NREL
NATIONAL RENEWABLE ENERGY LABORATORY

Life Cycle Greenhouse Gas Emissions from Electricity Generation

As clean energy increasingly becomes part of the national dialogue, lenders, utilities, and lawmakers need the most comprehensive and accurate information on GHG emissions from various sources of energy to inform policy, planning, and investment decisions. The National Renewable Energy Laboratory (NREL) recently led the Life Cycle Assessment (LCA) Harmonization Project, a study that gives decision makers and investors more precise estimates of life cycle GHG emissions for renewable and conventional generation, clarifying inconsistent and conflicting estimates in the published literature, and reducing uncertainty.

Over the last thirty years, thousands of LCAs have been published for a variety of electricity generation technologies. These LCAs have shown wide-ranging results. Variability can be attributed to technologies evaluated (e.g., differing system designs, commercial versus conceptual systems, system operating assumptions, technology improvements over time) and LCA methods and assumptions. Analysts at NREL developed and applied a systematic approach to review the LCA literature, identify primary sources of variability and, where possible, reduce variability in GHG emissions estimates through a procedure called "harmonization." This harmonization methodology is based on a two-step meta-analytical approach, which statistically combines the results of multiple studies, as follows:

Systematic Literature Review. NREL considered more than 2,100 published LCA studies on utility-scale electricity generation from wind, solar photovoltaic (PV), concentrating solar power (CSP), biopower, geothermal, ocean energy, hydropower, nuclear, natural gas, and coal technologies. Systematic review, comprising three rounds of screening by multiple experts, narrowed the field to select references that met strict criteria for quality, relevance, and transparency. Less than 15% of the original pool of references passed this review process.

Harmonization and Data Analysis. After the systematic review, NREL applied harmonization to adjust the published GHG emission estimates to a consistent set of methods and assumptions, specific to the technology under investigation, in two main stages:

- *System harmonization* ensured studies used a consistent set of included processes (e.g., system boundary, set of evaluated GHGs) and metrics (e.g., global warming potentials).
- *Technical harmonization* of key performance parameters (e.g., capacity factor, thermal efficiency) or primary energy resource characteristics (e.g., solar resource, fossil fuel heating value) ensured consistent values that reflect a modern reference system (typically a modern facility operating in the United States).

To date, NREL has completed harmonization of life cycle GHG emissions for wind, PV, CSP, nuclear, and coal technologies, with analysis of natural gas technologies forthcoming.

LCA of Energy Systems

LCA can help determine environmental burdens from "cradle to grave" and facilitate more consistent comparisons of energy technologies.

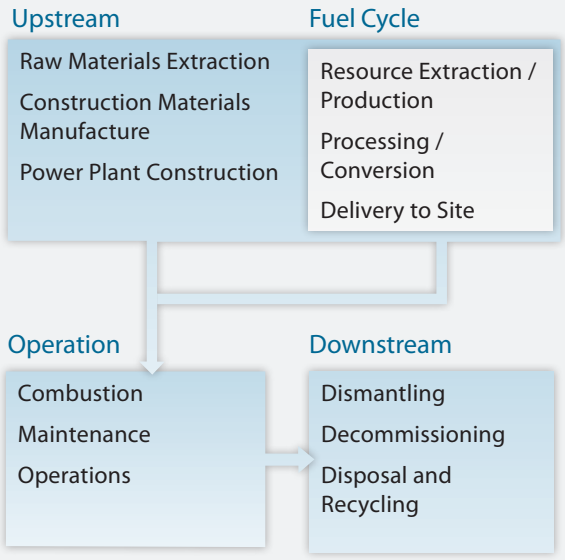

Figure 1. Generalized life cycle stages for energy technologies
Source: Sathaye et al. (2011)

Life cycle GHG emissions from renewable electricity generation technologies are generally less than those from fossil fuel-based technologies, based on evidence assembled by this project. Further, the proportion of GHG emissions from each life cycle stage differs by technology. For fossil-fueled technologies, fuel combustion during operation of the facility emits the vast majority of GHGs. For nuclear and renewable energy technologies, the majority of GHG emissions occur upstream of operation.

