Meta-Analysis of Estimates of Life Cycle Greenhouse Gas Emissions from Concentrating Solar Power

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META-ANALYSIS OF ESTIMATES OF LIFE CYCLE GREENHOUSE GAS EMISSIONS FROM CONCENTRATING SOLAR POWER

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Abstract

In reviewing life cycle assessment (LCA) literature of utility-scale CSP systems, this analysis focuses on clarifying central tendency and reducing variability in estimates of life cycle greenhouse gas (GHG) emissions through a meta-analytical process called harmonization. From 125 references reviewed, 10 produced 36 independent GHG emission estimates passing screens for quality and relevance: 19 for parabolic trough technology and 17 for power tower technology. The interquartile range (IQR) of published GHG emission estimates was 83 and 20 g CO_2eq/kWh for trough and tower, respectively, with medians of 26 and 38 g CO_2eq/kWh.

Two levels of harmonization were applied. Light harmonization reduced variability in published estimates by using consistent values for key parameters pertaining to plant design and performance. Compared to the published estimates, IQR was reduced by 69% and median increased by 76% for troughs. IQR was reduced by 26% for towers, and median was reduced by 34%. A second level of harmonization was applied to five well-documented trough LC GHG emission estimates, harmonizing to consistent values for GHG emissions embodied in materials and from construction activities. As a result, their median was further reduced by 5%, while the range increased by 6%. In sum, harmonization clarified previous results.

Keywords: parabolic trough, central receiver, power tower, dish stirling, life cycle assessment, meta-analysis

1. Introduction

Life cycle assessment (LCA) is well-recognized as a holistic and standard approach for quantifying environmental impacts of renewable energy technologies because they characteristically do not emit significant quantities of greenhouse gases (GHGs) during their operation. LCAs account for the impacts resulting from all activities that transpire over the life of a power plant, including those that are upstream and downstream from their operation. After an exhaustive literature search, many published LCAs were identified that estimate the life cycle (LC) GHG emissions of the three CSP technologies in greatest use today: parabolic trough (trough), power tower (tower), and parabolic dish (dish). Currently, significant variability can be found in estimates of LC GHG emissions reported in the CSP LCA literature, which is caused by a range of factors including the type of technology being investigated, scope of analysis, assumed performance characteristics, location, data source, and the impact assessment methodology used.

Aims of the present meta-analysis include identifying, explaining, and, where possible, reducing—through a meta-analytical process called "harmonization"—variability in as-published estimates of LC GHG emissions for utility-scale CSP systems. This was accomplished by establishing more consistent methods and assumptions between LCA studies. The purpose of this analysis (and its umbrella project that examines other electricity generation technologies, the LCA Harmonization Project of the United States' National Renewable Energy Laboratory which is supported by the Office of Energy Efficiency and Renewable Energy of the US Department of Energy) is to clarify estimates of central tendency and to reduce variability of estimates to better inform decision making and future analyses that rely on such estimates. The reader should keep in mind, however, the LC GHG emissions of a specific power plant will depend on many factors and could legitimately differ from the generic estimates generated by the harmonization approach described herein.

Three major LC phases are defined for the purposes of this study, with typical CSP activities listed:

- Upstream processes: extraction of raw materials, materials manufacturing, component manufacturing, site improvements, and plant assembly.
- Operational processes: manufacture of replacement components and their transportation to the site, fuel consumption in cleaning/maintenance vehicles, on-site natural gas combustion, and electricity consumption from the regional power grid.
- Downstream processes: plant disassembly and disposal or recycling of plant materials.

2. Harmonization Methods

2.1. Literature Collection/Screening Approach

An exhaustive search of English-language literature yielded 125 references pertaining to the environmental impacts of CSP electricity generation. Multiple GHG emission estimates from a single reference were possible if alternative CSP electricity generation scenarios or technologies were analyzed. Although a reference wasn't necessarily eliminated if only one of its estimates was screened out, most screening criteria applied to the reference as a whole, therefore the results of screening are reported at the level of the reference.

