Life Cycle Greenhouse Gas Emissions of Crystalline Silicon Photovoltaic Electricity Generation: Systematic Review and Harmonization

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<heading level 1> Keywords

LCA, meta-analysis, GHG, solar, global warming, irradiation

<heading level 1> Summary

Published scientific literature contains many studies estimating life cycle greenhouse gas (GHG) emissions of residential and utility-scale solar photovoltaics (PV). Despite the volume of published work, variability in results hinders generalized conclusions. Most variance between studies can be attributed to incongruous methods and assumptions. To clarify the published results for use in decision making and other analyses, we conduct a meta-analysis of existing studies, harmonizing key performance characteristics to produce more comparable and consistently-derived results.

Screening 397 life cycle assessments (LCAs) relevant to PV yielded 13 studies on crystalline silicon (c-Si) that met minimum standards of quality, transparency, and relevance. Prior to harmonization, the median of 42 estimates of life cycle GHG emissions from those 13 LCAs was 57 g CO_2e/kWh, with interquartile range (IQR) of 44-73. After harmonizing key performance characteristics (irradiation of 1,700 kWh/m^2/yr; system lifetime of 30 years; module efficiency of 13.2% or 14.0%, depending on the type of module; and performance ratio of 0.75 or 0.80, depending on type of installation), the median estimate decreased to 45 and IQR tightened to 39-49. The median estimate and variability were reduced compared to published estimates mainly because of a higher, on average, assumption for irradiation and longer system lifetime.

For the sample of studies evaluated, harmonization has effectively reduced variability, providing a clearer synopsis of the life cycle GHG emissions from c-Si PV. The literature used in this harmonization does not cover all possible c-Si installations and does not represent the distribution of deployed or manufactured c-Si PV.

<heading level 1> Introduction

<heading level 2> Background

Life cycle assessment (LCA) is a valuable tool for providing a comprehensive, “cradle-to-grave” view of the environmental burdens of a technology. LCA is often used to analyze renewable energy alternatives to conventional energy systems, especially for estimating greenhouse gas (GHG) emissions. LCA tracks not only the GHGs directly emitted during generation of electricity but also all of the indirect emissions associated with a particular fuel or technology. The indirect emissions result from upstream processes such as materials extraction, transportation, and plant construction, as well as downstream processes such as plant decommissioning, recycling of materials, and waste disposal. Figure 1 illustrates the processes included in the system boundary of photovoltaic (PV) LCAs.

Recently, the global sales of PV systems have grown rapidly. Currently, most PV systems in the United States (around 77% of market share in 2009) are made from crystalline silicon (U.S. EIA 2011). Crystalline silicon (c-Si) has been used for PV applications for decades and is considered to be the most established PV technology. C-Si photovoltaic cells use two types of silicon: monocrystalline and multicrystalline. As the names suggest, monocrystalline silicon (mono-Si) PV cells are made from wafers cut from an ingot of single crystalline silicon and multicrystalline silicon (multi-Si) PV cells are made from wafers containing many different crystals of silicon. Mono-Si cells typically have higher efficiencies and higher manufacturing costs than multi-Si (Hegedus and Luque 2003). Although c-Si PV electricity generation is generally accepted as an improvement over fossil fuel technologies with regard to GHG emissions, published scientific

literature reports considerable variance in estimates of life cycle GHG emissions for c-Si PV per unit electricity generated.

Few attempts have been made to review or clarify the results of PV LCAs. In two review papers, estimated GHG emissions for crystalline silicon PV have been found to range from under 50 g CO_2e/kWh to 200 g CO_2e/kWh (Pacca et al. 2007; Evans et al. 2009). Pacca and colleagues found that GHG emissions and other sustainability factors (energy payback time and net energy ratio) for c-Si and thin-film PV were sensitive to the amount of input energy for production and manufacture, module efficiency, solar irradiation, and system lifetime (Pacca et al. 2007). The analysis in that study looked at how those parameters would affect the specific result of one LCA. However, Pacca and coauthors did not look at the influence of those parameters on any previously published LCA. Two other studies have summarized LCA results in the literature (Sherwani et al. 2010; Evans et al. 2009), but none have attempted to standardize parameters in a meta-analysis.

