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Environmental Assessment and Metrics for Solar:

Case Study of SolFocus Solar Concentrator Systems

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Abstract—**Life-cycle assessment (LCA) is utilized to analyze SolFocus Inc. concentrator solar systems. A hybrid LCA methodology is explained that combines process and input-output LCA techniques. The use of the greenhouse gas return on investment metric for solar technologies is discussed as a complement to energy metrics. Finally, preliminary results of a hybrid LCA for the SolFocus concentrator technology are presented. It is found that transportation and electricity consumption play a significant role in energy consumption and greenhouse gas emissions.**

I. INTRODUCTION

Alternative energy technologies are being developed as "low carbon" alternatives to fossil fuel energy generation, with the ultimate goal of providing reasonably priced energy while mitigating climate change. To understand how well various technologies meet this goal, previous researchers have conducted life-cycle assessments to determine emissions per kWh and energy payback time (EPBT). In 2008, Fthenakis et al. conducted an assessment of greenhouse gas, NOx, SOx, Cd, and heavy metal emissions for various energy technologies including fossil fuels, multicrystalline silicon, monocrystalline silicon, ribbon silicon, and CdTe [8]. Alsema, additionally, reviewed the GHG emissions of fossil fuel technologies, nuclear, biomass, wind, multicrystalline silicon, and CdTe [1]. Peharz et al. investigated the EPBT of the FLATCON fresnel concentrator solar technology in 2005 [13], one of only a few EPBT analyses of concentrator technology. Their conclusions and more are summarized in Table I.

TABLE I
REVIEW OF ENERGY TECHNOLOGY LCA RESULTS.

Technology	EPBT (years)	GHG (g/kWh)	Reference
Si	2.2-2.7	30-55	[7] [8]
CdTe	1.1	21-25	[7] [8]
Concentrator PV	0.7-1.3	-	[13]
Solar Thermal	2.2-3.9	34.7-37.6	[18] [11]
Wind	0.27-0.7	8.8-18.5	[3] [2]
Coal	-	900	[1]
CC Gas Turbine	-	400	[1]
Nuclear	-	20-40	[1]

While the previous studies are extremely useful for understanding the basic feasibility of new technologies in terms of environmental impact, there are two important drawbacks to these studies: (1) It is often the case that a single LCA database that is specific to a given region of the world is used for an LCA assessment; therefore, it is inherently assumed that the electricity mix is constant for what actually may be a varied mix of electricity supply across the supply chain. (2) In many solar energy assessments, transportation is not included or is only included in the final leg of the supply chain from assembly to installation.[1] The potential importance of transportation was discussed by Zhang et al. in an initial assessment of SolFocus concentrator PV technology where transportation to and from assembly was found to contribute 10-20% to the Energy Payback Time [20]. Additionally, Peharz et al. included the final leg of transportation and found it contributed 10% to the EPBT.

Furthermore, the metrics used by previous researchers do not acknowledge differences in installation site based on what is offset by the new technology. For example, a technology installed to replace coal-fired power is preferable to one installed to replace hydro power, in terms of GHG emissions.

In this paper, metrics appropriate for a climate change mitigation goal are discussed and preliminary results of a SolFocus Concentrator PV life-cycle assessment are presented.

II. METRICS FOR SOLAR ENERGY

The most common energy metric used by solar researchers today is the Energy Payback Time (EPBT). EPBT is described as the number of years a technology must output electricity to "payback" the energy required for its manufacture. However, because EPBT does not acknowledge differences in technology lifetime, researchers have also suggested the Energy Return on Investment (EROI) metric, which is calculated as the technology lifetime (standard assumption is 20 to 30 years) divided by the EPBT [12] [16] (equation 1). EROI indicates how many MJ of primary energy are saved from consumption for every MJ of primary energy consumed.

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[1] Note that assessments using economic input-output databases (for example [11]) automatically include transportation in the way the LCA database is created, however they assume only regional distances are crossed.

$$EROI[\frac{E_{saved}}{E_{consumed}}] = \frac{Lifetime}{EPBT} \quad (1)$$

EPBT is considered to be simply a measure of technological efficiency, however a conversion factor is required in the EPBT formula that translates produced electricity back to primary energy using the local electricity mix efficiency (C_{elec}). Therefore, EPBT is actually an indicator of the number of years a technology must offset the use of primary energy from another electricity source, to offset the total energy required over its lifetime (E_{LCA}) (equation 2). Given this definition, EPBT is not only a measure of technological efficiency but also of installation tradeoffs regarding the offset electricity mix and available solar radiation. 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.

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

The greenhouse gas emissions metric used by previous researchers is the GHG/kWh. The GHG/kWh metric is calculated as the LCA determined greenhouse gas emissions divided by the total kWh output by the system over its lifetime (dependent on solar radiation at installation site). A drawback of the GHG/kWh metric is that it does not encourage installations to replace electricity where conversion is least efficient. The GHG/kWh is equivalent if a technology replaces a coal fired power plant or if it replaces a hydro facility.

Therefore, the greenhouse gas payback time (GPBT) and return on investment (GROI) are proposed here for assessing energy technology supply chains and installations. Following the example set by EPBT and EROI, which incorporate the conversion efficiency of electricity at the location site, GPBT (equation 3) and GROI (equation 4) are proposed to indicate which technology and supply chain scenario will enable the fastest route to climate change mitigation. Similar to EROI, GROI indicates the GHG emissions prevented for every unit of GHG emitted.

$$GPBT[years] = \frac{GHG_{LCA}}{C_{GHG} * Elec_{AnnualUseful}} \quad (3)$$

$$GROI[\frac{GHG_{saved}}{GHG_{emitted}}] = \frac{Lifetime}{GPBT} \quad (4)$$

Determining C_{elec} and C_{GHG} requires an understanding of the consumer, the current electricity supply, and alternative new installations [15]. These nuances have been ignored in previous calculations of C_{elec}. There is a difference between a technology installed directly at the point of use and one installed to the grid; solar technology installed at the point of use offsets both the production and distribution losses, while a grid-tied option only offsets production. Additionally, there is a difference between providing electricity to new customers, who would require additional capacity in the grid regardless of technology, and providing electricity to customers who already have full access to the current electricity grid.

