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Molten salt power towers operating at 600–650 °C: Salt selection and cost benefits

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ABSTRACT

This analysis examines the potential benefit of adopting the supercritical carbon dioxide (sCO_2) Brayton cycle at 600–650 °C compared to the current state-of-the-art power tower operating a steam-Rankine cycle with solar salt at approximately 574 °C. The analysis compares a molten-salt power tower configuration using direct storage of solar salt (60:40 wt% sodium nitrate: potassium nitrate) or single-component nitrate salts at 600 °C or alternative carbonate- or chloride-based salts at 650 °C.

The increase in power cycle efficiency offered by the sCO_2 Brayton cycle is expected to reduce the size and cost of the solar field required for a given thermal energy input. Power cycle capital cost is expected to decrease compared to the superheated steam-Rankine cycle, based on projections from sCO_2 cycle developers. Maximizing the ΔT of the storage system is required for viable deployment of sensible-salt TES. In this regard, the partial-cooling sCO_2 cycle is noted as a better option than the recompression sCO_2 cycle. In the current analysis it is assumed that a $\Delta T = 180$ K can be achieved with the partial-cooling cycle. Even with $\Delta T = 180$ K, the potential benefits of the sCO_2 Brayton cycle are partially or completely offset by increased thermal storage cost, albeit for reasons that differ for the different salts. An approximate 5% reduction in levelized cost of energy (LCOE) is achieved with either solar salt at 600 °C or ternary magnesium chloride salt at 650 °C.

The potential of using pure sodium nitrate or potassium nitrate is considered because the cold tank temperature for the sCO_2 power cycle is estimated at 420 °C, which would allow use of a salt with a higher melting point than solar salt. Sodium nitrate is the most cost effective, resulting in an overall LCOE reduction of 8.5%; however, sodium nitrate is known to have lower thermal stability than potassium nitrate.

The strong influence of salt cost and hot-tank cost on overall economics led to the analysis of single-tank thermocline options. The thermocline design significantly reduces salt inventory (by 50% or more) and in many cases also reduces the tank size versus the hot salt tank of the 2-tank system. It is speculated that integration of encapsulated phase-change material (PCM) in the thermocline could further increase the thermal-storage energy density and reduce storage tank volume. The thermocline cases led to three scenarios with relative LCOE reductions of approximately 10%; however, this must be tempered by possible operational inefficiencies of the thermocline temperature profile.

1. Introduction

The U.S. Department of Energy launched the SunShot Initiative in 2011 with the goal of making solar electricity cost-competitive with conventionally generated electricity by 2020. The stated metric of this initiative is a levelized cost of energy (LCOE) for utility-scale solar power of 0.06 USD/kWh (see, for example, Mehos et al., 2016).

The state-of-the-art concentrating solar power (CSP) system is assumed to be a molten-salt power tower employing a 60:40 wt% blend of sodium and potassium nitrate commonly known as “solar salt” at a hot-salt temperature of about 570 °C. The SunShot goal requires an additional cost reduction of at least 50% from the current cost of this technology in the U.S. market (Mehos et al., 2016; IRENA, 2016). In addition to solar-field cost reductions, analysis suggests that the SunShot goal requires development of new heat-transfer fluids (HTFs) and power systems operating at a temperature where the net power system thermal-to-electric conversion efficiency will reach about 50%, for example, near 700 °C. A molten-salt power tower is not the only possible path for next-generation CSP; however, the operating flexibility, energy-storage efficiency, and industry familiarity with this design makes

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Nomenclature

A_{rec}	receiver area
Cp	salt heat capacity
F	view factor of receiver surface to ambient
T_{mp}	salt melting or liquidus point
T_{max}	salt maximum bulk operating temperature based on thermal stability
T_{rec}	receiver surface temperature
$\dot{Q}_{inter}$	power from the solar field intercepted by the receiver
$\dot{Q}_{rec}$	thermal power delivered by the receiver to the heat transfer fluid
α	receiver surface absorptance
ϵ	receiver surface emittance
η_{rec}	receiver overall efficiency based on intercepted power from the solar field and power delivered to the heat transfer fluid
$\eta_{rec,opt}$	receiver optical efficiency
$\eta_{rec,th}$	receiver thermal efficiency
$\bar{\eta}_{rec}$	receiver annual average efficiency
ρ	salt density
CAPEX	capital equipment expense
CSP	concentrating solar power
DOE	United States Department of Energy
HTF	heat transfer fluid
LCOE	levelized cost of energy
LPPA	levelized power purchase agreement
MSPT	molten salt power tower
NREL	National Renewable Energy Laboratory
PCM	phase change material
SAM	System Advisor Model
sCO_2	supercritical carbon dioxide
TES	thermal energy storage
USD	U.S. dollars

it a leading contender. However, evolving from 570 °C to 700 °C will necessitate a new HTF to be developed, owing to solar salt's decomposition around 600 °C. Furthermore, an advanced power cycle more amenable to CSP requirements than steam-based turbines must be employed to achieve the LCOE objective. Each technology shift will have several consequences on the CSP system.

