Technoeconomic Cost Analysis of NREL Concentrating Solar Power Gen3 Liquid Pathway

Preprint

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Technoeconomic Cost Analysis of NREL Concentrating Solar Power Gen3 Liquid Pathway

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Abstract. The National Renewable Energy Laboratory is leading the liquid (molten salt) power tower pathway for the U.S. Department of Energy's concentrating solar power Gen3 initiative. The Gen3 liquid pathway required updated designs to three major components: the tower and receiver, the thermal energy storage tanks, and the power cycle. We assume a 100 MW_e net system output and used the System Advisor Model (SAM) to complete a technoeconomic cost analysis of the Gen3 liquid pathway design and estimate its levelized cost of electricity. This paper summarizes the methodology and results of that analysis.

INTRODUCTION

As part of the SunShot Initiative, the U.S. Department of Energy (DOE) has set a goal of lowering the levelized cost of electricity (LCOE) of baseload concentrating solar power (CSP) to 5¢/kWh by 2030. To achieve this goal, the DOE, national laboratories, and an industry-led technology review committee developed a roadmap that describes three potential pathways for the next generation power tower CSP plant, called CSP Gen3 [1]. The National Renewable Energy Laboratory (NREL) is leading the liquid (molten salt) power tower pathway. As part of the Phase 1 effort, NREL completed a technoeconomic cost analysis of the Gen3 liquid pathway design. This paper summarizes the methodology and results of that analysis.

A goal of the CSP Gen3 roadmap is to lower the cost of CSP by operating at higher temperatures to increase system efficiency. The NREL-led design is conceptually identical to the Gen2 design – a power tower with a cylindrical external receiver utilizing a molten salt heat transfer fluid, 2-tank storage, and a power block (Figure 1). The CSP Gen3 liquid pathway design increases the temperature on the hot side of the CSP plant from 575 °C to 720 °C compared to the Gen2 design. The cold side temperature is increased from 290 °C to 500 °C. A ternary chloride salt blend is used in place of nitrate salt (i.e. "Solar Salt") to handle the higher temperatures. The Gen3 design also replaces the Rankine Cycle currently used with a more efficient partial-cooling supercritical carbon dioxide (sCO_2) Brayton Cycle. The higher temperatures and novel salt composition required a redesign of the receiver and thermal energy storage (TES) tanks, including higher-strength materials that can resist corrosion from chloride salts. Table 1 summarizes the Gen3 design operational changes compared to Gen2.

METHODOLOGY

NREL uses the System Advisor Model (SAM) (https://sam.nrel.gov/) to perform technoeconomic analysis of CSP systems. SAM is a free software tool used to model a variety of renewable energy technologies. It can model system performance and cost under a range of financial ownership models and other inputs [2], [3]. SAM has been used in the past to perform SunShot-related analysis for the DOE [4]. SAM models are pre-populated with default values for a “typical” installation and correlations for calculating component costs. The user can change the default values and cost estimates to represent a specific installation.

