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

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Addendum

Please see the following reference, and its supporting information, for more complete description of the methods and results reported here:

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LIFE CYCLE ASSESSMENT OF A PARABOLIC TROUGH CONCENTRATING SOLAR POWER PLANT AND IMPACTS OF KEY DESIGN ALTERNATIVES

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Abstract

Climate change and water scarcity are important issues for today's power sector. To inform capacity expansion decisions, life cycle assessment is used to evaluate a reference design of a parabolic trough CSP facility located in Daggett, California 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 life cycle, the reference CSP plant is estimated to emit 26 g CO_2eq per kWh, consume 4.7 L/kWh of water, and demand 0.40 MJeq/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.

Keywords: LCA, water consumption, greenhouse gas, GHG, energy payback, EPBT

1. Introduction

Operational carbon dioxide (CO_2) emissions from the United States electric power sector constituted 40% of energy-related CO_2 emissions in 2009, 98% of which was from combustion of coal and natural gas (1). Thermoelectric power was also responsible for 41% of all U.S. freshwater withdrawals in 2005, the largest end-use sector (2). Furthermore, water scarcity and drought will likely become more widespread during the 21st century as a result of climate change (3). 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.

Life cycle assessment (LCA) is recognized as a holistic and standard approach for quantifying environmental impacts of energy technologies, including those that use renewable resources. LCA accounts for the impacts resulting from up-stream and down-stream activities over the life cycle of a power plant. In this paper we evaluate a reference design for a parabolic trough CSP facility located in Daggett, California. This wet-cooled, 103 MW plant utilizes mined nitrates salts in its two-tank, thermal energy storage (TES) system. This is the first LCA of a CSP plant in the U.S. in over a decade and reflects modern plant designs.

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 life cycle water consumption. Quantified metrics of environmental performance include life cycle GHG emissions, water consumption, cumulative energy demand (CED), and the resultant energy payback time (EPBT). The design alternatives evaluated and compared herein include: wet versus dry cooling, two-tank indirect versus thermocline indirect TES systems, and mined versus synthetically-derived nitrate salt storage media.

2. Methods

2.1.Scope

The temporal vintage of the CSP plant design is year 2010 and the geographic reference is Daggett, California, U.S., whose annual direct normal irradiation (DNI) is among the highest in the U.S. (approximately 2,700 kWh/m2) [4]. The plant is assumed to operate for 30 years [5]. Following the guidelines described in the international standard series ISO 14040-44 [6], our hybrid LCA evaluates the following life cycle phases of the hypothetical trough plant: material and component manufacturing, plant construction, operation and maintenance (O&M), plant dismantling, and materials disposal. Infrastructure used in the transportation of materials, construction, and dismantling of the plant is amortized over the infrastructure element's useful lifetime. Impacts are allocated to four CSP systems: heat transfer fluid (HTF), solar field, TES, and power plant.

SimaPro v7.1 [7] LCA modeling software and the EcoInvent life cycle inventory (LCI) database [8] 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 was not available. An EIO LCA tool [9] was used to estimate life cycle burdens of select components and systems, including pumps, compressors, turbine generator set, and miscellaneous controls and electronic equipment. Costs of these components were extracted from primary data sources [5] and used as inputs to the U.S. 2002 Industry Benchmark EIO-LCA model [9].

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

- GHGs: Emissions of individual GHGs from the CSP plant life cycle are presented as the sum of each GHG weighted by its 100-year global warming potential (GWP) [3], divided by the total kWh generated by the plant over its lifetime, to obtain grams of CO_2 equivalents (g CO_2eq/kWh).
- Water Consumption: life cycle water consumption is calculated by summing the volume of surface and ground water consumed in all life cycle stages per unit of electricity generated (L/kWh). 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 & EPBT: CED is the sum of all primary energy supplied by both RE and non-RE sources across the life cycle of the CSP plant (based on [7, 10]). Units are in megajoule equivalents per unit of electricity generated (MJeq/kWh). EPBT is defined as the length of time required to generate as much energy as is embodied in its life cycle (i.e., CED). EPBT is calculated as CED_{tot} / (α * E_{net}), where, CED_{tot} is total life cycle CED of the CSP plant (MJeq), E_{net} is 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. (Note: It is unclear if all inputs to this equation are reported on a consistent heating value basis, i.e., higher or lower. However, the impact of potential inconsistency should not change the conclusions of this study.) The average value of α for years 2001-2005 for the United States has been reported as 3.34 [11].

