Life Cycle Greenhouse Gas Emissions of Crystalline Silicon Photovoltaic Electricity Generation

Systematic Review and Harmonization

David D. Hsu, Patrick O'Donoughue, Vasilis Fthenakis, Garvin A. Heath, Hyung Chul Kim, Pamala Sawyer, Jun-Ki Choi, and Damon E. Turney

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Summary

Published scientific literature contains many studies estimating life cycle greenhouse gas (GHG) emissions of residential and utility-scale solar photovoltaics (PVs). Despite the volume of published work, variability in results hinders generalized conclusions. Most variance between studies can be attributed to differences in 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 PVs 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 grams carbon dioxide equivalent per kilowatt-hour (g CO_2-eq/kWh), with an interquartile range (IQR) of 44 to 73. After harmonizing key performance characteristics (irradiation of 1,700 kilowatt-hours per square meter per year (kWh/m^2/yr); system lifetime of 30 years; module efficiency of 13.2% or 14.0%, depending on module type; and a performance ratio of 0.75 or 0.80, depending on installation, the median estimate decreased to 45 and the IQR tightened to 39 to 49. The median estimate and variability were reduced compared to published estimates mainly because of higher average assumptions for irradiation and system lifetime.

For the sample of studies evaluated, harmonization effectively reduced variability, providing a clearer synopsis of the life cycle GHG emissions from c-Si PVs. The literature used in this harmonization neither covers all possible c-Si installations nor represents the distribution of deployed or manufactured c-Si PVs.

Introduction

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 the 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,

Address correspondence to: David D. Hsu, Mail Stop RSF 300, National Renewable Energy Laboratory, 1617 Cole Blvd., Golden, CO, USA 80401. *Email*:david.hsu@nrel.gov

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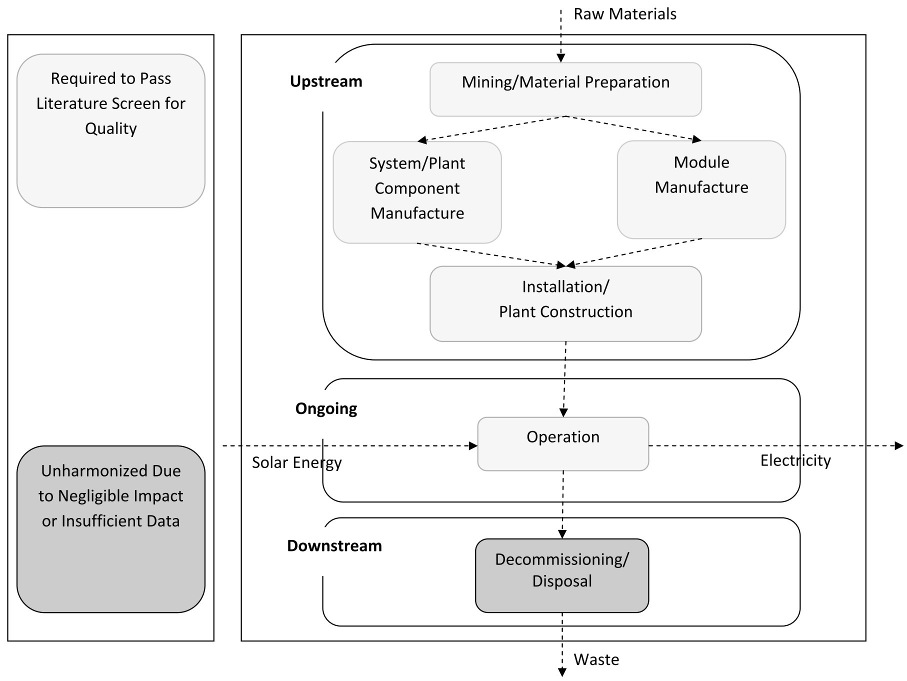

Figure 1 Process flow diagram illustrating the upstream, operational, and downstream life cycle stages of crystalline silicon electricity generating systems and system boundaries used in the harmonization process. Note the downstream impacts were unharmonized due to negligible impact or insufficient data.