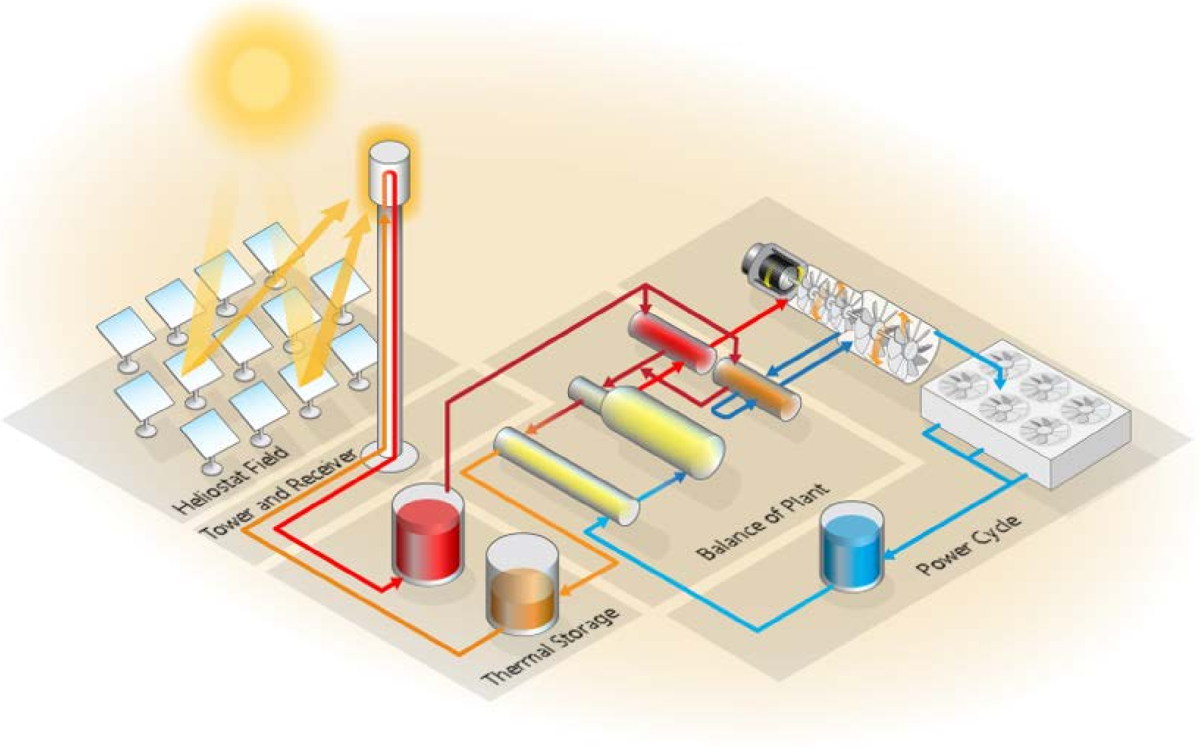

FIGURE 1. Conceptual drawing of concentrating solar power system using power tower and liquid molten salt

TABLE 1. Summary of proposed operational changes for CSP Gen3 Liquid Pathway design compared to CSP Gen2

	CSP Gen 2	**CSP Gen3 Liquid Pathway**
Hot Tank	565 °C	720 °C
Cold Tank	290 °C	500 °C
Salt	Solar Salt ($NaNO_3$-KNO_3 blend)	Ternary Chloride Salt ($MgCl_2$-KCl-NaCl blend)
TES	14 hours	14 hours
Solar Multiple	2.7	2.7
Power Cycle	Rankine Cycle $\eta_{th,cycle} = 41.2\%$	Brayton sCO_2 Cycle $\eta_{th,cycle} = 55\%$

We use SAM in this study to explore how changes in the Gen3 design, performance and component costs affect total system costs. The operational changes in Table 1 required new receiver, tank, and power cycle designs, as well as updates to salt properties and piping materials throughout the plant. Our analysis begins with the Gen2 design as the base case [4], Table 6 updated into a more recent version of SAM. We then model the plant using the inputs from Table 1 and the design and cost targets from the Gen3 roadmap [1] as the target case. The NREL teams designing each major system component provided updated performance estimates as the designs progressed. We incorporated these updates into the SAM model and measured the impact on LCOE. Finally, we combine all the updates to estimate the cost of the full NREL Gen3 liquid pathway design using molten chloride salts. The updates to system components are detailed in the next section.

SYSTEM ADVISOR MODEL (SAM) INPUTS

For this analysis we used SAM Version 2020.02.29[*]. We chose the "CSP power tower molten salt" model and a "PPA single owner (utility)" financial model. SAM uses location-specific weather files to evaluate system performance over a typical meteorological year. We are using an updated file for Daggett, California named "daggett_ca_34.865371_-116.783023_psmv3_60_tmy.csv" developed using 21 years of satellite observations every half-hour [5]. The file is available for download from the National Solar Resource Database through SAM.

