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Life Cycle GHG Emissions of Thin-film Photovoltaic Electricity Generation: Systematic Review and Harmonization

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Summary

We present the process and the results of harmonization of LCAs of commercial thin-film PVs, that is, a-Si, CdTe and CIGS. We reviewed 109 studies and harmonized the estimates of GHG emissions by aligning the assumptions, parameters, and system boundaries. During the

initial screening, we eliminated abstracts, short conference papers, presentations without supporting documentation, and unrelated analyses; 90 studies passed this initial screening. In the primary screening we applied rigorous criteria for completeness of reporting, validity of LCA methods, and modern relevance of the PV system studied. Additionally, we examined whether the product is a commercial one, whether the production line still exists, and whether the study's core data is original or secondary. These screenings produced five studies as the best representations of the carbon footprint of the modern thin-film PV technologies. These were harmonized through alignment of efficiency, irradiation, performance ratio, balance-of-system and lifetime. The resulting estimates for carbon footprint are 20, 14, and 26 g CO_2-eq./kWh, respectively, for a-Si, CdTe and CIGS, for ground-mount application under US-SW irradiation of 2400 kWh/m^2/yr, performance ratio of 0.8, and lifetime of 30 yrs. Harmonization for the rooftop PV systems with a performance ratio of 0.75 and the same irradiation resulted in carbon footprint estimates of 21, 14, and 27 g CO_2-eq./kWh, respectively for the three technologies. This screening and harmonization rectifies previous incomplete or outdated assessments and clarifies variations in carbon footprint across studies and amongst thin-film technologies.

<heading level 1> **Introduction**

Thin-film photovoltaic (PV) systems such as amorphous silicon (a-Si), cadmium telluride

(CdTe) and copper indium gallium diselenide (CIGS), are expanding rapidly due to their low cost, ease of manufacturing, advancing conversion efficiency, and competitive sustainability indicators. These indicators are becoming crucial in assuring the public's acceptance of energy technologies since climate change arguably is the most significant threat facing our planet. Life-cycle assessment (LCA) is a widely accepted, comprehensive tool for measuring the sustainability indicators of products and processes, including the generation of electricity through solar PV devices. Recent LCA studies show that PV technologies have very low environmental and human health impacts compared to those of conventional electricity generation (Hondo 2005; Fthenakis et al. 2008). A broad review of literature, however, reveals several PV LCA studies with widely varying estimates that greatly differ from one another. For example, reported life-cycle greenhouse gas (GHG) emissions of thin-film amorphous silicon (a-Si) PV systems range from 11 to 226 g CO_2-eq. per kWh of electricity produced (Yamada et al. 1995; Frankl et al. 2004). Such divergence reflects different assumptions on key parameters, for example, solar irradiation, performance ratio, and lifetime. Estimates also deviate because of the different types of installation possible including ground mount, rooftop, and façade. Most importantly, assessments made from outdated information collected from antiquated PV systems still are cited in the literature and used for guiding policy analyses.

NREL, Columbia University and BNL are engaged in a project for developing balanced comparisons of data and premises across these studies. The project team reviewed LCAs for all PV technologies, harmonizing them by enforcing identical system boundaries and assumptions. In the current paper, we describe the processes for reviewing, screening, and harmonizing the LCA of greenhouse gas emissions from thin-film photovoltaic (PV) technologies (i.e., a-Si, CdTe, and CIGS). We also discuss the likely future directions of these technologies, and their impact on sustainability indicators.

<heading level 1> Harmonization Methodology

<heading level 2> Life cycle of thin film PV

The photovoltaic (PV) systems considered by this study comprise the grid-connected PV modules and the balance of system (BOS) which includes cables, inverters, and support structures for modules. A BOS takes a different form in terms of equipment capacity and materials, between the ground-mount and rooftop installation, the two most common types. Systems mounted on building façades or with sun-tracking motors were not included in this study because LCA studies are rare for the necessary BOS equipment. The life cycle of thin film PV starts with raw materials acquisition, encompasses materials production, film deposition, module production, system assembly, system operation, and then ends with their disposal (figure 1). Also shown in the graph is the life cycle of the BOS, whose life cycle emissions will be added to those of PV for a complete analysis and be harmonized based on standard values. Note that the recycling stage of thin film PV life cycle was not included in the system boundary of this study and thin-film installations are relatively new and end of life has not described in detail yet. Listed below are detailed processes during the life cycle stages of thin-film PV systems.

