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Life Cycle Environmental Impacts resulting from the Manufacture of the Heliostat Field for a Reference Power Tower Design in the United States

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Abstract

Life cycle assessment (LCA) is recognized as a useful analytical approach for quantifying environmental impacts of renewable energy technologies, including concentrating solar power (CSP). An LCA accounts for impacts from all stages in the development, operation, and decommissioning of a CSP plant, including such upstream stages as the extraction of raw materials used in system components, manufacturing of those components, and construction of the plant. The National Renewable Energy Laboratory is conducting a series of LCA studies for various CSP technologies. This paper contributes to a thorough LCA of a 100 MW_{net} molten salt power tower CSP plant by estimating the environmental impacts resulting from the manufacture of heliostats. Three life cycle metrics are evaluated: greenhouse gas emissions, water consumption, and cumulative energy demand. The heliostat under consideration (the 148 m^2 Advanced Thermal Systems heliostat) emits 5,300 kg CO_{2eq}, consumes 274 m^3 of water, and requires 159,000 MJ_{eq} during its manufacture. Future work will incorporate the results from this study into the LCA model used to estimate the life cycle impacts of the entire 100 MW_{net} power tower CSP plant.

Keywords: life cycle assessment, concentrating solar power, heliostat, power tower, greenhouse gas emissions, water consumption, cumulative energy demand

1. Introduction

The electric power sector constituted 40% of all energy-related carbon dioxide (CO_2), a major greenhouse gas (GHG) contributing to anthropogenic climate change, emissions in 2009 [1]. As a means to reduce the nation's carbon footprint, the installed capacity of renewable energy technologies has been on the rise over the past decade and electricity generation from non-hydropower renewables has more than doubled since 1990 [2]. As the renewable energy sector's contribution to the nation's total electricity generation continues to grow, it is important to understand the potential environmental benefits associated with technologies such as concentrating solar power (CSP). Because operational environmental burdens are typically small for renewable energy technologies, life cycle assessment (LCA) is recognized as the most appropriate analytical approach for determining their environmental impacts of these technologies, including CSP. An LCA accounts for impacts associated with all stages in the life cycle (typically a 30-year period) of a CSP plant, which includes the extraction of raw materials, manufacture of components, plant construction, operation, and decommissioning.

The National Renewable Energy Laboratory (NREL) is undertaking a series of LCAs of modern CSP plants. In 2011, NREL published an LCA of a reference parabolic trough CSP plant design based in Daggett, CA [3]. The life cycle inventory of materials and performance data of the reference plant design, which has a 103 MW_{net}, wet-cooled power block and 6.3 equivalent full load hours (EFLH) of molten salt thermal energy storage (TES), were provided by WorleyParons Group (WPG). The three life cycle environmental metrics evaluated in the 2011 study were GHG emissions, water consumption, and cumulative energy demand (CED). Various design alternatives, including an alternate power block cooling method, TES configuration, and storage medium, were evaluated to develop a robust range of life cycle impact values that could be expected from similar parabolic trough plants being developed in the United States.

Analogous to our analysis of a reference parabolic trough design, NREL is completing a thorough LCA of a molten salt power tower CSP plant design based in Tucson, AZ. A detailed life cycle inventory (LCI) and annual performance data for the reference design will again be provided by WPG. The power tower will employ a 100 MW_{net}, dry-cooled power block and 6 EFLH of molten salt storage. As a part of this work, NREL has estimated the environmental impacts resulting from the manufacture of the heliostat to be used in the reference power tower plant design using published life cycle inventory data. This work represents an important step in the completion of the whole-plant LCA as the environmental impacts of the heliostat field have been shown in previous research to represent roughly half of the material inventory of a power tower CSP plant design and nearly the same percentage of life cycle GHG emissions [4].