The sections below describe the process and results of updating the CSP system component inputs to accommodate the Gen3 operating conditions. We start by assuming a 100 MW$_e$ net system output designed with a solar multiple of 2.7 and 14 hours of TES. A summary of the dimensions of the primary system components and the SunShot target costs for each is shown in Table 2. Financial assumptions from the *On the Path to SunShot* report were used [4]. Unless otherwise noted we used the default values in the SAM CSP power tower molten salt case.

TABLE 2. Dimensions of main system components for NREL Gen3 Liquid Pathway design and their SunShot cost targets

Tower and Receiver		**Thermal Energy Storage Tanks**	
Tower height	175 m	Tank height	11 m
Receiver height	20 m	Tank diameter (avg.)	41.1 m
Receiver diameter	35 m	Tank pairs	2
Number of panels	12	SunShot target	$\$15/\text{kWh}_{\text{th}}$
Tube outer diameter	34.8 mm		
Tube wall thickness	1.2 mm	**Heliostat Field**	
Coating emittance	91%	Number of heliostats	8,134
Coating absorptance	98%	Heliostat width	12.2 m
SunShot target	$\$150/\text{kW}_{\text{th}}$	Heliostat height	12.2 m
		SunShot target	$\$10/\text{m}^2$ site prep
Power Cycle			$\$75/\text{m}^2$ heliostat field
SunShot target	$\$900/\text{kW}_{\text{e}}$		

Molten Salt Properties

Nitrate-based solar salt used in Gen2 designs is thermally unstable above temperatures around 600°C, so a different heat transfer fluid (HTF) is needed to operate at the Gen3 temperature targets. NREL decided to use a ternary blend of chloride salts made up of magnesium chloride ($MgCl_2$), potassium chloride (KCl) and sodium chloride (NaCl). We used the user-defined HTF properties table in SAM to enter thermodynamic properties (specific heat, density, viscosity, kinematic viscosity, thermal conductivity, and enthalpy) for the ternary chloride salt for temperatures up to 750°C. SAM uses these properties to model salt behavior in the receiver, storage tanks, primary heat exchanger, and tubing/piping.

Receiver and Tower

NREL developed a receiver design for the Gen3 Liquid Pathway capable of withstanding the thermal and mechanical stresses of operating at a design outlet temperature of 720°C using the ternary chloride salt. The receiver is a 12-panel/2-flow-circuit design made of Inconel 740H and coated with a novel black-oxide surface coating developed by NanoSD. This coating gives the receiver surface a solar-weighted absorptance of 98% and an emittance of 91%. Receiver performance inputs were updated in SAM based on the results of the new Gen3 receiver

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[*] SAM is updated regularly. Both the current version and legacy versions are available for download at https://sam.nrel.gov/download.html

design model. The maximum receiver flux was lowered from 1,000 kW_{th}/m^2 to 450 kW_{th}/m^2 due to thermal stress limitations at the higher temperature. This roughly doubled the required receiver area. Estimated annual average receiver thermal efficiency, as defined in [6], also decreased from 89% for a Gen2 design to 77% due to higher emissive and convective losses at higher temperatures. Multiple designs were tested but we could not achieve a higher annual receiver thermal efficiency using chlorides salts and state-of-the-art materials.

