CONCENTRATING SOLAR THERMAL POWER GEN3 LIQUID PATHWAY

Progress, Potential, and Challenges

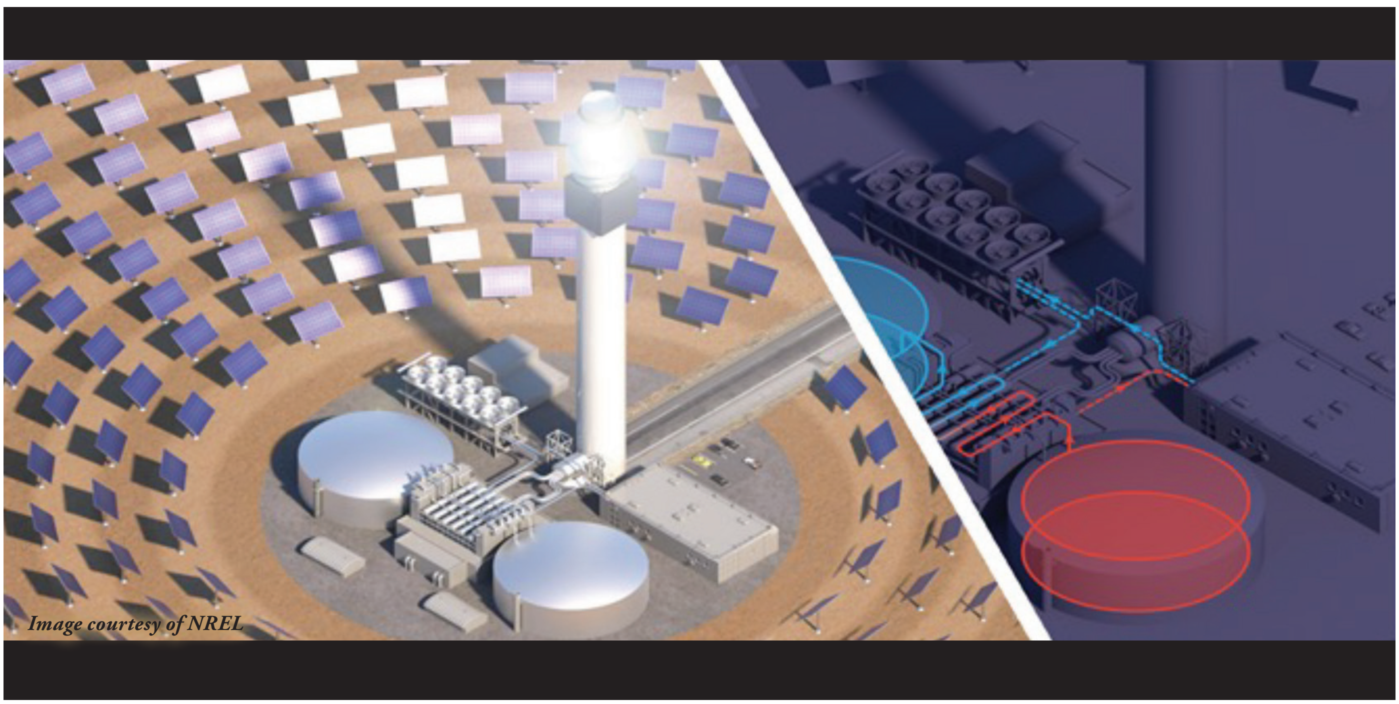

Image courtesy of NREL

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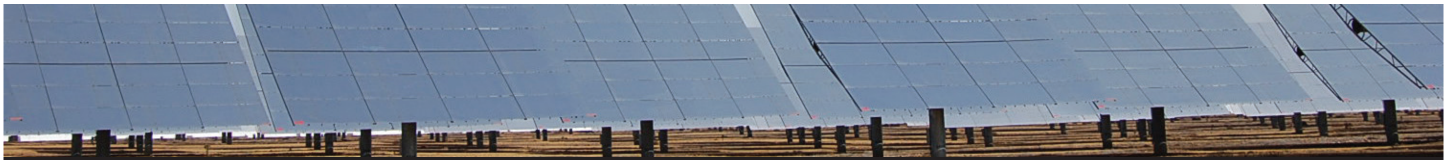

Executive Summary

Decade-long growth in concentrating solar thermal power (CSP) deployment has resulted in over 6,000 MW of operational capacity today. With nearly 1,800 MW of CSP capacity, the U.S. hosts over a quarter of global capacity, though most CSP development today is occurring outside the U.S. In the past several years, the first large-scale central receiver CSP systems entered commercial operation, including many with integrated thermal energy storage (TES) capability. Next-generation central receiver systems are targeting operating temperatures above 700°C and use of a closed Brayton power cycle with supercritical carbon dioxide (sCO_2) as the working fluid. These systems intend to deliver greater value through improved performance, dramatic cost reduction, and greater operating flexibility.

Under the U.S. Department of Energy (DOE) Concentrating Solar Power Generation 3 (Gen3 CSP) Program, a project team led by the National Renewable Energy Laboratory (NREL) is developing a Gen3 CSP technology using liquid heat transfer fluid (HTF). The 'Liquid-Phase Pathway to SunShot' project proposes the use of low-cost molten chloride salts for energy storage, mated with a solar receiver that employs liquid-metal sodium for heat capture and transfer to the storage salt. The storage salt would serve a primary heat exchanger to transfer heat to a closed sCO_2 Brayton power cycle to produce electricity. This approach leverages molten-salt technology from the current state-of-the-art CSP power towers embodied by plants such as the 19.9-MW Gemasolar, 110-MW Crescent Dunes, 150-MW Noor III, and 700-MW Noor Energy 1 CSP projects. Furthermore, the design builds on the knowledge gained over decades of liquid-metal sodium use as a high-temperature HTF in solar tests and nuclear-power applications.

This report summarizes the progress and potential of the "Liquid Pathway" to meet the objectives of the DOE Gen3 CSP Program, as well as remaining challenges. It also explores commercialization pathways and market opportunities for both Gen3 CSP and other power and energy applications.

CSP Industry Overview

CSP projects—both operational and under development—are located in areas with high direct normal irradiance (DNI) around the world. As of 2020, there are 99 operating CSP plants, totaling over 6,000 MW of capacity, include 1,740 MW in the U.S. [1] About half of these plants incorporate thermal energy storage with a total capacity of about 25 GWh_e. Figure 1 shows operational CSP plants (blue) and plants under construction (red) and under development (green). Global CSP capacity is expected to increase to 9 GW by 2024, and possibly 12 GW if construction timelines accelerate. Projects under development have an average of 9 hours of thermal energy storage capacity.

