Pathways to cost competitive concentrated solar power incorporating supercritical carbon dioxide power cycles

Matthew L. Bauer, Rajgopal Vijaykumar, Mark Lausten, and Joseph Stekli

950 L'Enfant Plaza
Washington D.C. 20024
SunShot Initiative
United States Department of Energy

Matthew Bauer serves as a technology manager in the Department of Energy's (DOE) Solar Energy Technology Office on contract from ManTech International Corporation. Matthew's research background is in the field of microscale heat transfer. Specifically, he has worked to develop novel heat transfer measurement methods and to tune materials' intrinsic thermophysical properties. Matthew received his PhD from the University of Virginia in mechanical engineering.

Rajgopal (Vijay) Vijaykumar is a technology manager in the DOE's SunShot initiative. Prior to joining the US DOE, Vijay worked at Bechtel on simulation, thermal hydraulics analyses, and design of power plants. Previously he worked at Aspntech developing models for simulation and estimating software, then as contractor to US DOE and US NRC on design and simulation of solar thermal and nuclear reactors. He holds a PhD in mechanical engineering from University of California, Los Angeles.

Mark Lausten is a Technology Development Manager in the DOE's SunShot Initiative CSP Program. Prior to joining the DOE CSP Program, Mark worked at a global EPC company in power generation system engineering, construction and commissioning. Mark has a BS in mechanical engineering from the University of Minnesota and an MBA, from the University of Maryland.

Joe Stekli is the Program Manager of the CSP Program and the Acting Program Manager of the Technology to Market Program within DOE's SunShot Initiative. Joe has held prior roles in government at ARPA-e and the White House Office of Management and Budget. Before joining the government, Joe spent 6 years as a process engineer in the semiconductor field. Joe has a BS in chemical engineering and a MBA, both from the Ohio State University.

Abstract

Reducing the cost and expanding the use of concentrated solar power (CSP) has been identified as a feasible means to transform electricity generation away from fossil fuels and towards renewable energy technologies. The ability of CSP plants to store thermal energy and supply electrical power during peak demand is uniquely advantageous amongst forms of renewable energy. While producing power during peak demand may earn a higher value for the electricity generated, improving the efficiency and reducing the cost of each major subsystem in a CSP plant remains integral to making CSP technology cost-competitive with traditional forms of electricity generation. By taking advantage of CSP's potential for high temperature operation, the maximum achievable Carnot efficiency can be increased. This motivates the use of high temperature supercritical carbon dioxide (sc-CO_2) power cycles to minimize the levelized cost of electricity (LCOE). Specifically, variations of the Brayton cycle using sc-CO_2 integrated with a CSP plant could generate electricity at a price competitive with traditional energy sources.

A key challenge to system level integration of high efficiency power cycles with CSP plants is the development compatible high temperature technologies to move thermal energy into a heat transfer fluid (HTF), through a thermal energy storage material (TESM), and ultimately into the power block working fluid. Each thermal energy intersection presents technical obstacles that can prevent the CSP plant from being cost competitive. No single material is yet an apparent choice for the high temperature HTF, TESM, nor their containment materials. New materials and thermal exchange designs are needed to minimize exegetic losses, maintain low cost, and demonstrate long term operability. Furthermore, the compatibility of the technologies being developed in parallel must be continually evaluated for feasibility and practically. Over the estimated 30 year lifetime of CSP plants optimized for high temperature and high efficiency power cycles with subsystems approaching 800°C, mechanical failures, material instability, and corrosive attacks can be significant and lead to potentially destructive results. Through the SunShot Initiative the DOE has invested in developing technologies that could be integrated into a high temperature CSP plant. This work broadly presents advancements made through these studies, known knowledge gaps and challenges, pathways in which CSP technologies could integrate as subsystems continue to develop, and defined technical parameters aligned with the DOE's target for cost competitive energy while employing a sc-CO_2 Brayton cycle.

