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Life Cycle Assessment of a Parabolic Trough Concentrating Solar Power Plant and the Impacts of Key Design Alternatives

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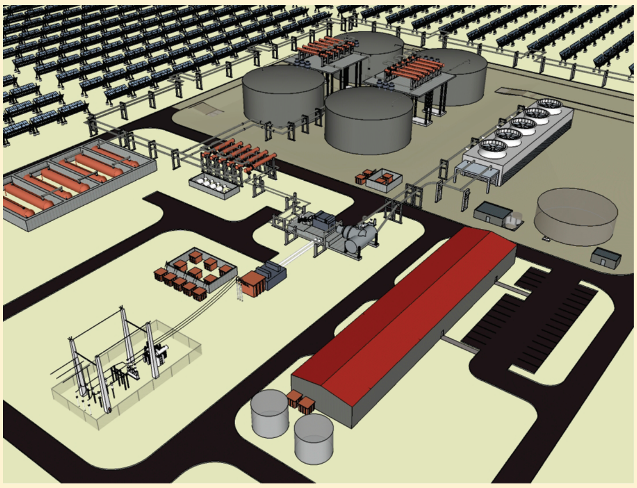
Supporting Information



ABSTRACT: Climate change and water scarcity are important issues for today's power sector. To inform capacity expansion decisions, hybrid life cycle assessment is used to evaluate a reference design of a parabolic trough concentrating solar power (CSP) facility located in Daggett, CA, along four sustainability metrics: life cycle (LC) greenhouse gas (GHG) emissions, water consumption, cumulative energy demand (CED), and energy payback time (EPBT). This wet-cooled, 103 MW plant utilizes mined nitrates salts in its two-tank, thermal energy storage (TES) system. Design alternatives of dry-cooling, a thermocline TES, and synthetically derived nitrate salt are evaluated. During its LC, the reference CSP plant is estimated to emit 26 g of CO_{2eq} per kWh, consume 4.7 L/kWh of water, and demand 0.40 MJ_{eq}/kWh of energy, resulting in an EPBT of approximately 1 year. The dry-cooled alternative is estimated to reduce LC water consumption by 77% but increase LC GHG emissions and CED by 8%. Synthetic nitrate salts may increase LC GHG emissions by 52% compared to mined. Switching from two-tank to thermocline TES configuration reduces LC GHG emissions, most significantly for plants using synthetically derived nitrate salts. CSP can significantly reduce GHG emissions compared to fossil-fueled generation; however, dry-cooling may be required in many locations to minimize water consumption.

INTRODUCTION

Motivation. Operational carbon dioxide (CO_2) emissions from the United States (U.S.) electric power sector constitute 40% of energy-related CO_2 emissions in 2009, 98% from combustion of coal and natural gas.[1] Thermoelectric power was responsible for 41% of all U.S. freshwater withdrawals in 2005, the largest end-use sector.[2] As a result of climate change, water scarcity and drought will likely become more widespread during the 21st century,[3] and nearly one-third of all U.S. counties may face a higher risk of water shortages by midcentury.[4] An important challenge is to identify technologies that deliver electricity services while minimizing both greenhouse gas (GHG) emissions and use of locally finite freshwater resources. To inform capacity expansion decisions, this research quantifies the GHG emissions and water consumption of a representative parabolic trough (trough) concentrating solar power (CSP) plant.

CSP Design Alternatives and Life Cycle Assessment (LCA). CSP is expected to play an important role in diversifying the U.S. electricity generation portfolio. Currently, there are 8700 MW of new contracts signed in the southwest U.S.,[5] federal investments have granted up to $62 million for research and development,[6] and 55 GW of CSP are projected to be deployed in the U.S. by 2050.[7] Trough CSP technology, one of several major CSP designs, utilizes line-focusing parabolic mirrors to concentrate direct normal insolation (DNI) onto a receiver tube containing heat transfer fluid (HTF). The HTF, typically a synthetic oil, is heated in the solar field and circulated to the power block where it drives a steam cycle. Plants that incorporate thermal energy storage (TES) move heat from the HTF to a storage medium, typically a blend of nitrate salts (hereafter referred to as salts), which is stored in insulated tanks.

Current standard TES design utilizes an indirect, two-tank configuration.[8] In this design, pumps move a mixture of molten salts from a "cold" tank through a series of heat exchangers, where heat is transferred from the HTF to the salts and into the "hot" tank. The hot tank stores thermal energy, which can be subsequently removed from storage to smooth fluctuations in power output during cloud episodes and to extend power generation after sunset. An alternative to the two-tank configuration is a thermocline system. This design maintains a thermal gradient within a single tank and replaces much of the salts with low-cost quartzite rock and sand.

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A common mixture of salts used in TES applications is 60 wt % sodium nitrate and 40 wt % potassium nitrate, also known as "solar salt".[9] These compounds can be mined or produced synthetically, with mined salts reported to currently represent at least 60% of the market share of salts used in TES applications.[10] The process of manufacturing salts synthetically is energy intensive, considerably more so than for mining. Therefore, it is important to consider both sources when determining the environmental impacts of a CSP plant with TES.

Conventionally, steam cycles employ wet-cooling systems that reject heat to the environment using evaporative cooling towers. This cooling method achieves high steam cycle efficiencies but has high water consumption rates. The water consumption rate of wet cooling is problematic for CSP because ideal locations identified for CSP deployment (the southwest U.S.) are also the most susceptible to water supply constraints.[11] Consequently, an alternative method of cooling—dry cooling—is being considered by major solar developers for future CSP plants.[12] Dry-cooling systems use an array of fans to force air over a network of heat exchangers, also known as an air-cooled condenser (ACC). This method of cooling eliminates the need for cooling tower makeup water, thus dramatically reducing operational water consumption but resulting in a less efficient steam cycle.[13]

LCA is recognized as a holistic and standard approach for quantifying environmental impacts of renewable energy (RE) technologies. LCA accounts for the impacts resulting from upstream and downstream activities over the life cycle (LC) of a power plant. Broadly, there are three methods used to conduct a LCA: (1) a "process-based" approach, in which a system is modeled from the "bottom up" using component masses and process energy flows; (2) a "top down" approach, where categories of costs are translated to environmental impacts via economic input−output (EIO) matrices and national-average emissions data for each affected industry; and (3) a hybrid approach, which combines both methods.