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. 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 PV 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 cells (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 the estimates of life cycle GHG emissions for c-Si PV per unit of 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 PVs have been found to range from less than 50 grams carbon dioxide equivalent per kilowatt-hour (g CO_2-eq/kWh) to 200 g CO_2-eq/kWh (Evans et al. 2009; Pacca et al. 2007).[1] Pacca and colleagues found that GHG emissions and other sustainability factors (energy payback time and net energy ratio) for c-Si and thin-film PVs 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 colleagues did not look at the influence of those parameters on any previously published LCAs. Two other studies have summarized LCA results in the literature (Evans et al. 2009; Sherwani et al. 2010), but none has attempted to standardize parameters in a meta-analysis.

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 in the available literature. The goal of this article is not to produce a single-point estimate answer that is representative of technology today, but rather the goal is to better understand the variability in results for the sample of quality, up-to-date

LCA studies, and thus better inform decision making and future analyses that rely on such estimates.

Harmonization Methodology

Conceptual Life Cycle Process Description

The life cycle of a c-Si PV system has upstream, operation, and downstream phases (figure 1). The upstream phase starts with the acquisition of raw materials, such as silica sand and iron ore. 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 for the solar module and the PV system as a whole. 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. The 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 S1 in the supporting information available on the journal's Web site. All components are then transported to the site and installed. Prior to operation, most GHGs in the life cycle of c-Si PVs 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 zero (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 of or recycled.

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 PVs, including c-Si, 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 (NREL).[2] (Several articles reporting harmonized results for other electricity generation technologies appear in this special issue, including Burkhardt and Heath [2012], Dolan et al. [2012], Kim et al. [2012], Warner and Heath [2012], and Whitaker et al. [2012].) 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 because the GHG emissions of solar PVs are heavily weighted toward upstream 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 PVs.

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]). The study also 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 at a minimum 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 PVs.

The last criterion eliminated many estimates that used outdated LCI data or made assumptions not applicable to current technologies. For example, Kannan and colleagues (2007) cite a report by Knapp and Jester (2001) as a 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 c-SI PVs.

Selection of the Harmonization Pool

After gathering the pool of articles that passed the second screen, we selected our group for harmonization on the basis of usability, nonduplication, 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 just graphically. Finally, values of several key parameters had to have been reported to be considered for harmonization. If the studies did not report the specific parameter value 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 required parameters were
   a. module conversion efficiency (the percentage of the solar energy converted to direct current [DC] electricity by the module [unitless]),
   b. performance ratio (the 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 (the average energy flux from the sun, in kilowatt-hours per square meter per year [kWh/m^2/yr]),[3] and
   d. system lifetime (the years that a PV system operates, with routine maintenance and repairs, before severe degradation in its ability to produce electricity).
2. Nonduplication: 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 these articles from our analysis. 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.
3. Consistency of application: We eliminated the work of Hayami and colleagues (2005) because that study looked at applications in space and thus was not included in the pool of our studies, which is limited to terrestrial applications. We also excluded the work of 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 tables 1 and 2.

Unlike a similar meta-analysis on thin-film LCAs (Kim et al. 2012), the literature used in this study by necessity was not 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 is often only

Table 1 Monocrystalline PV LCA studies that passed final screening, with parameter values and characteristics from those studies.

Author	*Year*	*Published GHG emissions (g CO_2-eq/kWh)*	*Solar irradiation (kWh/m^2/yr)*	*Module efficiency (%)*	*Performance ratio*	*System lifetime (years)*	*Mounting type (ground-mounted/ rooftop)*	*Region*
Alsema and de Wild-Scholten	2006	45	1,700	14	0.75	30	Rooftop	Southern Europe
Frankl et al.	2005	68	900	14	0.93	25	Rooftop	Central Europe
		36	1,800	14	0.87	25	Rooftop	Southern Europe
		76	900	14	0.86	25	Rooftop	Central Europe
		41	1,800	14	0.79	25	Rooftop	Southern Europe
		73	900	14	0.92	25	Rooftop	Central Europe
		39	1,800	14	0.86	25	Rooftop	Southern Europe
		69	900	14	0.88	25	Ground-mounted	Central Europe
		37	1,800	14	0.83	25	Ground-mounted	Southern Europe
Jungbluth et al.	2009	64	1,117	14	0.75	30	Rooftop	Switzerland
		69	1,117	14	0.75	30	Rooftop	
Pacca	2003	30	2,143	12.7	1	20	Ground-mounted	Arizona, USA
		100	1,752	12.7	1	20	Ground-mounted	Brazil

Notes: PV = photovoltaic; LCA = life cycle assessment; GHG = greenhouse gas; g CO_2-eq/kWh = grams carbon dioxide equivalent per kilowatt-hour; kWh/m^2/yr = kilowatt-hour per square meter per year.