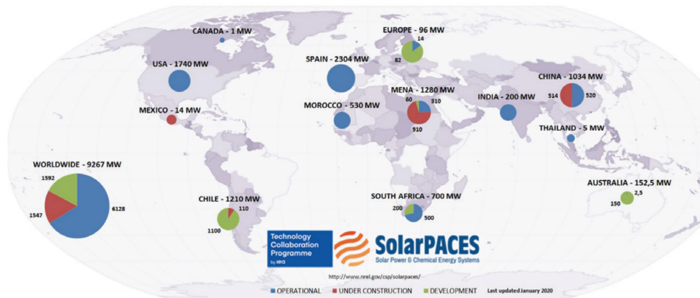

Figure 1. CSP capacity by country and region (Data Source: NREL/SolarPACES Project Database, last updated January 2020. Courtesy of IEA SolarPACES)

While CSP deployment is modest compared to nearly 800 GW photovoltaic (PV) capacity, individual country targets indicate increasing interest in CSP. Countries with deployment targets above 1 GW are listed in Table 1, with totals upwards of

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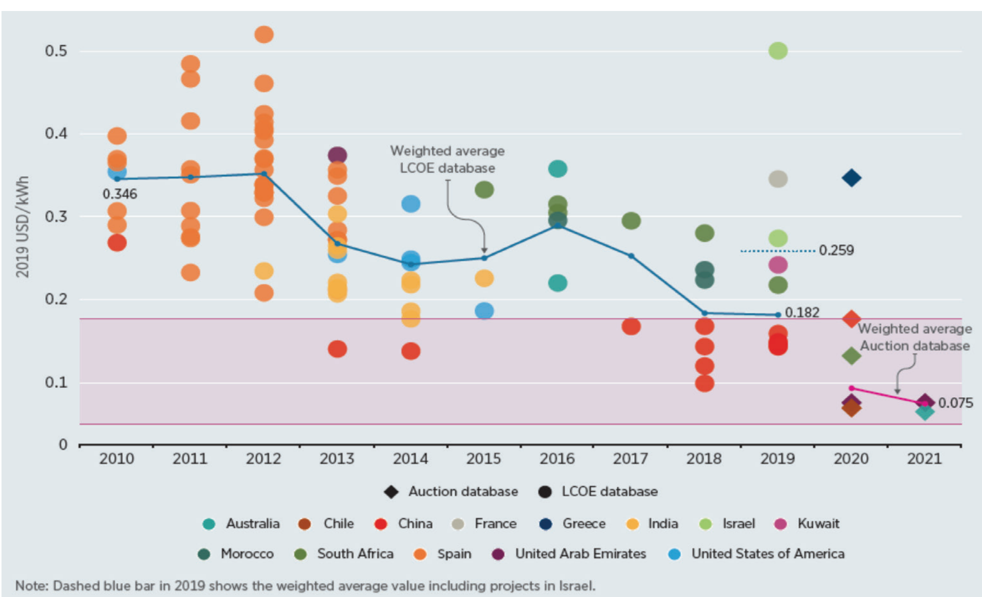
35 gigawatts (GW) by 2035. Public policy has been the primary driver of CSP deployment, along with energy programs and financial support mechanisms. For example, the generous feed-in tariffs in Spain successfully resulted in 2.3 GW of CSP deployment in 2006-2014. Spain's Ministry of Energy performed detailed studies in recent years to determine the least cost option to achieve resource adequacy under EU 2030 decarbonization requirements, while anticipating that the fraction of PV and wind generators will inevitably increase. The conclusion was that the overall system cost would be less with CSP providing system stability rather than through the addition of more PV and wind plants [2]. Consequently, 7 GW of CSP by 2030 with 12 hours of storage capacity was added to the Integrated National Energy and Climate Plan (NECP). In several other countries, recent requests for proposal (RFPs) and auctions have been designed to encourage CSP bids.

The type of technology being deployed is shifting from parabolic trough (Generation 1) technology that uses synthetic oil HTF to central receiver (Generation 2) technology that uses molten nitrate salt HTF. Both technologies use a steam-Rankine cycle, but parabolic trough is limited to operating temperatures near 390°C, whereas central receiver systems operate around 565°C. The relative maturity is important to consider in evaluating the cost and performance of technologies. Today, 83 parabolic troughs are operating globally, representing about 83% of installed capacity [1]. The Spanish fleet of 44 parabolic trough plants, with and without thermal energy storage, demonstrated over 96% availability during 2016-2019 [1]. In contrast, there are 16 central receiver plants, most of which were built in the past five years, with a total capacity of 1.3 GW. About 84% of new capacity under development is central receiver, aka power tower, technology.

Between 2010 and 2019, the global weighted average levelized cost of electricity (LCOE) fell by 47% for CSP projects commissioned during that timeframe [4], as shown in Figure 2. While individual LCOE values and auction prices are not directly comparable and data are limited, the trend line shows that CSP costs have fallen substantially and that the rate of reductions may be accelerating, given PPA prices announced for 2020 and 2021. Recent international project bids have fallen below $70/MWh in high-quality DNI regions.

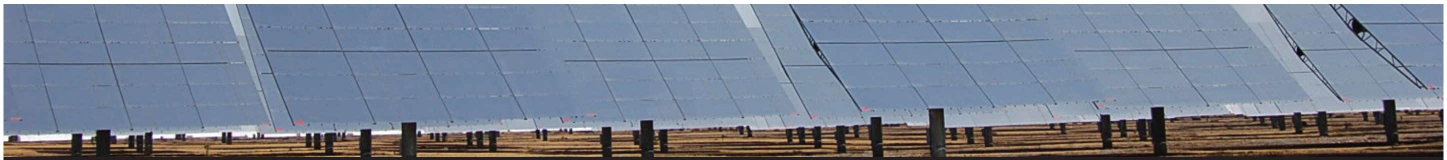
Table 1. Country CSP targets > 1 GW (Data Source: REN21 [3])

Country	CSP Deployment Target
Algeria	2 GW by 2030
China	5 GW by 2020
Egypt	11 GW by 2035
India	100 GW by 2022 (CSP and PV)
Kuwait	1.1 GW by 2030
Morocco	4.56 GW by 2030 (CSP and PV)
Saudi Arabia	2.7 GW by 2030
Spain	7 GW by 2030
Syria	1.3 GW by 2030



Source: IRENA Renewable Cost Database and IRENA Auction and PPA Database.

Figure 2. Global CSP Project Costs, Auction Prices, and Averages, 2010-21. Circles represent individual CSP projects and are centered on LCOE values calculated using standardized assumptions across all projects; diamonds represent individual projects and are centered on reported auction prices for a given delivery date; and plot lines present global averaged LCOE and auction price trends. [4] (Courtesy of IRENA)



U.S. DOE Gen3 CSP Program

Since 2007, the U.S. DOE has invested almost $400 million in advancing CSP technology. Beginning with the 2010 launch of the SunShot Initiative, DOE-funded R&D has focused on cost-performance targets for key subsystems and components, as illustrated in Figure 3. Goals are based on criteria published in the CSP Gen3 Roadmap [5] and a subsequent funding opportunity announcement (Gen3 FOA) [6]. By 2030, DOE's current goals for full-scale Gen3 CSP systems are $50/MWh for baseload plant designs (revised from the $60/MWh target specified in the Gen3 FOA) and $100/MWh for peaker plants. In 2018, DOE awarded $72 million to support development of Gen3 CSP technologies. Three Topic 1 project teams led by NREL, Sandia National Laboratories, and Brayton Energy were selected to develop integrated thermal systems for three solar receiver HTF pathways—liquid, solid particle, and gas-phase materials—respectively.

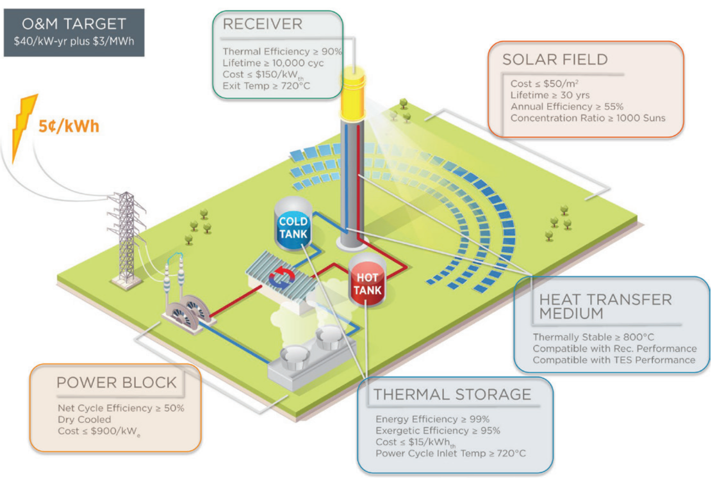


Figure 3. DOE Gen3 CSP 2030 goals (Courtesy of U.S. DOE Solar Energy Technologies Office)

Relative to current Gen2 system costs, DOE's 2030 Gen3 CSP LCOE targets require substantial additional cost reductions and performance improvements through the various subsystems. If some component targets are exceeded, it may be possible to relax requirements for other components.