<heading level 2> Purpose and Goal

In this article, we take existing LCA studies that report a range of GHG emissions and impose standardized estimates of several key performance characteristics in order to enhance their consistency and improve the ability to collectively consider their results. In this process of "harmonization," we explore the sources of variance and reduce the variability caused by the use of inconsistent performance characteristics. The harmonized results are therefore not meant to improve or correct previous estimates, nor will they reflect any specific c-Si PV project or even all c-Si installations, given gaps in coverage of available literature. The goal of this article is not

to produce a single-point estimate answer that is representative of technology today; rather, the goal is to better understand the variability in results for the sample of quality, modern-relevant LCA studies and thus, better inform decision making and future analyses that rely on such estimates.

<heading level 1> Harmonization Methodology

<heading level 2> Conceptual Life Cycle Process Description

The life cycle of a c-Si PV system has upstream, operation, and downstream phases. The upstream phase starts with the acquisition of raw materials, such as silica sand and iron ore (figure 1). After these raw materials are acquired, energy is required to process them into other materials, such as crystalline silicon and steel. Energy is then required to manufacture the components of the solar module and those needed for the entire PV system (balance of system). The building block of a PV system is a PV cell. A PV cell is a semiconductor device that converts solar energy into electricity. A module is a panel of electrically connected solar PV cells and, in addition to the cells, includes the frame and glass. A PV array consists of several connected modules. The PV system consists of the array plus balance-of-system (BOS) components, which are needed to provide structural support and to deliver electricity to a facility or the grid. BOS includes wiring, mounting hardware, and inverters. Batteries are normally part of the BOS, but none of the studies in the final harmonization pool nor the final harmonized scenario included battery storage. For an illustration of PV cell, module, and array, see figure A-1 in the supplementary material. All components are then transported to the site and installed. Prior to operation, most GHGs in the life cycle of c-Si PV have been emitted [e.g., (Frankl et al. 2005)]. After the solar PV system has been installed, the operation life cycle phase includes

activities such as module washing, preventive maintenance (e.g., replacement of inverters) and replacement of any components that break. PV systems have minimal operation and maintenance requirements, and as such, the GHG emissions from this stage are small [e.g., estimated to be close to 0 from (Frankl et al. 2005; Uchiyama 1997)]. After the PV system reaches the end of its life, the downstream life cycle phase includes system decommissioning, with parts disposed or recycled.

<heading level 2> Collection of Literature and Initial Screening

The study began with a literature search, amassing 397 journal articles, reports, theses, conference papers, technical reports, trade publications, and presentations relating to LCAs of PV, including crystalline silicon, thin film, and other PV technologies. Multiple GHG emission estimates from a single study were possible if alternative PV generation scenarios or technologies were analyzed. Each estimate of life cycle GHG emissions was independently subjected to two rounds of review, consistent with the screening methodology of the umbrella LCA Harmonization study conducted by the National Renewable Energy Laboratory. (Several articles reporting harmonized results for other electricity generation technologies appear in this special issue (Burkhardt et al. 2011; Dolan et al. 2011; Kim et al. 2011; Warner et al. 2011; Whitaker et al. 2011).) Although an entire reference was not necessarily eliminated if only one of its estimates was screened out, most screening criteria applied to the study as a whole, thereby likely eliminating all estimates in a study.

An initial screen removed studies lacking sufficient documentation necessary for harmonization: conference papers less than or equal to five double-spaced pages; trade journal articles less than or equal to three published pages; and presentations, posters, and conference abstracts. In addition, studies published prior to 1980 were filtered out due to obsolete technology and data

inventories. References not available in English were also removed. Although a life cycle, by definition, includes several stages of a product's life from manufacture to end-of-life, PV LCAs do not need to focus on all life cycle stages since the GHG emissions of solar PV are heavily weighted toward the life cycle stages upstream of operation, such as material production and component manufacturing [e.g., (Frankl et al. 2005)]. Thus, studies that did not account for downstream life cycle phases were not removed from consideration in this analysis. This initial screen yielded 241 studies, of which 129 studies evaluated c-Si PV.

<heading level 2> Secondary Screening

The second screen consisted of three main criteria:

1. Quality: The study had to employ a currently accepted LCA methodology (e.g., following ISO 14040 series standards) (ISO 2006). Also, the study had to have at least considered life cycle impacts from the materials extraction and component manufacturing stages, which have been found to be the largest contributors to total GHG emissions for c-Si PV systems [e.g., (Frankl et al. 2005)].

2. Transparency: The study must have minimally described its methods, sources and values of input data (life cycle inventory (LCI) data, performance characteristics, etc.) and the LCA results.

