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Life Cycle Assessment of Thermal Energy Storage: Two-Tank Indirect and Thermocline

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LIFE CYCLE ASSESSMENT OF THERMAL ENERGY STORAGE: TWO-TANK INDIRECT AND THERMOCLINE

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EXTENDED ABSTRACT

In the United States, concentrating solar power (CSP) is one of the most promising renewable energy (RE) technologies for reduction of electric sector greenhouse gas (GHG) emissions and for rapid capacity expansion. It is also one of the most price-competitive RE technologies, thanks in large measure to decades of field experience and consistent improvements in design. One of the key design features that makes CSP more attractive than many other RE technologies, like solar photovoltaics and wind, is the potential for including relatively low-cost and efficient thermal energy storage (TES), which can smooth the daily fluctuation of electricity production and extend its duration into the evening peak hours or longer.

Because operational environmental burdens are typically small for RE 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 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 (NREL) is undertaking an LCA of modern CSP plants, starting with those of parabolic trough design. Our LCA follows the guidelines described in the international standard series ISO 14040-44 [1]. To support this effort, we are comparing the life-cycle environmental impacts of two TES designs: two-tank, indirect molten salt and indirect thermocline. To put the environmental burden of the TES system in perspective, one recent LCA that considered a two-tank, indirect molten salt TES system on a parabolic trough CSP plant found that the TES component can account for approximately 40% of the plant's non-operational GHG emissions [2]. As emissions associated with plant construction, operation and decommissioning are generally small for RE technologies, this analysis focuses on estimating the emissions embodied in the production of the materials used in the TES system.

A CSP plant that utilizes an indirect, molten salt, TES system transfers heat from the solar field's heat transfer fluid (HTF) to the binary molten salts of the TES system via several heat exchangers. The "cold tank" receives the heat from the solar field HTF and conveys it to the "hot tank" via another series of heat exchangers. The hot tank stores the thermal energy for power generation later in the day. A thermocline TES system is a potentially attractive alternative because it replaces the hot and cold tanks with a thermal gradient within a single tank that significantly reduces the quantity of materials required for the same amount of thermal storage. An additional advantage is that the thermocline design can replace much of the expensive molten salt with a low-cost quartzite rock or sand filler material.

This LCA is based on a detailed cost specification for a 50 MWe CSP plant with six hours of molten salt thermal storage, which utilizes an indirect, two-tank configuration [3]. This cost specification, and subsequent conversations with the author, revealed enough information to estimate weights of materials (reinforcing steel, concrete, etc.) used in all components of the specified two-tank TES system. To estimate embodied GHG emissions per kilogram of each material, two life cycle inventory (LCI) databases were consulted: EcoInvent v2.0 [4], which requires materials mass data as input, and the US Economic Input-Output LCA database [5], which requires cost data as input. IPCC default global warming potentials (GWPs) give the greenhouse potential of each gas relative to that of carbon dioxide [6]. Where certain materials specified in Kelly [3] were not available in the LCI databases, the closest available proxy for those materials was selected based on such factors as peak process temperature, and similar input materials and process technology. The thermocline system was modeled using the two-tank system design as the foundation, from which materials were subtracted or substituted based on the differences and similarities of design [7].

Table 1 summarizes the results of our evaluation. Embodied emissions of GHGs from the materials used in the 6-hour, 50 MWe two-tank system are estimated to be 17,100 $MTCO_{2e}$. Analogous emissions for the thermocline system are less than half of those for the two-tank: 7890 $MTCO_{2e}$. The reduction of salt inventory associated with a thermocline design thus reduces both storage cost and life cycle greenhouse gas emissions. While construction-, operation- and decommissioning-related emissions are not included in this assessment, we do not expect any differences between the two system designs to significantly affect the relative results reported here. Sensitivity analysis on choices of proxy materials for the nitrate salts and calcium silicate insulation also do not significantly affect the relative results.

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TABLE 1: COMPARISON OF THE EMBODIED LIFE-CYCLE GREENHOUSE GAS EMISSIONS FROM THE MATERIALS USED IN TWO-TANK INDIRECT AND THERMOCLINE INDIRECT MOLTEN SALT THERMAL ENERGY STORAGE SYSTEMS DESIGNED TO SUPPLY 6 HOURS OF THERMAL STORAGE FOR 50 MW CSP PLANTS

	MATERIAL	MATERIAL MASS [kg]		EMISSIONS ($MTCO_{2e}$)	
		TWO-TANK	THERMOCLINE	TWO-TANK	THERMOCLINE
Thermal Mass	Silica Sand	-	17,900,000	-	376
	Molten Salt (40% Potasium Nitrate 60% Sodium Nitrate)	25,600,000	7,680,000	8,470	2,540
Oil-to-Salt Heat Exchanger	Calcium Silicate	77,800	38,900	4.9	2.4
	Stainless Steel	411,000	179,000	1850	927
Storage Tank(s)	Calcium Silicate	51,300	25,700	3.2	1.6
	Carbon Steel	885,000	456,000	1,270	654
	Mineral Wool	283,000	158,000	382	212
	Stainless Steel	6,110	3,080	31.7	16.0
Storage Tank Foundations	Carbon Steel	258,000	134,000	371	192
	Concrete	3,850,000	2,070,000	474	255
	Foam Glass	90,700	44,000	105	51.0
	Refractory Brick	667,000	432,000	1,540	996
Nitrogen Ullage System	Calcium Silicate	4,930	2,460	0.31	0.16
	Carbon Steel	20,000	17,900	28.7	25.8
	Nitrogen	429,000	28,100	184	12.1
Pumps	-	-	-	1,930	1,190
Compressors	-	-	-	6.6	6.6
Elevated Platform	Carbon Steel	194,000	194,000	278	279
	Concrete	1,290,000	1,290,000	159	159
TOTAL:				17,100	7890

Notes: Three significant figures are used to convey the uncertainty in the input data and assumptions. Materials listed are those specified in Kelly [3]; proxy materials were used for LCA modeling in some cases. Materials and masses are not reported for pumps and compressors because the EIO-LCA was used to estimate GHG emissions in those cases [5].

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