A common feature of Gen3 technologies is use of a closed sCO_2-Brayton power cycle. Above its critical point, CO_2 acts as a supercritical fluid, allowing large changes in density to be achieved through small changes in pressure and temperature. Using sCO_2 greatly reduces the required energy for compression in a Brayton cycle, increasing thermal-to-electric conversion efficiency. Whereas, current power towers like Ivanpah and Crescent Dunes are designed to serve a steam-Rankine power cycle with superheated steam conditions, Gen3 CSP systems are expected to achieve thermal conversion efficiencies multiple percentage points higher, as shown in Figure 4. The CSP Gen3 Roadmap [5] identified advanced supercritical CO_2 Brayton power cycles, such as the recompression and the partial-cooling configurations, as having the potential to achieve the Gen3 target of 50% efficiency, even when combined with dry cooling. The partial-cooling configuration tends to operate over higher pressure ratios across the turbine, so it has higher power density than the recompression cycle [7]. Consequently, the cycle requires less recuperation (i.e., smaller recuperator area). The higher pressure ratio leads to a larger temperature difference across the turbine, and, therefore, the solar receiver, primary heat exchanger and any thermal storage system. For CSP applications with sensible-heat storage, the temperature differential across storage is an important factor in storage cost and overall economics. Each Gen3 CSP system is required to have a turbine inlet temperature of 700°C or higher.

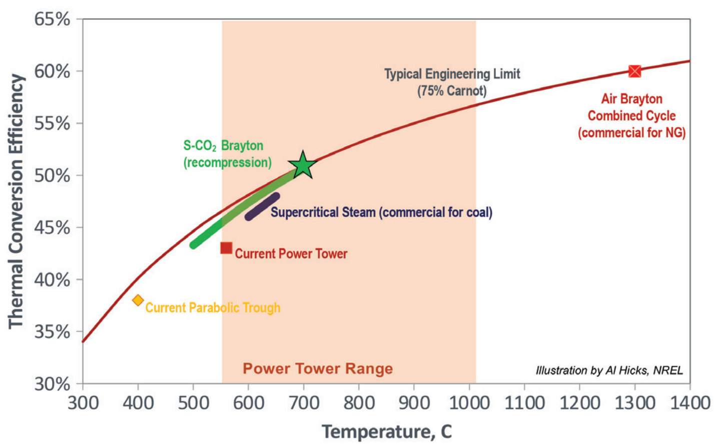


Figure 4. Advanced power cycle options (Courtesy of NREL)

Phase 2 of the DOE Gen3 CSP Program concluded in March 2021. In the final quarter of Phase 2, Topic 1 project teams were required to submit a continuation application that describes how the project team has mitigated technology risk, details plans for implementation of an integrated 1-MW_{th} Phase 3 pilot-scale test facility, presents an economic evaluation of a 100-MW_e-scale commercial system, and outlines a market adoption plan for technology scale up. The budget for Phase 3 is $31.2 million, based on the funding target set by the DOE program (federal share of $25 million plus 20% minimum cost share). Sandia's particle-based system was selected for Phase 3 award.

NREL Liquid Pathway Gen3 Project

The commercial representation of the proposed Liquid Pathway Gen3 design incorporates a high-efficiency sodium receiver operating at ~740°C, with a liquid-liquid heat exchanger feeding a two-tank, molten-chloride storage system, as depicted in Figure 5. Chloride salt is dispatched to a sCO_2 power cycle to provide electric power to the grid. The design integration is a conceptual match for the current sodium receiver ➜ solar salt storage➜ steam-Rankine power cycle promoted by CSP-developer Vast Solar, which will facilitate commercial acceptance and development. To advance this sodium/salt Gen3 system, the Liquid Pathway team proposed the design and construction of a pilot-scale system, per the goals of the DOE Gen3 Program, in the CSP Gen3 Phase 3 Continuation Application [8].

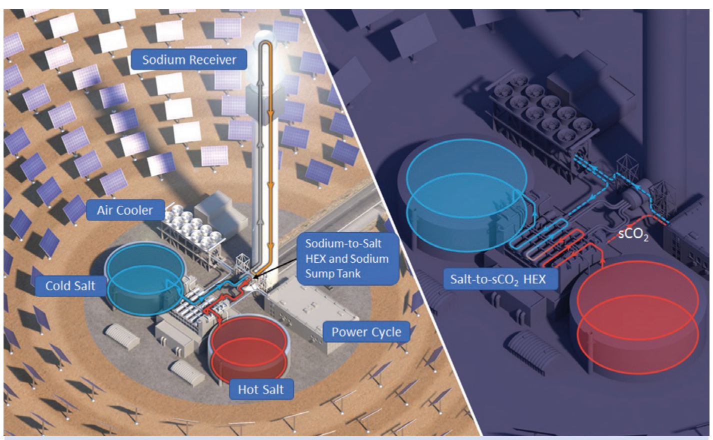


Figure 5. Sodium/Salt Gen3 system showing on-sun charging of the salt storage system (Courtesy of NREL)

The Liquid Pathway design uses a field of two-axis, sun-tracking mirrors, called heliostats, to redirect DNI to a sodium receiver at the top of a tower. The sodium HTF is pumped to the top of the tower and is heated in planar banks of thin-walled receiver pipes, before returning to ground level. The hot sodium serves a sodium-to-salt heat exchanger that utilizes salt from the cold storage tank. Heated salt is stored in the hot salt tank. To produce power, the hot salt flows through a primary salt-to-sCO_2 heat exchanger, and the sCO_2 drives a turbine to produce electricity. Cooled salt then returns to the cold salt tank.

Importantly, the dual-fluid design of the Liquid Pathway allows each HTF to operate where best suited. The unparalleled properties of sodium are dedicated to the solar receiver, leading to higher receiver efficiency and lower freeze risk. Figure 6 shows a sodium receiver concept adapted from John Cockerill with all of the components at the top of the tower. In the Gen3 design, the sodium-to-salt heat exchanger, pumps, and sump tank are located adjacent to the base of the tower, as depicted in Figure 5. The Gen3 design uses a low-cost, ternary chloride salt blend ($MgCl_2$-KCl-NaCl) as the sensible-heat thermal storage media capable of operation at temperatures exceeding 700°C. Both the sodium and salt media are available in bulk quantities from existing commercial suppliers. The salt would be provided to the Liquid Pathway project by ICL as anhydrous carnellite, a feedstock used by the magnesium industry.

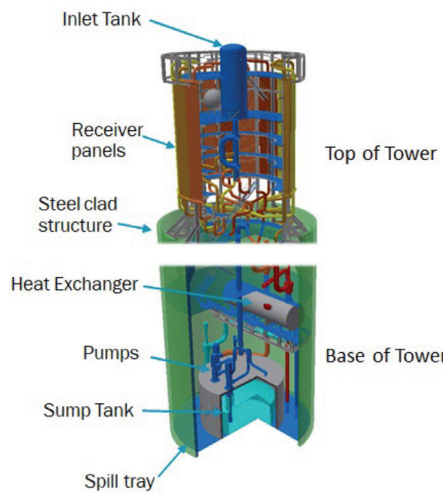


Figure 6. Conceptual sodium receiver design, adapted from John Cockerill [9]

Controlling impurities in the sodium and salt fluid loops is critical to avoid corrosion. Cold trapping, a technique whereby impurities are removed by precipitation utilizing the difference in solubility of impurities in sodium at different temperatures [10], is commonly used in sodium systems to maintain oxygen below a few parts per million (ppm). For the salt loop, removal of impurities begins during the salt melting process during system startup. A small amount of magnesium metal (~0.1 wt%) is added during the melting process to remove impurities. During operation, active monitoring and control of the salt potential, corrosion product concentrations (e.g., Cr^{2+}, Fe^{2+}), and salt impurity concentrations (O_2, MgOHCl) is necessary. These measurements are essential to monitor and control the corrosion potential of the salt on the facility's containment alloys.