Through multiple screening steps, studies were assessed with regard to the quality of the LCA and GHG emission accounting methods (including a requirement that 2 of the 3 major LC phases were evaluated), the completeness of reporting including the inputs and the results of the analysis, and the modern or near-future relevance of the technology. Only GHG emission estimates that were reported numerically (i.e., not only graphically) and provided sufficient detail on the analyzed system to evaluate the reasonableness of the data were included for harmonization. Duplicate estimates from one study quoting another or from the same author group publishing the same estimate multiple times were not retained for analysis.

Surviving the screens were a total of 13 references that provided 42 GHG emission estimates (19 trough, 17 tower, and 6 dish). Because the pool of literature for dish CSP only provided six LC GHG emission estimates after screening, this paper will focus on the results obtained for the trough and tower technologies. Thus, 36 estimates for trough and tower systems were evaluated with a first level of harmonization (Table 1). A more intensive level of harmonization requires more complete documentation of inputs and assumptions, for which five trough studies providing five estimates were selected (Table 2).

2.2. Harmonization Approach

Two levels of harmonization were devised. The first level harmonizes at a more gross level the entire set of literature estimates of LC GHG emissions passing screens. It does so by proportional adjustment of the estimate of LC GHG emissions to consistent values for several influential performance characteristics and, by addition or subtraction, to a common system boundary (at the level of major LC stage). For brevity, we refer to this first level of harmonization as "light" harmonization.

The second, more resource-intensive level of harmonization was reserved for those studies that completed the light harmonization process and passed the additional screen for exceptional documentation of LCI data. Because the LC GHG emissions of CSP technologies are typically not dominated by the combustion of fossil fuels, unlike coal and natural gas, the embodied GHG emissions of plant materials and emissions from construction and decommissioning represent the majority of total LC GHG emissions. Therefore, the goal of this second level of harmonization is to further reduce variability in the published estimates of LC GHG emissions by selecting consistent global warming intensity (GWI – defined in section 2.4) values for all items reported in the LCI of each of the five studies which passed the additional screening process. From this point forward, we will refer to this second level of harmonization as, "GWI Harmonization."

Throughout the screening and harmonization process, estimates were not audited for accuracy and no exogenous assumptions were employed.

2.3. Light Harmonization Parameters

Several characteristics pertaining to scope and plant performance are reported in nearly all studies and can be extracted with minimal effort—these characteristics act as light harmonization parameters. Table 1 reports the as-published values of the parameters used for light harmonization and other important characteristics of each study. Each light harmonization parameter was set to a standardized value and used to calculate a new, harmonized LC GHG emission estimate. If the value for a harmonization parameter was not reported, that harmonization step was not applied to that estimate. The description of each parameter and the value selected for light harmonization are listed below.

Solar Fraction: The percentage of electricity produced only from solar energy. A CSP facility with a solar fraction of 1 (or 100%) is defined here as a "solar-only" operating plant. A facility with a solar fraction less than 1 is a "hybrid" operating plant that combusts natural gas (hereafter referred to as natural gas co-firing) to generate a portion of its electrical output. The harmonization value for solar fraction was chosen to be 100% to better estimate the GHG emissions resulting from a solar-only CSP plant.

Direct Normal Irradiance (DNI): The amount of solar energy per unit area incident upon the collector area of the solar field during one year. The harmonization value for DNI was chosen to be 2400 kWh/m2/yr. This value was not chosen to be reflective of any one location, but rather is a "high" quality solar resource (CSP developers typically require about 2,000 kWh/m2/yr to justify construction) [1] that is incident upon thousands of square kilometers in several global locations, including areas in northern Africa, Australia, central South America, northern China, the Middle East, and the southwest U.S. [2].

Lifetime: The assumed life span of the power plant used for the LCA analysis. The harmonization value for lifetime was chosen to be 30 years. This 30 year lifetime duration is frequently used in CSP LCA and in economic analyses of CSP plants (e.g., [3]).

Solar-to-Electric Efficiency: The percentage of solar energy converted to electricity at the CSP facility. The harmonization values for solar-to-electric efficiency are chosen to be 15%, 20%, and 25%, for trough, tower, and dish technologies, respectively. These solar-to-electric efficiencies are representative of current state-of-the-art designs for each technology [1].