2. Methods

2.1 LCA methodology

There are three common methods used to conduct an LCA: 1) a "process-based" approach in which a system is modeled from the "bottom up" using individual component masses and process energy flows, 2) a "top down" approach where categories of costs are translated to environmental impacts through the use of economic input-output (EIO) matrices and national-average emissions data for each affected industry, and 3) a combined, or "hybrid" approach. This work described herein uses the hybrid LCA method to evaluate the impacts of the heliostat of a power tower CSP plant based upon three metrics: GHG emissions, life cycle water consumption, and CED. As the environmental impacts associated with CSP plant construction, operation and decommissioning are generally small, this analysis focuses on estimating the GHG emissions, water consumption, and CED embodied in the production of the materials used in heliostats (i.e., extraction of raw materials and manufacturing of components). The impacts associated with the remaining components (i.e,. power block, thermal energy storage, and tower systems) and life cycles phases (i.e., construction, operation, and decommissioning) will be accounted for the in the whole-plant LCA to follow this work.

Emissions of individual GHGs that result from the upstream process during the manufacturing of the heliostat components are presented as the sum of each GHG weighted by its 100-year global warming potential (GWP) [5] to obtain kilograms of CO_2 equivalents (kg CO_{2eq}). Likewise, the total water consumption is calculated by summing the volume of surface and groundwater consumed in all upstream processes during this stage of the heliostat's life cycle. As used here, 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" [6]. Finally, CED is calculated as the sum of all primary energy supplied by both renewable and non-renewable sources during the life cycle phase under consideration. The life cycle metrics evaluated herein have been normalized to two functional units for ease of comparison: 1 heliostat and 1 m^2 of heliostat aperture area (e.g. kg CO_{2eq}/heliostat and kg CO_{2eq}/m^2). Our LCA methodology is consistent with the guidelines outlined in the international standard series ISO 14040-44 [7].

2.2 Material and life cycle inventory data

The heliostat being considered for the reference power tower plant design is the Advanced Thermal Systems (ATS) 148 m^2 glass/metal heliostat (see Figure 1). The ATS heliostat has operated successfully at the National Solar Thermal Test Facility (NSTTF) in Albuquerque, NM for over 20 years and yet is still considered a current low-cost baseline heliostat design in the US [8]. A thorough description of the ATS heliostat design and embodied materials are provided in a heliostat cost reduction study conducted by Sandia National Laboratories [8]. The study also provided the cost of the major electrical and control systems used for heliostat operation. The material and cost data were extracted from the heliostat cost reduction study and are being used as inputs for the LCA model.

SimaPro v7.122 LCA modeling software [9] and the EcoInvent LCI database [10] were used to estimate upstream GHG emissions, energy flows, and embodied water for minimally processed or bulk materials (e.g. carbon steel and concrete). The internet-based EIO LCA tool provided by the Green Design Institute of Carnegie Mellon University [11] was used to model impacts of components in two situations: 1) where the materials inventory for a specific component was not available, and 2) where we deemed that the environmental impacts resulting from a product's manufacture could not be accurately evaluated by summing the cumulative impacts of constituent raw materials. The latter situation occurs for what we call "highly manufactured components" like motors, pumps, heaters, and turbines. For these highly manufactured components, one must consider not only the energy required to manufacture the raw materials, which are embedded in the component, but also the energy required to process those raw materials and assemble the final product. EIO LCA models are able to capture this additional energy because the environmental impacts of an entire industry (e.g., pump and pumping equipment manufacturing) are accounted for, which includes process and assembly energy.