Table 2 Multicrystalline PV LCA studies that passed final screening, with parameter values and characteristics from those studies.

Author	*Year*	*Published GHG emissions (g CO2e/kWh)*	*Solar irradiation ($kWh/m^2/yr$)*	*Module efficiency (%)*	*Performance ratio*	*System lifetime (years)*	*Mounting type (ground-mounted/ rooftop)*	*Region*
Alsema and de Wild-Scholten	2000	60	1,700	13	0.75	30	Ground-mounted	Western Europe
		30	1,700	15	0.75	30	Ground-mounted	
		20	1,700	17	0.75	30	Ground-mounted	
Alsema	2006	35	1,700	13.2	0.75	30	Ground-mounted	Southern Europe
Frankl et al.	2005	82	900	13	0.93	25	Ground-mounted	Central Europe
		44	1,800	13	0.87	25	Ground-mounted	Southern Europe
		93	900	13	0.86	25	Rooftop	Central Europe
		50	1,800	13	0.79	25	Rooftop	Southern Europe
		88	900	13	0.92	25	Rooftop	Central Europe
		47	1,800	13	0.86	25	Rooftop	Southern Europe
		85	900	13	0.88	25	Rooftop	Central Europe
		46	1,800	13	0.83	25	Rooftop	Southern Europe
Fthenakis and Alsema	2006	36	1,700	13.2	0.75	30	Rooftop	Europe
Hondo	2005	53	1,314	14	0.77	30	Rooftop	Japan
		44	1,314	14	0.77	30	Rooftop	
Jungbluth et al.	2009	57	1,117	13.2	0.75	30	Rooftop	Switzerland
		62	1,117	13.2	0.75	30	Rooftop	
Lenzen et al.	2006	106	2,060	13	0.85	25	Rooftop	Australia
		217	2,060	12	0.8	20	Rooftop	
		53	2,060	14	0.9	30	Rooftop	
Pacca et al.	2006	72	1,359	12.92	0.95	30	Rooftop	Michigan, USA
Pehnt et al.	2002	102	950	13.4	0.85	25	Rooftop	Central Europe
		57	1,700	13.4	0.85	25	Rooftop	North Africa
Pehnt	2006	104	1,100	13.4	0.85	25	Rooftop	Germany
Stoppato	2008	20	1,697	16	0.83	28	Ground-mounted	Turkey
Tripanagno-stopoulos et al.	2006	55	1,644	12.4	0.85	30	Rooftop	Greece
		51	1,644	12.4	0.85	30	Rooftop	
		62	1,644	12.4	0.85	30	Rooftop	

Notes: PV = photovoltaic; LCA = life cycle assessment; g CO_2-eq/kWh = grams carbon dioxide equivalent per kilowatt-hour; $kWh/m^2/yr$ = kilowatt-hour per square meter per year.

available through the manufacturers. Because the c-Si analysis is not based exclusively on empirical manufacturing data, the results of this article do not represent the current state of c-Si manufacturing.

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 and colleagues (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 a 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. This is done, for instance, by adjusting several influential performance characteristics to consistent estimates and common system boundaries. The latter, less intensive approach was chosen for c-Si PVs, 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 PVs:

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

where *GHG* is the mass emissions of GHGs weighted by their global warming potential (GWP) per unit of electricity generated (g CO_2-eq/kWh), *W* is the GWP-weighted mass of GHGs emitted over the lifetime of the PV system (g CO_2-eq), *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 a large portion of the current U.S. PV installations and is a targeted region for concentrating solar power, a technology often compared to silicon PVs. Because of the relevance of the southwest United States, we also report in this article and in the supporting information on the Web 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 PVs production technology in Western Europe in 2005–2006 (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 observations 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).