The new receiver costs were estimated using the detailed cost breakdown presented in Solar Reserve's SunShot APOLLO report [7]. The receiver in this report also uses 12-panels. It has an outlet temperature of 720°C and a peak incident flux of 1.2 MW_{th}/m^2. This is much greater than the 450 kW_{th}/m^2 (0.45 MW_{th}/m2) incident flux calculated for the NREL design. The peak allowable flux in the APOLLO design was based on a 10,000 cycle life and a downward adjustment of allowable strain from low-cycle fatigue data to roughly capture creep-fatigue interaction [7]. However, more recently available information on creep-damage and creep-fatigue interaction at Gen3 conditions [8] suggests that these flux conditions are likely too aggressive. The NREL design used the procedures recently suggested by [8] (including both thermoelastic and inelastic methodologies) to predict creep-fatigue damage accumulation and lifetime. We updated the costs based on scaling the receiver component, accounting for size, material strength, and material cost. According to vendor quotes, the Inconel 740H selected for the NREL receiver design is 7% cheaper than the Haynes 230 used in the Apollo report. We contracted Nooter/Eriksen to review our methodology and assumptions. Results are summarized in Table 3. For non-equipment costs, we adopted the methodology in the APOLLO report and assume general and administrative costs were 28% and profit was 25% of receiver equipment costs. Finally, given that both the receiver and tower in the APOLLO report are similar in dimensions to the NREL design, we assumed that the installation costs are also similar and used the report's estimate of $55 million. The results are summarized in Table 4. The NREL receiver is significantly more expensive than the estimate in the Apollo report. This is mainly due to the lower peak incident flux of the NREL receiver which results in more surface area and greater material costs.

TOWER RISER AND DOWNCOMER

The higher temperatures in the Gen3 design (see Table 1) require upgrades to the piping materials that carry the molten salt. [7] did not include detailed costs for the tower riser and downcomer that carry molten salt to and from the receiver. Instead we used the detailed material and labor cost breakdown in a report by Abengoa Solar [9] and adjusted for piping size requirements, material strength, and material cost. Figure 2 shows how material strength decreases with temperature. The Abengoa design used carbon steel on the cold side, but at 500°C carbon steel loses much of its strength. All steel alloys considered lose strength above 600°C. After accounting for material cost (based on vendor quotes), strength, and corrosion concerns, we assumed that the cold side material was upgraded from carbon steel to lined SS347H, and that the hot side material was changed from SS347H to lined SS347H. The liner is a proprietary coating that protects the steel pipe from corrosion and costs $\$150/ft^2$ based on vendor quotes. The Abengoa report assumed two towers and required more horizontal piping than we need for our single tower design. Based on guidance from Nooter/Eriksen we assumed that the horizontal runs are 20% of the vertical runs. We also updated the cost of the cold salt pumps to reflect that they would be made of stainless steel. Together, the tower riser and downcomer plus insulation and cold salt pumps add $25.5M or $\$45/kW_{th}$ to the cost of the tower and receiver.

THERMAL ENERGY STORAGE TANKS

The Gen3 design required a complete redesign of the TES tanks due to the high temperatures and use of chloride salts. After several iterations, the NREL team developed a design that uses an internally insulated carbon steel shell around a 3-layer refractory liner: corrosion-resistant brick at the salt interface (hot face), insulating firebrick (IFB) behind the hot face, and microporous insulating board adhered to the inner tank shell wall. The tank height is 11 m and tank diameters are limited to about 40 m. To supply thermal storage, 4 tanks (2 hot tanks and two cold tanks) are needed. The "wetted loss coefficient" in SAM was set to 0.35 W_{th}/m^2-K so that heat losses from the tank in SAM match the tank design heat flux of 276 W/m^2, which corresponds to 2% thermal energy loss over 24 hours. The cost of the TES system is estimated to be $\$60/kWh_{th}$, which is four times greater than the Gen3 roadmap target of $\$15/kWh_{th}$. The TES design will be addressed in greater detailed in forthcoming publications from team members.

