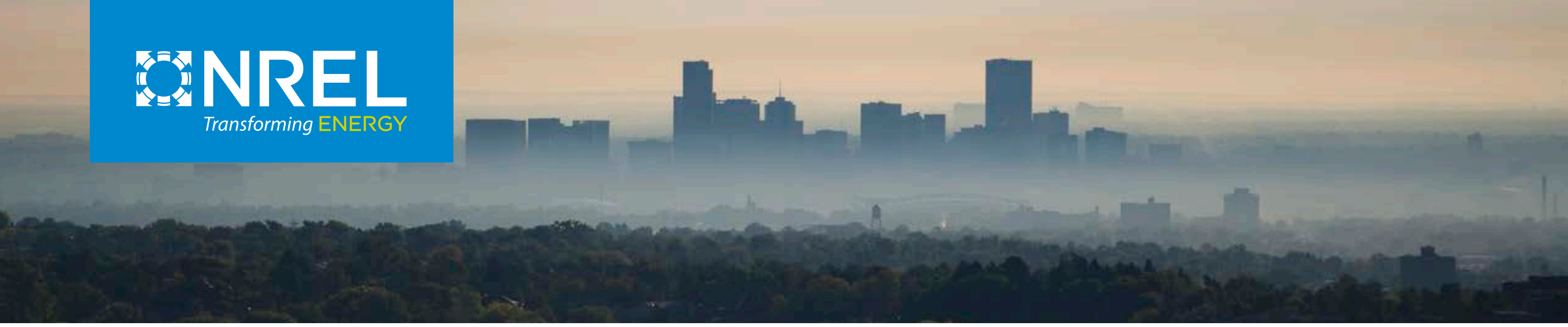


*Photo by Dennis Schroeder, NREL 22610*

# Life Cycle Greenhouse Gas Emissions from Electricity Generation: Update

**As clean energy increasingly becomes part of the national dialogue, lenders, utilities, and lawmakers need the most comprehensive and accurate information on greenhouse gas (GHG) emissions from various sources of energy to inform policy, planning, and investment decisions.**

Since the National Renewable Energy Laboratory (NREL) published original results from the Life Cycle Assessment Harmonization Project (Heath and Mann 2012), it has updated estimates of electricity generation GHG emissions factors as part of several recent studies. This fact sheet updates an earlier version (NREL 2013).

## Systematic Review

NREL considered approximately 3,000 published life cycle assessment studies on utility-scale electricity generation from wind, solar photovoltaics, concentrating solar power, biopower, geothermal, ocean energy, hydropower, nuclear, natural gas, and coal technologies, as well as lithium-ion battery, pumped storage hydropower, and hydrogen storage technologies. A systematic review, comprising three rounds of screening by multiple experts, selected references that met strict criteria for quality, relevance, and transparency. Less than 15% of the original pool of references passed this review process.

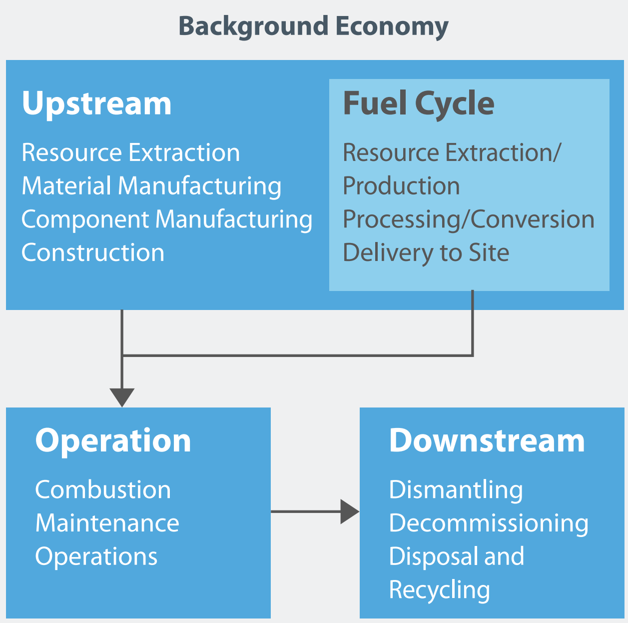
The addition of battery and hydrogen storage technologies introduces a unique set of challenges and assumptions to the compilation of emissions factors. The primary challenges stem from the fact that storage technologies are characterized by two different types of capacity

- Energy Capacity: how much energy a given resource can store, denoted in units of kilowatt hours (kWh)
- Power Capacity: how much energy a given resource can deliver, denoted in units of kilowatts (kW).

## Life Cycle Assessment of Energy Systems

Life cycle assessments (LCA) can help quantify 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 from those from fossil fuel-based technologies, according to evidence assembled from the LCA Harmonization project. Further, the proportion of GHG emissions from each lifecycle 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, most GHG emissions occur upstream of operation.

