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Life Cycle Greenhouse Gas Emissions from Solar Photovoltaics

Over the last thirty years, hundreds of life cycle assessments (LCAs) have been conducted and published for a variety of residential and utility-scale solar photovoltaic (PV) systems. These LCAs have yielded wide-ranging results. Variation could be attributed to differences in technologies evaluated (i.e., differing system designs, commercial versus conceptual systems, system operating assumptions, technology improvements over time) and LCA methods and assumptions. The National Renewable Energy Laboratory (NREL) recently led the Life Cycle Assessment (LCA) Harmonization Project, a study that helps to clarify inconsistent and conflicting life cycle GHG emission estimates in the published literature and provide more precise estimates of life cycle GHG emissions from PV systems. Analysts developed and applied a systematic approach to review LCA literature, identify primary sources of variability and, where possible, reduce variability in life cycle GHG emissions estimates through a process called "harmonization."

Published results from 400 studies of PV systems including crystalline silicon (c-Si) (mono-crystalline and multi-crystalline) and thin film (TF) (amorphous silicon [a-Si], cadmium telluride [CdTe], and copper indium gallium diselenide [CIGS]) were reviewed and screened. Seventeen studies passed the screening (providing 46 estimates of life cycle GHG emissions for these PV technologies) and were included in this analysis. Harmonization was performed by adjusting published GHG emission estimates to achieve consistent values (Table 1) for these key technical parameters:

1. *Solar irradiation*, the average energy flux from the sun, in kilowatt-hours per square meter per year (kWh/m^2/yr).
2. *Operating lifetime* of the PV system and components (years).
3. *Module efficiency*, the percentage of the solar energy converted to direct current electricity by the module.
4. *Performance ratio*, the ratio of alternating current electricity actually produced by the system, after accounting for losses, to

Table 1. Harmonization Parameters

Parameter	Value
Solar Irradiation (kWh/m^2/yr)	1,700 | 2,400
System Lifetime	30 years
Crystalline Silicon Module Efficiency	
Mono-crystalline	14.0%
Multi-crystalline	13.2%
Thin Film Module Efficiency	
Amorphous silicon (a-Si)	6.3 %
Cadmium telluride (CdTe)	10.9%
Copper indium gallium diselenide (CIGS)	11.5%
Performance Ratio	
Ground-Mounted	0.80
Rooftop	0.75

Life Cycle Stages	Upstream Processes	Operational Processes	Downstream Processes
Photovoltaics (PV)  ~40 g CO_2eq/kWh	• Raw Materials Extraction • Materials Production • Module Manufacture • System/Plant Component Manufacture • Installation/Plant Construction	• Power Generation • System/Plant Operation and Maintenance	• System/Plant Decommissioning • Disposal
	~60% - 70%	~21% - 26%	~5% - 20%
Coal  ~1,000 g CO_2eq/kWh	• Raw Materials Extraction • Construction Materials Manufacture • Power Plant Construction	• Coal Mining • Coal Preparation • Coal Transport • Coal Combustion • Power Plant Operation and Maintenance	• Power Plant Decommissioning • Waste Disposal • Coal Mine Land Rehabilitation
	<1%	>98%	<1%

Source: *Burkhardt et al. (2012) and Whitaker et al. (2012) Photos from iStock/19291390 and iStock/1627655, Top (left to right): Photo from iStock/13737597, NREL/PIX 18553, iStock/12123595, NREL/PIX 16933, NREL/PIX 18968, NREL/PIX 19163*

LCA of Energy Systems

LCA can help determine environmental burdens from "cradle to grave" and facilitate comparisons of energy technologies. Comparing life cycle stages and proportions of GHG emissions from each stage for PV and coal shows that, for coal-fired power plants, fuel combustion during operation emits the vast majority of GHGs. For PV power plants, the majority of GHG emissions are upstream of operation in materials and module manufacturing.

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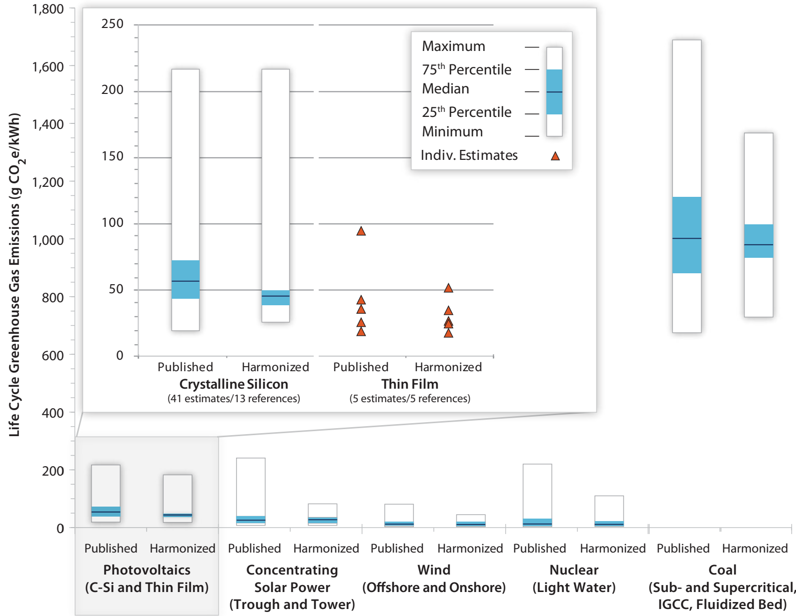