1) Upstream Processes

- Raw material acquisition: for example, mining ores, extracting petroleum, and growing woods

- Materials production: for example, alloying, purification, treatment, mixing, and polymerization

- Film deposition: for example, chemical vapor deposition and vapor transport deposition

- Module production: contact formation, encapsulation, wiring, and assembly

- Module and BOS installation: installing module, inverter, and support structures

2) Operational Processes

- Electricity generation: office use for utility scale plant

- Maintenance: scheduled and unscheduled repair and maintenance

3) Downstream Processes

- Decommissioning and disposal: demolition and transportation

- Recycling: collection, disassembly, shredding, and material separation

<heading level 2> **Literature Screening**

<heading level 3> **Initial screening**

We reviewed 109 studies on the life-cycle environmental profile of thin-film PV electricity generation systems. The studies were taken from journal articles, conferences, doctoral theses, and technical reports. During our first screening stage, we examined the studies' research methods to ascertain consistency with the standard LCA framework. We screened out those LCA studies that did not include the major life-cycle stages, or upstream material and energy flows. Studies conducted before 1980 were eliminated as we deemed them outdated, and documents in the form of presentations, posters, and abstracts also were rejected as lacking sufficient documentation. Ninety one LCA studies of thin- film photovoltaics passed this first stage screening process. Table S1 in Supporting Information presents a detailed breakdown of these studies. Most frequently studied is amorphous silicon (a-Si), at 51 times, followed by CdTe, at 37 times. We attributed this focus to the fact that these technologies have been manufactured and commercialized for longer than other thin-film technologies. The total number of technology scenarios at this stage of the harmonization, 124, surpasses the number of LCA studies, 91, because some studies examine multiple thin-film technologies or multiple scenarios for the same technology. Technologies reviewed but unspecified in table S1 include, a-Si/nc-Si, GaAs, InGaP, GaInP/GaAs, dye-sensitized-, and quantum- dot CdSe.

<heading level 3> **Primary screening**

More rigorous quality criteria were set during the second stage of screening for 1) completeness of reporting results and methods, 2) validity of the LCA methods, and, 3) relevance to present-day technologies. We established detailed sub-criteria to facilitate the screening, and to assure consistent, transparent analyses:

1) <u>Completeness of reporting results and methods</u>

Under this criterion, we reviewed whether the studies included critical components of LCA such as functional units, scoping, inventory analyses, and impact analyses. For our current harmonization, we eliminated studies that did not examine the greenhouse-gas emissions. In fact, a wide range of environmental metrics associated with thin-film PV technologies have been evaluated under the LCA framework: they include risks, toxic emissions, primary energy, energy- payback times, land use, and water use. We did not consider such PV LCAs, although many are recent and valid, because they did not investigate GHG emissions. The number of studies that included estimates of GHG emissions is 15, 13, and 7 for a-Si, CdTe, and CIGS, respectively (table S1).

2) Validity of the LCA methods

In PV LCA, it is essential to explicitly present the key parameters of analysis, that is, conversion efficiency, performance ratio, irradiation, and lifetime, along with the sources of the information, such as manufacturer, data collector, and age of the data. The IEA's guideline (Alsema et al. 2009) details such requirements for PV LCA.

3) Relevance to present-day technologies.

We rejected LCA articles that do not represent modern technologies. To determine modernity we considered module efficiency, manufacturer, scale of production and module design. In addition, studies based on a hypothetical manufacturing line, future projections, and conceptual modeling were screened out under this constraint. We considered only those investigations based on inventory data from real-world production lines, except those for pilot-scale productions that we deemed relevant. We accepted only the original sources of LCA results, meaning that we excluded studies that do not contain original investigation

Our chosen metric for GHG emissions (G) is CO_2-equivalent emissions per kWh, which is derived as follows:

$$G = \frac{W}{I \times \eta \times PR \times LT \times A}$$

where W= greenhouse-gas emissions from the life cycle of PV system (g CO_2-eq.); I = irradiation (kWh/m^2/yr); η = conversion efficiency; PR= performance ratio; LT= lifetime (yrs); and, A= area of module (m^2). The major emissions considered as GHG emissions in these evaluations include CO_2, CH_4, N_2O, chlorofluorocarbons (CFCs), and per fluorocarbons (PFCs), converted to CO_2 equivalent using global warming potential on the 100-year time scale.

Several studies report emissions per m^2 of module area or manufacturing capacity. Studies focusing on the environmental impact of processing thin-film PV often express emissions in this form. Such estimates were converted to emissions per unit of electricity generation (i.e., kWh) when sufficient information was given, information like quantum efficiency and system efficiency; otherwise, we discarded such studies. We also excluded studies that report “avoided GHG” emissions that are unconvertible to our functional unit. Finally, we omitted studies reporting normalized global-warming indicators rather than presenting GHG emissions. Tables 1 through 3 list the studies that include life-cycle GHG emissions. Table S2 in Supporting Information presents those studies with ‘other’ technologies that are not presented here. We note that these estimates are not harmonized, and thus, are inconsistent with each other in terms of system boundary, and technical parameters, like performance ratio and lifetime expectancy, solar irradiation, and other assumptions.