Because we are reporting GHG emissions per unit of electricity generated, a harmonization standard was not needed for the system or module area.

For the 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 of 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 can be harmonized by multiplying the reported parameter by a multiplicative factor: 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 multiplied by a factor of 0.944 (1,700 divided by 1,800) to achieve the harmonized lifetime electricity production, assuming a location in southern Europe. The harmonized result is calculated by dividing the study's GHG emissions by the harmonized lifetime electricity production. Similarly, the harmonized results in this article can be easily calculated for a different parameter estimate using a different multiplicative factor.

The lifetime GHG emissions, however, cannot be harmonized using an analogous multiplicative approach, as the numerator of equation (1) comprises the sum of GHG emissions (weighted by GWPs) from each life cycle stage. GHG emis-

Table 3 List of parameters that were harmonized in this study and the standard values used in harmonization.

Parameter	*Units*	*Value*
System lifetime	Years	30
Performance ratio		
Ground-mounted	Unitless	0.80
Rooftop	Unitless	0.75
Module efficiency		
Monocrystalline	Initial % (lifetime average %)	14.0 (13.0)
Multicrystalline	Initial % (lifetime average %)	13.2 (12.3)
Solar irradiation	kWh/m^2/yr	1,700

Note: kWh/m^2/yr = kilowatt-hour per square meter per year.

sions from the operation and downstream life cycle stages result mainly from activities (e.g., operation and maintenance, dismantling), and have been shown to be small (e.g., Frankl et al. 2005). In contrast, for the upstream stage, which contributes the majority of GHG emissions, embodied GHG emissions 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 and 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 (silicon material lost from sawing).

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 from 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. The median is used as the main measure of central tendency and interquartile range (IQR) (75th minus 25th percentile values) is used as the main measure of variability. 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.

Results and Discussion

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 S1 in the supporting information on the Web lists the published and harmonized results for each of the scenarios in the harmonization pool. Table 4 reports that the median published life cycle GHG emissions estimate for c-Si PVs is 57 g CO_2-eq/kWh; the harmonized median is 45 g CO_2-eq/kWh. The main reason for this decrease in median is because we selected a higher irradiation standard 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_2-eq/kWh (table 5). See figures S2 and S3 in the supporting information on the Web for additional results based on a harmonized irradiation of 2,400 kWh/m^2/yr.