1 Background and Motivation

The first documented CSP plant, developed by Frank Shuman, became operational in 1913 in a suburb of Cairo, Egypt. This project, titled Solar Engine One, used a parabolic trough collector system to operate a 55 HP steam engine.[1] After several decades of minimal advancement, the energy crises of the 1970's generated new interest in alternative energy development, including CSP. During the 1980's nine CSP plants were constructed in the Mojave Desert, titled Solar Energy Generating System (SEGS) I-IX, with a combined capacity of 394 MW. Each SEGS plant uses parabolic trough mirrors to heat a mineral oil which serves as a heat transfer fluid (HTF) delivering heat to a steam Rankine cycle operating with a turbine inlet temperature near 385°C. The technologies used in the SEGS plants continue to form the design basis for many of the recently constructed CSP plants due to the maturity of the technology and associated supply chain. During this time period, California's Solar One demonstration plant was completed. It represented a second form of CSP plant, the solar power tower. The DOE constructed Solar One in the early 1980's and repurposed it in the mid-nineties as Solar Two. This second demonstration proved the feasibility of molten salt power tower technology which has become the second generation of CSP technology to experience wide-scale deployment.

After the completion of the final SEGS plants in 1989, few commercial CSP plants were built over the next 20 years. In the mid-2000's, Spain led the reemergence of CSP by bringing online over two dozen plants, many of which included 6 hours of thermal energy storage, representing nearly 2 GW worth of capacity. CSP re-emerged in the United States more gradually, starting in 2007 with the construction of the Nevada Solar One plant, a 75 MW parabolic trough plant without storage. From 2013 to 2015, five of the largest CSP plants ever constructed were completed in the Southwest United States, with their construction catalyzed through the availability of loan guarantees from the DOE. Two of these plants, Mojave and Genesis, contained new trough designs but did not include storage. The Ivanpah plant was the world's first commercial direct steam power tower and was also the largest solar plant in the world at time of construction, totaling 392 MW of capacity. The recently completed Solana project uses a parabolic trough layout that incorporates 6 hours of thermal energy storage. Finally, Tonopah is the world's largest molten salt power tower plant at 110 MW of capacity while including 8 hours of storage. All these plants continue to use conventional steam Rankine turbine technology, with the turbine inlet temperatures of the trough plants at approximately 385°C while the tower plants operate at about 550°C. These plants operate under planned purchase agreements (PPAs) with agreed prices as low as 13.5 ¢/kWh. Plants that contain thermal energy storage have demonstrated lower PPA prices but higher capital costs.[2]

While recent advances in CSP deployment and cost reduction are both rapid and significant, the technology remains at a cost disadvantage compared to other forms of large scale power generation within the U.S. The U.S. DOE created the SunShot Initiative with the goal of making all forms of solar energy, including CSP, cost competitive with traditional sources of electricity generation by 2020, without subsidy. To reach this goal, development objectives for CSP have centered on achieving a LCOE of 6 ¢/kWh$_e$.[3] Amongst renewable energy technologies, CSP has a unique advantage due to its ability to cost-effectively store thermal energy for use as demand dictates. CSP plants offer the flexibility of being able to produce power for a selected few hours of the day when energy is most in demand (similar to a natural gas 'peaker' plant), continuously throughout the day as a baseload resource, or any other scenario based on the generation needs of the specific market. In 2010, at the start of the SunShot Initiative, a new CSP plant was estimated to be capable of generating electricity at a LCOE of 21 ¢/kWh$_e$ without subsidy; three years later that cost is estimated to have already fallen to 13 ¢/kWh$_e$.

With the continued need for step function cost reductions in order to achieve the SunShot goal, DOE continues to invest in technology improvements in all the subsystems that compose a CSP plant. These subsystems are: collectors or optics for concentrating light, receivers or the material designed to absorb photons, thermal energy storage, and the power cycle. Each of these subsystems have an associated set of technical and economic performance objectives that, when accomplished simultaneously, achieve the SunShot goal of 6¢/kWh$_e$. The metrics are summarized in Figure 1. One of the key drivers of the achievement of this goal is the development of a power block with a net thermal-to-electric efficiency of $\geq$ 50% and cost of $\leq$ \$900/kW$_e$ while utilizing dry cooling. Achievement of these cost and performance goals has catalyzed SunShot to seek beyond traditional, and even advanced, steam Rankine cycles. The sc-CO_2 Brayton cycle, operating at a turbine inlet temperature around 720°C, has been identified as the most promising technology capable of achieving SunShot's cost and performance goals for a power block.