Figure 2 plots the estimates of GHG emissions from the listed studies. The values for CdTe and CIGS show a relatively narrower range than those for a-Si and ‘other’ technologies, which partially may be related to the reporting years for each technology. The LCAs of CdTe and CIGS were determined after 2000, while some estimates for a-Si were pre-2000, a fact that is linked to the history of a-Si technology. The median estimate of CdTe’s emissions is the lowest while that of CIGS is the highest. The maximum value for a-Si correspond to the early estimates by Yamada (1995), while the lower one represent the case of building-integrated PVs (BIPVs) with credits for glass substitution in Frankl et al (2004). The maximum estimate for emissions in the life-cycle of CdTe PV describes a hypothetical installation case in a remote area by Ito et al (2009) wherein 75% of the GHG emissions are from constructing the BOS, including the transmissions lines, transport of components, the cable, foundation, and array support, that was designed for usage in Japan (earthquake region) (Ito 2010). The lower one corresponds to a roof-top system with 9% efficient modules in Europe (Fthenakis and Kim 2007; Raugei 2010).

Further screening based on criteria 2) and 3) eliminated those technologies that are future projections, for example, Hondo (2005); Uchiyama (1996a; 1996b; 1997), those based on hypothetical cases, for example, Ito et al (2008; 2009; 2010), Kato et al (1998; 2001), and those lacking detailed parameters, for example, Martin (1997), and Meier (2002). In particular, under criterion 3) we accepted only studies based on LCI data from actual production lines with modern relevance. Table 4 lists those nine studies, encompassing 12 cases, which fall under this classification.

During the final stage of screening, we also considered the following: Whether the product is a commercial one; whether the production line still exists; and, whether the study references the same data from previous studies, e.g. Fthenakis (2005; 2006; 2007). At this stage, we contacted the authors of these papers to verify if the technologies described in the LCA are relevant to modern practices. We confirmed that the a-Si and CdTe lines, detailed in SENSE (2008) and Raugei (2007) were phased- out after their studies, while the CIGS line still is operating at an expanded scale. Table 5 lists those studies that passed the final screening. It is noted that the estimates of CIGS by Raugei (2007) were based on a prototype line; according to the author the electricity demand was probably overstated (Raugei 2010). Also, the higher glass demand (25 kg/m^2) reflected a very high percentage of breakage in the prototype line (Raugei et al. 2007; Raugei 2010). The investigation by SENSE (2008) was for a 15-MW_p line. Since the current line produces 30 MW_p, the GHG emissions presented therein likely are not up-to-date (Held 2010). The estimate of CdTe by Fthenakis et al (2009) is based on data collected from the First Solar's plant in Perrysburg Ohio, and from the plant in Frankfurt-Oder in 2008, that is, an update of Fthenakis et al (2008) that described the operational-conditions in 2005. The improvement in efficiency of PV modules over this time also was significant, i.e., from 9 to 10.9%, which partially contributes to the reduction in GHG emissions between the two investigations.

<heading level 2> **Harmonization Approach**

For the LCA Harmonization project as a whole, two levels of harmonization were devised. The more intensive and in-depth level envisions a process similar to that employed by Farrell et al, (2006) to harmonize the LCA results on ethanol, whereby analyses of life cycle GHG emissions are carefully disaggregated to produce a detailed meta-model enabling to adjust parameters, realign system boundaries within and across life cycle phases, and review all data sources for adequacy (Farrell et al. 2006). A less intensive level approach, which is adequate for a larger set of literature, could harmonize GHG emissions estimates at a more gross level, for several influential performance characteristics and to common system boundaries. The former was chosen for harmonizing life cycle GHG emissions of thin-film PV technologies of which qualified population is relatively small and thus suitable for intensive analysis.

During the harmonization stage, we adjusted key parameters of the life- cycle impact, such as module efficiency, lifetime, performance ratio, solar irradiation, and efficiency degradation. In addition, assumptions on the system's boundary were examined, for example, types of balance of system (BOS) and frame. For obtaining the LCA of a complete system, the balance of system (BOS) components must be considered, together with the PV- module system that includes inverters, cables, and mounting structures for ground-mounted BOS. The GHG emissions from rooftop BOS used in this harmonization were adapted from the latest information from the Crystal Clear project (de Wild - Scholten 2009), that is, 5 g CO_2-eq./kWh under 1700 kWh of insolation, with 14% module efficiency, and performance ratio of 0.75. The same information for the ground-mounted BOS is taken from the LCA study of the Tucson Electric Power (TEP) power plant in Springerville, AZ, where the GHG emissions correspond to 5.5 g CO_2-eq./kWh, with 12.2% module efficiency, under average US insolation of 1800 kWh/m^2/yr, and performance ratio of 0.8 (Mason et al. 2006). Emissions from the structural part of the BOS are adjusted according to the conversion efficiency of PV because a high-efficiency module requires less structural material to produce a unit kWh, in contrast to emissions from the inverter portion of the BOS which are unchanged. We note that, for harmonization, we selected the frameless design of thin- film CdTe and CIGS PVs. Unlike crystalline silicon modules that require an aluminum frame for structural stability, typically ~3 kg per m^2 of panel, CdTe and CIGS thin-film modules with a double- glass design do not necessarily require a frame. The current triple-junction a-Si module deposited on a stainless- steel substrate, manufactured by United Solar, uses as a frame one with a very thin aluminum profile, specifically, 15 g of anodized extruded aluminum per m^2 of module, except for building-integrated applications (Pacca et al. 2006).