Unlike Gen2 molten salt systems that operate at atmospheric conditions, the Gen3 salt storage tanks, pumps, and piping require a slight overpressure of nitrogen ullage gas system to prevent intrusion of atmospheric oxygen and moisture. The ullage gas system includes an acid gas scrubber that is used during initial salt melting and later for scrubbing of the vented ullage gases. Acid gases are generated when moisture or oxygen enters the system and signify the presence of those impurities.

Sodium and salt are subject to freezing risks at different temperatures. The bulk solidification temperature for the ternary chloride salt is ~400°C, while salt vapors may deposit at temperatures around 480°C.[1] Thermal management strategies include use of insulation and trace heating on piping, headers, and valves to prevent solidification. Ceramic fiber heaters may be justified for commercial-scale systems. Liquid metal sodium freezes at 98°C and is much easier to handle from a freeze risk perspective than salt. The greater risk from sodium is its reactivity in air (see sidebar).

The Liquid Pathway team is led by the National Renewable Energy Laboratory (NREL) and includes industry, academic and national laboratory contributors. Sandia National Laboratories, working closely with Bridgers & Paxton (B&P), serves as the host site and system integrator. Industrial and academic partners provide expertise related to system components such as valves, tanks, and heat exchangers designed to work with the high-temperature fluids. Partners of the Australian Solar Thermal Research Institute (ASTRI) lead the development of the sodium receiver and sodium handling system.

The Liquid Pathway leverages an extensive list of suppliers and developers in CSP and nuclear industries. This market presence may shorten the timeline to commercial deployment of the proposed Gen3 technology.

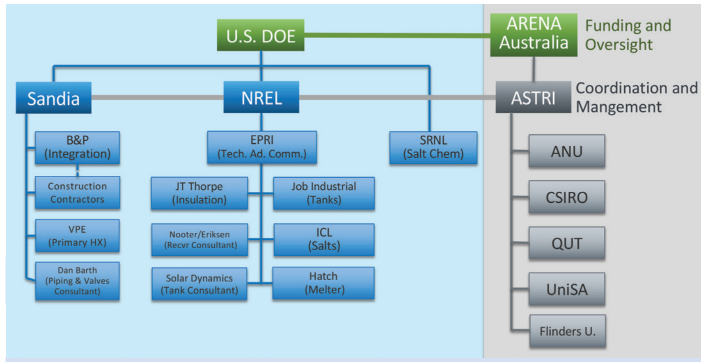


Figure 7. Liquid Pathway team member roles (Courtesy of NREL)

Sodium Safety

Safety is central to the successful use of liquid sodium in the Liquid Pathway. Sodium is a flammable metal which reacts violently with water and chlorinated hydrocarbons. At the temperatures of interest for CSP, most spillages of liquid sodium can be expected to result in fires. Sodium fires produce a dense white smoke which contains highly alkaline materials, which can cause irritation and rapid tissue destruction through chemical and thermal burns. If a sodium fire contacts a concrete surface, chemical reactions can occur and the heat may vaporize moisture in the concrete, causing the surface to spall. In contrast, sodium thermodynamic reaction with the ternary chloride salt would lead to formation of Mg metal—a corrosion inhibitor—and NaCl.

Several specific measures are implemented for design safety in the proposed CSP plant. Sodium inventory is kept at a minimum and confined to the receiver, tower, and close proximity to the tower base in the Gen3 design. Concrete structures are avoided, or protected by steel jacketing. Argon or nitrogen is used as a cover gas to prevent oxygen and moisture intrusion. Systems are designed to allow gravity drain back to a sodium sump and to prevent in leakage of water from rain, snow, groundwater, or from adjacent areas or structures. Although fire response protocols would be formally determined in a Hazard Analysis for the pilot and future commercial systems, the safest response is typically to allow drainage of the sodium to the sump tank and wait to let any sodium that has escaped containment burn out. Sodium-fire response training is key to familiarizing local firefighting teams with the unique features of sodium, since sodium reacts violently with the conventional fire extinguishing material, i.e., water. The project team issued an in-depth report on "Sodium Safety and Protocols for CSP" as a project milestone.

1 Binary-chloride salt vapors (e.g., $KMgCl_3$) may freeze at higher temperatures than the bulk salt.

In addition to the official project team, the Liquid Pathway benefits greatly from an ecosystem of industrial suppliers and developers working with liquid sodium and chloride salt HTFs. In particular, Vast Solar has provided guidance on sodium handling and components, while receiver manufacturer John Cockerill has given the team significant help on receiver design, construction, and cost. Molten salt component suppliers Flowserve (pumps and valves), Sulzer (pumps), Flexitallic (gaskets and seals), Guichon (valves) and Gosco (valves) have shared information and/or hardware with the project team. Questions regarding sodium handling and system design have been guided by experts at Creative Engineers, Inc. (USA), Argonne National Lab, and the French Alternative Energies and Atomic Energy Commission (CEA France). Materials selection and compatibility with these fluids has leveraged work in the wider DOE "Salt Collective" research arena, with specific engagement from the Electric Power Research Institute (EPRI) and Special Metals (alloy properties), Powdermet (protective cermet coatings), Liquid Metal Holdings (protective thermal-spray coatings), Argonne National Lab (salt chemistry sensor), Oak Ridge National Lab (corrosion and small-scale testing), and Universities of Wisconsin and Arizona (salt chemistry). This research and supply-chain network, and the similarity of design with the existing CSP fleet of power towers, facilitates the route to commercial implementation once the technology has been demonstrated.

The Liquid Pathway has been further aided by engagement with the project Technical Advisory Committee (TAC), led by Cara Libby of EPRI. The TAC attended quarterly reviews and was essential to the receiver selection process. New TAC members were brought onboard at the end of Phase 1 to bolster the team's knowledge of sodium systems after the sodium receiver was selected in the down selection. They included professionals in engineering, procurement, and construction (EPC), engineers with industrial sodium experience, CSP developers, and experts in high-temperature nuclear coolants.

Commercial System Design and Advantages

During project Phase 1 the team compared the benefits and risks of salt storage mated to a salt receiver or a sodium receiver. This review was undertaken via a structured analytic hierarchy process (AHP) facilitated by EPRI [11]. The AHP participants, which included the TAC and project leadership team, concluded that the sodium receiver had both a significantly higher benefit (19.3%) and a lower LCOE (11.4%), with only a slightly higher risk (3%) than the salt alternative. Benefit and risk scoring criteria and results are shown in Figure 8. For the benefit hierarchy, a higher score represents a higher benefit, whereas for the risk hierarchy, a higher score represents a higher risk.