Global Warming Potentials (GWPs): A metric used to measure the radiative forcing of a given GHG over a 100-year time period relative to that of CO_2 ($GWP_{CO2} = 1$). The GWPs of two major GHGs, methane (CH_4) and nitrous oxide (N_2O), were harmonized by updating the GWP values to those reported in the latest IPCC assessment report [4].

Auxiliary Natural Gas Combustion: Natural gas used during miscellaneous O&M activities, such as heat transfer fluid (HTF) freeze protection activities and system start-up procedures. This auxiliary natural gas use, which does not include co-fired natural gas, is often neglected in CSP LCAs, especially those which evaluate solar-only plants. Therefore, the published system boundaries have, in many cases, been expanded to include auxiliary natural gas combustion. Auxiliary natural gas use is estimated using the value assumed in [5]. Because the only estimate for auxiliary natural gas combustion was representative of trough technology, this system boundary expansion was applied only to trough estimates, as the uses of auxiliary natural gas will vary by technology. The harmonization value for auxiliary natural gas combustion was chosen to be 91,000 MJ/MW of installed capacity per year of operation.

Auxiliary Electricity Consumption: Electricity drawn from the regional grid used to satisfy the plant's parasitic load when the plant is not generating its own power. Like auxiliary natural gas, this too is often neglected in LCAs of CSP plants; therefore, published system boundaries have, in many cases, been modified to include operational electricity consumption. Auxiliary electricity consumption is estimated using the only two values reported in the pool of 13 quality-screened trough references: [6] reports an electricity consumption rate of 327 MWh/MW per year while [5] reports 36 MWh/MW per year. Because it is unclear what causes the discrepancy between the two electricity consumption values, the average (181 MWh/MW/yr) is taken as the harmonization value, although a sensitivity analysis is also conducted on the wide range in estimates. Like auxiliary natural gas, since the only estimates for auxiliary electricity consumption are representative of trough technology, this system boundary expansion is applied only to trough estimates.

Equation 1 displays how most of the above-listed parameters are used to estimate life cycle GHG emissions

$$GHG_{light} = \frac{\sum_{n=1}^{3} GHG_n GWP_n}{E(\eta, DNI, t)} \qquad (1)$$

where, the numerator of equation 1 is sum of the three major GHGs (CO_2, CH_4, N_2O) emitted during the plant's LC, converted to carbon dioxide equivalents using up-to-date GWPs. The denominator of equation1 is the LC energy output from the plant and is a function of solar-to-electric efficiency (η), DNI, and lifetime (t). In general, the as-published LC GHG emission values are harmonized through two main operations:

- Multiplying the denominator of equation 1 by the ratio of the harmonized parameter value and the published parameter value
- Adding or subtracting GHG emissions from the numerator or energy output from the denominator.

2.4. GWI Harmonization

Although there are several additional aspects of a LCA that could be addressed during more intensive harmonization, all cannot be addressed due to limitations in data availability and documentation. The embodied emissions of plant materials and other construction activities reported in the LCI are important variables that strongly influence the total LC GHG emissions of a CSP plant. Because there may be dozens of unique materials and processing activities reported in the LCI of a study, each with its own GWI, even small inconsistencies in the GWI may lead to significant variability in the final LC GHG emission value. To address this source of variability, we selected consistent values for the GWI of each material and construction activity in each of the five studies' LCIs.

GWIs are defined as the mass of GHGs emitted from the production of common materials and from other activities (e.g., transportation, diesel burned in building machines) per functional unit (e.g., mass of material, unit distance transported). With the exception of the nitrate salt storage medium and the synthetic oil heat transfer fluid (HTF), the GWI of all other LCI entries were estimated using unit processes from the EcoInvent v2.0 LCI database [7]. The EcoInvent LCI database is commonly accepted as one of the industry's leading databases and contains up-to-date information that is thoroughly documented and peer reviewed. Because it is the only electrical infrastructure common to all entries in the EcoInvent database, all materials that undergo harmonization are assumed to use the average U.S. electricity generation profile. Using engineering judgment, each material in the LCIs of the five studies was paired with an EcoInvent entry (or [5]).