Deploying a new CSP technology operating at approximately 700 °C entails a level of risk that makes financing such a technology difficult. Developing the necessary technologies in a step-wise approach—first demonstrating system concepts and power technologies at 600 °C to 650 °C and later evolving to higher-efficiency systems at 700 °C—offers a lower-risk path. Furthermore, financing high-risk technologies that can approach one billion dollars is highly challenging, and progressing toward SunShot in steps that CSP industry members can support and implement is essential for the health of the industry and the commercial viability of newly developed technologies.

2. Approach

This study examines the benefits of operating a molten-salt power tower with an advanced power cycle at 600–650 °C—temperatures that are low enough to use the same or similar alloys to that in current CSP plants while allowing for increases in power-cycle efficiency. The proposed power cycle is the supercritical carbon dioxide (sCO_2) recompression Brayton cycle that is the subject of international development activity.

NREL's System Advisor Model (SAM) is a simulation tool with technology models for various solar and other renewable energy systems. In this analysis, SAM version 2017.01.17 was used to model a molten-salt power tower (MSPT). SAM's default MSPT model was modified to simulate higher salt temperatures and power-cycle efficiencies. Physical property data for the different salts were added to the SAM model via the *user-defined HTF* feature.

2.1. Salt selection and properties

Current parabolic trough and power tower systems use solar salt to provide thermal energy storage. Physical properties of this salt are well documented (SQM, 2016). One limitation of solar salt is a thermal decomposition temperature in the range of 600 °C, which limits the upper temperature of power tower systems employing solar salt as the HTF and thermal storage media. A number of alternative salts have been proposed and explored; for this analysis we focus on the salts listed in Tables 1 and 2.

In addition to showing specific heat capacity, density and viscosity, Table 1 highlights the volumetric heat capacity, ρC_p, relative to the value for solar salt. Volumetric heat capacity is an important factor in determining the volume of the storage tanks, given that tank size is inversely proportional to $\rho C_p \Delta T$. The only salts with a larger volumetric heat capacity than solar salt are sodium nitrate and the ternary carbonate.

In addition to solar salt, this analysis considers pure sodium nitrate and potassium nitrate. Despite its higher T_{mp}, pure sodium nitrate is considered a possible salt for use with the sCO_2 Brayton cycle because this power cycle optimizes to a higher cold-salt temperature (~400 °C) than the steam-Rankine cycle (~300 °C). While exhibiting cost and heat capacity benefits versus solar salt, sodium nitrate is predicted to have lower thermal stability versus potassium nitrate (Bauer et al., 2013a, 2013b). Thus, the study also considers pure potassium nitrate as an alternative with similar physical properties but greater thermal stability than solar salt.

Beyond the nitrate salts we consider chloride and carbonate salts as

Table 1
Properties of solar salt and alternative salts. T_{mp} represents the melting point or approximate liquidus point for non-eutectic salts. Physical properties shown at approximately 600 °C unless noted.

Salt	T_{mp} (°C)	T_{max} (°C)	Heat Cap. C_p (kJ/kg K)	Density ρ (kg/L)	Relative ρC_p	Visc. (cP)	Refs.
Solar salt (baseline)	238	585	1.55	1.71	1.00	1.03	SQM (2016)
$NaNO_3$	306	520	1.62[a]	1.82[a]	1.11	–	Bauer et al. (2013a)
KNO_3	334	600	1.40[a]	1.78[a]	0.94	–	Cordaro et al. (2011)
$KCl/MgCl_2$	426	> 800	1.03	1.94	0.75	1.88	Mohan et al. (2018), and Williams (2006)
$MgCl_2/NaCl/KCl$	385	> 800	1.14	1.93[b]	0.83	–	Mohan et al. (2018)
$ZnCl_2/NaCl/KCl$	200	> 800	0.92	2.08	0.72	4.5	Li et al. (2016)
$K_2CO_3/Na_2CO_3/Li_2CO_3$	398	800	1.79	2.01	1.36	10.7	An (2016)

[a] Approximately 450 °C.

[b] Value taken from binary $NaCl/MgCl_2$ salt in Mohan et al. (2018).