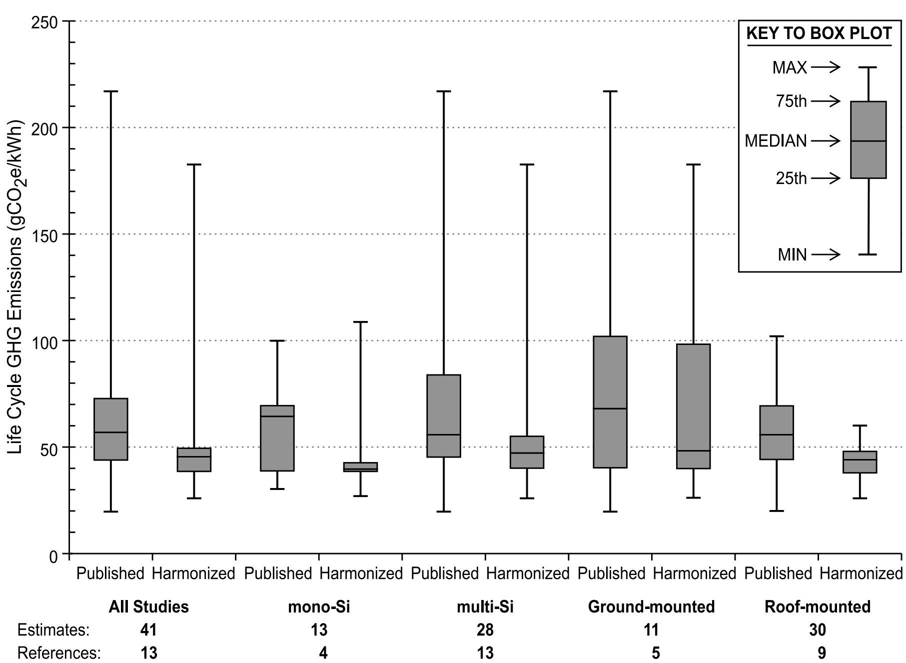

Figure 2 Box plots comparing published and harmonized (irradiation of 1,700 kilowatt-hours per square meter per year [kWh/m^2/yr]) estimates of life cycle greenhouse gas (GHG) emissions from all crystalline silicon (c-Si) LCAs passing screens and grouped according to c-Si PV technology (mono-Si = monocrystalline silicon; multi-Si = multicrystalline silicon) and mounting type. "References" and "Estimates" indicate the number of independent studies and published GHG emission estimates that were harmonized in each step, respectively.

Table 4 Descriptive statistics of published and harmonized (irradiation of 1,700 kWh/m^2/yr) results, including the impact of each harmonization step applied individually for all c-Si LCAs passing screens. (All values except percentages and counts reported in g CO_2-eq/kWh.)

	Published studies	*Harmonized (all steps)*	*Irradiation*	*System lifetime*	*Performance ratio*	*Efficiency*
Mean	63	52	54	54	68	67
Standard deviation	34	29	39	23	38	33
Minimum	19	26	19	18	19	25
25th percentile	44	39	38	37	42	47
Median	57	45	45	53	56	61
75th percentile	73	49	53	64	84	78
Maximum	217	183	263	145	231	212
Interquartile range	29	11	15	27	42	31
Range	198	157	243	126	213	187
Change in mean	—	−18%	−15%	−14%	8%	6%
Change in SD	—	−14%	18%	−31%	14%	−2%
Change in IQR	—	−62%	−48%	−5%	45%	8%
Change in range	—	−21%	23%	−36%	8%	−6%
Count of estimates	41	41	41	41	41	41
Count of references	13	13	13	13	13	13

Notes: kWh/m^2/yr = kilowatt-hour per square meter per year; c-Si = crystalline silicon; LCA = life cycle assessment; g CO_2e/kWh = grams carbon dioxide equivalent per kilowatt-hour; SD = standard deviation; IQR = interquartile range. "References" and "Estimates" indicate the number of independent studies and published greenhouse gas emission estimates that were harmonized in each step, respectively.

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, thus 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_2-eq/kWh, which is close to the median of the published estimates of 57 g CO_2-eq/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.

Table 5 Descriptive statistics of as-reported and harmonized (irradiation of 2,400 kWh/m^2/yr) results, including the impact of the irradiation harmonization step applied individually for all c-Si LCAs passing screens. (All values except percentages and counts reported in g CO_2-eq/kWh.)

	Published studies	*Harmonized (all steps)*	*Irradiation (2,400 kWh/m^2/yr)*
Mean	63	37	38
Standard deviation	34	20	28
Minimum	19	18	14
25th percentile	44	27	27
Median	57	32	32
75th percentile	73	35	38
Maximum	217	129	186
Interquartile range	29	8	11
Range	198	111	172
Change in mean	—	−42%	−40%
Change in SD	—	−39%	−17%
Change in IQR	—	−73%	−63%
Change in range	—	−44%	−13%
Count of estimates	41	41	41
Count of references	13	13	13

Notes: kWh/m^2/yr = kilowatt-hour per square meter per year; c-Si = crystalline silicon; LCA = life cycle assessment; g CO_2e/kWh = grams carbon dioxide equivalent per kilowatt-hour; SD = standard deviation; IQR = interquartile range. "References" and "Estimates" indicate the number of independent studies and published greenhouse gas emission estimates that were harmonized in each step, respectively.

Harmonization reduced the IQR for the entire group of studies from 44 to 73 g CO_2-eq/kWh to 39 to 49 g CO_2-eq/kWh, a reduction of 62% (table 4). Similar to 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 S2 in the supporting information on the Web reports that the median estimate of published GHG emissions is 64 g CO_2-eq/kWh for mono-Si and 56 g CO_2-eq/kWh for multi-Si. The harmonized GHG medians decline to 40 g CO_2-eq/kWh for mono-Si and 47 g CO_2-eq/kWh for multi-Si. The proximity of these harmonized GHG emissions could be expected. Efficiency advantages of 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_2-eq/kWh for ground-mounted systems and 56 g CO_2-eq/kWh for roof-mounted systems (see table S2 in the supporting information on the Web). Harmonization reduces the median published estimate to 48 g CO_2-eeq/kWh for ground-mounted systems and 44 g CO_2-eq/kWh for roof-mounted systems. The similar harmonized results for ground-mounted and roof-mounted c-Si PVs suggest that the type of mounting is not a large factor in GHG emissions.