The goals of this study are to use hybrid LCA to expand on the limited literature that estimates the environmental impacts of CSP plants and, for the first time, to compare the environmental performance of several important design alternatives for trough CSP plants and quantify the plant's LC water consumption. Quantified metrics of environmental performance include LC GHG emissions, water consumption, cumulative energy demand (CED), and the resultant energy payback time (EPBT). The design alternatives evaluated and compared herein include (1) wet versus dry cooling, (2) two-tank indirect versus thermocline indirect TES systems, and (3) mined versus synthetic nitrate salt storage media.

Several studies have evaluated LC environmental impacts of CSP plants (e.g., refs 14−18); however, most evaluated CSP facilities that are not representative of those being built in the U.S. today. This is the first detailed LCA to be conducted on a U.S.-based system in over a decade and reflects modern plant designs.

METHODS

Scope. The temporal vintage of the CSP plant design is the year 2010 and the geographic reference is Daggett, CA, U.S., whose annual DNI is among the highest in the U.S. (approximately 2700 kWh/m^2).[19] The plant is assumed to operate for 30 years.[13] Following the guidelines described in the international standard series ISO 14040−44,[20] our hybrid LCA evaluates the following LC phases of the hypothetical trough plant.

- Manufacturing: extraction of raw materials, transportation to the manufacturing facility, component manufacturing processes, and transportation of the final product to regional storage.
- Construction: activities associated with site improvements, transporting components to the site, and plant assembly.
- Operation and maintenance (O&M): manufacture of replacement components and their transportation to the site, water consumption in the power block and for mirror cleaning, fuel consumption in cleaning/maintenance vehicles, on-site natural gas combustion, and electricity consumption from the regional power grid.
- Dismantling: energy required to disassemble the major CSP plant systems.
- Disposal: energy required to transport demolition waste to the landfill, incinerator, recycling plant, or re-manufacturer and the energy required for final disposal. So as not to underestimate environmental impacts resulting from disposal, benefits accrued from recycling are allocated using the "cut-off" method.[21] By this "closed-loop" method, no credit is gained for displacing production of virgin materials at disposal; rather, impacts that would have resulted from land filling or incineration of a material are avoided.Infrastructure used in the transportation of materials, construction, and dismantling of the plant is amortized over the infrastructure element's useful lifetime.

Life cycles of the following systems are evaluated to identify areas of high impact.

- HTF system: the HTF, header piping, nitrogen ullage system, and circulation pumps.
- Solar field system: frames, mirrors, heat collection elements (HCEs), tracking, controls, drive systems, and foundations.
- TES system: storage media, tanks, foundations, insulation, piping, heat exchangers, and pumps.
- Power plant system: components typically associated with the power block (e.g., turbine generator set), in addition to other balance-of-plant components, such as buildings, roads, and parking lots.

SimaPro v7.1[22] LCA modeling software and the EcoInvent life cycle inventory (LCI) database[23] were used throughout this study. Employing engineering judgment, materials specified in the reference plant design have been paired with an EcoInvent process to provide GHG emissions, energy flows, and embodied water when primary data were not available. An EIO LCA tool[24] was used to estimate LC burdens of select components and systems, including pumps, compressors, turbine generator set, and miscellaneous controls and electronic equipment (see Supporting Information). Costs of these components were extracted from primary data sources[13] and used as inputs to the U.S. 2002 Industry Benchmark EIO-LCA model.[24]

LC metrics are normalized to a functional unit of 1 kWh generated. The method by which each LC metric is evaluated is described below.

- GHGs: Emissions of individual GHGs from the CSP plant LC are presented as the sum of each GHG weighted by its 100-year global warming potential (GWP)[3] to obtain grams of CO_2 equivalents (g CO_{2eq}/kWh).
- Water consumption: LC water consumption is calculated by summing the volume of surface and groundwater consumed in all LC stages per unit of electricity generated (L/kWh).

Table 1. Specifications of Wet- (Reference Plant) and Dry-Cooled Designs [13]

	wet	dry	units
gross capacity	118	120.5	MW
parasitics (at design point)	15	17.6	MW
net capacity	103	103	MW
Rankine cycle efficiency	37.4	35.4	%
annual generation	426 700	438 800	MWh
capacity factor	0.47	0.49	
grid electricity consumption	3700	3990	MWh/yr
natural gas consumption	8900	15 600	MMBtu/yr
solar field aperture area	987 500	1 063 000	m^2
HTF mass	4270	4600	metric ton
TES storage capacity	1990	2140	MWh_{th}
total plant fenceline area	4 100 000	4 140 000	m^2

Water consumption is defined as the amount of water that is "evaporated, transpired, incorporated into products or crops, consumed by humans or livestock, or otherwise removed from the immediate water environment".[2]