We list the reference parameters selected below; they are the figures most accepted as reflecting current PV technologies. For module efficiency, the latest values in LCA literature are used.

1) Solar irradiation:

Southwestern US (Phoenix, AZ)–- 2400 kWh/m^2/yr

Southern Europe – 1700 kWh/m^2/yr

2) Module efficiency:

CdTe - 10.9%

CIGS – 11.5%

a-Si – 6.3%

3) Degradation in efficiency: 0.5% per year (Alsema et al. 2009)

4) Performance ratio:

Ground-mount-0.8

Rooftop- 0.75

5) Lifetime: 30 yrs

6) BOS data source:

Ground-mount - (Mason et al. 2006)

Rooftop - (de Wild - Scholten 2009)

7) Global Warming Potential (GWP):

Account for non-CO_2 GHG emissions (CH_4, N_2O, CFCs, PFCs and so on)

IPCC 2007 values (Forster et al. 2007)

<heading level 1> **Results**

Table 5 shows the harmonized estimates based on the irradiance of US Southwest where construction of major ground-mount PV power plants is in progress or on the way, which is 2400 kWh/m^2/yr. The cases with irradiance of 1700 kWh/m^2/yr can be found in table S3 of Supporting Information Harmonized estimates for each parameter as well as the combined harmonized values are presented. Figure 3 illustrates the harmonized and pre-harmonized data for the studies of ground mount installation under 2400 kWh/m^2/yr. First, our harmonization greatly lowers the overall ranges of GHG estimates for the life-cycle of thin film PVs, e.g., from 12-70 to 9-32 g CO_2-eq./kWh for modules, and from 19-95 to 14-36 g CO_2-eq./kWh for the total ground-mount PV system. The harmonization of rooftop BOS produced a similar range of 10-34 g CO_2-eq./kWh for modules, and 14-38 g CO_2-eq./kWh for the total system. We note that if we exclude the earlier estimates of CdTe (Fthenakis et al. 2008) and CIGS (Raugei et al. 2007) from figure 2, the current harmonized estimates for the three thin-film PV systems are even lower, at 20, 14, and 26 g CO_2-eq./kWh, respectively, for a-Si, CdTe, and CIGS, for ground-mount applications under the reference conditions. The most significant drop during harmonization (from 95 to 36 g CO_2-eq./kWh) was that for the total system estimate of CIGS based on a 20-yr lifetime and with an aluminum frame (Raugei et al. 2007). Simply extending the module's lifetime from 20- to 30-yrs alone reduces the module-only estimate of both a-Si (Pacca et al. 2006) and CIGS (SENSE 2008) by 30%. By additionally adjusting the degradation in efficiency of from 1.1% to 0.5% per year, and increasing solar irradiation from 1359 kWh/m^2/yr in the original study to a value of 1700 kWh/m^2/yr, the former estimate drops by ~40%, although the performance ratio diminished from 0.95 to 0.75. The harmonization results based on the irradiance of 1700 kWh/m^2/yr is illustrated in figure S1 of Supporting Information.

<heading level 1> **Discussion**

Both the as published- and harmonized- LCA results indicate that the carbon footprint of thin film PV technologies fall significantly as the production capacity increases, reflecting technological advances in process- and device-designs. For example, between 2005 and 2008, First Solar's annual production capacity of CdTe PV jumped from 25 to 716 MW_p, and, during the same period, the module efficiency of CdTe PV increased from 9% to 10.9% and the GHG estimate fell by ~30% (Fthenakis et al. 2008; Fthenakis et al. 2009). Scaling up a CIGS PV prototype to a 15 MW_p commercial line for Würth Solar also corresponds to a significant (i.e., ~50%) reduction of GHG emissions (Raugei et al. 2007; SENSE 2008). We also expect further reductions in GHG estimates for a-Si as the capacity of United Solar has been expanding rapidly (178 MW_p/yr as of 2009) and the data now available may be outdated (Energy Business Review 2010). Relatively small improvements in efficiency also occurred in a-Si PV; the current efficiency of a-Si PV modules is 6.7%, compared with the 6.3% used in the most recent LCA we report herein.