3. Modern relevance: The evaluated technology must be relevant to current or near future c-Si PV.

The last criterion eliminated many estimates that used outdated LCI data or made assumptions not applicable to current technologies. For example, Kannan et al. (2007) cites a report by Knapp and Jester (2001) as its source of data for the materials and energy required in manufacturing; the

Knapp and Jester report describes early production by Siemens in California, which utilized now obsolete production methods.

The second screen reduced the number of studies to 77, 58 of which assessed crystalline silicon photovoltaics.

<heading level 2> Selection of Harmonization Pool

After gathering the pool of articles that passed the second screen, we selected our group for harmonization on the basis of usability, non-duplication, and consistency of application.

1. Usability: Articles must report life cycle GHG emissions; many articles that passed the second screen, although rigorous studies, did not report life cycle GHG emissions. Also, to limit transcription error, the results had to be reported numerically not only graphically. Finally, quantitative estimates of several key parameters must have been reported to be considered for harmonization. If the studies did not report the specific parameter estimate for each scenario evaluated, but those parameters could be calculated from information in the study using no exogenous assumptions, the scenario estimate was included. We also contacted authors for additional information, and if they provided the information, the scenario estimate was included even if the published version did not include all the necessary parameters. The specific parameters required to have been reported were

    a. module conversion efficiency (the percentage of the solar energy converted to direct current (DC) electricity by the module) (unitless),

b. performance ratio (ratio of the alternating current (AC) electricity actually produced by the PV system, after accounting for system losses, to the electricity calculated based on the DC-rated module efficiency and irradiation) (unitless),

c. irradiation (average energy flux from the sun ($kWh/m^2/yr$), and

d. system lifetime (years that a PV system operates, with routine maintenance and repairs, before severe degradation in its ability to produce electricity).

4. Non-duplication: Only original LCA results passed. Many studies cite results from other articles but do not contain any improvements or reinterpretations to the LCA of GHG emissions; we eliminated such articles from our collection. For example, review papers that did not generate original emissions estimates were excluded. In cases where the same research group published serially on the same technology, when two studies did not report significantly different LCIs or results, we only included the latest or most complete reference; including multiple studies from the same research groups could artificially tighten the distribution.

5. Consistency of application: We eliminated Hayami et al. (2005) because that study looked at applications in space and thus was not included in the pool of our studies that are limited to terrestrial applications. We also excluded Nawaz and Tiwari (2006) as we could not separate the contribution of battery storage from that for the PV system.

The final screening of the harmonization pool resulted in 13 studies and 41 estimates. The studies used in our meta-analysis are listed with the key performance characteristics of each estimate in table 1 and table 2.

Unlike a similar meta-analysis on thin films LCAs (Kim et al. 2011), the literature used in this study was not required to be based on real-world manufacturing data. Silicon PV processing technology is fairly mature and much process information is publicly available. Thin film processes, such as amorphous silicon, cadmium telluride, and copper indium gallium selenide, are less prevalent, and information on those processes often is only available through the manufacturers. Because the c-Si analysis is not based on only empirical manufacturing data, the results of this article do not represent the current state of c-Si manufacturing.

<heading level 2> Harmonization Approach

For the LCA Harmonization project as a whole, two levels of harmonization were devised. The more resource-intensive level uses a process similar to one employed by (Farrell et al. 2006) to harmonize the results of LCAs on ethanol, whereby a subset of the available literature estimates of life cycle GHG emissions was carefully disaggregated to produce a detailed meta-model based on adjusted parameter estimates, realigned system boundaries within each life cycle phase, and review of all data sources. A less intensive approach harmonizes a larger set of literature estimates of life cycle GHG emissions at a more gross level, by, for instance, adjustment to consistent estimates for several influential performance characteristics and to common system boundaries. The latter, less intensive approach was chosen for c-Si PV, as will be discussed later. The literature available generally did not provide enough detail to apply the more intensive approach.

We created a spreadsheet-based meta-model to harmonize GHG results based on similar assumptions. The harmonization methodology is described in the context of the equation needed to calculate the GHG emissions for solar PV:

$$GHG = \frac{W}{I \times \eta \times PR \times LT \times A} \quad (1)$$

where *GHG* is the mass emissions of GHGs weighted by their global warming potentials (GWP) per unit electricity generated (g CO_2e per kWh), *W* is the GWP-weighted mass of GHGs emitted over the lifetime of the PV system (g CO_2e), *I* is the irradiation (kWh/m^2/yr), η is the lifetime average module efficiency (%), *PR* is the performance ratio, *LT* is the system lifetime (yr), and *A* is the total module area (m^2). This calculation, used in most PV LCA studies, encompasses two characteristics of the technology. The numerator sums all of the GHG emissions from all components and life cycle phases and weights each GHG by GWP, while the denominator calculates the power output over the lifetime of the PV system. In the harmonization process, several factors affecting the denominator are standardized, and *GHG* is recalculated based on these new factors, producing a "harmonized" result.