Ground-mounted systems have a larger harmonized IQR (40 to 98) compared to rooftop-mounted systems (IQR of 38 to 48). The larger IQR for ground-mounted systems is partly explained by higher estimates from Lenzen and colleagues (2006) than the rest of the harmonized ground-mounted systems. Lenzen and colleagues provide three estimates of GHG emissions for ground-mounted systems. Their harmonized results range from 88 to 182 g CO_2-eq/kWh; their published results range from 53 to 217 g CO_2-eq/kWh. Harmonization affected this study, but not enough to bring the results in line with the other studies on ground-mounted systems. Lenzen and colleagues based their study on solar PV production in Australia, which gets 75% of its electricity from coal (U.S. EIA 2007). This percentage of electricity from coal is much higher than in the United States or Europe. The high GHG emission intensity of grid electricity for PV production in Australia likely accounts for the elevated estimates. This grid electricity would lead to high GHG emissions in any life cycle stage requiring electricity, but particularly in manufacturing. For example, GHG emissions estimates from Lenzen and colleagues (2006) from BOS are quite high compared to the estimates reported in the work of Mason and colleagues (2006). The BOS contribution based on the work of Mason and colleagues (2006) is 27% lower than the estimate from Lenzen and colleagues (2006). Mason and colleagues estimated the GHG emissions using U.S. electricity from BOS for a ground-mounted system; the results of their study have been used in other LCA studies (Alsema 2000; Alsema and de Wild-Scholten 2006; Pacca 2003). However, Lenzen and colleagues do not provide enough disaggregated data to harmonize based on grid electricity or to substitute a BOS estimate from Mason and colleagues.

Table 4 reports published and harmonized descriptive statistics for all of the c-Si estimates, including the impact of the individual harmonization steps. Tables S3 and S4 in the supporting information on the Web present the same statistics broken into multicrystalline and monocrystalline technology

