA is important for comprehensive LCA and Zhang is investigating modifications to quantify and improve the accuracy of such an estimate; therefore future versions of SCOPE will incorporate labor values in some form.

V. Case Study: SolFocus

SolFocus is developing utility scale concentrator photovoltaic systems. Their design and manufacture are still under development; however, available cost estimates and preliminary manufacturing data make the SCOPE methodology applicable and particularly useful for this analysis. Although the SCOPE tool is still under development, the application of the SCOPE methodology to SolFocus systems, given available data, results in the supply chain tree shown in Figure 6. Note in Figure 6 that transportation is not yet included for every component.

For this assessment, installation is assumed to occur in Arizona, USA with a DNI of 6.9 $kWh/m^2/day$. The panels are assembled in India, and most components come from China, India, Spain, or the U.S. The installation is utility scale and assumed to replace rather than supplement the local electricity mix; therefore production, circularity, and distribution of the current electricity mix are offset.

To explore the variability in energy and GHG metrics, four scenarios are considered: (1) no transportation over the life of the supply chain (2) transportation of goods across the SolFocus supply chain using the most efficient methods possible (truck, rail, water freight) (3) transportation using only air freight as a worst case scenario (4) same as 3 except installation in France rather than Phoenix with a DNI of 5.3 $kWh/m^2/day$. In each scenario the transportation distances are constant. The results shown in Table I do not include labor or an adjusted EIOLCA value. Phoenix is considered a good site while France is considered marginal; DNI values can be even higher in Africa, Australia and other parts of the southwest United States.

The GPBT shows the largest sensitivity to installation variations because it is directly proportional to the offset GHG/kWh as was seen in Figures 4 and 5. GHG/kWh is more variable than E/kWh. Each metric is also sensitive to the type of transit used throughout the life-cycle as seen between scenarios 2 and 3. These results indicate the potential for supply chain and installation optimization using the SCOPE tool. The impact of variations in electricity mix at each supplier site on these metrics have not yet been explored.

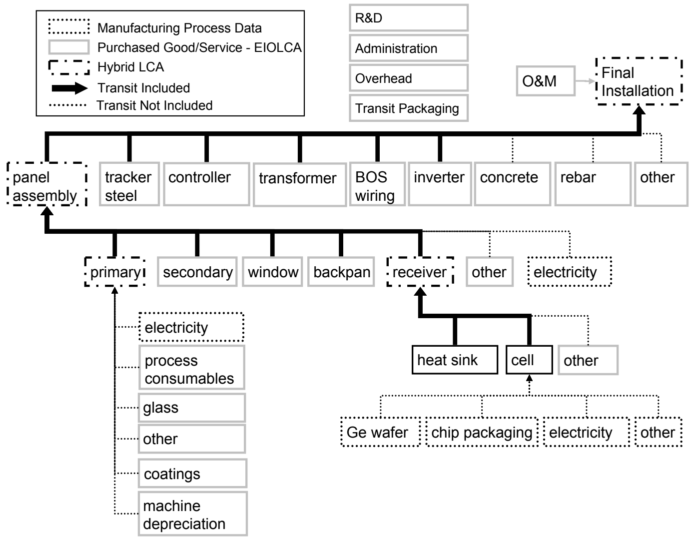

Fig. 6. SolFocus Tree Determined by Inputs to Decision Tool.

TABLE I

Influence of Transportation on Energy and GHG Metrics

	No Transit - USA Install	Efficient Transit - USA Install	All Air Freight Transit - USA Install	All Air Freight Transit - France Install
EPBT	0.6	0.7	4.3	5.0
GPBT	1.1	1.4	5.8	49
GHG/kWh	21	29	115	150

VI. Discussion

This paper proposes a tool to satisfy the following needs of solar energy environmental analysis:

1. Metrics: The metric of greenhouse gas return on investment and energy return on investment are suggested for analysis of new energy systems. GROI is particularly useful as it promotes the fastest path to climate change mitigation. Note that metrics should be used following the "right tool for the job" rule, where GROI and EROI are only useful if greenhouse gases or energy balances, respectively, are the concern.
2. Life Cycle Assessment Tool: A hybrid LCA approach utilizing modified EIOLCA and process data is suggested for development of a widely usable tool. This tool can be used by someone with a range of available data from a simple bill of materials to detailed manufacturing data.
3. Optimization & Decision Making Early in Design: Visibility of tradeoffs allows for a manual optimization of EROI and GROI using SCOPE; a built-in optimization scheme is the focus of future work. Additionally, a product can be designed iteratively with SCOPE, starting with an analysis based on resource availability to determine materials and manufacturing choices in the product design phase. Once a design is settled upon, the SCOPE tool can again be used with additional data for more detailed logistics analysis.
4. Technological Comparison: The advantage of a tool like this is its ability to provide output that is either comparable between technologies (by removing transportation and assuming constant installation and manufacturing conditions) or specific to a particular supply chain and installation scenario.

Preliminary results for SolFocus concentrator systems across the range of scenarios tested indicate that the EPBT of SolFocus Panels can vary from 0.6 to 5 years depending on installation and manufacturing locations. The GPBT can vary from 1.1 to 49 years depending on the same factors, and is seen to be more greatly sensitive to location factors than an energy-based metric; this sensitivity is a result of the greater variation in GHG/kWh values across countries than is seen for MJ/kWh values.

VII. Future Work

Throughout this paper certain pieces of missing data and areas needing development have been discussed. In particular, transportation and electricity mix data are currently given as CO2 rather than GHG values. In addition to these data needs, the following are considered for future work:

1. Energy use and greenhouse gas emission metrics are discussed in this paper because energy use is relevant to the efficiency of solar technology and greenhouse gas emissions are relevant to climate change; however an additional key concern of climate change is water scarcity. In the United States, 48% of water is withdrawn by the electricity industry [12]. Solar has the distinct advantage of not requiring water during its use-phase; therefore, the installation of solar to replace thermal power plants in water scarce regions of the world could prevent water use and thermal pollution of waterways. Tradeoffs then emerge between EROI, GROI, and water scarcity that will require further investigation and understanding to design minimal impact manufacturing supply chains. Note that additional environmental metrics could be added as well, such as toxicity and acidification potential.
2. SCOPE does not currently account for the trips required by engineers, managers, and executives to work collaboratively, ensure quality control, and provide feedback. In the U.S., business trips are primarily made by automobile or airplane, which are known to be a major emitters of greenhouse gases; therefore, it is possible for the effects of business trips to be substantial.
3. While SCOPE provides decision makers the ability to understand environmental tradeoffs between supplier location and transportation, decision makers must also consider lead times, flexibility, and quality of suppliers before making a decision; cost and operations considerations must eventually be included in SCOPE for it to be a viable and useful tool for decision makers.
4. Estimation of error will be an important final step to an analysis using SCOPE. As inputs on costs, weights, distances, and more are entered into the tool, confidence intervals could be included that would result in a confidence interval on the final solution.

Acknowledgment

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