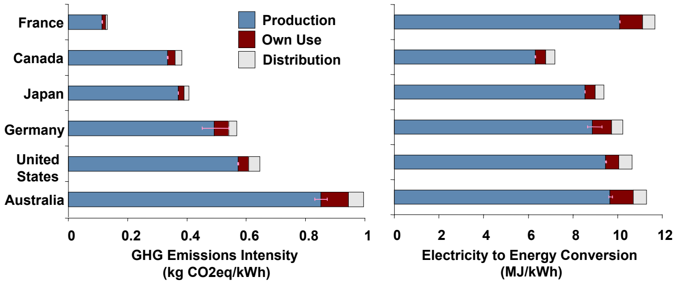

Fig. 1. Electricity Mix Greenhouse Gas Intensity and Energy Conversion Variations by Country [10] [19] [15].

It is important to realize that energy does not directly reflect environmental impact or greenhouse gas emissions and could be deceiving for decision makers seeking to reduce these impacts. This can be seen in an investigation of the primary energy and greenhouse gas emissions associated with the average electricity mix in different countries (Figure 1), which was found using data from the International Energy Agency [10] and the United Nations Framework Convention on Climate Change [19]. Given a decision on whether to locate a facility in Australia or the United States, the primary energy intensity of the electricity mix is not very different between the two locations. However, the greenhouse gas intensity difference of electricity is significant. This realization allows for honest tradeoffs between solar resource availability, supply chain transportation, offset electricity (C_{GHG}), and supplier electricity use.

III. CASE STUDY: SOLFOCUS CONCENTRATOR

A. Methodology

A hybrid life-cycle approach, as suggested by Hendrickson et al. [9] and Zhang et al. [20], is used to analyze the SolFocus concentrator technology. Included in this analysis are the following life-cycle aspects: materials, manufacturing yield, shipping yield, component transportation, final transportation, local energy efficiency, inverter replacement, and overhead; end of life is not yet incorporated. SolFocus manufacturing systems are still in their design phase, therefore cost estimates including overhead and machinery depreciation are used to evaluate each component's environmental impact through the U.S. economic input output life-cycle assessment database (EIOLCA) [5]. The photovoltaic cell environmental impact is approximated from work by Peharz et al. [13].

Transportation GHG emissions and energy use is based on transportation studies by Facanha et al. [6], Spielmann et al. [17], and Corbett et al. [4] (results previously summarized by Reich-Weiser et al. [14]).

B. Results

Results are presented in Figures 2 and 3. For clarity, transportation is split into transportation of the final product to its installation (included in previous assessments [13] [20]) and the intermediate transportation of goods throughout the supply chain. Two important realizations are made by these results: (1) supply chain transportation and electricity usage are important factors in the life-cycle energy and greenhouse gas emissions (2) use of an energy or greenhouse gas metric changes the relative importance of each component to the total impact. Note that the "cell" value in these figures includes electricity to make the cell - this electricity is not included again in the "electricity" component.

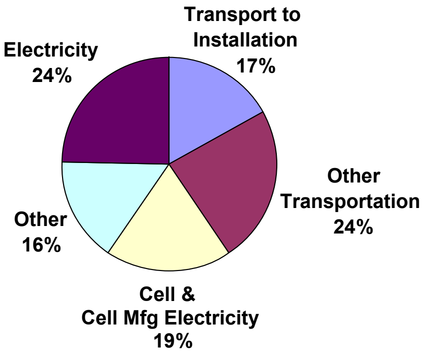

Fig. 2. GHG Breakdown for SolFocus Concentrator System.

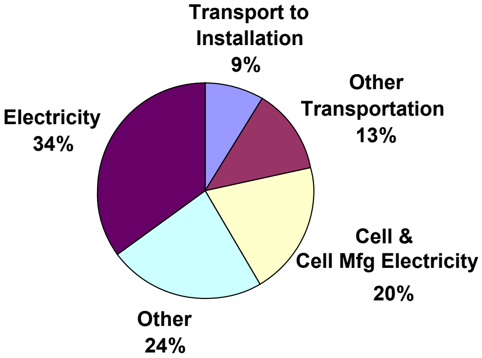

Fig. 3. Energy Breakdown for SolFocus Concentrator System.

The system is found to have an EPBT of 0.7 years, an EROI of 40 (MJ of energy saved for every MJ consumed), and a GROI of 20 (tons of GHG saved for every ton of GHG emitted). Assumptions are a lifetime of 30 years and installation in Phoenix, Arizona (DNI[2] of 6.9 kWh/m^2/day). Transportation values are based on a global supply chain, with assembly in India. Electricity values assume the average United States electricity mix. These results indicate that the SolFocus technology shows promise compared with previous assessments of alternative solar technologies.

IV. Summary and Future Work

Supply chain decisions relevant to electricity mix and transportation are found to have a dramatic influence on EROI and GROI, requiring further investigation. Future work will involve optimizing supply chain decisions based on insolation, transportation, electricity mix, and offset electricity at installation tradeoffs to design minimal impact solar supply chains.

Acknowledgments

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