	Photovoltaics	Concentrating Solar Power	Wind	Nuclear	Coal
Estimates	46	36	126	99	164
References	17	10	49	27	53

Summary of results of the systematic review and harmonization of estimates of life cycle GHG emissions for selected electricity generation technologies, with a focus on PV technologies. See www.nrel.gov/harmonization for more information.

the electricity calculated based on the direct current-module efficiency and irradiation.

GHG emission estimates were also harmonized to a consistent system boundary, as well as global warming potentials for methane and nitrous oxide. Other potential sources of variability that were not considered in this study include silicon wafer thickness and silicon type for the c-Si PV system, and the upstream electricity mix used in manufacturing processes for both the c-Si and TF PV systems.

The life cycle GHG emissions for c-Si and TF PV power systems are compared with other electricity generation technologies in the figure on this page. These results show that:

- Total life cycle GHG emissions from solar PV systems are similar to other renewables and nuclear energy, and much lower than coal.
- Harmonization increases the precision of life cycle GHG emission estimates for c-Si and TF PV, reducing variability in the interquartile range (75th minus 25th percentile value) by 65%.
- Harmonization has a small effect on the central estimate for each technology, reducing the median by approximately 20%. Median values for both PV technologies are below 50 g CO_2e/kWh.
- Life cycle GHG emissions from c-Si and TF PV technologies appear broadly similar; the small number of estimates for TF technologies limits robust comparisons.

Of the harmonization parameters investigated, adjusting reported results to a consistent solar irradiation assumption had the greatest impact on reducing the variability in estimated GHG emissions from c-Si PV technologies. Solar irradiation directly influences the power generated from a PV system and varies by location and season, time of day, and weather. In the LCA literature on PV technologies, the assumed solar irradiation ranged from 900 to 2,200 kWh/m^2/yr. When these values were adjusted to 1,700 kWh/m^2/yr (typical for southern Europe), the variability in the interquartile range of life cycle GHG emissions for c-Si PV technologies was reduced by 48%. Using a higher irradiation estimate than 1,700 kWh/m^2/yr (i.e., 2,400 kWh/m^2/yr which is typical for the Southwestern U.S.) would result in proportionally lower GHG emissions.

Adjustment to a consistent operating lifetime is also a driving factor in decreasing the variability of the harmonized data. Additional analysis comparing mono-Si and multi-Si technologies suggest that these do not significantly differ in life cycle GHG emissions. In addition, no significant differences in GHG emissions from ground-mounted and roof-mounted systems were observed for c-Si or TF PV technologies.

Given the large number of previously published life cycle GHG emission estimates for c-Si and TF PV systems and their narrow distribution after harmonization, the results of this research provide an initial estimate potentially useful for decision makers and investors. Additional studies on TF systems are needed to understand the key sources of variability in life cycle GHG estimates. LCAs of both c-Si and TF PV should continue as module and utilization efficiencies improve and as PV manufacturing locations shift. Future assessments should also consider the systems-level effects of integrating variable generation sources onto the existing grid to better understand the impacts on GHG emissions from conventional generation sources.

References

Hsu, D.; O'Donoughue, P.; Fthenakis, V.; Heath, G. ; Kim, H.; Sawyer, P.; Choi, J.; Turney, D. (2012). "Life Cycle Greenhouse Gas Emissions of Crystalline Silicon Photovoltaic Electricity Generation: Systematic Review and Harmonization." *Journal of Industrial Ecology* (16:S1); pp. S122-S135.

Kim, H.; Fthenakis, V.; Choi, J.; Turney, D. (2012). "Life Cycle Greenhouse Gas Emissions of Thin-film Photovoltaic Electricity Generation: Systematic Review and Harmonization." *Journal of Industrial Ecology* (16:S1); pp. S110-S121.

Whitaker, M.; Heath, G.; O'Donoughue, P.; Vorum, M. (2012.) "Life Cycle Greenhouse Gas Emissions of Coal-Fired Electricity Generation: Systematic Review and Harmonization." *Journal of Industrial Ecology* (16:S1); pp. S53-S72.

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NREL is a national laboratory of the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, operated by the Alliance for Sustainable Energy, LLC.

NREL/FS-6A20-56487 • November 2012

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