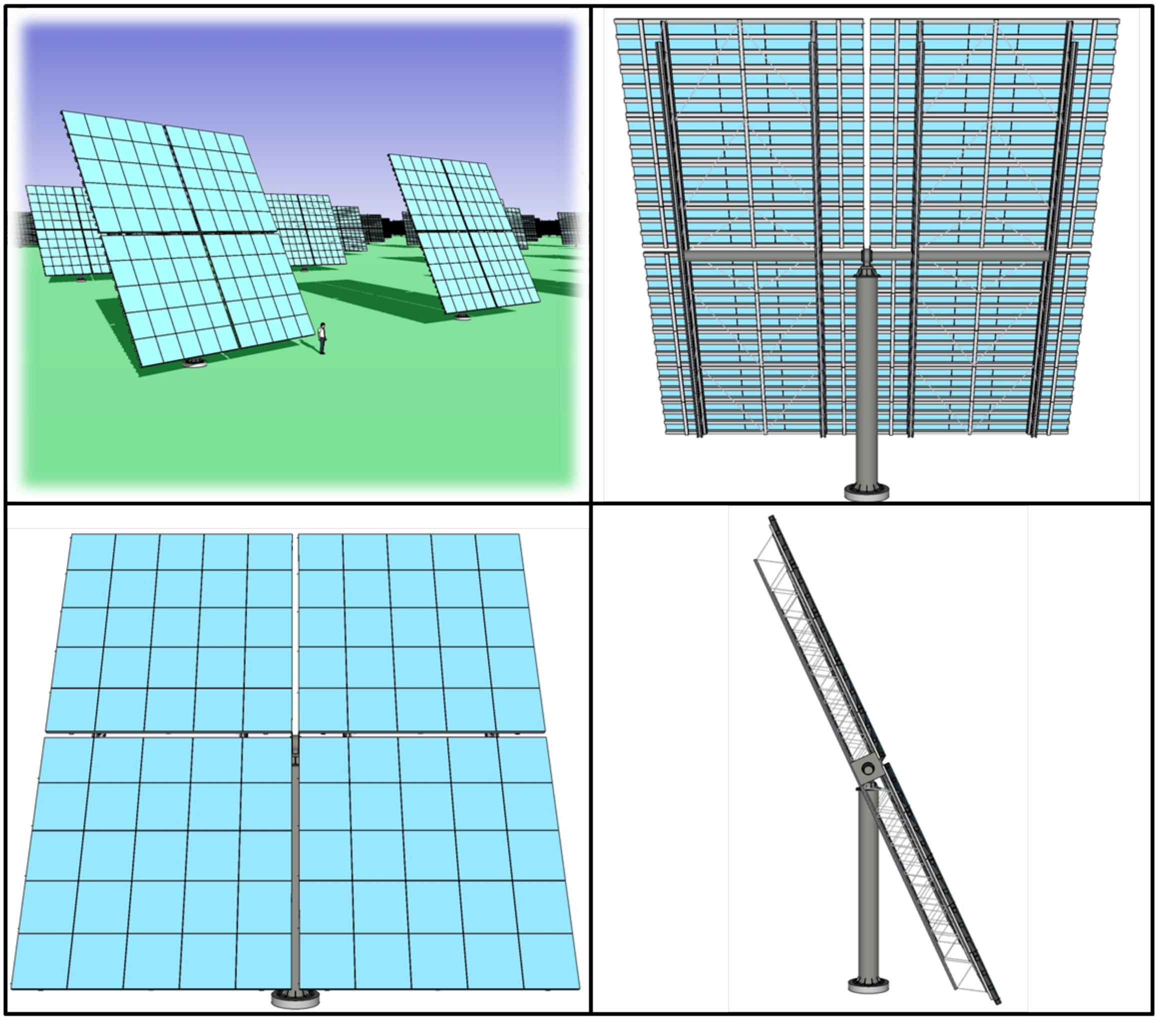

Fig. 1. A visual interpretation of the 148 m^2 ATS heliostat shown from different angles. All dimensions are approximate and are based on data from [8]

4. Summary of results

The heliostat has been broken into six main subsystems: cross bracing structure and attachments, gear drive, mirror module assemblies, pedestal assembly, torque tube assemblies, and trusses and attachment plates. The life cycle impacts have also been disaggregated by major components within each subsystem. The total cost and embodied masses of each of these subsystems have been provided in Table 1, along with the estimated GHG emissions, CED, and water consumption associated with their manufacture. Due to limited information, the environmental impacts resulting from the concrete foundation, controls and cabling, drive motors and limit switches, and field wiring have not yet been estimated. The contractor (WPG) will provide materials and cost data for the aforementioned components such that the heliostat LCI is made complete.