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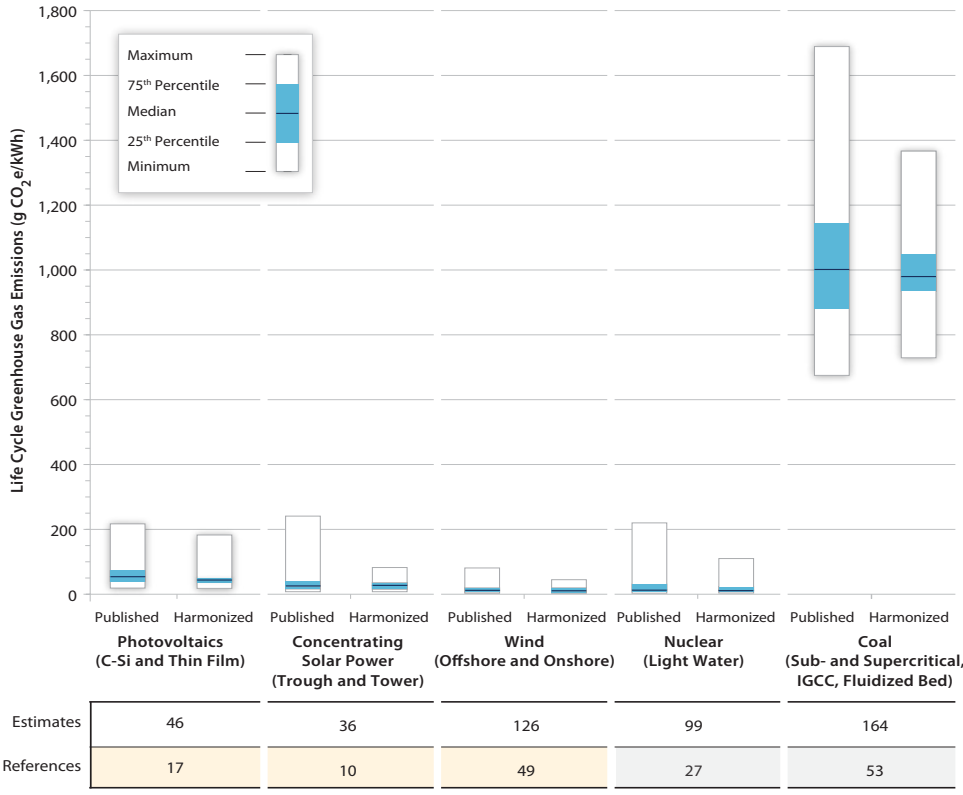

	Photovoltaics (C-Si and Thin Film)	Concentrating Solar Power (Trough and Tower)	Wind (Offshore and Onshore)	Nuclear (Light Water)	Coal (Sub- and Supercritical, IGCC, Fluidized Bed)
Estimates	46	36	126	99	164
References	17	10	49	27	53

Electricity Generation Technology	Photovoltaics (C-Si and Thin Film)	Concentrating Solar Power		Wind (Onshore and Offshore)	Nuclear (Light Water)	Coal (Sub- and Supercritical, IGCC, Fluidized Bed)
		Trough	Tower			
Driving Parameter	Solar Irradiation (kWh/m²/year)	Solar Fraction (%)	Operating Lifetime (years)	Capacity Factor (%)	Operating Lifetime (years)	Carbon Dioxide Emission Factor (kg CO_2/kWh)
Definition	Amount of solar energy incident upon a unit area of collector in the solar field during one year	Percentage of electricity produced only from solar energy	Assumed lifetime for the LCA or facility	Ratio of actual electricity generated to the maximum potential electricity generation	Assumed lifetime for the LCA or facility	Mass of carbon dioxide emitted per kilowatt-hour of net electricity generated—a function of thermal efficiency, coal carbon content, and coal lower heating value
Published Range	900-2,143	75-100	25-40	9-71	25-60	0.64-1.64
Harmonized Value	1700	100	30	Onshore: 30 Offshore: 40	40	0.97

Published and harmonized estimates of life cycle GHG emissions for solar (PV and CSP), wind, nuclear, and coal technologies are compared in the figure on this page. The figure includes the median value, the number of estimates, and the number of references analyzed for each technology. These results show that:

- Total life cycle GHG emissions from renewables and nuclear energy are much lower and generally less variable than those from fossil fuels. For example, from cradle to grave, coal-fired electricity releases about 20 times more GHGs per kilowatt-hour than solar, wind, and nuclear electricity (based on median estimates for each technology).
- Harmonization reduces the variability of GHG emissions estimates to varying degrees (from about 25% to 70%) for the technologies evaluated. The key drivers of variability are a subset of the factors harmonized for each technology, with the most important listed in the table.
- Harmonization has little impact on the median value of the technologies evaluated. A shift of 20% or less was typically observed for analyzed technologies.

Harmonization provides increased precision and helps clarify the impacts of specific electricity generation choices, producing more robust and policy-relevant results. Project developers, investors, manufacturers, and utilities can use harmonized estimates as building blocks to making their own estimates for specific projects or to inform policy and investment decisions.

See also:

- For general information about the LCA Harmonization project: www.nrel.gov/harmonization
- For data visualization and downloading: http://en.openei.org/lca
- For journal articles from the LCA Harmonization Project and other LCA meta-analyses: http://jie.yale.edu/LCA-meta-analysis.

References

Sathaye et al. (2011). "Renewable Energy in the Context of Sustainable Development." In *IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation*, [O. Edenhofer et al. (eds)], Cambridge University Press, 84 pp., http://srren.ipcc-wg3.de/report/IPCC_SRREN_Ch09.pdf/.

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