To harmonize, we first selected standard values for power production parameters in the denominator of equation 1. These factors vary over the literature. Irradiation depends on location. Several studies (Alsema 2000; Alsema and de Wild-Scholten 2006; Pehnt et al. 2002; Fthenakis and Alsema 2006) use an irradiation value of 1,700 kWh/m^2/yr, corresponding to the average irradiation in southern Europe. We report results based on an irradiation of 1,700 kWh/m^2/yr to be aligned with much of the published literature. However, the average irradiation in the United States is higher at 1,800 kWh/m^2/yr for latitude-tilt, south-facing planes. In addition, the southwest United States accounts for much of the current U.S. PV installations and is a targeted region for concentrating solar power, a technology often compared to silicon PV. Because of the relevance of the southwest United States, we also report in this article and supplementary material the harmonized results for 2,400 kWh/m^2/yr, based on irradiation in

Phoenix, Arizona (Moore et al. 2005). The modules are assumed to be at a latitude-tilt for the location, and the effect of the tilt is assumed to be included in the performance ratio. Even though some of the input LCI data in the studies may be specific to a particular region, the studies were harmonized to one location because PV systems manufactured in one location can be installed and operated in another location.

Module efficiencies are always improving, but in this study, we chose an initial efficiency of 14.0% for mono-Si and 13.2% for multi-Si based on the Crystal Clear database – a collection of data representing c-Si PV production technology in Western Europe in 2005-06 (de Wild-Scholten 2007). The efficiencies degrade over the system lifetime by 0.5% (relative to the initial efficiency) per year (Granata et al. 2010), resulting in an average efficiency over the 30-year lifetime of 13.0% for mono-Si and 12.3% for multi-Si. The lifetime average efficiency was used in harmonization.

The lifetime of a PV system was set at 30 years, as recommended by guidelines from the International Energy Agency (IEA) (Alsema et al. 2009). Many companies provide a 25-year limited warranty for their solar panels, so 30 years is a realistic working lifetime. Additionally, based on observation of solar modules operating longer than 20 years, one study concluded that the modules were unlikely to reach a definite point of failure but instead were likely to gradually degrade (Skoczek et al. 2009).

Since we are reporting GHG emissions per unit electricity generated, a harmonization standard was not needed for system/module area.

For performance ratio, rooftop and building-integrated systems were assigned a performance ratio of 0.75, and ground-mounted systems were assigned a performance ratio of 0.80; both these

performance ratios were recommended in the IEA guidelines (Alsema et al. 2009). Table 3 lists all harmonization parameters and their selected values.

Because the factors affecting the lifetime power production are multiplied together, each estimate of lifetime electricity production from references passing the screens, and thus GHG emissions per unit electricity, can be harmonized by multiplying the reported result by a multiplicative factor for each parameter: the ratio of the harmonized parameter standard to the as-reported parameter value. For example, if the irradiation in a study is 1,800 kWh/m^2/yr, the lifetime kilowatt-hours are increased by a factor of 1.059 (1,800 divided by 1,700) to achieve the harmonized result, assuming a location in southern Europe. Similarly, the harmonized results in this article can be calculated for a different parameter estimate easily using a different multiplicative factor.

The lifetime GHG emissions, however, cannot be harmonized using an analogous multiplicative approach since the numerator of equation 1 comprises the sum of GHG emissions (weighted by GWPs) from each life cycle stage. GHG emissions from the operation and downstream life cycle stages result mainly from activities (e.g., O&M, dismantling), and have been shown to be small (e.g., Frankl et al., 2005). By contrast, for the upstream stage, the stage that contributes the majority of GHG emissions, GHG emissions embodied in the materials used in the PV components are most important. Potential factors for harmonization in the numerator include (1) entire life cycle stages such as downstream emissions (recycling, decommissioning), which may potentially be standardized to one value, (2) system boundary, namely the inclusion/exclusion of stages or process within a stage, such as research and development, (3) individual parameters that affect one or more life cycle stages, such as wafer thickness and kerf loss.

In our analysis, the numerator was not harmonized due to insufficient reporting across all studies with the exception of one study whose GWPs were harmonized. In that instance, the harmonization step was conducted separate to the main harmonization and reported separately from the general results.