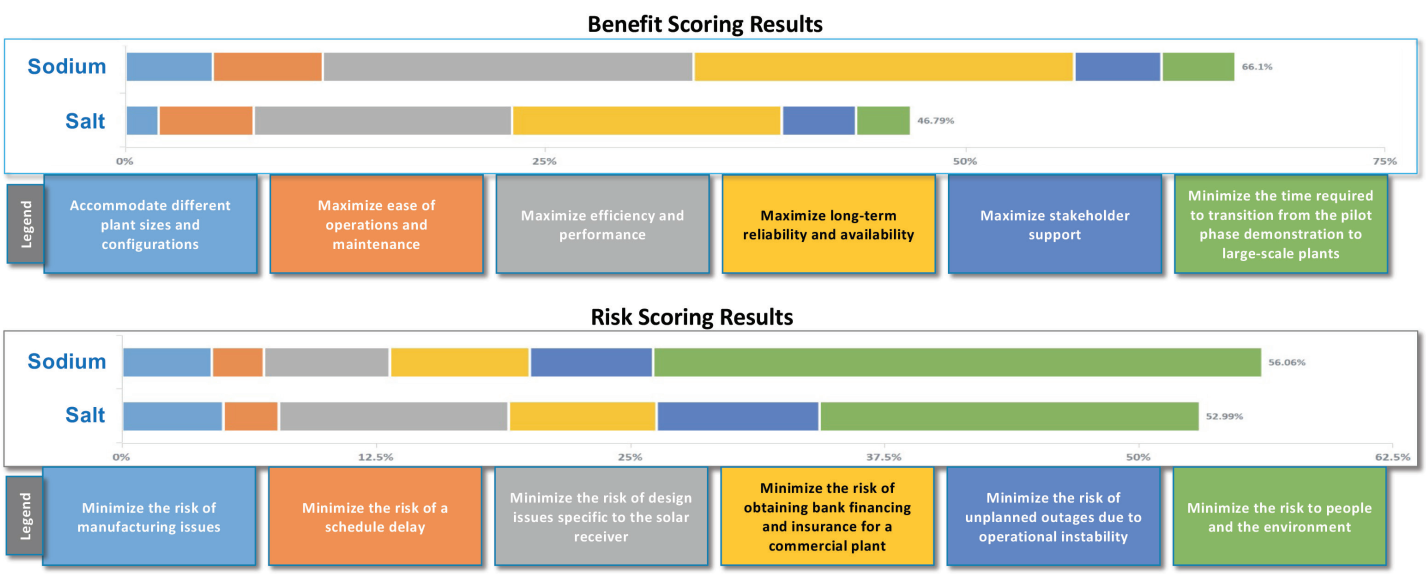


Figure 8. Benefit (top) and risk (bottom) scoring results.

Key observations included:

- While the score for criterion *Minimize risk to people and the environment* was the primary factor that resulted in a higher risk for sodium, it did not seem to impact the score for *Minimize the risk of obtaining bank financing and insurance for a commercial plant*, which received roughly the same score for both receiver types. The group concluded that even with the added risk from sodium, it would be feasible to educate bank engineers and the public about sodium as a safe technology.
- In the benefit hierarchy, the sodium alternative scored higher than the salt alternative across all six criteria. The three biggest differentials between the salt and sodium criteria scores were (i) *Accommodate different plant sizes and configurations*, (ii) *Maximize efficiency and performance*, and (iii) *Maximize long-term reliability and availability*.

The sodium receiver's operational benefits are due to sodium's superior thermophysical properties versus the chloride salt, such as lower melting point (98°C vs. 400°C), lower volume change on freezing/melting (3% vs. ~20%), lower viscosity (~10x lower), and greater thermal conductivity (64 vs. 0.4 W/m-K). These attributes lead to greater operational flexibility and greater allowable flux on the receiver (i.e., a smaller, cheaper and more efficient receiver), as showcased by developer Vast Solar in their SolarPACES 2019 Innovation Award acceptance presentation and at their 5-MW_{th} Jemalong facility (Figure 9). The overall result is a lower projected LCOE, despite the need for a sodium/salt heat exchanger. While the current Vast Solar design operates at less than 600°C, the proposed Gen3 design (Figure 10) will endeavor to move the technology to higher temperatures and efficiencies. The proposed pilot-scale demo aims to de-risk the technology by replicating commercial-scale design conditions within pilot-scale limitations.

Vast Solar Liquid Sodium Power Tower

Technology developer Vast Solar has derisked sodium handling for CSP applications through a 5-MW_{th} (1.1 MW_e) pilot facility in Jemalong, New South Wales, Australia comprised of five integrated tower-field modules. A 50-MW commercial hybrid plant is planned in Mt. Isa, Queensland to support 24/7 local power and mining loads using a combination of CSP with TES, PV, battery storage, and gas reciprocating engines. The commercial receiver design will operate at sodium temperatures up to about 600°C and employ thermal energy storage with nitrate solar salt. (Courtesy of Vast Solar)

Figure 9. Vast Solar's 5-MW_{th} (1.1 MW_e) Jemalong pilot facility (Courtesy of Vast Solar)

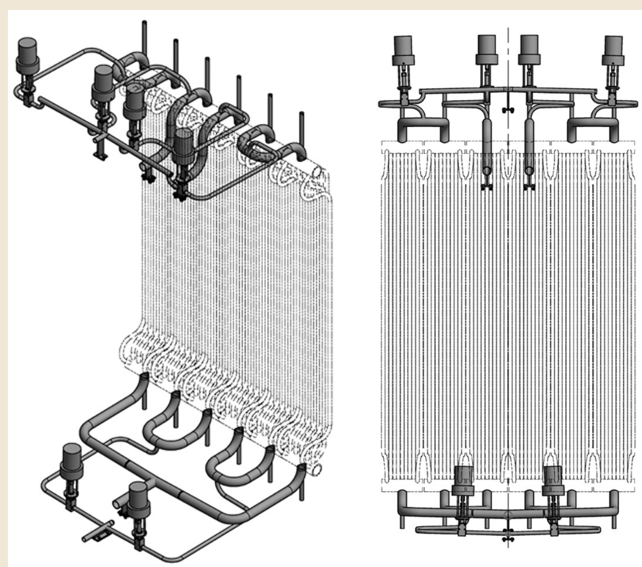


Figure 10. High-temperature sodium receiver under development by ASTRI (two views) (Courtesy of FE Consultants under funding from ASTRI)

LCOE Estimate for Commercial-Scale System

In the team's Phase 1 comparison of a salt-only and salt/sodium design, both units were modeled as 100-MW_e single-tower systems. As noted above, the salt/sodium design was selected. The versatility offered by a sodium receiver opens the design space to include modular or multitower systems as evidenced by the Vast Solar system design. Accordingly, in Phase 2, the team explored multitower designs, examining the tradeoff between economy-of-scale and benefits of smaller size systems. This analysis led to the selection of a 50-MW_e unit, which would be duplicated to form a 100-MW_e power facility to meet the DOE FOA requirement for a 100-MW_e system. Advantages of the 50-MW_e unit design include significant optical efficiency benefit, ability to utilize smaller towers (with potential cost savings), smaller salt tanks (allowing for a single pair of salt tanks per tower), better capacity match to the nascent sCO_2 power cycle, adaptability to fringe-of-grid and small-grid markets (e.g., Australia, which is perceived as a likely early adopter), easier financing and shorter construction times, and learning-by-doing replication. The twinned facility also offers operational redundancy where 50% generation can be maintained while maintenance is performed on the second unit. Bigger facilities can employ a "power park" design that allows for shared staff and support infrastructure [12]. These advantages overwhelmed the negative effects of the smaller plant capacity, namely higher cost-per-kW capacity and slightly lower efficiency of the power cycle.

Performance and capital cost estimates for the proposed commercial-system design were developed by the team during Phase 2 (Table 2). The SolarTherm CSP system model was used to generate LCOE estimates for the proposed design with a reference case of best-estimate costs and a parametric study that statistically varied each cost input, typically +/- 25%. This analysis resulted in a probability distribution of LCOE as shown in Figure 11 with a mean of \$58/MWh_e (USD), meeting the FOA target of \$60/MWh_e.