2.2. 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. [5]. This plant has a net capacity of 103 MW, incorporates 6.3 hours 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 [5, 12]. 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 [12].

	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	3,700	3,990	MWh/yr
Natural Gas Consumption	8,900	15,600	MMBtu/yr
Solar Field Aperture Area	987,500	1,063,000	m^2
HTF Mass	4,270	4,600	metric ton
TES Storage Capacity	1,990	2,140	MWh_{th}
Total Plant Fenceline Area	4,100,000	4,140,000	m^2

Table 1. Specifications of Wet- (Reference Plant) and Dry-Cooled Designs [5]

Primary data were obtained from manufacturers of several CSP plant components. Manufacturers of glass mirrors [13], heat collection elements (HCE) [14], and mined salts [15-17] 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.) [18]. To complete the life cycle accounting, the quantity of raw materials required to manufacture HTF and their associated impacts was estimated. Data regarding consumption of water during manufacturing processes were 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 [19-22] and personal communication with an industry expert [23]. Impacts resulting from manufacture of synthetic salts are approximated using reactions obtained from industrial chemical literature and LCI data from EcoInvent [8]. We assume that synthetic potassium nitrate is produced by reacting potassium chloride with nitric acid [24], and that synthetic sodium nitrate is produced by neutralizing nitric acid with sodium hydroxide [25].

3. Results and Discussion

3.1. Results for Reference Plant

Life cycle GHG emissions of the reference plant are estimated to be 26 g CO_2eq/kWh. Table 2 reports life cycle impacts by system and life cycle phase for both wet- and dry-cooled plant designs. The manufacturing phase is responsible for 46% of life cycle 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 life cycle 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 life cycle emissions).

The O&M phase is responsible for 39% of life cycle GHG emissions. Consumption of grid electricity used to satisfy the parasitic loads during hours with no electricity generation accounts for 67% of these emissions; this value is dependent upon the regional electricity generation fuel source mix and is reduced if the plant incorporates more TES. Natural gas consumption, which is used during daily 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 life cycle GHG emissions. This value is dependent upon the regional electricity generation fuel source mix and is reduced if the plant incorporates more TES.

Life cycle water consumption of the reference plant is estimated to be 4.7 L/kWh. Eighty-nine percent 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 make-up, blowdown quench, and steam cycle make-up water (71%, 14%, and 8% of life cycle water consumption, respectively). 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 life cycle consumption), while mirror washing accounts for 0.12 L/kWh (3% of life cycle consumption). The majority of the remaining water consumption is attributed to water consumed during the manufacturing phase (10% of life cycle, or 0.47 L/kWh).

CED of the reference plant is estimated to be 0.40 MJeq/kWh. The two largest contributions to life cycle 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 MJeq/kWh, yields a $CED_{tot} = 5.12 \times 10^9$ MJeq. The resulting EPBT of the reference plant is 1.0 year.

3.2. Results for Design Alternatives

The dry-cooled power block is estimated to reduce life cycle water consumption by 77% (and operational power block water consumption by 96%) but increase life cycle GHG emissions and CED by 8%. 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 air-cooled condenser, 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 [5].

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 [21]. As a result, total life cycle 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 MJeq/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 MJeq/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 [26, 27]. Although absorption of N_2O with water is a part of the manufacturing process, a small fraction is unavoidably emitted to the atmosphere [27].

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, life cycle 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.

Life Cycle Phase	Plant System	GHG [g CO2eq / kWh]		WATER [L / kWh]		CED [MJeq / kWh]	
		Wet	**Dry**	**Wet**	**Dry**	**Wet**	**Dry**
Manufacturing	HTF	2.5	2.6	0.10	0.10	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 Subtotals		**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 2. Life Cycle Impact Metrics Disaggregated by Phase and System for Wet- (Reference Plant) and Dry-Cooled Designs

3.3 Discussion

The results of this study pertain to the specific hypothetical plant design employed here. However, given the robustness of the set of estimates of life cycle GHG emissions from this and previous research, it is likely that life cycle 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 life cycle 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 life cycle water consumption for CSP, with uncertainty in certain inputs (e.g., water consumed for production of HTF and salts), additional research is necessary to confirm and expand on the results reported here. Measurement of water consumption both at the plant and in the production of input materials, would be particularly beneficial. 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.

4. Conclusion

Based on this and previous analysis (e.g., [28, 29]), CSP can significantly reduce GHG emissions compared to fossil-fueled generation, although dry-cooling may be required in many locations to minimize water consumption. However, life cycle 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.

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