The results were categorized by technology type (mono-Si and multi-Si) and by mounting type. Mounting includes rooftop mounting, commonly used for residential PV systems, and ground-mount, commonly used for utility-scale PV systems. We report descriptive statistics of the reported GHG emissions and the harmonized GHG emissions. Median is used as the main measure of central tendency and interquartile range (IQR) (75^{th} minus 25^{th} percentile values) is used as the main measure of variability, because these measures are more robust to outliers than mean, range, and standard deviation. For each harmonization step, changes in the median and IQR are compared with published estimates to describe the impact of the harmonization step.

<heading level 1> Results and Discussion

<heading level 2>Published and Harmonized Results

The distribution of published life cycle GHG emissions becomes narrower and shifts down after harmonization. Figure 2 compares the original, published estimates of life cycle GHG emissions to the cumulative results of all harmonization steps. Table A-1 in the supplementary material lists the published and harmonized result for each of the scenarios in the harmonization pool Table 4 reports that the median published life cycle GHG emissions estimate for c-Si PV is 57 g CO_2e/kWh; the harmonized median is 45 g CO_2e/kWh. The main reason for this decrease in median is because we selected a higher irradiation ~~standard~~ reference level than that used by many of the constituent studies. The studies had a median irradiation of 1,700 kWh/m^2/yr and a

mean of 1,481 kWh/m^2/yr, while we harmonized to a value of 1,700 kWh/m^2/yr. If the studies were harmonized to 2,400 kWh/m^2/yr, then the median of the harmonized estimates would be 32 g CO_2e/kWh (table 5). See figure A-2, and figure A-3 in the supplementary material for additional results based on a harmonized irradiation of 2,400 kWh/m^2/yr.

The second reason the harmonized median estimate was reduced compared to the published median is change in the assumed system lifetime. The median system lifetime reported by the studies is 25 years, and we harmonized to a value of 30 years, therefore amortizing the one-time upstream emissions over a longer period and higher lifetime electricity generation. If the studies were harmonized to a system lifetime of 25 years, then the harmonized median would be 55 g CO_2e/kWh, which is close to the median of the published estimates of 57 g CO_2e/kWh. The harmonized medians chosen for this article should be a more accurate representation of the studies for the system lifetimes expected for c-Si PV systems in a region with similar irradiation to southern Europe.

Harmonization reduced the IQR for the entire group of studies from 44–73 g CO_2e/kWh to 39–49 g CO_2e/kWh, a reduction of 66% (table 4). As with explaining the shift in the median, the factors most responsible for tightening the IQR are irradiation and system lifetime. Both of these factors reduced most published estimates with high GHG emissions and narrowed the range.

Table A-2 in the supplementary material reports that the median estimate of published GHG emissions is 64 g CO_2e/kWh for mono-Si and 56 g CO_2e/kWh for multi-Si, respectively. The harmonized GHG medians reduce to 40 g CO_2e/kWh for mono-Si and 47 g CO_2e/kWh for multi-Si. The closeness of these harmonized GHG emissions could be expected. Efficiency advantages

by mono-Si may be balanced out by a more energy-intensive process. Harmonization appears to clarify that life cycle GHG emissions of these two c-Si technology types are likely similar.

Segregated by mounting type but not by technology group, the median of the published values is 68 g CO_2e/kWh for ground-mounted systems and 56 g CO_2e/kWh for roof-mounted systems (see table A-2 in supplementary material). Harmonization reduces the median published estimate to 48 g CO_2e/kWh for ground-mounted and 44 g CO_2e/kWh for roof-mounted. The similar harmonized results for ground-mounted and roof-mounted c-Si PV suggest that the type of mounting is not a large factor in GHG emissions.

Ground-mounted systems have a larger harmonized IQR (40-98) compared to rooftop-mounted systems (IQR of 38-48). The larger IQR for ground-mounted systems is partly explained by higher estimates from Lenzen et al. (2006) than the rest of the harmonized ground-mounted systems. Lenzen et al. provide three estimates of GHG emissions from ground-mounted systems. The harmonized results from Lenzen et al. range from 88-182 g CO_2e/kWh, compared to their published results from 53-217 g CO_2e/kWh. Harmonization affected this study, but not to bring the results in line with the other studies on ground-mounted systems. Lenzen et al. based the study on solar PV production in Australia, which gets 75% of its electricity from coal (U.S. EIA 2007). This amount of electricity from coal is much higher than the amount used in the United States and Europe. High GHG emission intensity of grid electricity for PV production likely accounts for the higher estimates. This grid electricity would lead to high GHG emissions in any stage requiring electricity, particularly those in manufacturing. For example estimates from Lenzen et al. (2006) show a high GHG contribution from BOS compared to what has been reported in Mason et al. (2006). Mason et al. estimated the GHG emissions using U.S. electricity from BOS for a ground-mounted system, and the results of that study have been used in other