TABLE 3. Summary of components cost estimates for receiver from Apollo report [7] and the scaling metrics, factors and results used for the NREL receiver

Description	Price	Updated Price NREL Gen3	Scaling Metric	Scaling Factor
12 Receiver panels + 200 spare tube assemblies	$23,246,000	$43,853,728	Metal mass & type	1.89
Salt piping, air piping, drain piping & air tubing material and large bore piping fabrication	$10,667,000	$16,762,429	Receiver radius + height	1.57
Pipe supports	$356,000	$559,429	Receiver radius + height	1.57
Valves and I&C	$417,000	$417,000	None	1.00
Structure, ladderway, grating & handrails	$1,536,000	$3,518,209	Receiver area	2.29
Insulation & lagging	$685,000	$1,076,429	Receiver radius + height	1.57
Electrical equipment (heat tracing, JBs, FTPs, lightning protection)	$512,000	$804,571	Receiver radius + height	1.57
ECV	$2,349,000	$2,349,000	None	1.00
Heat shields	$3,584,000	$7,511,377	Receiver radius	2.10
Crane	$478,000	$478,000	None	1.00
Elevator	$500,000	$500,000	None	1.00
Salt valves	$2,538,000	$3,807,000	+50%	1.50
Receiver outlet vessel	$2,154,000	$1,664,455	flow rate	0.77
Lifting/tailing frame	$20,000	$20,000	none	1.00
Cost (Equipment Delivered to Site)	$49,042,000	$83,321,626	cumulative	1.70
Cost ($/kW$_{th}$)	**$87**	**$147**		

TABLE 4. Summary of cost estimates for tower, receiver and piping equipment, construction, and installation

Description	Receiver in Apollo Report [7]		NREL Receiver (this study)	
Receiver Cost (Equipment Delivered to Site)	$49.0M	$87/kW$_{th}$	$83.0M	$147/kW$_{th}$
General & Administrative Costs (28%)	$13.7M	$24/kW$_{th}$	$23.3M	$41/kW$_{th}$
Profit (25%)	$12.3M	$22/kW$_{th}$	$20.8M	$37/kW$_{th}$
Tower and Receiver Installation	$55.0M	$97/kW$_{th}$	$55M	$97/kW$_{th}$
Riser/Downcomer and Cold Salt Pumps	n/a	n/a	$25.5M	$45/kW$_{th}$
Total	$130M	$230/kW$_{th}$	$182M	$368/kW$_{th}$