	Model Inputs		Model Outputs					
			Process-Based	Cost-Based	Mass-Based	Cost-Based	Mass-Based	Cost-Based
Subsystems/Components[b]	**Mass[c] [kg]**	**Cost [2006$]**	**GHG [$kgCO_{2eq}$]**		**Water [m^3]**		**CED [MJ_{eq}]**	
Cross Bracing Structure and Attachments	**247**	**-**	**393**	**-**	**7.65**	**-**	**5,970**	**-**
Beams	150	-	239	-	4.64	-	3,620	-
Brackets	7.26	-	11.5	-	0.225	-	175	-
Fasteners	10.0	-	15.9	-	0.309	-	241	-
Long Diagonals	52.2	-	83.0	-	1.62	-	1,260	-
Short Diagonals	16.3	-	25.9	-	0.505	-	394	-
Stabilizers	6.35	-	10.1	-	0.197	-	153	-
Wind Ties	4.99	-	7.93	-	0.154	-	120	-
Gear Drive	**5.44**	**4,000**	**8.65**	**2,230**	**0.168**	**108**	**131**	**33,800**
Azimuth Subassembly	-	3,000	-	1,670	-	81.1	-	25,300
Elevation Subassembly	-	1,000	-	557	-	27.0	-	8,440
Fasteners	5.44	-	8.65	-	0.168	-	131	-
Mirror Module Assemblies	**2,330**	**80.0**	**2,530**	**-**	**64.0**	**-**	**46,800**	**-**
Adhesive[d]	72.6	-	333	-	18.6	-	6,480	-
Assembly	-	80.0	-	-	-	-	-	-
Cross Members	68.0	-	108	-	2.11	-	1,640	-
Fasteners	36.3	-	57.7	-	1.12	-	876	-
Glass Mirror Facets[e]	1,500	-	999	-	22.0	-	22,100	-
Hat Sections	649	-	1,030	-	20.1	-	15,700	-
Pedestal Assembly	**1,550**	**52.0**	**2,470**	**50.1**	**48.1**	**1.95**	**37,500**	**660**
Flange	62.1	-	98.7	-	1.92	-	1,500	-
Pedestal Pipe	1,490	-	2,370	-	46.1	-	36,000	-
Machine Flat Surface	-	10.0	-	9.64	-	0.375	-	127
Drilling (12 holes per pedestal)	-	12.0	-	11.60	-	0.451	-	152
Welding	-	20.0	-	19.30	-	0.751	-	254
Misc. Machining	-	10.0	-	9.64	-	0.375	-	127
Torque Tube Assemblies	**975**	**-**	**1,550**	**-**	**30.2**	**-**	**23,500**	**-**
Fasteners	10.9	-	17.3	-	0.337	-	263	-
Flange	64.4	-	102	-	1.99	-	1,550	-
Torque Tube Pipe	900	-	1,430	-	27.9	-	21,700	-
Trusses and Attachment Plates	**454**	**-**	**721**	**-**	**14.0**	**-**	**11,000**	**-**
Mounting Adaptor Plate	33.6	-	53.4	-	1.04	-	811	-
Truss Subassembly	420	-	668	-	13.0	-	10,100	-
Subtotal	-	-	7,670	2,280	164	110	125,000	34,400
Grand Total (per heliostat)	**-**	**-**	**9,950**		**274**		**159,000**	
Grand Total (per m^2 of aperture area)			**67.2**		**1.85**		**1,070**	

a: The values under columns labeled "Process-Based" represent the impacts resulting from using material masses and the process-based LCA approach to estimate the component's environmental impacts. The values under columns labeled "Cost-Based" represent the impacts resulting from the EIO LCA approach, using component cost data from [8] and the EIO LCA model [11] provided by Carnegie Mellon University.

b: Subsystem subtotals are provided in bold.

c: Unless otherwise noted, the material composition of each component is carbon steel. The EcoInvent process used to estimate the component's environmental impacts is "Reinforcing steel, at plant/RER with US electricity U" [10].

d: The EcoInvent process used to estimate the impacts of "Adhesive" is "Adhesive for metals, at plant/DE with US electricity U" [10].

e: The EcoInvent process used to estimate the impacts of "Glass Mirror Facets" is "Solar glass, low-iron, at regional storage/RER U" [10].

Table 1. Environmental Impacts resulting from the Manufacture of One 148 m^2 ATS Heliostat