LCA studies (Alsema 2000; Alsema and de Wild-Scholten 2006; Pacca 2003). The BOS contribution based on Mason et al. (2006) is 27% lower than the estimate from Lenzen et al. (2006). However, Lenzen et al. do not provide enough disaggregated data to harmonize based on grid electricity or to substitute in a BOS estimate from Mason et al.

Table 4 reports published and harmonized descriptive statistics for all of the c-Si estimates including the impact of the individual harmonization steps. Tables A-3 and A-4 in the supplementary material present the same statistics broken into multi-crystalline and mono-crystalline technology groups, respectively. Table A-2 compares the descriptive statistics for the entire pool of studies and the various mounting/technology subsets.

Figure 3 shows the impact of each harmonization parameter acting independently in frames A-E. Harmonizing the performance ratio, efficiency, and system boundary minimally reduced the scatter; the largest reductions in variability were caused by harmonizing the system lifetime and irradiation levels. The impact of harmonizing an individual parameter represents the change in GHG emissions resulting from the deviation in the as-published parameter value to the standard value used for harmonization. Thus, the change in results does not represent the general sensitivity of the life cycle GHG emissions to the harmonization parameter.

Several studies experienced large changes as a result of harmonization. Estimates from Frankl et al. (2005) and Pehnt et al. (2002) represent two of the largest deviations. Table A-1 in the supplementary material reports results of each step of the harmonization process applied to each estimate of LC GHG emissions considered. Figure A-4 in the supplementary material shows the results of each harmonization step applied successively on the pool of estimates considered here. Similar to its impact on many other estimates, much of the deviation between the published and

harmonized estimates can be explained by differences in irradiation. Both Frankl et al. (2005) and Pehnt et al. (2002) had estimates where the irradiation was below 1,000 kWh/m^2/yr, and therefore, when the irradiation was harmonized to 1,700 kWh/m^2/yr, the GHG emission estimate was reduced substantially.

<heading level 2> Comparison of Results to Prior Study

The results of this study align well with the conclusions from the previous study of solar PV LCAs by Pacca et al. (2007). In that study, the authors reported that the input energy in production and manufacture had a significant impact on the GHG emissions. The authors also investigated the sensitivity of the net energy ratio to irradiation, module efficiency, and system lifetime. Over the range tested by the authors, they found that the irradiation had a slightly greater effect than system lifetime and both had a greater effect than module efficiency. If we take net energy ratio as a proxy for GHG emissions, then our results for the relative impact of the parameters are in line with Pacca et al. (2007). The comparison also suggests that energy required in production and manufacture is an important performance characteristic that should be considered for future analyses. Fthenakis et al. (2008) showed this effect by presenting different cases for the electricity mixture in silicon production; the study found that moving from a hydropower and natural gas electricity mix to a U.S. electricity mix (with over 50% from coal) will increase the GHG emissions from crystalline silicon by approximately 50%.

<heading level 2> Limitations

<heading level 3>Factors Not Harmonized

This meta-analysis primarily focused on standardizing values for input parameters that determine the total lifetime kilowatt-hours of electricity produced by the solar PV system, and no

adjustments were made to the lifetime GHG emissions portion of the numerator in equation (1). This numerator is the sum of the GHG emissions from the life cycle stages. The calculation of the numerator can be directly affected in three ways. First, the numerator is affected by the GHG emission contribution from each specific life cycle stage. Second, the GHG emissions from each stage are affected by parameters specific to each stage's processes. For example, the amount of silicon used to produce a PV cell is driven by the wafer yield, which in turn depends on wafer thickness and kerf losses (silicon material lost from sawing). Third, the calculation of the GHG emissions themselves depend on what GHG species are accounted for and what GWP is used to calculate total GHGs on a CO_2-equivalent basis.

Specific life cycle stage GHG emission contributions are difficult to harmonize. The difficulty is not whether the life cycle stage is considered at all, but rather that GHG emissions related to each stage are not typically disaggregated in LCA studies. For instance, many studies did not account for end-of-life issues (i.e., the downstream life cycle stage). Decommissioning and recycling of the solar modules have not been well studied. In one study, the decommissioning and recycling accounted for an average of only 4% of the as-reported GHG emissions (Frankl et al. 2005). Therefore, while not harmonizing to ensure inclusion of the downstream life cycle phase will likely underestimate true LC GHG emission from c-Si PV, the degree of underestimation is likely small and will not change the conclusions reached here.