In the harmonization process, we allowed variability in some LCA parameters. Geographic location of the PV module plant affects the upstream grid-mix, and consequently, the GHG emissions factors per kWh of electricity used for producing PV. The estimates by Raugei et al (2007) and SENSE (2008), along with the German examples by Fthenakis et al (2009) assume the UCTE-grid mix for electricity consumption, while those by Pacca et al (2006), Fthenakis et al (2008) and the US case by Fthenakis et al (2009) assume the average US-grid mix. The European estimate has lower GHG emissions than the one for the United States. Although the effect may be minor, the database for the same grid-mix often varies across studies. For example, Raugei et al (2007) employed the ETH-ESU database, while SENSE (2008) used the Gabi database for the same UCTE grid-mix. In addition, the system boundaries drawn for LCA often are diverse or not clearly defined across studies. For example, the US case discussed by Fthenakis et al (2009) includes R&D related electricity uses in the system's boundaries, while other studies do not include it or do not specify if it is included.

This study reviews and harmonizes only the GHG emissions metric which deemed central in assessing the life cycle of electricity generation technologies. In a complete environmental assessment, other metrics such as energy payback time, toxicities, resources uses, need to be concurrently evaluated, which was not attempted here. Accordingly, readers should practice caution when comparing across electricity generation technologies based on this analysis.

<heading level 1> **Conclusion**

We reviewed 109 LCA studies on thin-film photovoltaics. After rigorously screening the completeness, validity, and data quality of each LCA, we selected five studies as representative of the carbon footprint of the modern thin-film PV technologies. We harmonized the major parameters of PV LCA, including solar irradiation, performance ratio, and lifetime. The resulting latest estimates of GHG emissions are 20, 14, and 26 g CO_2-eq./kWh, respectively, for a-Si, CdTe, and CIGS, for ground-mount application under solar irradiation of 2400 kWh/m^2/yr, a performance ratio of 0.8, and a lifetime of 30 yrs. For the same technologies, the harmonized, latest estimates for rooftop application under solar irradiation of 2400 kWh/m^2/yr and a performance ratio of 0.75 correspond to 21, 14, and 27 g CO_2-eq./kWh. The screening and harmonizing described in this paper significantly reduced the uncertainty on estimates for GHG emissions for thin-film PVs. In addition, harmonization allowed us to appraise the real variations of carbon footprint across device technologies, production scales, and the age of the data in thin-film PV LCAs. In fact, the ranges of the estimates of GHGs from thin-film PVs were drastically narrowed through harmonization, that is, to ~40% and ~50%, respectively, for module- and total system- rooftop application. Overall, this harmonization reduced the uncertainty and ambiguity of the reported values of the carbon footprint of these technologies, and contributed to rectifying previous incomplete or outdated assessments.

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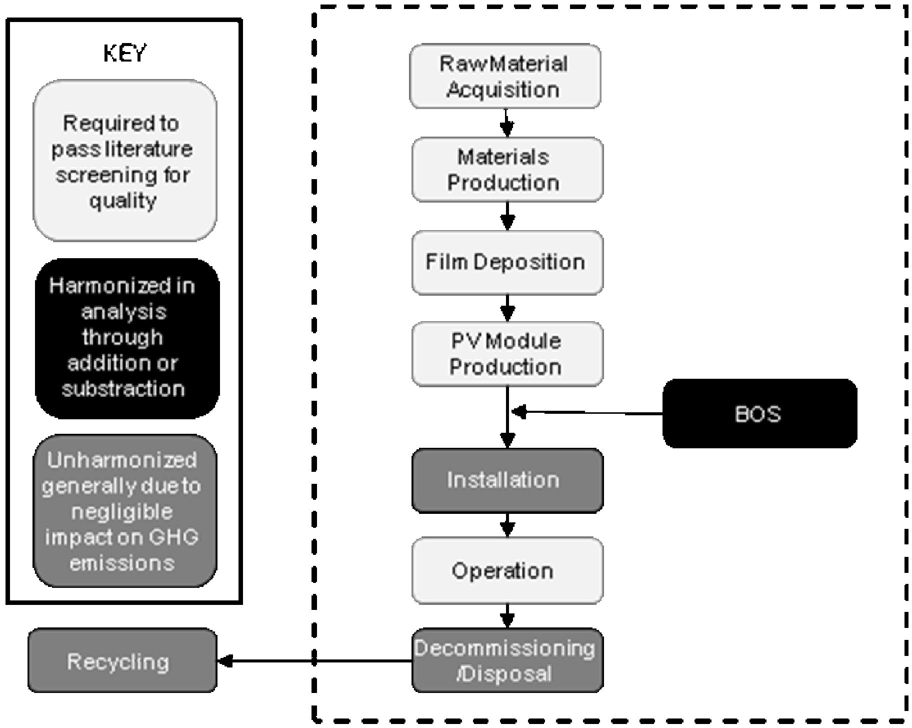

Figure 1: The life cycle of thin film PV systems. Dotted lines correspond to the system boundary for harmonization study.