- CED and EPBT: CED is the sum of all primary energy supplied by both RE and non-RE sources across the LC of the CSP plant (based on refs 22 and 25). Units are in megajoule equivalents per unit of electricity generated (MJ_{eq}/kWh). EPBT is defined as the length of time required to generate as much energy as is embodied in its LC (i.e., CED). EPBT is calculated as

$$\mathrm{EPBT} = \frac{\mathrm{CED}_{\mathrm{tot}}}{\alpha E_{\mathrm{net}}}$$

where, $\mathrm{CED}_{\mathrm{tot}}$ is the total LC CED of the CSP plant (MJ_{eq}), E_{net} is the annual net output of the CSP plant (MJ/year), and the constant α is the ratio of source-to-site energy of average U.S. grid electricity (dimensionless). The constant α ensures that numerator and denominator are commensurate in terms of primary energy. The average value of α has been reported by the U.S. Environmental Protection Agency, for years 2001−2005, as 3.34.[26]

Reference Plant Design and Data Sources. The hypothetical trough CSP plant, on which this LCA is based, was designed by a major CSP plant contract engineering firm, WorleyParsons Group (WPG), and is intended to be representative of actual plants being designed and built today in the U.S.[13] This plant has a net capacity of 103 MW, incorporates 6.3 h of storage (using a two-tank indirect configuration and mined salts), and is wet-cooled. Hereafter we refer to this plant as the "reference plant". To evaluate impacts of switching the reference plant design to one using dry-cooling technology, WPG also reported all necessary modifications required to maintain the reference plant's 103 MW net output.[13,27] Table 1 lists the main specifications of the wet- and dry-cooled CSP plants. WPG provided mass and composition of materials embodied in subsystems of each plant, manufacturing locations of the aforementioned materials, and material- and energy-related information regarding O&M activities.[27]

Primary data were obtained from manufacturers of several CSP plant components. Manufacturers of glass mirrors,[28] HCEs,[29] and mined salts[10,30,31] provided detailed information on embodied materials, transportation methods, energy flows, and direct GHG emissions of manufacturing processes. Solutia, Inc., provided proprietary data regarding direct and indirect emissions resulting from in-house manufacturing processes and transportation of their high-temperature HTF, Therminol VP-1 (Therminol is a registered trademark of Solutia, Inc.).[32] To complete the LC accounting, the quantity of raw materials required to manufacture HTF and their associated impacts were estimated. Data regarding consumption of water during manufacturing processes was provided for the glass mirrors. For all other materials, direct and indirect water consumption was estimated employing EcoInvent processes of closely related materials.

The two-tank and thermocline TES systems were modeled using design parameters found in TES studies[9,33−35] and personal communication with an industry expert.[36] Impacts resulting from manufacture of synthetic salts are approximated using reactions obtained from industrial chemical literature and LCI data from EcoInvent.[23] We assume that synthetic potassium nitrate is produced by reacting potassium chloride with nitric acid[37] and that synthetic sodium nitrate is produced by neutralizing nitric acid with sodium hydroxide.[38]

RESULTS AND DISCUSSION

Reference Plant. LC GHG emissions of the reference plant are estimated to be approximately 26 g CO_{2eq}/kWh. The manufacturing phase is responsible for 46% of LC GHG emissions. The largest contributors to manufacturing-phase emissions are the solar collector assemblies (SCAs) and the HTF. The SCAs, which consist of mirrors, HCEs, and frames, contribute 33% of manufacturing emissions, or 15% of LC emissions. Embodied GHG emissions of these SCAs are considerable, owing to the large masses of energy-intensive materials in the solar field. Because of the large volume required and its relatively high normalized impacts, the HTF is the next largest contributor to manufacturing GHG emissions (15% of manufacturing phase or 7% of LC emissions). Table 2 reports LC impacts by system and LC phase for both wet- and dry-cooled plant designs.

The O&M phase is responsible for 39% of LC GHG emissions. Consumption of grid electricity used to satisfy the parasitic loads during hours with no electricity generation accounts for 67% of these emissions. Natural gas consumption, which is used during system start-up and for HTF freeze protection activities, and manufacture of replacement components are the next largest contributors to O&M phase GHG emissions, at 18% and 13% of operational emissions, respectively. Note that grid electricity consumed by all CSP plant systems contributes 6.8 g CO_{2eq}/kWh to total LC GHG emissions. This value is dependent upon the regional electricity generation fuel source mix and is reduced if the plant incorporates more TES.

LC water consumption of the reference plant is estimated to be 4.7 L/kWh; 89% can be attributed to the O&M phase (4.2 L/kWh). The power block is responsible for 3.5 L/kWh from cooling tower makeup, blowdown quench, and steam cycle makeup water (71%, 14%, and 8% of LC water consumption, respectively; see Table 3). Cooling water consumed by regional power plants that generate the grid electricity used by the CSP plant accounts for 0.24 L/kWh (5% of LC consumption), while mirror washing accounts for 0.12 L/kWh (3% of LC consumption). The majority of the remaining water consumption is attributed to water consumed during the manufacturing phase (10% of LC or 0.47 L/kWh).

Table 2. LC Impact Metrics Disaggregated by System and Phase for Wet- (Reference Plant) and Dry-Cooled Designs