Without knowing the contribution of each life cycle stage, we cannot determine the effect of an individual stage's process parameters. For example, Pehnt et al. (2002) report that over 30% of total GHG emissions are from silicon and wafer production. Adjusting for a parameter that would affect a life cycle stage is not straightforward. One such parameter that would affect the wafer production life cycle stage is wafer thickness. The studies considered in this analysis

spanned a range of wafer thicknesses from 200 μm (Stoppato 2008) to 300 μm (Pehnt 2006; Fthenakis and Alsema 2006). Silicon wafers have become thinner over time, with at least one company now producing wafers as thin as 180 μm (LDK 2010). This information is only usable for harmonization if the proportion of the GHG emissions specifically due to silicon and the wafer yield are known. Because most studies did not provide the level of resolution needed to adjust GHG emissions to a common estimate of wafer thickness, wafer thickness was not harmonized. We recognize that it could contribute significantly to the difference in values between studies, given that significant GHG emissions come from the silicon and wafer manufacturing used in the PV module and suggest this as a useful area of future harmonization research.

Other manufacturing inputs such as silicon type (solar grade or more energy-intensive semiconductor grade) and grid electricity GHG emission intensity also may contribute significantly to variability in estimates of life cycle GHG emissions but, lacking detailed data, these factors were also not harmonized. The conclusion of the Pacca et al. (2007) study that GHG emissions are sensitive to input energy for production and manufacture show that adjustments to the numerator of equation (1) have potentially significant impacts.

The calculation of the GHG emissions is affected by the choice of GWP and the GHGs tracked by the study. In this article, we did not harmonize for different GWPs used in studies, with the exception of one study. More recent studies, such as Jungbluth et al. (2009), used IPCC 2007 (Forster et al. 2007) GWPs for methane and nitrous oxide. However, studies published before 2007 would have used older GWPs. Studies often did not report mass emissions of individual GHGs, so updated GWPs could not be applied. For instance, the IPCC 2001 GWPs (IPCC 2001) are not significantly different from the current IPCC GWPs (23 CH_4 and 296 N_2O compared to

25 and 298, respectively) (Forster et al. 2007). Thus, not harmonizing GWPs would likely have minimal effect on the overall harmonization results.

Not all GHGs are accounted for in the studies considered here. Most studies did not account for gases with extremely high GWPs, for example, tetrofluoromethane (CF_4) and hexafluoroethane (C_2F_6) which have 100-year GWPs of 6,500 and 9,200, respectively. Both are used in the manufacture of crystalline silicon solar PV cells. However, based on estimates from the Crystal Clear database (de Wild-Scholten 2007), emissions of perfluorinated compounds are estimated to contribute less than 1 g CO_2e/kWh to life cycle GHG emissions from c-Si PV. Therefore, not accounting for these gases should not significantly change the results of this study. Several studies neglected to report methane and nitrous oxide emissions (Alsema 2000; Hondo 2005; Jungbluth et al. 2009). Based on Frankl et al. (2005), these GHGs account for 6% of total LC GHG emissions. As a result, failure to account for these GHG emissions, while leading to an underestimate of true LC GHG emissions, should not change the conclusions of this paper.

<heading 3>Project Scope

This study sought to explain and reduce the variability in existing estimates of life cycle GHG emissions of c-Si PV by identifying critical parameters that varied between studies and by harmonizing them to allow for a consistent comparison of different studies' estimates and a clarified, collective result. As such, the estimates generated during the harmonization process were not designed to reflect plant-specific factors that influence the life cycle GHG emissions of an individual c-Si PV project. The GHG emissions of a specific c-Si PV project depend on many factors and legitimately could differ from the generic estimates generated by the harmonization approach. Furthermore, this work leverages a population of studies that is not necessarily

representative of the technology as deployed or of its potential. Although the most relevant, high-quality studies for each technology were selected, the studies reviewed might not represent all cases or even an average case of manufacture, deployment, or use. Just as this study is not backward-looking, it is also not forward-looking and does not project out technological advances.

<heading level 2> Recommendations for Future Work

Crystalline silicon PV technology has been commercial for several decades, and changes in the manufacturing process technology that would dramatically change GHG emissions are not expected. However, opportunities exist to maintain and improve the relevance of LCA studies as the industry changes.