The GWIs of nitrate salts and HTF were estimated using values reported in [5], which were obtained directly from manufacturers, to improve the accuracy of their GWIs compared to the use of EcoInvent. Nevertheless, there are uncertainties in the use of the manufacturers' data; see [5] for further discussion. Using the GWI harmonization approach outlined here, not only are GWIs of common materials made consistent but are also updated to the latest available information. Table 2 lists the five studies selected for GWI harmonization and the LCI database used.

Because GWI harmonization is labor intensive, it was decided to focus resources on just one CSP technology. Trough was selected because it had the most LC GHG emission estimates that provided the documentation necessary for GWI harmonization. In addition, troughs account for the largest share of the current CSP market [1].

3. Results and Discussion

Of 125 references identified in an exhaustive literature search, 10 references related to trough and tower systems passed screens to provide a total of 36 LC GHG emissions estimates for two CSP technologies: 19 for trough technology and 17 for tower.

The IQR of the published LC GHG emission estimates was 83 and 20 g CO_2eq/kWh for trough and tower, respectively. The median of the published estimates was 26 and 38 g CO_2eq/kWh for trough and tower, respectively.

The harmonization parameter that is most effective in reducing variability in the published LC GHG emission estimates for trough CSP is the solar fraction. When applied independently, the IQR decreases by 85% after solar fraction harmonization. Two factors contributed to the magnitude of the decrease: high LC GHG emissions from natural gas co-firing compared to solar-only CSP, and the relatively large fraction of the trough literature evaluating hybrid plants. As for the published LC GHG emission estimates for towers, because only 2 references (providing 2 LC GHG emissions estimates) evaluated hybrid plants, the largest reduction in IQR results from the lifetime harmonization step (-25%). This reduction is realized because 9 of the 17 LC GHG emissions estimates for towers assume a lifetime less than 30 years, while only 2 estimates assume a lifetime greater than 30 years.

The harmonization parameter that has the most significant impact on central tendency is the addition of auxiliary electricity consumption; the median estimate of LC GHG emissions for trough estimates increase by 50% from application of this harmonization step alone. Because of its influence on total LC GHG emissions, a bounding sensitivity analysis was applied to the estimate of consumed electricity that was assumed for trough systems for the purposes of harmonization, resulting in median values of LC GHG emissions ranging from 31 to 69 g CO_2eq/kWh based on light harmonization.

Harmonizing the as-published data cumulatively by all of the harmonization parameters decreases the trough IQR by 69% (to 26 g CO_2eq/kWh) and increases median by 76% (to 46 g CO_2eq/kWh). As for the tower dataset, IQR and median are reduced by 26% (to 15 g CO_2eq/kWh) and 34% (to 25 g CO_2eq/kWh), respectively. The median value of LC GHG emissions for trough technology increases significantly due to most previous studies neglecting to account for auxiliary electricity consumption, which has been found to contribute a significant portion of LC GHG emissions [5]. The harmonized estimate of LC GHG emissions for tower systems would likely increase similarly if harmonization for electricity consumption were undertaken, where a lack of data prevented this step from being applied.

A second, more resource-intensive level of harmonization (GWI harmonization) was applied to five LC GHG emissions estimates of troughs, which provided sufficient documentation to carry out additional analysis. By harmonizing the values of GWIs for each material and construction activity provided in the LCI of each study, the median value of the 5 LC GHG emissions was reduced by an additional 5% (to 69 g CO_2eq/kWh), while the range increased by 6% (to 49 g CO_2eq/kWh), compared to the results of light harmonization. When these results are pooled with the remaining 14 LC GHG emissions estimates obtained from light harmonization, the results from GWI harmonization reduce the IQR by an additional 9%.