Table 2. High-level performance and cost parameters for the 50-MW_e unit

Item	50 MW_e module
Energy per year (MWh):	391,982
Capacity factor (%):	89.5
Receiver thermal input at design point (MW_{th}):	385
Receiver thermal output at design point (MW_{th}):	350
Annual field efficiency (%)	48.0
Annual solar to thermal efficiency (%):	41.3
Annual solar to electric efficiency (%):	19.3
Power block gross rating at design point (MW_e):	55.6
Power block efficiency at design point (%):	47.9
Full load hours of storage (h):	12.0
Storage capacity (MWh_t):	1,393
Total salt inventory, working and heel (tonnes):	22,925
Solar multiple:	3.0
Receiver diameter (m):	14.0
Receiver height (m):	14.5
Tower height (m):	150
Number of heliostats:	14,461
Single heliostat mirror area (m^2):	50.0
Total field area (m^2):	722,832
Total capital (installed cost, USD)	\$ 324,800,000

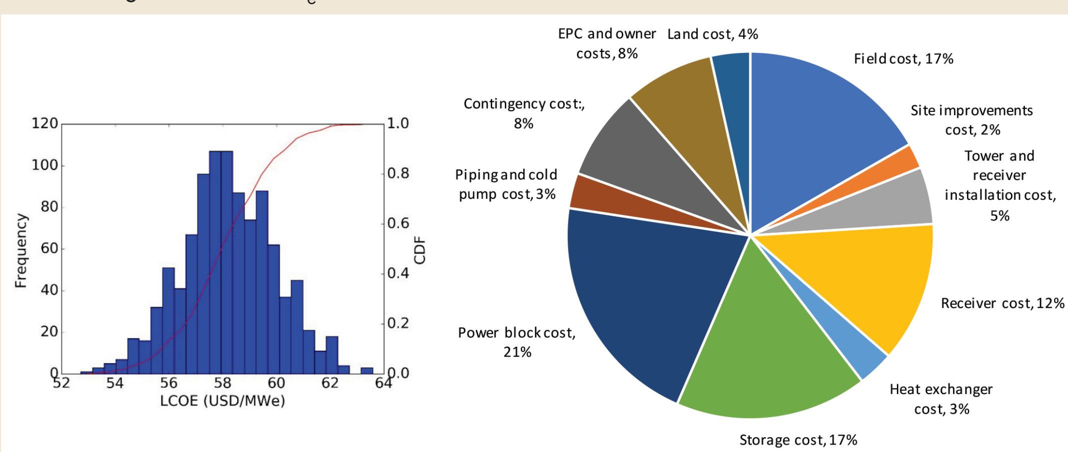


Figure 11. Left: Probability distribution for the LCOE of the 50-MW_e commercial system. Right: Breakdown of total capital costs for the 50-MW_e system. (Courtesy of NREL)

Major Accomplishments in Phases 1 and 2

During the project's Phase 1 and 2 research periods, significant knowledge was gained to derisk the technology.

- *Developed tank design that addresses temperature and corrosion challenges*. Tank design and liner materials were investigated, and a refractory liner defined that withstands the temperature and corrosion challenges of the salt. This design built on knowledge from the magnesium and refractory industries. The salt tank design employs a hot-face brick liner shown to be resistant to salt attack and that forms a protective forsterite phase in the presence of magnesium salt. This design insulates and protects the tank shell so that carbon steel can be used for the shell itself.
- *Demonstrated salt melting protocol*. Melting and purification of the salt was demonstrated at the laboratory and bench scale. Building on research from DOE's wider research program in molten chloride salts (aka, the *Salt Collective*), the team developed a protocol for melting the multi-ton quantity of salt required for the pilot scale system. This protocol has been tested with the melting of a 200-kg batch of salt at Oak Ridge National Laboratory.
- *Selected sodium receiver for further development*. Prior to the sodium vs. salt comparison and down selection, the project evaluated multiple salt and sodium receiver designs. Two designs were selected for the head-to-head down selection, which concluded that a sodium receiver design could achieve a lower LCOE and offered greater operational benefits compared to the salt design.
- *Designed pilot-scale receiver to derisk commercial-scale receiver design*. The proposed pilot-scale sodium receiver design is representative of the selected commercial-scale receiver that would be used in a 2 x 50-MW_e power facility. The pilot-scale receiver is estimated to have a thermal efficiency of approximately 84%, not accounting for intercept losses, which are negatively influenced by the small receiver size and large heliostats at the test site. The exit sodium temperature is 740°C. The commercial-scale design is estimated to have an overall receiver efficiency of 88%, accounting for all thermal and intercept losses.
- *Developed creep-fatigue protocol to estimate receiver lifetime*. Maximum allowable flux on the receiver is limited by creep-fatigue damage of receiver tubes. Detailed inelastic analysis explored the design constraints for the receiver in collaboration with experts at Argonne and Idaho National Labs. A protocol was developed for estimating receiver lifetime in the creep-fatigue regime that avoids the conservatism inherent in simpler (elastic) design procedures. Testing of the pilot-scale system will provide confidence in estimated receiver lifetime and a means to further calibrate the protocol. The high flux allowances currently under consideration translate to lower cost and higher efficiency in a commercial design.
- *Confirmed materials and fabrication method for primary heat exchanger*. The primary salt-to-sCO_2 heat exchanger (PHX) will use a printed circuit heat exchanger design (PCHE). Etching and bonding tests during Phase 2 confirmed the ability to fabricate such a unit out of Inconel 617 and H230. The high-nickel alloy PCHE design allows for a compact heat exchanger that can withstand both the sCO_2 pressure and differing corrosive effects of the two fluids. The commercial availability of PCHE technology gives a high degree of confidence to the estimated performance of these units.

Remaining Major Risks

Risks associated with the proposed Liquid Pathway were identified and tracked throughout the project in a formal Risk Registry. The risk registry captured project risks across over 17 component and subsystem categories and currently tracks over 400 identified risks associated with design, operation, and performance of the pilot-scale system. Current significant risks include:

- Integrity of the tank liner
- Performance of the salt valves
- Impact of salt vapor on system components
- Salt piping freeze recovery
- Pressure and chemical sensor performance
- Online corrosion control
- 740H alloy compatibility with sodium
- Risk of fire from hot and reactive fluids

Addressing these risks and demonstrating reliable operation is the goal of the Phase 3 pilot-scale demonstration system. Challenges are expected as the team works to understand the nuances of working with a chloride molten salt and the unique aspects of a liquid-metal sodium receiver. Fortunately, there are established protocols and knowledge available from the magnesium industry, other molten salt handling guidelines, and the historic use of sodium as a thermal transfer fluid. The design builds on the knowledge gained over decades of use of liquid-metal sodium as a high-temperature heat transfer fluid (HTF) in solar tests and nuclear-power applications.

Phase 3 Demonstration System

The overall goal of the integrated system demonstration is to derisk the Liquid Pathway approach and facilitate the development of the liquid pathway technology for Gen3 CSP. The general system layout is shown in Figure 12. Specific objectives include:

- **Operational Performance**
  - Demonstrate operational modes including dynamic and steady-state conditions.
  - Demonstrate safe operation of a sodium receiver and sodium loop. While sodium provides superior heat transfer capabilities in the receiver, the safety and reactivity concerns surrounding sodium can have significant implications on perception and acceptance of the technology.

Relevant R&D Accomplishments Performed Outside of the Liquid Pathway Project

The Liquid Pathway project has benefited from several complementary projects funded under Topic 2 of the Gen3 CSP FOA, alloy materials research funded by EPRI and the DOE nuclear program, and other research around the world. These include projects examining chloride salt chemistry, salt-chemistry sensors, salt pumps, salt valves, coatings to protect against salt corrosion, and the prototype test Facility to Alleviate Salt Technology Risks (FASTR) at Oak Ridge National Lab.