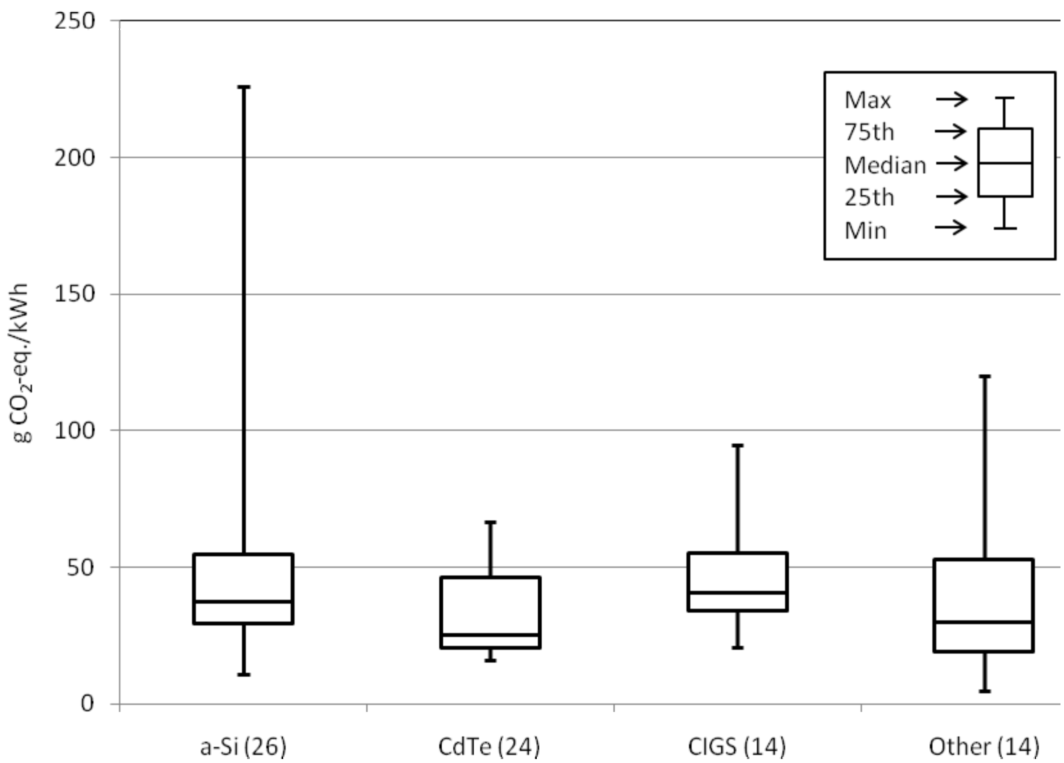

Figure 2: Box plot of GHG emissions reported in thin-film PV LCA studies.

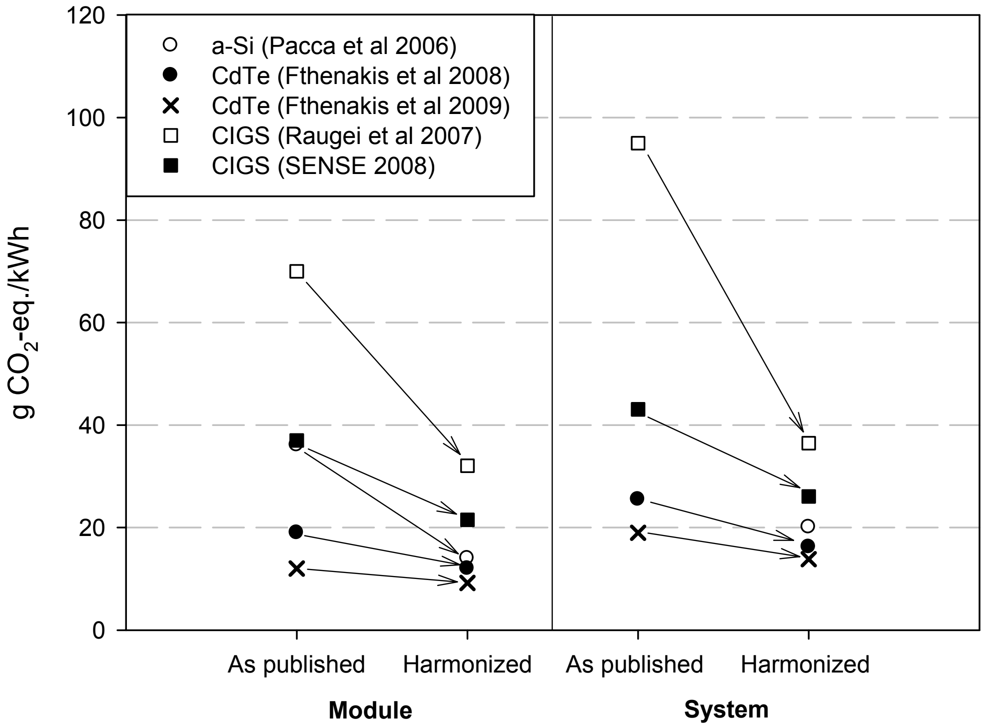

Figure 3: Harmonization of GHG emission estimates that passed the final screening for ground-mount installation without an aluminum frame. Module efficiency: CdTe – 10.9%; a-Si – 6.3%; CIGS – 11.5%; lifetime = 30 yrs; irradiation = 2400 kWh/m^2/yr and performance ratio = 0.8; . The arrows show the effect of harmonization on individual technology scenarios.