5. Conclusion

Published estimates of LC GHG emissions from CSP passing screens ranged from near zero to nearly 250 g CO_2eq/kWh, leading to confusion over CSP's GHG emission profile and relative benefits compared to fossil-fueled generation technologies. By adjusting published estimates to consistent gross system boundaries and to consistent values for key input parameters, the meta-analytical process called harmonization clarifies the existing literature in ways useful for decision-makers and analysts. The median estimate of life cycle GHG emissions from parabolic trough CSP after harmonization is 69 g CO_2eq/kWh and for power tower CSP is 25 g CO_2eq/kWh. The difference is mainly due to one aspect of CSP plant operation – auxiliary electricity consumption – that could not be included in harmonization for tower systems owing to lack of data. Variability, as indicated by the IQR, for trough CSP estimates was reduced by more than 70% while for tower CSP the IQR was reduced by 26%. Greater reduction in variability through harmonization of the trough estimates results from the fact that more trough LCAs evaluated hybrid CSP plant designs than tower LCAs. Furthermore, both CSP technologies have characteristic life cycle GHG emissions significantly below those for fossil fueled electricity generation technologies [19].

The LC GHG emissions of a specific power plant will depend on many factors and could legitimately differ from the generic estimates generated by the harmonization approach, but the results presented in this article provide a useful first approximation of LC GHG emissions for generic CSP facilities.

#	Ref.	Pub. Year	Tech.	Cap. (MW)	C.F. (%)	S.F. (%)	DNI ($kWh/m^2/yr$)	Life (yrs)	Eff. (%)	Temp. Vint.	Data Type	Study Loc.
1	[8]	2006	1	50	37	76	2,373	30	14	H	T	USA
2	[5]	2011	1	103	47	100	2,724	30	16	H	T	USA
3	[5]	2011	1	103	49	100	2,724	30	15	H	T	USA
4	[5]	2011	1	103	47	100	2,724	30	16	H	T	USA
5	[5]	2011	1	103	47	100	2,724	30	16	H	T	USA
6	[5]	2011	1	103	47	100	2,724	30	16	H	T	USA
7	[9]	2006	1	10^4	88	100	2,835	30	12	F	T	DZA
8	[9]	2006	1	10^4	87	100	2,802	30	12	F	T	EGY
9	[9]	2006	1	10^4	89	100	2,865	30	12	F	T	LBY
10	[6]	2008	1	50	44	85	2,016	25	16	H	T	ESP
11	[10]	1997	1	80	35	75	NR	30	NR	C	T	USA
12	[11]	2008	1	50	44	82	2,000	30	15	C	T	ESP
13	[11]	2008	1	200	73	100	2,000	35	16	F	T	ESP
14	[11]	2008	1	200	73	100	2,000	35	16	F	T	ESP
15	[11]	2008	1	400	73	100	2,000	40	16	F	T	ESP
16	[11]	2008	1	400	73	100	2,000	40	16	F	T	ESP
17	[11]	2008	1	200	73	100	2,000	35	19	F	T	ESP
18	[11]	2008	1	400	73	100	2,000	40	19	F	T	ESP
19	[12]	1998	1	80	36	75	2,300	30	14	C	T	USA
20	[13]	1990	2	100	40	100	2,848	30	19	C	T	USA
21	[6]	2008	2	17	71	85	1,997	25	17	H	T	ESP
22	[14]	1999	2	100	38	100	2,500	25	16	C	T	AUS
23	[14]	1999	2	100	38	100	2,500	25	16	C	T	AUS
24	[14]	1999	2	30	26	100	2,500	25	15	F	T	AUS
25	[14]	1999	2	100	35	100	2,500	25	18	F	T	AUS
26	[14]	1999	2	30	26	100	2,500	25	15	F	T	AUS
27	[14]	1999	2	100	35	100	2,500	25	18	F	T	AUS
28	[14]	1999	2	30	26	100	2,500	25	15	F	T	AUS
29	[14]	1999	2	100	35	100	2,500	25	18	F	T	AUS
30	[15]	1992	2	100	38	100	1,914	30	20	H	T	USA
31	[11]	2008	2	15	71	82	2,000	30	16	C	T	ESP
32	[11]	2008	2	180	73	100	2,000	35	18	F	T	ESP
33	[11]	2008	2	180	73	100	2,000	40	18	F	T	ESP
34	[12]	1998	2	30	30	75	2,300	30	14	C	T	N/A
35	[12]	1998	2	30	36	63	2,300	30	14	C	T	N/A
36	[12]	1998	2	30	36	75	2,300	30	14	C	T	N/A