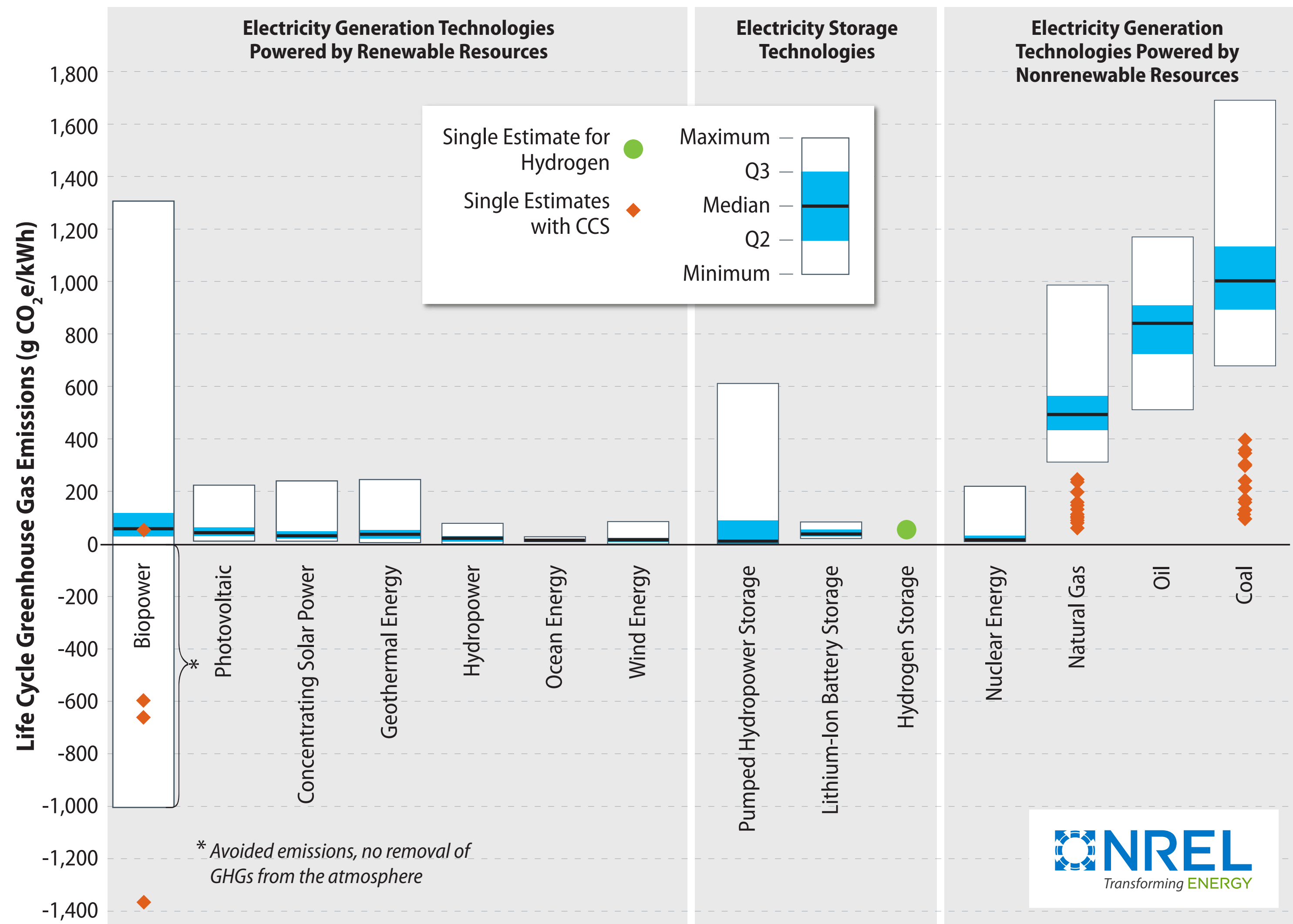
Also, certain storage technologies, especially lithium-ion batteries, can be designed to operate for a variety of grid services, such as time-shifting or frequency regulation. To align the estimates of GHG emissions impacts from the storage technologies with those of other generation technologies, we considered only references that enabled the calculation of emissions per unit of electricity delivered over the lifetime of the storage system. Thus, we have excluded references that report only emissions factors per unit of power capacity.