Table 1: Thin- film a-Si PV LCA studies reporting GHG emissions

Reference	g CO_2-eq./kWh	Solar Irradiation (kWh/m^2/yr)	Module Efficiency (%)	PR	Lifetime (yrs)	Type	Note
(Yamada et al. 1995)	226 125 101	1200 1200 1200	8 13 16	0.72 0.72 0.72	20 20 20	G G G	Production scale = 0.01 GW_p/yr Production scale = 1 GW_p/yr Production scale = 100 GW_p/yr
(Uchiyama 1996a)	29	N/A	12.6 (cell)	N/A	30	R	3 kW_p, production scale = 1 GW_p/yr
(Uchiyama 1996b)	29	N/A	12.6 (cell)	N/A	30	R	3 kW_p; production scale = 1 GW_p/yr
(Uchiyama 1997)	29	N/A	12.6 (cell) 8.6 (system)	N/A	N/A	R	Production scale = 1 GW_p/yr
(Martin 1997)	38	N/A	N/A	N/A	30	G	Power plant
(Kato et al. 1998)	62 48 33	1427 1427 1427	8 10 12	0.81 0.81 0.81	20 20 20	R R R	3 kW_p ; production scale=10 MW_p/yr 3 kW_p ; production scale =30 MW_p/yr 3 kW_p ; production scale=100 MW_p/yr
(Kato et al. 2001)	58 44 30	1430 1430 1430	8 10 12	0.81 0.81 0.81	20 20 20	R R R	Production scale= 10 MW_p/yr Production scale =30 MW_p/yr Production scale =100 MW_p/yr
(Meier 2002)	39	1840	5.7	0.74	30	R	8 kW_p; building-integrated
(Frankl et al. 2004)	43.4 38.6 62.3 36.9 29 10.9	1740 2000 1200 1740 1740 1740	6 6 6 6 6 6	0.875 0.86 0.885 0.9 0.875 0.875	20 20 20 20 20 20	R R R R R R	Retrofit; Rome Retrofit; Southern Spain Retrofit; Central Europe Building integrated; Rome Integrated skylight roof; Rome Integrated skylight roof substituting glass; Rome
(Hondo 2005)	26	N/A	8.6	N/A	30	N/A	Future case, 1 GW_p/yr production
(Pacca et al. 2006)	34.3	1359	6.3	0.95	20	R	Building integrated case in Ann Arbor, MI

(Pacca et al. 2007)	34.3	1359	6.3	0.95	20	R	Building integrated case in Ann Arbor, MI
(SENSE 2008)	31	1700	5.5	0.912	20	G	GHG estimate for Rome
(Ito et al. 2008)	57	2017	6.9	0.771	30	G	100 MW_p ; Gobi desert
(Dominguez-Ramos et al. 2010)	27	1825	7	0.78	30	G	Installed in Spain

PR=performance ratio; I = irradiation; N/A = not available; G = ground-mount; R=rooftop

Table 2: Thin- film CdTe PV LCA studies reporting GHG emissions

Reference	g CO_2-eq./kWh	Solar Irradiation (kWh/m^2/yr)	Module efficiency (%)	PR	Lifetime (yrs)	Type	Note
(Kato et al. 2001)	51	1430	10.3	0.81	20	R	Production scale=10 MW_p/yr
	42	1430	11.2	0.81	20	R	Production scale =30 MW_p/yr
	33	1430	12.4	0.81	20	R	Production scale=100 MW_p/yr
(Alsema et al. 2006)	25	1700	9	0.75	30	G	
(Fthenakis and Kim 2006)	24	1800	9	0.8	30	G	
(Fthenakis and Alsema 2006)	21	1700	8	0.75	30	R	European production
	25	1700	9	0.8	30	G	US production
(Fthenakis and Kim 2007)	16	1700	9	0.75	30	R	Installed in Europe
	22	1800	9	0.75	30	R	Installed in the US
	17	2280	9	0.75	30	R	Installed in the US
	21	2060	9	0.8	30	G	Installed in the US
(Raugei et al. 2007)	48	1700	9	0.75	20	R	
(Fthenakis et al. 2008)	21	1700	9	0.8	30	G	UCTE grid mix
	26	1700	9	0.8	30	G	US grid mix
(SENSE 2008)	66	1200	10	0.912	20	G	
	46	1700	10	0.912	20	G	
	36	2200	10	0.912	20	G	
(Ito et al. 2008)	47	2017	9	0.772	30	G	100 MW_p system in Gobi desert
(Fthenakis et al. 2009)	19	1700	10.9	0.8	30	G	US production
	17.7	1700	10.9	0.8	30	G	German production
	19.5	1700	10.9	0.8	30	G	German production
(Ito et al. 2009)	66.5	2017	9	0.77	N/A	G	1 GW_p system in Gobi desert
(Ito et al. 2010)	50	1702	N/A	0.78	N/A	G	1 GW_p system in Gobi desert
(Dominguez-Ramos et al. 2010)	17	1825	9	0.78	30	G	German production,installed in Spain