		GHG ($g\ CO_{2eq}/kWh$)		water (L/kWh)		CED (MJ_{eq}/kWh)	
life cycle phase	plant system	wet	dry	wet	dry	wet	dry
manufacturing	HTF	2.5	2.6	0.10	0.100	0.051	0.053
	power plant	1.9	2.4	0.076	0.085	0.033	0.037
	solar field	4.6	4.8	0.15	0.16	0.071	0.074
	TES	2.7	2.8	0.15	0.15	0.037	0.038
construction	HTF	0.14	0.15	0.0012	0.0012	0.0018	0.0018
	power plant	0.19	0.21	0.0041	0.0030	0.0032	0.0034
	solar field	0.77	0.81	0.022	0.023	0.012	0.013
	TES	0.64	0.67	0.0054	0.0057	0.010	0.011
operation	HTF	2.2	2.3	0.081	0.085	0.039	0.041
	power plant	6.2	6.9	4.0	0.29	0.10	0.12
	solar field	0.61	0.64	0.14	0.14	0.010	0.011
	TES	0.99	1.03	0.029	0.030	0.016	0.017
dismantling	HTF	0.018	0.018	0.000079	0.000077	0.00027	0.00027
	power plant	0.014	0.014	0.000062	0.000061	0.00021	0.00021
	solar field	0.090	0.088	0.00039	0.00038	0.0013	0.0013
	TES	0.0019	0.0018	0.0000080	0.0000079	0.000028	0.000028
disposal	HTF	0.50	0.52	0.00087	0.00090	0.00025	0.00025
	power plant	0.14	0.08	0.00021	0.00022	0.00010	0.00012
	solar field	0.77	0.81	0.0013	0.0013	0.00063	0.00066
	TES	0.68	0.71	0.0048	0.0050	0.0088	0.0093
life cycle phase		wet	dry	wet	dry	wet	dry
manufacturing		12	13	0.47	0.50	0.19	0.20
construction		1.7	1.8	0.033	0.033	0.028	0.029
operation		10	11	4.2	0.55	0.17	0.19
dismantling		0.12	0.12	0.00053	0.00053	0.0019	0.0018
disposal		2.1	2.1	0.0071	0.0074	0.0098	0.010
grand total		**26**	**28**	**4.7**	**1.1**	**0.40**	**0.43**

Table 3. On-Site Operational Water Requirements (L/kWh) of Wet- and Dry-Cooled Plant Designs[13]

	wet	dry
cooling tower makeup	3.4	
wet surface air cooler makeup		0.008
blowdown quench & steam cycle makeup	0.066	0.067
steam cycle makeup (for daily startup)	0.038	0.053
mirror washing	0.12	0.12
total	**3.6**	**0.25**

CED of the reference plant is estimated to be 0.40 MJ_{eq}/kWh. The two largest contributions to LC CED are from the manufacturing and O&M phases (48% and 42%, respectively). Because GHG emissions are largely proportional to energy use, SCAs and HTF were also found to significantly contribute to manufacturing phase CED (33% and 20%, respectively). Main contributors to O&M phase CED are electricity consumption, natural gas combustion, and the manufacture of replacement components. Over its 30-year lifetime, the reference plant generates an estimated 12.8×10^9 kWh, which, multiplied by the CED of 0.40 MJ_{eq}/kWh, yields a $CED_{tot} = 5.12 \times 10^9\ MJ_{eq}$. The resulting EPBT of the reference plant is 1.0 year.

Dry-Cooling Design. Because of its larger parasitic load relative to the wet-cooled design, the dry-cooled plant requires a higher grossing turbine to maintain the same net capacity as the wet-cooled design. The capital costs of the dry-cooled plant are slightly higher (about 8%)[39] owing primarily to a larger solar field area and more embodied materials. However, on cooler days, dry-cooled plants outperform wet-cooled plants in terms of total energy output, despite a less efficient steam cycle. Because the auxiliary load of the dry-cooling system is a function of dry-bulb temperature, which drops more rapidly than wet-bulb temperature, the higher grossing turbine of the dry-cooled system and reduced parasitic load on cooler days results in a 3% increase in annual energy production compared to the reference design.[39]

By switching from a wet- to dry-cooled system, the total LC GHG emissions increase by 8% to 28 $g\ CO_{2eq}$/kWh (Table 2).

Because the dry-cooled system produces more energy over its lifetime, the increase in normalized GHG emissions is slightly less than the absolute increase in GHG emissions over the plant lifetime (which increase by 10%). Of the GHG emissions attributable to switching from wet to dry cooling, 46% result from the O&M phase, 45% from the manufacturing phase, and 9% from the remaining phases. The increase in manufacturing-phase GHG emissions mainly arises from the addition of the ACC, the greater number of SCAs required, and the larger resulting volume of HTF compared to the wet-cooled design. Higher O&M emissions of the dry-cooled system are primarily due to additional natural gas consumed in the auxiliary boiler and additional electricity consumption used to meet the larger parasitic load.[13]

By eliminating the cooling tower (and thus, cooling tower makeup water requirement), the dry-cooled plant design achieves a 77% reduction in LC water consumption (to 1.1 L/kWh). The dry-cooled power block directly consumes 0.13 L/kWh during operation as compared to 3.5 L/kWh in the wet-cooled design. Water used to clean the troughs and the indirect water use associated with auxiliary energy requirements (grid electricity and natural gas) of the dry-cooled system increase slightly. Also, a small wet-surface air cooler is required to provide low-temperature cooling water for some turbine components. Small increases in nonoperational water consumption result from the larger fenced land area and embodied plant mass.

LC CED follows similar trends, as seen in the GHG emissions reductions achieved by switching from the wet- to dry-cooled plant designs. The LC CED increases by 8%, resulting in an EPBT totaling 13 months for this dry-cooled variant to the reference plant design.

TES Configuration & Salt Type. Three combinations of alternative designs of the TES system and salt type are compared to the reference plant design. First, by switching from a two-tank to a thermocline TES design but still assuming mined salts, significantly less material is required due to the reduced tankage requirement and two-thirds reduction of salt mass.[34] As a result, total LC GHG emissions and CED of the thermocline-based reference plant are estimated to be 7% lower than the two-tank designed reference plant (to 24 g CO_{2eq}/kWh and 0.37 MJ_{eq}/kWh, respectively) and water consumption is estimated to be reduced by about 2% (to 4.6 L/kWh).