Published estimates of life cycle GHG emissions for biomass, solar (photovoltaics and concentrating solar power), geothermal, hydropower, ocean, wind (land-based and offshore), nuclear, oil, and coal generation technologies as well as storage technologies are compared in **Figure 2.**

These estimates are drawn from three groups of studies:

- Studies conducted as part of NREL's Life Cycle Assessment Harmonization Project ("Life Cycle Assessment Harmonization," NREL, https://www.nrel.gov/analysis/life-cycle-assessment.html)
- U.S. Department of Energy "vision" studies, including Hydropower Vision (DOE 2016), Wind Vision (DOE 2015), Geothermal Vision (Millstein et al. 2019) and On the Path to SunShot (Wiser et al. 2016)
- Grid-scale lithium-ion battery and hydrogen fuel cell stationary storage literature compiled under the Los Angeles 100% Renewable Energy Study (Nicholson et al. 2021)

**Figure 2. Life cycle greenhouse gas emission estimates for selected electricity generation and storage technologies, and some technologies integrated with carbon capture and storage (CCS).**




| | Biopower | Photovoltaic | Concentrating Solar Power | Geothermal Energy | Hydropower | Ocean Energy | Wind Energy | Pumped Hydropower Storage | Lithium-Ion Battery Storage | Hydrogen Storage | Nuclear Energy | Natural Gas | Oil | Coal |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Estimates** | 276 (+4) | 46 | 36 | 35 | 149 | 10 | 186 | 16 | 29 | 1 | 99 | 80 (+13) | 24 | 164 (+11) |
| **References** | 57 (+2) | 17 | 10 | 15 | 22 | 5 | 69 | 4 | 3 | 1 | 27 | 47 (+11) | 10 | 53 (+9) |

**Notes for Figure 2**: The number of estimates is greater than the number of references because many studies considered multiple scenarios. Numbers reported in parentheses pertain to additional references and estimates that evaluated technologies with CCS.

**Table 1** includes the median values for four life cycle phases (one-time upstream (e.g., materials acquisition and plant construction), ongoing combustion (where applicable), ongoing noncombustion (e.g., operation and maintenance), and one-time downstream (e.g., plant decommissioning and disposal/recycling)) as well as a total life cycle emissions factor. 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, or nuclear electricity (based on median estimates for each technology).

Note that because different numbers of references may be used in the calculation of each entry in Table 1, the sum of the median estimates of each life cycle phase for a given generation technology might not equal the median of the total life cycle emissions factors (the sum of the medians need not equal the median of the sums). Indeed, the sum of the individual phase median values may be greater than the median total, as is the case with concentrating solar power.

**Table 1. Median Published Life Cycle Emissions Factors for Electricity Generation Technologies, by Life Cycle Phase**

| | Generation Technology | One-Time Upstream | Ongoing Combustion | Ongoing Non Combustion | One-Time Downstream | Total Life Cycle | Sources |
|---|---|---|---|---|---|---|---|
| Renewable | Biomass | NR | — | NR | NR | 52 | EPRI 2013<br>Renewable Electricity Futures Study 2012 |
| Renewable | Photovoltaic[a] | ~28 | — | ~10 | ~5 | 43 | Kim et al. 2012<br>Hsu et al. 2012<br>NREL 2012 |
| Renewable | Concentrating Solar Power[b] | 20 | — | 10 | 0.53 | 28 | Burkhardt et al. 2012 |
| Renewable | Geothermal | 15 | — | 6.9 | 0.12 | 37 | Eberle et al. 2017 |
| Renewable | Hydropower | 6.2 | — | 1.9 | 0.004 | 21 | DOE 2016 |
| Renewable | Ocean | NR | — | NR | NR | 8 | IPCC 2011 |
| Renewable | Wind[c] | 12 | — | 0.74 | 0.34 | 13 | DOE 2015 |
| Storage | Pumped-storage hydropower | 3.0 | — | 1.8 | 0.07 | 7.4 | DOE 2016 |
| Storage | Lithium-ion battery | 32 | — | NR | 3.4 | 33 | Nicholson et al. 2021 |
| Storage | Hydrogen fuel cell | 27 | — | 2.5 | 1.9 | 38 | Khan et al. 2005 |
| Nonrenewable | Nuclear[d] | 2.0 | — | 12 | 0.7 | 13 | Warner and Heath 2012 |
| Nonrenewable | Natural gas | 0.8 | 389 | 71 | 0.02 | 486 | O'Donoughue et al. 2013 |
| Nonrenewable | Oil | NR | NR | NR | NR | 840 | IPCC 2011 |
| Nonrenewable | Coal | <5 | 1010 | 10 | <5 | 1001 | Whitaker et al. 2012 |

### Notes for Table 1

All values are in grams of carbon dioxide equivalent per kilowatt-hour (g $CO_2e$/kWh)

[a] Thin film and crystalline silicon

[b] Tower and trough

[c] Land-based and offshore

[d] Light-water reactor (including pressurized water and boiling water) only

NR = Not Reported.

**Funding for this fact sheet was provided by the Joint Institute for Strategic Energy Analysis in support of its Energy and Atmospheric Systems Catalyzer, a collaborative effort that explores the multidirectional relationships across climate, air quality, and energy systems.**

### See Also

General information about life cycle assessments: "Life Cycle Assessment Harmonization," NREL, https://www.nrel.gov/analysis/life-cycle-assessment.html

Data visualization and data downloads: "LCA Harmonization," OpenEI, https://openei.org/apps/LCA/

Additional distributional statistics and subtechnology emissions factors augmenting Table 1: https://data.nrel.gov/submissions/171

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