PR=performance ratio; I=irradiation; UCTE = Union for the Co-ordination of Transmission of Electricity; N/A= not available; G = ground-mount; R = rooftop

Table 3: Thin film CIGS PV LCA studies reporting GHG emissions

Reference	g CO_2-eq/kWh	Solar Irradiation ($kWh/m^2/yr$)	Module efficiency (%)	PR (%)	Lifetime (yrs)	Type	Note
(Frankl et al. 2004)	43.4 38.6 62.3 36.9 32 20.5	1740 2000 1200 1740 1740 1740	9 9 9 9 9 9	0.875 0.86 0.885 0.9 0.875 0.875	20 20 20 20 20 20	R R R R R R	Retrofit ; Rome Retrofit; Southern Spain Retrofit; Central Europe Building integrated; Rome Integrated skylight roof ; Rome Integrated skylight roof substituting glass; Rome
(Raugei et al. 2007)	95	1700	11	0.75	20	R	
(SENSE 2008)	61 43 33	1200 1700 2200	11.5 11.5 11.5	0.912 0.912 0.912	20 20 20	G G G	
(Ito et al. 2008)	38.5	2017	11	0.776	30	G	100 MW_p system in Gobi desert
(Ito et al. 2009)	58.8	2017	10.1	0.77	N/A	G	1 GW_p system in Gobi desert
(Ito et al. 2010)	44	1702	N/A	0.78	N/A	G	1 GW_p system in Gobi desert
(Dominguez-Ramos et al. 2010)	33	1825	10	0.78	30	G	German production, installed in Spain

PR=performance ratio; I=irradiation; N/A = not available; G = ground-mount; R = rooftop

Table 4: LCA Studies based on actual production data

Technology	Reference	Manufacturer	Data Year	Production Scale for Data
a-Si	(Pacca et al. 2006)	United Solar	2004	Commercial -28 MW_p/yr
a-Si	(Pacca et al. 2007)	United Solar	2004	Commercial -28 MW_p/yr
a-Si	(SENSE 2008)	Free Energy Europe	2003-2006	Pilot
CdTe	(Fthenakis and Kim 2006)	First Solar	2005	Commercial - 25 MW_p/yr
CdTe	(Fthenakis and Alsema 2006)	First Solar	2005	Commercial -25 MW_p/yr
CdTe	(Fthenakis and Kim 2007)	First Solar	2005	Commercial -25 MW_p/yr
CdTe	(Fthenakis et al. 2008)	First Solar	2005	Commercial -25 MW_p/yr
CdTe	(Fthenakis et al. 2009)	First Solar	2008	Commercial -716 MW_p/yr
CdTe	(SENSE 2008)	Antec Solar	2003-2006	Pilot
CdTe	(Raugei et al. 2007)	Antec Solar	2004	Pilot
CIGS	(Raugei et al. 2007)	Würth Solar	2004	Pilot
CIGS	(SENSE 2008)	Würth Solar	2003-2006	Commercial- 15 MW_p/yr

Table 5: As published and harmonized life cycle GHG emissions (g CO_2-eq./kWh)

Technology	Reference	As Published		Harmonized									
				Module								System	
		Module	System	η	LT	I	PR (G)	PR (R)	Other[b]	All (G)	All (R)	G	R
a-Si	(Pacca et al. 2006)	36	N/A	36	24	20	43	46	31	14	15	20	21
CdTe	(Fthenakis et al. 2008)	19	26	16	19	13	19	20	21	12	13	16	17
CdTe	(Fthenakis et al. 2009)	12[a]	19[a]	12	12	9	12	13	13	9	10	14	14
CIGS	(Raugei et al. 2007)	70	95	67	47	50	66	70	76	32	34	36	38
CIGS	(SENSE 2008)	37	43	37	25	26	42	45	40	22	23	26	27

[a] average of three estimates: [b] accounting for non-CO_2 GHG emissions, using current GWP values (Forster et al. 2007), and assuming 0.5% per year degradation of module efficiency (Alsema et al. 2009): η = module efficiency; LT= lifetime; I=solar irradiation; PR=performance ratio; G=ground-mount; R=rooftop;