Second, if synthetic salts are used instead of mined salts within the reference plant's two-tank TES configuration, GHG emissions are estimated to increase by 52%, CED by 24%, and water consumption by 3% (to 39 g CO_{2eq}/kWh, 0.50 MJ_{eq}/kWh, and 4.9 L/kWh, respectively) compared to the reference plant. GHG emissions increase considerably because nitrous oxide (N_2O; GWP = 298) emissions resulting from synthetic salt production are significantly higher than those resulting from mined salts. The majority of N_2O emissions result from the production of ammonia, which is subsequently reacted to produce the nitric acid used in salt production reactions.[40,41] Although absorption of N_2O with water is a part of the manufacturing process, a small fraction is unavoidably emitted to the atmosphere.[41]

Lastly, if both synthetic salts and a thermocline configuration are used, negative effects of the synthetic salts are attenuated by the reduced salt requirement of the thermocline system. Under this scenario, LC GHG emissions of the reference plant are estimated to increase by only 10% (to 28 g CO_{2eq}/kWh) while water consumption and CED are effectively unchanged.

Comparison of Reference Plant Results to Previous Trough CSP Estimates. Overall, the results of this work are consistent with those from other studies yet obtained through a more refined analysis of a modern plant design. Previous estimates of LC GHG emissions of trough CSP plants range from 12 to 185 g CO_{2eq}/kWh.[14−18] (Recall, estimated LC GHG emissions of the reference plant are 26 g CO_{2eq}/kWh.) The high end of this range[15,16,18] includes estimates for hybrid plants (i.e., powered by solar and natural gas), while the low end includes projections[14,18] for future facilities (years 2025−2050) with advanced design concepts, which are experimental at present. In contrast, Lechón et al.[15] and Viebahn et al.[18] conducted thorough analyses of a design based on the Andasol-1 plant in Spain (a 50 MW trough plant with 7.5 h of molten salt TES), which is similar in design to our reference plant.

Viebahn et al.[18] estimates LC GHG emissions to be 33 g CO_{2eq}/kWh, of which roughly 90% (30 g CO_{2eq}/kWh) is attributed to the manufacturing and construction phases. The study assumes solar-only operation (i.e., no natural gas cofiring) and use of synthetic salts in a TES system, but it does not account for auxiliary electricity consumption during operation. If we neglect operational electricity consumption and assume the use synthetic salts, LC GHG emissions from the reference plant of this study are estimated to be 32 g CO_{2eq}/kWh, 83% (27 g CO_{2eq}/kWh) of which is attributed to manufacturing and construction, similar to that reported by Viebahn.

Lechón et al.[15] estimates LC GHG emissions of their hybrid operating plant design to be 185 g CO_{2eq}/kWh, 87% of which is a result of natural gas provision (17 g CO_{2eq}/kWh) and combustion (95 g CO_{2eq}/kWh) and auxiliary electricity consumption (49 g CO_{2eq}/kWh). The study also assumes the use of synthetic nitrate salts. Ignoring the O&M phase, their estimate becomes 24 g CO_{2eq}/kWh. If O&M phase contributions are omitted and we assume the use of synthetic salts, LC GHG emissions from the reference plant of this study become 29 g CO_{2eq}/kWh.

Lechón et al.[15] reports a LC CED of 2.45 MJ/kWh and 0.19 MJ/kWh to "build and dismantle" the plant. Using a different method than that outlined in this study, Lechón reports an EPBT of 12.5 months. If calculated using Lechón's methods, the EPBT of the reference plant for this study is 6.7 months.

Although there are no previous estimates of LC water consumption for trough CSP plants, there are, however, several estimates of operational water consumption. The amount of water consumed to cool the power block and clean mirrors is largely dependent on the local environment and will therefore vary based on a combination of several factors (e.g., solar field size, ambient temperatures, particulate loads, and DNI). Previous estimates of operational water consumption range from 2.10 to 3.80 L/kWh[42] for wet-cooled systems and 0.175 to 0.300 L/kWh[42,43] for dry-cooled systems (see Figure 1).

Comparison of Reference Plant Results to Other Technologies. On the basis of the range of LC GHG emissions established in this study and others, CSP plants have LC GHG emissions approximately 3−7% of natural gas- and coal-fired systems.[44] The estimated LC GHG emissions resulting from photovoltaics, wind, and nuclear power are similar to CSP when compared to fossil-fueled systems.[44] The reference plant's estimated EPBT is comparable to those reported for wind power.[45] During their operation, the average wet-cooled nuclear, coal, and combined cycle natural gas plant consumes less water per unit of energy (2.9, 2.6, and 1.4 L/kWh, respectively) than a wet-cooled CSP plant (3.5 and 0.12 L/kWh for cooling and cleaning activities, respectively) due to their higher power block efficiency and less frequent cycling.[43] As for dry-cooled, trough CSP plants,

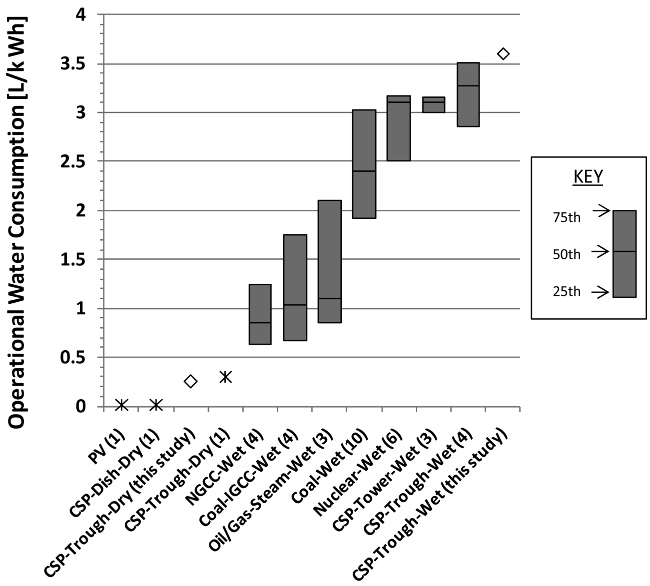

Figure 1. Operational water consumption requirements of various power generation-cooling technology combinations (based on data from ref 42). Numbers in parentheses quantify the number of estimates within the category. Categories with one previous estimate are depicted with an "∗". The values assumed in this analysis are depicted with a diamond.

direct operational water consumption (0.13 L/kWh for cooling and 0.12 L/kWh for cleaning) is approximately 90% less than that of wet-cooled CSP plants. It should be noted that dish/Stirling CSP systems are inherently dry-cooled, and power tower CSP systems can implement dry-cooling at lower cost compared to trough systems because of their higher operating temperature.