While the silicon type may not dramatically change GHG emissions, the process will likely become more efficient as learning continues. As a result, material utilization efficiency should improve, which would lower GHG emissions. In addition, module efficiency is expected to continue to improve. Module efficiency has a direct effect on the lifetime electricity produced. If module efficiencies improve without significantly increasing the manufacturing energy requirements, GHG emissions per unit electricity generated will drop, and LCA studies should be updated accordingly.

Another notable change in the PV industry is the geographical shift in PV manufacturing. China has become the largest producer of both the silicon feedstock and PV modules and is expected to continue increasing its share of production (RTS Corporation 2009; Navigant Consulting 2009). Chinese electricity is highly dependent on coal and, therefore, is GHG intensive (Di et al. 2007). At the same time, Chinese manufacturing companies may also install PV to supply part of

the electricity needed for manufacturing, thereby decreasing the facility's GHG emissions. One study estimated that substitution of PV electricity for grid electricity in manufacturing multicrystalline modules could decrease GHG emissions by almost 70% (Pacca 2007). None of the studies in this meta-analysis specifically accounted for Chinese manufacture. LCA studies should start accounting for increased manufacturing in China to better reflect current technology.

Improvements in our knowledge of GHG emissions from end-of-life processes will likely not significantly change current estimates of life cycle GHG emissions from PV systems, but nevertheless studies on this topic would provide greater confidence that this is the case.

Attributional LCAs are the most prevalent type of LCA published to-date and are therefore relied upon for this retrospective, meta-analysis. Attributional LCAs consider the direct emission impacts of a process. By contrast, consequential LCAs consider indirect emission impacts, often the result of economic relationships between the evaluated technology and other technologies. For instance, deployment of an electricity source depending on a variable resource (sunshine) leads to an increased need for balancing reserves provided by fossil power plants (Pehnt et al. 2008; Gross 2007). Conversely, since PV generates electricity during peak demand periods, increased use of PV should reduce the use of the marginal, peaking generator, which is often an inefficient natural gas combustion turbine (Denholm et al. 2009; Perez et al. 2008). Additional studies are needed to characterize these indirect impacts.

Lastly, this study is limited to GHG emissions, which is just one of many environmental impacts associated with electricity generation. To fully grasp the environmental burdens of a technology, one must consider the entire gamut of life cycle impacts including other airborne emissions, waterborne pollutants, and water consumption.

<heading level 1> Conclusion

We screened an extensive body of publicly available estimates of life cycle GHG emission from solar c-Si PV LCAs. After screening 397 total PV references for quality, transparency, relevance and usability, the range in previous estimates from 13 references relevant to c-Si PV was 20-217 g CO2e/kWh. Through conducting a meta-analytical process called harmonization that aligned several input parameters (irradiation of 1,700 kWh/m^2/yr; system lifetime of 30 years; module efficiency of 13.2% or 14.0%, depending on the type of module; and performance ratio of 0.75 or 0.80, depending on type of installation), we provide a clearer sense of crystalline silicon PV life cycle GHG emissions in ways intended to be useful for policymakers and analysts. The median published estimate of life cycle GHG emissions for c-Si PV was 57 g CO_2e/kWh with an IQR of 44–73 g CO_2e/kWh. The harmonization process refined the median GHG result for all crystalline silicon PV to 45 g CO_2e/kWh with an IQR of 39–49 g CO_2e/kWh (a decrease of 66% from the as-published IQR). The parameters with the most impact on reducing the spread of the data and reducing the median estimate were system lifetime and irradiation.

Although the life cycle GHG emissions of a specific c-Si project will depend on many factors and legitimately can differ from the estimates generated by the harmonization approach, given the tightness of the distribution of harmonized estimates across two key c-Si technologies (mono- and multi-crystalline silicon), the harmonized results represent an initial estimate potentially useful for policymakers. In addition, policymakers readily can adapt the results to obtain a credible estimate of the life cycle GHG emissions for electricity generated by c-Si based on different performance parameters. The distribution of results after meta-analysis show a life cycle GHG emission much lower than values typical for fossil fuel electricity (Whitaker et al. 2011 ; Dolan et al. 2011). The results provide a more consistent basis for comparing crystalline

silicon with conventional and other renewable electricity technologies. Life cycle analyses of PV should continue as module and material utilization efficiencies improve and as PV manufacturing is shifted to Asia, potentially increasing life cycle impacts, and the impacts of introducing variable generation resources onto the grid are better characterized.

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