- **Developed and tested protective coatings for salt piping and tanks.** Projects led by Powdermet [13] and Liquid Metal Holdings [14] have developed and tested protective coatings for use in chloride salts. Other research has examined the potential of cladding as a protective liner in pipes and tanks. The cermet coatings developed by Powdermet are applicable as a wear-protective layer in pumps, valves, and fittings and have been quoted to the team for use in the project. The thermal spray coatings developed by Liquid Metal Holdings can be applied to tanks and large-diameter piping. Both of these approaches allow for use of lower-cost substrate alloys and longer life components.

- **Developed sensor to monitor salt loop impurities.** Monitoring of the salt chemistry is essential for corrosion control, and Argonne National Lab has developed an electrochemical sensor shown to effectively measure salt redox potential and corrosion indicators in laboratory and bench scale testing. This technology will be deployed and tested at the pilot system to monitor salt conditions.

- **Designed pumps compatible with Gen3 molten chloride salt.** Pump suppliers Sulzer, Flowserve, and Hayward Tyler engaged with the Liquid Pathway team on the design of molten-chloride salt pumps. These pumps leverage extensive knowledge of long-shaft, vertical-turbine salt pumps used in current CSP plants. Changes are made to adjust for the differing corrosion, salt property, and temperature conditions of the Gen3 molten chloride salt. Sulzer and Flowserve provided pump designs, performance specifications, and pricing for the pilot-scale salt pumps, as well as budget estimates for the commercial-scale system.

- **Identified candidate Gen3 molten chloride salt valves.** Chloride salt valve technology borrows heavily from the knowledge of current molten salt valves. High-nickel alloys, globe-valve design, and bellows seals are recommended for dealing with chloride salts. The Liquid Pathway project consulted with valve suppliers Flowserve, Guichon, Trillium, Gosco, and Jarecki, during Phases 1 and 2. Both Flowserve and Gosco have supplied valves for bench-scale testing, although these tests have been delayed due to pandemic-related issues.

- **Established FASTR system for component testing.** Recognizing the value in preliminary prototype component testing, DOE funded the FASTR project. This chloride-salt test facility provides similar piping size, temperature, and flow rates as expected in the proposed 1-MW_{th} pilot scale system. Hampered by pandemic related delays, FASTR's anticipated start in summer 2020 was pushed back into late fall. Recently, the FASTR team successfully melted their 200-kg batch of salt and charged the system. However, the delays meant that FASTR was unable to inform the Gen3 down select decision, although the facility is key to derisk components prior to potential integrated-system demonstration.

- Demonstrate operation at the target thermal rating of 1 MW_{th} and outlet temperature of 740°C. Many potential failure modes for the receiver system could arise from operation at target outlet temperatures that are well above those encountered in current commercial CSP systems. Thus, operating the receiver and sodium-salt heat exchanger at the target conditions is critical to derisk the functionality and survivability of the technology.
- Demonstrate thermal ramp rates for all three fluid loops (sodium, salt, sCO_2) and quantify limits of dynamic performance. CSP receiver systems operate under inherently dynamic conditions owing to variability in solar flux and weather. Responsiveness, controllability, and survivability under dynamic conditions are paramount to successful system performance.
- Demonstrate safe operation and survivability of components in response to emergency conditions, including power loss for heliostat control or receiver flow control, simulated critical component failures, or excursion of properties including receiver flux and temperature conditions from the desired set point.

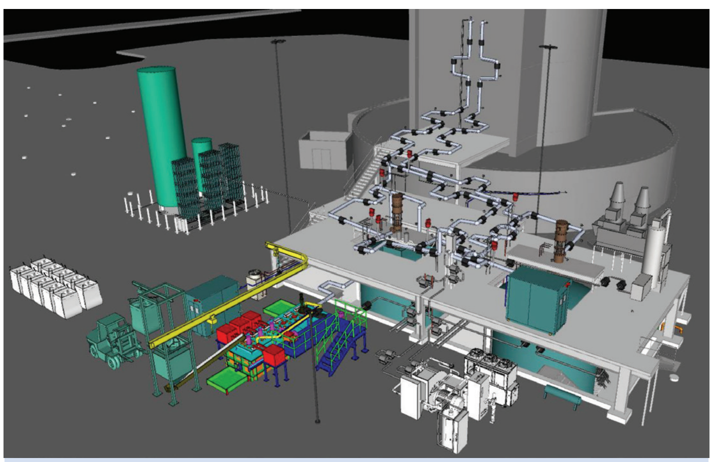


Figure 12. System layout at the tower base of Sandia's National Solar Thermal Test Facility: Melter in color at front left, N_2 ullage gas supply in left rear, scrubber in right rear on the elevated deck, and PHX with sCO_2 system in foreground at right. TES tanks are seen in green under the elevated deck. Receiver level not shown. (Courtesy of NREL)

- **Model Validation**
  - Characterize heat loss and receiver thermal performance. Validated pilot-scale performance models will provide confidence in commercial-performance projections.
  - Characterize salt tank heat loss and thermal performance.
- **Salt Tank**
  - Characterize the performance of foundation cooling in the pilot-scale tanks to refine performance models for air cooling of commercial-scale tank foundations. Successful implementation may point to cheaper designs for large salt tanks.
  - Demonstrate tank liner integrity and performance.
- **Pumps, Valves and Piping System**
  - Demonstrate salt and sodium pump and valve operational capabilities at Gen3 conditions.
  - Assess impact of salt vapors on system components and tank headspace.
  - Demonstrate operation and durability of heat tracing in the valve and piping network and sodium and salt freeze recovery.
- **Materials and Corrosion**
  - Demonstrate receiver panel fabricability. Fabrication of the 1-MW_{th} pilot-scale receiver system will provide a detailed assessment of the workability of the materials, ease of manufacturing for the 740H alloys and tube dimensions, and fabrication cost.
  - Demonstrate sodium cold trap operation and salt corrosion control. Maintaining purity levels in the sodium and salt fluids is essential to their long-term performance and the durability of the system.
  - Test corrosion rates and compatibility of alloys and coatings with sodium and salt at the hot-side and cold-side temperature conditions.
  - Complete sampling and post-test evaluations to validate material degradation and gain confidence in the ability to predict damage and degradation, and thereby to design components to a specified commercial-scale service life.

Pilot-Scale System Cost Estimate

The estimated budget for the Phase 3 project as calculated by the team's 90% Design Report is approximately $57 million dollars (estimated range $52 to $68 million). This estimate is roughly double the $31.2 million funding target set by the DOE program (federal share of $25 million plus 20% minimum cost share).

Market Adoption Pathway

Globally, there is a growing need for flexible, zero carbon generators that can provide resource adequacy and support grid stability needs [2]. This presents an opportunity for Gen3 CSP technologies with thermal energy storage, depending on the commercialization timeline and ability to demonstrate performance, cost, reliability, and other important metrics. The Gen3 Liquid Pathway technology offers several unique attributes that facilitate market adoption.