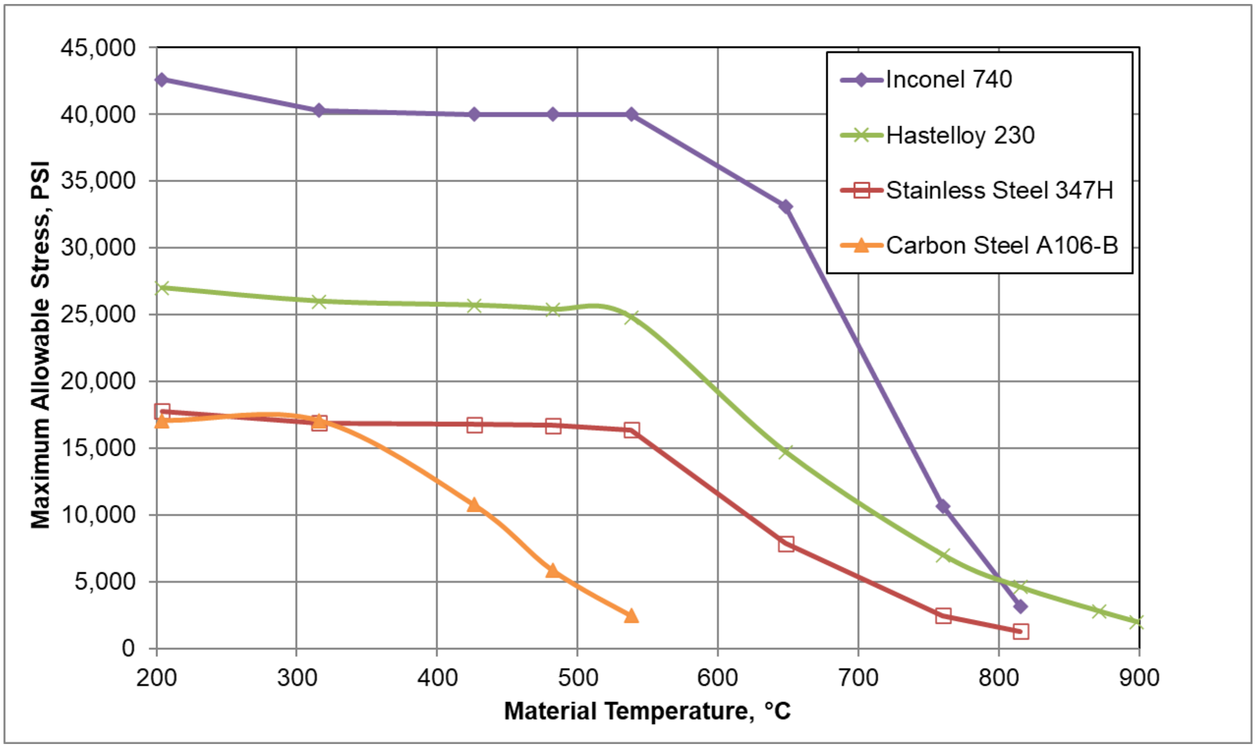

Figure 2. Material strength vs. temperature for materials mentioned in this study (ASME BPVC.II.D.C-2015)

SUPERCRITICAL CARBON DIOXIDE POWER CYCLE

The NREL Gen3 CSP design replaces the conventional steam-Rankine power cycle used in Gen2 with a supercritical carbon dioxide (sCO_2) Brayton power cycle. Prior analysis [10] showed that the sCO_2 cycle can achieve a higher cycle efficiency than steam-Rankine cycles and is also less complex, smaller in size, and has a lower thermal mass. SunShot goals [1] state a target cycle gross thermal efficiency of 55%, but NREL analysis found that a 51% thermal efficiency was more realistic. The power cycle model included off-design performance estimates [11]. After reviewing a paper on the costs of sCO_2 cycle components [12] and talking with the authors, we used the SunShot power cycle cost target of $900/kW$_e$ for the power cycle and primary heat exchanger. Based on those conversations, our power cycle cost estimate is likely conservative.

RESULTS AND DISCUSSION

We ran a sequence of cases in SAM to estimate the levelized cost of electricity (LCOE) of the Gen3 Liquid Pathway design. This model allowed us to measure the impact of changes in operational parameters and major CSP system component designs on total system costs. The cases and their results are discussed below and summarized in Table 5. Although the financial assumptions were consistent across all cases, changes to the assumptions could have a significant impact on the LCOE values. The reader is encouraged to compare the relative costs between cases rather than focus on absolute costs.

- **Gen2 SunShot**: This case updates the 2020 SunShot Tower case using the Gen2 design [4], Table 6 into the current version of SAM, including an updated weather file. This case uses the SunShot target cost assumptions (Table 2) and assumes a 55% thermal efficiency for a steam Rankine cycle. That efficiency is unrealistically high for a steam Rankine cycle but was used as a baseline against the Gen3 cases so that we can directly assess the impact of the Gen3 operational parameters and design compared to the Gen2 design.
- **Gen3 SunShot**: This case updates the Gen2 SunShot case using the Gen3 Liquid Pathway operating parameters, technologies such as the sCO_2 Brayton cycle, and chloride salt blend. Component cost targets

are the same as in the Gen2 SunShot case. We used NREL design values in Table 2 for system component dimensions. Since most cost and system performance inputs are identical to the Gen2 SunShot case, this case mainly demonstrates the impact of receiver efficiency at Gen3 temperatures. As discussed above, we could not develop a Gen3 receiver design with an annual average receiver efficiency above 80% due to increased convective and radiative losses at temperatures of 720°C. The net effect is that the Gen3 design temperature requires a larger heliostat field and has a slightly higher cost. This case was also used as a baseline for studying the impact of NREL system component designs and cost estimates in the cases below.