Abbreviations: # = scenario number; Ref. = reference number; Pub. Year = year of publication for the given reference; Tech. = technology type. 1 = trough, 2 = tower, 3 = parabolic dish; Cap. = capacity; C.F. = capacity factor; S.F. = solar fraction; DNI = direct normal irradiance; Life = lifetime; Eff. = solar-to-electric efficiency; Temp. Vint. = temporal vintage (C = existing technology case study, H = existing technology hypothetical study, F = future technology); Data type: E = primarily empirical data, T = primarily theoretical data; Study Loc. = primary country or location for the study based on United Nations 3-letter codes [16]; "NR," or "not reported," indicates no value reported for that parameter.

Table 1: Published values of light harmonization parameters and other important characteristics of studies that passed quality and relevance screens.

Scenario	Author	Pub. Year	LCI Database
2	Burkhardt	2011	EcoInvent v2.0 [7]
10	Lechon	2008	EcoInvent v1.2 [7]
11	Martin	1997	TEMIS [17]
12	Viebahn	2008	EcoInvent v1.3 [7]
19	Weinrebe	1998	ETH Zurich [18]

Scenario corresponds to the scenario number, as shown in Table 1. Pub. Year = Publication year.

Table 2: List of references used in GWI harmonization and their LCI database.

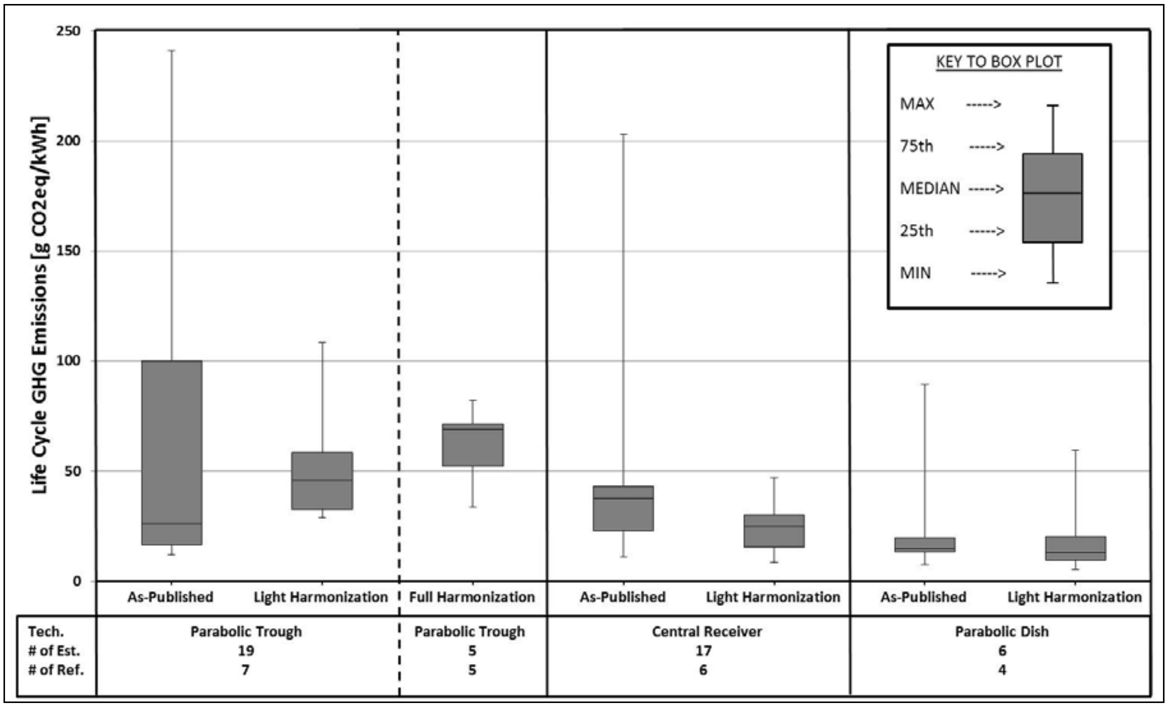

Figure 1: As-published and harmonized box plots for all CSP electricity generation technologies.

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