5. Comparison to other work

Lechón and colleagues have also conducted an LCA on both parabolic trough and power tower CSP systems for a location in Spain [4]. Enough information has been provided in the study to approximate the impacts on a per heliostat or per aperture area basis. In addition, Lechón and colleagues also evaluate two of the three life cycle metrics considered here: life cycle GHG emissions and CED. Lechón and colleagues estimate that the manufacturing of the solar field in the power tower plant design contributes 5.61 g CO_{2eq}/kWh to the total life cycle GHG emissions, with the contributions from its construction, operation, and decommissioning considered separately. If we assume that the majority of these emissions result from the heliostat structure alone (i.e., ignoring cabling and other ancillary solar field components as we have for the ATS heliostat analysis), each heliostat in [4] emits 5,300 kg CO_{2eq} during its manufacture, or 55.1 kg CO_{2eq} per m^2 of aperture area (based on a lifetime electricity production value of 2,600 GWh, 2,750 heliostats, and 264,825 m^2 of aperture area [4]). Likewise, one heliostat from [4] requires 75,600 MJ_{eq} during its manufacture, or 785 MJ_{eq} per m^2 of aperture area. See Table 2 for a summary of the comparison between the heliostat assumed in [4] and the 148 m^2 ATS heliostat evaluated here.

	Lechon et al. 2008 [4]	Current Study (148 m^2 ATS heliostat)	% Change
Aperture Area per Heliostat [m^2]	96.3	148	54%
GHG Emissions [kg CO_{2eq}/heliostat]	5,300	9,950	88%
GHG Emissions [kg CO_{2eq}/m^2]	55	67	22%
CED [MJ_{eq}/heliostat]	75,600	159,000	110%
CED [MJ_{eq}/m^2]	786	1,070	36%

Table 2. Comparison of Environmental Impacts Resulting from the Manufacture a Heliostat

One should note that the embodied emissions and CED associated with the manufacture of each 148 m^2 ATS heliostat are significantly greater (88% and 110% greater, respectively) than the heliostat evaluated in [4]. A key contributor to this increase in manufacturing impacts is likely due to the significant increase in size of the heliostat; the 148 m^2 ATS heliostat has a 54% larger aperture area than the heliostat used in [4]. It is not unreasonable to assume that the mass of embodied materials, and therefore embodied GHG emissions and CED, will increase proportionally to aperture area; however, this would not explain the entire increase in manufacturing impacts.

A more informative metric to refer to for this comparison would be the GHG emissions and CED required per aperture area, which increase by 22% and 36%, respectively. An increase in this metric showcases key differences in LCI and LCA assumptions in each study. Our work assumes a U.S.-based plant location and that the U.S. electrical grid is used in the manufacturing processes of most embodied materials. The plant location assumed in [4] is southern Spain and, although not explicitly stated, it is likely that the Spanish (or European average) electrical grid is used in the majority of the manufacturing processes used in the study. The U.S. electrical grid emits 10% more CO_2 per unit of electricity generated when compared to European electrical grid, or 18% more when compared to the Spanish electrical grid [12, 13]. The larger carbon intensity of the U.S. electrical grid may further lend an explanation to why the GHG emissions per aperture of heliostat are 22% larger than that reported in [4]. In addition to differences the electrical grid, our work uses hybrid LCA to evaluate the impacts of the heliostat, while [4] may only use a process-based approach to evaluate the impacts of their heliostat. The use of EIO LCA typically results in higher impacts as it captures process energy and other ancillary activities that occur upstream in the value chain that are not captured in the process-based approach. Finally, it is reasonable to assume that the heliostat used in [4] may require less material per m^2 of aperture area due to advances in heliostat design and material science; recall, the 148 m^2 ATS heliostat has been in operation for over 20 years, while power tower plants in Spain, and the work published by Lechón and colleagues, have been completed much more recently.

5. Conclusions and future work

The National Renewable Energy Laboratory is conducting a series of LCA studies for various CSP technologies. The current paper. contributes toward the completion of a full LCA of a 100 MW_{net} molten salt power tower CSP plant to be built in Tucson, AZ. Using published life cycle inventory data [8], this analysis provides estimates of the GHG emissions, water consumption, and CED required to manufacture one 148 m^2 ATS heliostat. The heliostat under consideration emits 5,300 kg CO_{2eq}, consumes 274 m^3 of water, and requires 159,000 MJ_{eq} during its manufacture. Annual performance data and a detailed life cycle inventory of the remaining subsystems for this reference plant design will be provided by an engineering consulting firm. Future work will incorporate the results reported here into a detailed LCA model used to estimate the life cycle impacts of the entire power tower plant. In addition, the life cycle impacts resulting from the heliostat will be carefully compared to other estimates (such as that provided in [4]) in order to identify and resolve key differences in the LCA and heliostat design assumptions.

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