- **NREL Receiver**: This case uses the NREL tower, receiver, and piping cost estimates in the Gen3 SunShot case. Since the receiver performance is already in the Gen3 SunShot case, this case only assesses the cost of the tower and receiver. The NREL design is more than twice the $150/kW$_{th}$ SunShot cost target. Cost increases stem from a larger receiver due to a lower peak incident flux than anticipated, combined with increased piping costs due to the use of more expensive materials to handle the increased temperatures.
- **NREL Thermal Storage**: This case uses the NREL thermal energy storage tank cost estimates of $60/kW$_{th}$ in the Gen3 SunShot case. Like the receiver, TES costs are driven up by material and design requirements to handle temperature, corrosivity, and thermomechanical stress on the tank shell.
- **NREL Power Cycle**: This case uses the NREL power cycle design efficiency in place of the SunShot target. NREL modeling and analysis determined that a 55% thermal efficiency was not realistic for the operating conditions and current sCO_2 technologies. We used 51% instead. The power cycle costs were conservatively estimated at the SunShot target of $900/kW$_e$, so this case studies only the impact of power cycle efficiency on cost.
- **NREL Gen3 Design**: This case includes all NREL design cost and performance estimates and is the final estimate for the NREL Gen3 design LCOE. We also optimized the system by using the SAM "Parametrics" tool to find the solar multiple/storage duration combination that minimized LCOE. The planned 2.7/14-hour design has an LOCE of 10.9¢/kWh. The impact of the total NREL Gen3 design on LCOE is slightly more than the sum of the contributions, likely due to compounded efficiency losses in the receiver and power cycle, and is still well above the Gen3 SunShot case LCOE and the 5¢/kWh SunShot target.

TABLE 5. Summary of inputs and results for SAM Gen2 and Gen3 cases. Changes in inputs from case to case are in bold.

	Gen 2 SunShot	Gen 3 SunShot	NREL Receiver Costs	NREL Thermal Storage	NREL Power Cycle	NREL Gen3 Design
Salt Type	Solar (Nitrate) Salt	**Chloride Salt Blend**	Chloride Salt Blend	Chloride Salt Blend	Chloride Salt Blend	**Chloride Salt Blend**
Hot Tank Temperature	565°C	**720°C**	720°C	720°C	720°C	**720°C**
Cold Tank Temperature	290°C	**500°C**	500°C	500°C	500°C	**500°C**
Solar Multiple/ Storage Duration	2.7/14 hours	2.7/14 hours	2.7/14 hours	2.7/14 hours	2.7/14 hours	2.7/14 hours
Receiver Efficiency	89%	**77%**	77%	77%	77%	**77%**
Power Cycle/ Thermal Efficiency	Steam Rankine 55%	**sCO_2 Brayton 55%**	sCO_2 Brayton 55%	sCO_2 Brayton 55%	sCO_2 Brayton **51%**	**sCO_2 Brayton 51%**
Cost Inputs	SunShot	SunShot	**Tower and Receiver: $368/kW$_{th}$**	**Thermal Storage: $60/kW$_{th}$**	SunShot	**NREL Estimates**
LCOE (¢/kWh, Real$)	**5.8**	**6.1**	**8.1**	**7.9**	**6.6**	**10.9**

Based on the results of the component design analysis and the SAM LCOE, we decided to switch to a receiver design that uses sodium as the heat transfer fluid. The design was developed by Australian National University, a partner on the Gen3 Liquid Pathway project team, as an alternative to using molten salt. The sodium-based approach shows significant benefits in receiver efficiency and ease of operation, along with greater system design flexibility. Power cycle efficiency and TES tank costs remain challenges to lowering the LCOE of the Gen3 Liquid Pathway design to the SunShot 5¢/kWh goal.

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