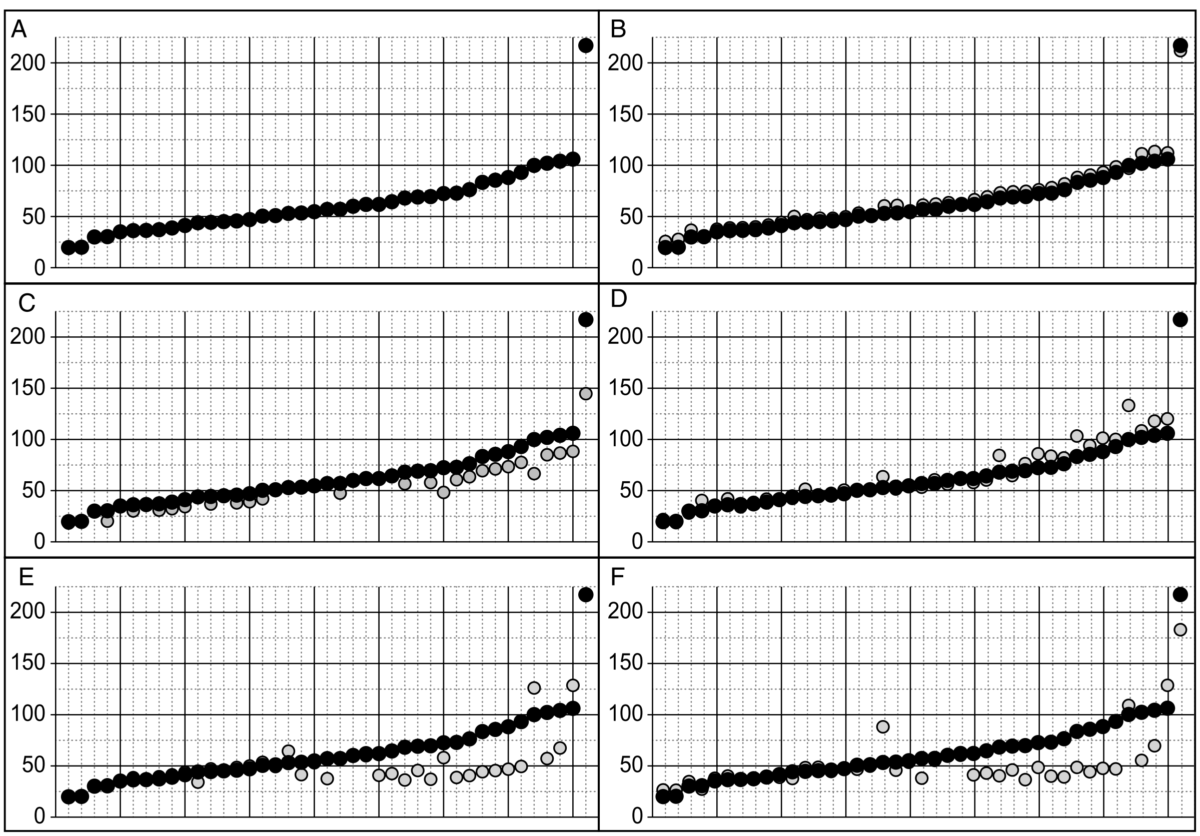

Figure 3 For a harmonized irradiation of 1,700 kilowatt-hours per square meter per year (kWh/m^2/yr), rank-order estimates ($n = 41$) of life cycle greenhouse gas (GHG) emissions (grams carbon dioxide equivalent per kilowatt-hour [g CO_2-eq/kWh]) for crystalline silicon (c-Si) electricity generation, drawn from literature that passed screens for quality, transparency, relevance, and usability. Impact of each harmonization step (gray circles), acting individually, compared to the published estimates (black circles). Frame (A) published; then, harmonized by (B) module efficiency; (C) system lifetime; (D) performance ratio; (E) irradiation; and (F) all steps (acting cumulatively). Numerical data associated with each point are reported in table S1 in the supporting information on the Web.

groups, respectively. Table S2 compares the descriptive statistics for the entire pool of studies and the various mounting and technology subsets.

Figure 3 shows the impact of each harmonization parameter acting independently in frames B through E. Harmonizing the performance ratio, efficiency, and system lifetime 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 reflects the change in GHG emissions resulting from the shift from the 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 and colleagues (2005) and Pehnt and colleagues (2002) represent two of the largest deviations. Table S1 in the supporting information on the web reports the results of each step of the harmonization process applied to each estimate of life cycle GHG emissions considered. Figure S4 in the supporting information on the Web 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 and colleagues (2005) and Pehnt and colleagues (2002) had estimates where the irradiation was less than 1,000 $kWh/m^2/yr$, therefore, when the irradiation was harmonized to 1,700 $kWh/m^2/yr$, the GHG emission estimate was reduced substantially.

Comparison of Results to Prior Studies

The results of this study align well with the conclusions from the previous study of solar PV LCAs by Pacca and colleagues (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 that both irradiation and lifetime 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 those of Pacca and colleagues (2007). The comparison also suggests that the energy required in production and manufacture is an important performance characteristic that should be considered for future analyses. Fthenakis and colleagues (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 more than 50% from coal) will increase the GHG emissions from c-SI by approximately 50%.

Limitations

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. 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, 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 life cycle 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 and colleagues (2002) report that more than 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 micrometers (μm) (Stoppato 2008) to 300 μm (Fthenakis and Alsema 2006; Pehnt 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 may also 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 and colleagues (2007) study that GHG emissions are sensitive to input energy for production and manufacture shows that adjustments to the numerator of equation (1) have potentially significant impacts.