Recommendations. Results of this and other LCA studies indicate that trough CSP plants can provide electricity with significantly lower rates of GHG emission when compared to fossil-fuel-based sources. In addition, because of their ability to integrate efficient and relatively low-cost storage into their design, CSP plants offer dispatchable power and have the potential to act as reliable base-load power if equipped with 12 h of storage.[44] The combination of TES and coincidence of solar radiation with typical afternoon load peaks places CSP in a position to help meet U.S. electricity demand with low carbon emissions.

LC GHG emissions of CSP plants with TES are strongly dependent upon the source of salts. In the event that synthetic salts must be used, it would be beneficial to utilize a thermocline design. Using a thermocline TES design can ameliorate the increased burdens associated with synthetic salts.

In places like the southwest U.S., where water shortages are worsening and there is an excellent solar resource, the method by which proposed CSP plants will be cooled has emerged as a visible political issue.[46] Solar developers who integrate dry cooling into their CSP plant designs reduce the risk associated with constructing plants in drought-prone regions and hedge against the possibility of future policies that strictly regulate water use for power plant operation. It is anticipated that most new thermoelectric power plants in the southwest U.S. will be encouraged to implement dry cooling, and some CSP developers have already adopted that configuration as their standard design.[12]

Limitations and Future Research. Although the results reported here are the products of a thorough engineering analysis, there remain areas of uncertainty that merit further scrutiny:

- Because the system boundary for the GHG inventory of HTF manufacture[32] was unclear, it is possible that GHG emissions associated with the manufacture of certain raw materials have been double-counted by the authors, in which case it is likely that the impacts of the HTF would be overestimated. The overall effect of this possible overestimation is considered minimal—estimated to be at most a 5% increase in LC GHG emissions. Furthermore, the HTF manufacturer, Solutia, Inc., has ongoing efforts to reduce GHG emissions. Updated GHG data may be requested through Solutia, Inc.[32]
- Although the thermocline TES design has not yet matured to the point of utility-scale deployment, a 2.3 MWh pilot system has been designed and tested.[9] Concerns still exist regarding the thermocline design, including its impact on power cycle performance and potential "thermal ratcheting" of the storage tank. Thermoclines produce a gradually varying temperature output as they near the end of their charging and discharging cycles. If not properly accounted for, this temperature profile may decrease power cycle or solar field efficiency. Thermal ratcheting refers to the increase in hoop stress that builds in the bottom of the tank (and may lead to tank rupture) as the filler material settles because of thermal expansion and contraction of the tank during charging cycles. Ongoing research aims to better characterize both concerns.
- The impacts of using alternative "open-loop" allocation methods for the disposal phase are not explored here. Open-loop allocation methods, such as avoided allocation, shift environmental burdens resulting from a material's production into the future by assigning an energy credit, resulting from displacement of new materials, to the party responsible for recycling the material. Using such a method would presumably reduce LC impacts of the plant. However, this reduction is expected to be small given the minor contribution of the disposal phase to the LC impacts quantified here. Lechón et al.[15] reports a negative CED value for the dismantling plus disposal phases, which we assume was achieved using an open-loop allocation method. This negative credit, however, reduces the LC CED by less than 1%.

The results of this study pertain to the specific hypothetical plant design employed here. However, given the robustness of the set of estimates of LC GHG emissions from this and previous research, it is likely that LC environmental impacts for a reasonably diverse set of plant designs will be similar. Regarding the applicability of these results to plants in other locations, as a first approximation, it is reasonable to assume that a change in DNI will proportionally affect the plant's power output and therefore inversely proportionally affect the LC impacts per unit electricity generated. However, other characteristics relating to location, such as monthly average wet- and dry-bulb temperatures, can affect plant performance and design in ways that will make the final results differ from a strictly inversely proportional relationship to DNI. Therefore, further research would be required to achieve a more precise estimate for other plant locations.

As this is the first estimation of LC water consumption for CSP, additional research is necessary to confirm the results reported here. In particular, determining an accurate estimate of water consumed during manufacture of salts and HTF are areas where further research is needed. Moreover, an additional cooling method—hybrid cooling—which uses a combination of wet and dry cooling, should be evaluated to quantify the impacts of a more complete portfolio of cooling options for solar developers and policymakers.

■ ASSOCIATED CONTENT

S Supporting Information. Additional data, assumptions, figures, and results. This material is available free of charge via the Internet at http://pubs.acs.org.

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■ REFERENCES

(1) U.S. Energy Information Administration. Table 12.1. Carbon Dioxide Emissions from Energy Consumption by Source. In *Monthly Energy Review April 2010*; Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K. B., Tignor, M., Miller, H. L., Eds.; http://www.eia.doe.gov/mer/pdf/pages/sec12_3.pdf (accessed Sept 2010).

(2) Kenny, J.; Barber, N.; Hutson, S.; Linsey, K. *Estimated Use of Water in the United States in 2005*. U.S. Geological Survey, 2009; http://pubs.usgs.gov/circ/1344/pdf/c1344.pdf (accessed Sept 2010).