Evolutionary Design Reduces Risk

One of the major challenges of the Gen3 program is to develop advanced technology that is sufficiently familiar to existing technology developers to facilitate acceptance and market adoption. The Gen3 CSP Roadmap documents stakeholder preference for a path familiar to industry to reduce risk [5]:

> ***"All utilities that participated in the survey think that demonstration projects at nominally 10-MW scale are a necessary and important step to mitigate technology risk if the project design significantly deviates from what has been built previously.*** An exception may be advanced molten-salt technology, ***which could gradually evolve from technology available today."***

All current commercial CSP plants utilize liquid HTFs for thermal energy capture and conversion. The Liquid Pathway approach leverages molten-salt experience from the current state-of-the-art CSP power towers, including the 19.9-MW Gemasolar, 110-MW Crescent Dunes, 150-MW Noor III, and 700-MW Noor Energy 1 CSP projects. This provides an existing ecosystem of technology providers and system developers that will be familiar with the technologies and design methodology inherent in the proposed Gen3 Liquid Pathway approach. Many of the design standards and industry practices, such as those documented in NREL's 2020 CSP Best Practices Study [15], are applicable to the proposed Liquid Pathway technology.

The engagement of current CSP-industry suppliers in the development and testing of Gen3 pumps and valves may also accelerate the commercial potential of the liquid pathway technology. For example, working with industrial salt suppliers ICL and Albemarle ensures that the proposed Gen3 storage salt will be available in commercial quantities.

The most direct connection with the CSP marketplace lies in Vast Solar's development of sodium/salt systems as represented by their proposed Mount Isa 50-MW_e commercial project,[2] which is nearing financial closure. Success in this endeavor will garner attention and experience with sodium handling and receiver operations at a CSP plant. As important, this first project will demonstrate acceptance of the investor community in a CSP plant of 50-MW_e scale working with sodium. Phase 3 system components can potentially be demonstrated at larger scale in future commercial projects before necessitating a full Gen3-style integrated plant. For example, large sodium/salt heat exchangers are planned in the Mount Isa project, which will also include commercial demonstration of sodium pumps, valves, and handling procedures. These components and subsystems may be deployed initially at lower temperature and capacity, but the ability to gain commercial experience with them—outside of CSP research funding—is essential to bring the DOE Gen3 vision to the marketplace.

It is also notable that the proposed pathway offers the opportunity to advance the technology first to ~650°C receiver temperatures, where materials risk is significantly lower, before evolution to higher temperatures. This route to >700°C operation has also been stated by the DOE-funded STEP Initiative in its development of the sCO_2 power cycle.

Multi-Industry Interest Accelerates Technology Development Timeline

The proposed Liquid Pathway technology also dovetails with work in the nuclear power sector, where companies such as TerraPower, Moltex, Kairos, and others are working on advanced molten-salt reactor systems with CSP-similar needs for high-temperature salt pumps, valves, and storage systems. This wider field of applications entices investment, bridges the pre-commercial demonstration valley with multi-MW test and demonstration projects, and helps speed early commercial deployment and drive down cost.

[2] https://www.evwind.es/2020/07/24/australian-mining-town-picked-for-first-large-concentrated-solar-power-plant/76001

Chloride-Salt Thermal Energy Storage Technology Applications

The chloride-salt thermal energy storage technology has applicability to the nuclear and fossil power industries, potentially opening up development opportunities with other partners. The potential of low-cost chloride salts for thermal energy storage has garnered interest and spawned R&D activity around the world, including work in the USA, Australia, Germany, and China. Stand-alone thermal energy storage, also known as thermal batteries or Carnot Batteries, and Gen IV nuclear reactor systems would also potentially benefit from chloride salt storage.

Nuclear-power developer TerraPower is developing both a molten chloride fast reactor (MCFR) and a sodium-cooled reactor design for future power generation. Their Natrium reactor combines a sodium-cooled reactor with energy storage in nitrate salt. The design was recently selected for an $80 million DOE demonstration award with the plan for a reactor to be operational within the next seven years.[3] The MCFR design uses a binary $MgCl_2$/NaCl salt coolant with properties very similar to the ternary salt promoted by the Liquid Pathway team. Both systems currently interface with nitrate salt for thermal energy storage to facilitate reactor stability and load-following dispatchability. Transition to a chloride salt for energy storage offers significant benefits if the technology can be demonstrated to be reliable and cost effective. Potential advantages vs. nitrate salts include:

- Higher temperature energy storage that translates into higher power cycle thermal conversion efficiency
- Better chemical compatibility between sodium and the storage salt in the Natrium system
- Better chemical compatibility between the binary $MgCl_2$/ NaCl coolant and the storage salt in the MCFR system
- Lower cost media (although overall storage cost for the chlorides currently exceeds that for nitrates due to the estimated tank costs.)
- Applicability to a wider range of industrial applications beyond the power sector, due to the higher temperature stability of chloride vs. nitrate salts.

The development of sodium/salt power systems from the nuclear and solar industry perspectives could be accelerated through greater cooperation in the development and demonstration of this technology.

[3] https://www.terrapower.com/doe-natrium-demonstration-award/

Commercial System Cost Estimate Meets Gen3 CSP Target

CSP will need to compete against different generation sources in different markets, and the requirements for cost and other attributes vary. The estimated LCOE of the liquid pathway design is projected to have a high probability of achieving the $60/MWh target set by the Gen3 CSP program. This value is lower than current tenders, bid prices, and target costs in several international markets [2].

Smaller Unit Size Offers Greater Flexibility

The unit-system scale of 50-MW_e aids the transition from demonstration to commercial scale. The system size allows for salt tanks that do not exceed the dimensions of current nitrate-salt tanks. Importantly, the 50-MW_e unit capacity facilitates early adoption for those locations that may favor smaller capacity generators (e.g., Chile, South Africa, Spain, Australia) [2]. For fire-prone regions like California and Australia, smaller facilities could be located closer to industrial and municipal load centers to reduce the risk associated with long-range transmission lines. The presence of Vast Solar also provides close ties to the large mining operations and fringe-of-grid locations in Australia that match with smaller CSP capacity systems.

The smaller capacity also meshes more readily into the development path of the sCO_2 Brayton power cycle, offering nearer-term deployment than with larger, more capital-intense projects. Multi-unit "power parks" provide a solution for markets that seek larger capacity facilities (see Figure 13). Co-located generation units have been projected to yield LCOE cost reduction of up to 19% via construction learning and shared O&M infrastructure [12].

Figure 13. The proposed 50-MW_e modular design would shorten project construction time while allowing for larger, multi-unit facilities if desired. Photo: Ivanpah Solar Electric Generating Station, USA (Courtesy of NREL)

Outlook

Markets around the world are acknowledging the need for more carbon-free, dispatchable power such as offered by CSP and modular nuclear power systems [2]. With announced country deployment targets for tens of GWs of CSP in the next decade, there is considerable market opportunity for Gen3 CSP. An accelerated commercialization path will be necessary to serve this market. The Liquid Pathway team has developed a multi-prong approach to advancing development of Gen3 CSP components, as well as integrated system development.

Much like the Solar Two report spurred interest and confidence in the Gen2 molten-nitrate salt tower technology, a successful pilot-scale Gen3 CSP demonstration—combined with successful deployment of a 50-MW_e sodium-CSP plant by Vast Solar—has the potential to accelerate the timeline for commercial introduction of the Liquid Pathway Gen3 technology. The flexible design allows the technology to be sized for different market applications. While the CSP development path within the United States will be guided by the particle pathway choice selected by the U.S. DOE, there are opportunities for continued development and utilization of Gen3 Liquid Pathway technology. Sodium receiver use in commercial projects is gaining traction outside of the U.S. and may benefit from development work performed in this project. When sCO_2 power cycle technology achieves commercial scale, it may be coupled with Gen2 molten-salt power towers and require salt-to-sCO_2 primary heat exchanger technology. Finally, advanced molten-salt nuclear reactors are expected to benefit from high-temperature salt pumps, valves, and storage systems developed under the Liquid Pathway project. Overall, the Liquid Pathway addressed numerous challenges with component and subsystem design, material compatibility, monitoring and controls, and other advances that are expected to benefit multiple industries.

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