The calculation of 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 that of Jungbluth and colleagues (2009), used the Intergovernmental Panel on Climate Change (IPCC) 2007 GWPs for methane (CH_4) and nitrous oxide (N_2O) (Forster et al. 2007). However, studies published before 2007 would have used older GWPs. Studies often do 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 a 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 c-SI 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_2-eq/kWh to life cycle GHG emissions from c-Si PVs. Therefore not accounting for these gases should not significantly change the results of this study. Several studies neglected to report CH_4 and N_2O emissions (Alsema 2000; Hondo 2005; Jungbluth et al. 2009). Based on the work of Frankl and colleagues (2005), these GHGs account for 6% of total life cycle GHG emissions. As a result, failure to account for these GHG emissions, while leading to an underestimate of true life cycle GHG emissions, should not change the conclusions of this article.

Project Scope

This study sought to explain and reduce the variability in existing estimates of life cycle GHG emissions of c-Si PVs 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 deployed technology or 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.

Recommendations for Future Work

Crystalline silicon PV technology has been commercially available 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 silicon feedstock and PV modules and is expected to continue increasing its share of production (Navigant Consulting 2009; RTS Corporation 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 et al. 2007). None of the studies in this meta-analysis specifically accounted for Chinese manufacturing. 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 LCAs published to date and are therefore relied upon for this retrospective meta-analysis. Attributional LCAs consider the direct emission impacts of a process. In 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 (Gross et al. 2007; Pehnt et al. 2008). Conversely, since PV generates electricity during peak demand periods, increased use of PV should reduce the use of marginal, peaking generators, which are often inefficient natural gas combustion turbines (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 gamut of life cycle impacts, including other airborne emissions, waterborne pollutants, and water consumption.

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 to 217 g CO_2-eq/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 a performance ratio of 0.75 or 0.80, depending on the type of installation), we provide a clearer sense of c-Si 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 PVs was 57 g CO_2-eq/kWh with an IQR of 44 to 73 g CO_2-eq/kWh. The harmonization process refined the median GHG result for all c-Si PVs to 45 g CO_2-eq/kWh with an IQR of 39 to 49 g CO_2-eq/kWh (a decrease of 66% from the 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 can legitimately 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 multicrystalline silicon), the results represent a potentially useful estimate for policymakers. In addition, policymakers can readily 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 life cycle GHG emissions much lower than the values typical for fossil fuel electricity (Dolan et al. 2012; Whitaker et al. 2012). The results provide a more consistent basis for comparing c-Si with conventional and other renewable electricity technologies. Life cycle analyses of PVs should continue as module and material utilization efficiencies improve, as PV manufacturing is shifted to Asia (potentially increasing life cycle impacts), and as the impacts of introducing variable generation resources onto the grid are better characterized.

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Notes

1. One gram (g) = 10^{-3} kilograms (kg, SI) ≈ 0.035 ounces (oz). Carbon dioxide equivalent (CO_2-eq) is a measure for describing the climate-forcing strength of a quantity of greenhouse gases using the functionally equivalent amount of CO_2 as the reference. One kilowatt-hour (kWh) ≈ 3.6 × 10^6 joules (J, SI) ≈ 3.412 × 10^3 British thermal units (Btu).
2. Heath and Mann (2012) provide additional background about the screening method used in the NREL harmonization project. Additional data and results of the project are available at http://openei.org/apps/LCA.
3. One square meter (m^2, SI) ≈ 10.76 square feet (ft^2).

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About the Authors

David D. Hsu is a senior engineer at the National Renewable Energy Laboratory (NREL) in Golden, CO, USA. **Patrick O'Donoughue** is an analyst at NREL. **Pamala Sawyer** is a former intern at NREL. **Garvin A. Heath** is a senior scientist at NREL. **Vasilis M. Fthenakis** is a senior scientist at Brookhaven National Laboratory in Upton, NY, USA, and a professor of earth and environmental engineering at Columbia University in New York, NY, USA. **Hyung Chul Kim** is an associate research scientist at Brookhaven National Laboratory and at Columbia University. **Jun-Ki Choi** is a Goldhaber distinguished fellow at Brookhaven National Laboratory. **Damon E. Turney** is an associate researcher at Brookhaven National Laboratory.

Supporting Information

Additional supporting information may be found in the online version of this article:

Supporting Information S1: This supporting information provides detailed data gathered from each article that passed screening, as well as more explanatory figures of the effects of harmonization. Also included is a full list of the sources that were screened.