(3) IPCC. *Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*; Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K. B., Tignor, M., Miller, H. L., Eds.; Cambridge University Press: New York. http://www.ipcc.ch/publications_and_data/ar4/wg1/en/contents.html (accessed Sept 2010).

(4) Spencer, T.; Altman, P. Natural Resources Defense Council. Climate Change, 2010. Climate Change, Water, and Risk: Current Water Demands Are Not Sustainable. http://www.nrdc.org/globalWarming/watersustainability/files/WaterRisk.pdf (accessed Sept 2010).

(5) Kearney, D.; Morse, F. Bold, Decisive Times for Concentrating Solar Power. *Solar Today* **2010**, 32–35.

(6) U.S. Department of Energy. Secretary Chu Announces up to $62 Million for Concentrating Solar Power Research and Development. 2010. http://www.energy.gov/8958.htm (accessed Sept 2010).

(7) Blair, N.; Mehos, M.; Short, W.; Heimiller, D. *Concentrating Solar Deployment System (CSDS)—A New Model for Estimating U.S. Concentrating Solar Power (CSP) Market Potential;* Technical Report NREL/CP-620-39682; National Renewable Energy Laboratory: Golden, CO, April 2006. http://www.nrel.gov/docs/fy06osti/39682.pdf (accessed Sept 2010).

(8) National Renewable Energy Laboratory. U.S. Parabolic Trough Power Plant Data. http://www.nrel.gov/csp/troughnet/power_plant_data.html (accessed Sept 2010).

(9) Brosseau, D. A.; Hlava, P.; Kelly, M. *Testing Thermocline Filler Materials and Molten Salt Heat Transfer Fluids for Thermal Energy Storage Systems Used in Parabolic Trough Solar Power Plants*; Technical Report SAND2004-3207; Sandia National Laboratories: Albuquerque, NM, July 2004. http://www.nrel.gov/csp/troughnet/pdfs/brosseau_sand-2004_3207_final.pdf (accessed Sept 2010).

(10) Casubolo, G. (SQM) Personal communication (with G.A.H. of NREL), Mar 24, 2010.

(11) Carter, N. T.; Campbell, R. J. *Water Issues of Concentrating Solar Power (CSP) in the U.S. Southwest*; Order No. R40631; Congressional Research Service: Washington, DC, 2009. http://www.g-a-l.info/Solar-Water-Use-Issues-in-Southwest.pdf (accessed Sept 2010).

(12) Woody, T. Solar Developer Abandons Water Plans. *New York Times*, Nov 16, 2009; http://green.blogs.nytimes.com/2009/11/16/solar-developer-abandons-water-plans/ (accessed Sept 2010).

(13) Turchi, C. *Parabolic Trough Reference Plant for Cost Modeling with the Solar Advisor Model (SAM)*; NREL Report No. TP-550-47605; National Renewable Energy Laboratory: Golden, CO, 2010, pp 122; http://www.nrel.gov/docs/fy10osti/47605.pdf

(14) *Trans-CSP Trans-Mediterranean Interconnection for Concentrating Solar Power*; German Aerospace Center (DLR), 2006. http://www.dlr.de/tt/trans-csp (accessed Sept 2010).

(15) Lechon, Y.; De La Rua, C.; Saez, R. Life Cycle Environmental Impacts of Electricity Production by Solar Thermal Power Plants in Spain. *J. Sol. Energy Eng.* **2008**, *130* (2), 0210121–0210127.

(16) Martin, J. A Total Fuel Cycle Approach to Reducing Greenhouse Gas Emissions: Solar Generation Technologies as Greenhouse Gas Offsets in the U.S. Utility Systems. *Solar Energy* **1997**, *59*, 195–203.

(17) Norton, B.; Eames, P.; Lo, S. Full-Energy-Chain Analysis of Greenhouse Gas Emissions for Solar Thermal Electric Power Generation Systems. *Renewable Energy* **1998**, *15*, 131–136.

(18) Viebahn, P.; Kronshage, S.; Trieb, F.; Lechon, Y. *Final Report on Technical Data, Costs, and Life Cycle Inventories of Solar Thermal Power Plants*; Project no: 502687; New Energy Externalities Developments for Sustainability, Project co-funded by the European Commission within the Sixth Framework Programme (2002−2006), 2008. http://www.needs-project.org/docs/results/RS1a/RS1a%20D12.2%20Final%20report%20concentrating%20solar%20thermal%20power%20plants.pdf (accessed Sept 2010).

(19) National Solar Radiation Data Base. Typical Meteorological Year 3: 723815—Daggett Barstow-Daggett AP. http://rredc.nrel.gov/solar/old_data/nsrdb/1991-2005/tmy3/ (accessed Sept 2010).

(20) *Environmental Management−Life Cycle Assessment−Requirements and Guidelines*; ISO 14044:2006; International Organization for Standardization (ISO): Geneva, Switzerland, 2006.

(21) Frischknecht, R. *Cut-off vs. Avoided Burden in Metals' Recycling: In View of Environmental Sustainability, Risk Perception and Eco-Efficiency*, 33rd LCA Discussion Forum, Lausanne, Switzerland, Nov 22, 2007. http://www.lcainfo.ch/DF/DF33/Frischknecht%20-%20ESU-services%20-%20LCA%20DF33.pdf (accessed Sept 2010).

(22) *SimaPro v7.1.8.*; PRe Consultant: Amersfoort, The Netherlands, 2008. http://www.pre.nl/simapro/ (accessed Sept 2010).

(23) *EcoInvent v2.0*; Swiss Center for Life Cycle Inventories: Duebendorf, Switzerland, 2008. http://www.ecoinvent.org/ (accessed Sept 2010).

(24) Carnegie Mellon University Green Design Institute. Economic Input−Output Life Cycle Assessment (EIO-LCA), US 1997 Industry Benchmark model [Internet]; 2008. http://www.eiolca.net (accessed March 2010).

(25) Frischknecht, R.; Jungbluth, N.; Althaus, H.; Bauer, C.; Doka, G.; Dones, R.; Hischier, R.; Hellweg, S.; Humbert, S.; Kollner, T.; Loerincik, Y.; Margni, M.; Nemecek, T. *Implementation of Life Cycle Impact Assessment Methods; Data v2.0*; Swiss Centre for LCI: Duebendorf, CH, 2003. http://www.ecoinvent.org/fileadmin/documents/en/03_LCIA-Implementation.pdf.

(26) ENERGY STAR Performance Ratings Methodology for Incorporating Source Energy Use. http://www.energystar.gov/ia/business/evaluate_performance/site_source.pdf (accessed Sept 2010).

(27) WorleyParsons Group. *Material Input for Life Cycle Assessment*; Technical Report No. 59002505−NREL-0-LS-019-0005; National Renewable Energy Laboratory: Golden, CO, 2009.

(28) Undisclosed Manufacturer. Proprietary data on parabolic trough mirrors, Provided to NREL under a non-disclosure agreement, 2010.

(29) Undisclosed Manufacturer. Proprietary data on HCEs, Provided to NREL under a non-disclosure agreement, 2010.

(30) SQM. *Greenhouse Gas Emission Report*; Unpublished Report by G. Casubolo provided to NREL, Feb 5, 2010.

(31) SQM. *Big Bag 1.2 Specification and Description*; Unpublished Report by G. Casubolo provided to NREL, Mar 24, 2010.

(32) Gamble, C. (Solutia Inc.) NREL GHG Emissions Response For Therminol VP-1 Heat Transfer Fluid. E-mail to author, Jun 11, 2010.

(33) Kelly, B.; Kearney, D. *Thermal Storage Commercial Plant Design Study for a 2-Tank Indirect Molten Salt System—Final Report*; Technical Report NREL/SR-550−40166; National Renewable Energy Laboratory: Golden, CO, July 2006. http://www.nrel.gov/csp/troughnet/pdfs/40166.pdf (accessed Sept 2010).

(34) Pacheco, J.; Showalter, S.; Kolb, W. Development of a Molten-Salt Thermocline Thermal Storage System for Parabolic Trough Plants. *J. Sol. Energy Eng.* **2002**, *124*, 153–159.

(35) Heath, G.; Turchi, C.; Decker, T.; Burkhardt, J.; Kutscher, C. Life Cycle Assessment Of Thermal Energy Storage: Two-Tank Indirect And Thermocline. Energy Sustainability 2009, San Francisco, CA, Jul 19−23, 2009; http://www.nrel.gov/docs/fy09osti/45857.pdf (accessed Sept 2010).

(36) Kelly, B. (Nexant, Inc.) Personal communication (with Garvin Heath of NREL), Aug 4−5, 2008.

(37) Potassium Compounds. *Kirk-Othmer Encyclopedia of Chemical Technology* [Online]; John Wiley & Sons, Posted 2005. http://onlinelibrary.wiley.com/doi/10.1002/0471238961.1615200106180509.a01.pub2/pdf. (accessed Sept 2010).

(38) Sodium Nitrate and Nitrite. *Kirk-Othmer Encyclopedia of Chemical Technology* [Online]; John Wiley & Sons, Posted 2006. http://mrw.interscience.wiley.com/emrw/9780471238966/kirk/article/sodipoko.a01/current/pdf (accessed Sept 2010).

(39) WorleyParsons Group. *Analysis of Wet and Dry Condensing 125 MW Parabolic Trough Power Plants*; Technical Report NREL-2-ME-REP-0002-R0; National Renewable Energy Laboratory: Golden, CO, 2009.

(40) Ammonia. *Kirk-Othmer Encyclopedia of Chemical Technology* [Online]; John Wiley & Sons: New York, posted 2010. http://mrw.interscience.wiley.com/emrw/9780471238966/kirk/article/ammocz-up.a01/current/pdf (accessed Sept 2010).

(41) Nitric Acid, Nitrous Acid, and Nitrogen Oxides. *Ullmann's Encyclopedia of Industrial Chemistry* [Online]; John Wiley & Sons: New York, posted 2000. http://mrw.interscience.wiley.com/emrw/9783527306732/ueic/article/a17_293/current/pdf (accessed Sept 2010).

(42) Fthenakis, V.; Kim, H. Life-Cycle Uses of Water in U.S. Electricity Generation. *Renewable Sustainable Energy Rev.* **2010**, *908*, 1–10.

(43) WorleyParsons Group. *FPLE—Beacon Solar Energy Project Dry Cooling Evaluation*; Technical Report FPLS-0-LI-450−0001 Rev B; FPL Energy: Miami, FL. http://www.energy.ca.gov/sitingcases/beacon/documents/applicant/2008-02-01_DRY_COOLING_EVALUATION_TN-49597.PDF (accessed Sept 2010).

(44) Kharecha, P. A.; Kutscher, C. F.; Hansen, J. E.; Mariza, E. Options for Near-Term Phaseout of CO_2 Emissions from Coal Use in the United States. *Environ. Sci. Technol.* **2010**, *44*, 4050–4062.

(45) Kubiszewski, I.; Cleveland, C. J.; Endres, P. K. Meta-analysis of net energy return for wind power systems. *Renewable Energy* **2010**, *35*, 218–255.

(46) Woody, T. Water Use by Solar Projects Intensifies. *New York Times*, Oct 27, 2009. http://green.blogs.nytimes.com/2009/10/27/water-use-by-solar-projects-intensifies/ (accessed Sept 2010).