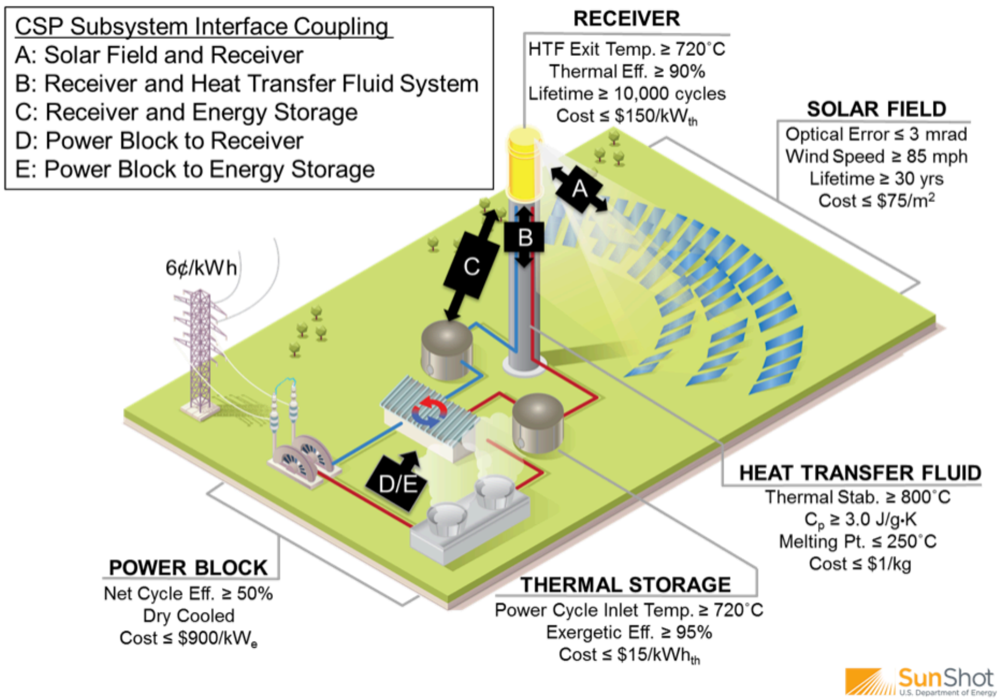

Figure 1: Overview of CSP plant in a power tower layout. Associated cost and performance metrics described in 2015 CSP: Apollo funding opportunity.[4]

Another potential benefit of transitioning away from the steam Rankine cycle to a sc-CO_2 Brayton cycle is that ideal cost targets can be met in smaller plants with significantly reduced capacities, likely under 50 MW. Implementing such modular plants may reduce the total capital expenditures (CAPEX) required, decrease construction time, and allow for cost effective CSP to be deployed in targeted applications. Modular plant construction divides the power cycle into either "stand-alone" or horizontal, vertical, single-level, or stacked modules. The units contain support structures, equipment, piping, tracing, insulation, electrical and instrumentation systems, HVAC, siding, fire protection and ladders. Using this method of construction, clients can accelerate their project schedule and reduce costs while taking advantage of improved quality and safety. Supercritical CO_2 turbines are compact and efficient with single casing y design; in contrast, steam turbines need multiple stages (high, intermediate and low-pressure casings) and additional inlet and outlet piping for steam. Placing the turbine and compressor on single and multiple shafts in an integral design reduces the size of the compressor-turbine system. In contrast, the recuperators and heat exchangers from primary fluids tend to be larger in size. However, fabricating the entire assembly in a modular shop, and transporting the assembly for field integration, would reduce the cost and schedule length. Such an approach can be extended to the heliostats as well, eliminating the need for a site glass shop. Transitioning both the collector field and power block construction to a modular assembly could allow plant fabrication time to be reduced from several years to a single year and for a drastic reduction in the soft costs of the plant.

The lofty goals of drastic cost reduction deployed by the SunShot Initiative create a host of technical challenges and first-of-kind design needs which remain unsatisfied. To date, the largest sc-CO_2 turbine being developed will generate around 10 MW of power with an operating temperature around 700°C. No commercial sc-CO_2 turbines exist near this temperature. New CSP plants have only recently advanced from a 391°C peak temperature to 565°C due to the adoption of molten salts over traditional thermal oils. Pursuing a turbine inlet temperature of 720°C and a realistic thermal receiver temperature near 800°C presents new material compatibility challenges and additional risk retirement needs to ensure a plant can successfully operate for over 30 years. While significant advancements have been made within the last 5 years in both the power cycle and remainder of a CSP plant, specific gating challenges, focused improvements, and technology down selection must be pursued and accomplished to achieve cost competitive CSP. To this end, the remainder of the paper presents the requisite technical and cost metrics of each subsystem. The subsequent section describes the cost and thermodynamic requirements of a compatible Brayton cycle as well as recent technical advances in its components. In a similar manner, Section 3 describes the competing technologies being developed to accept thermal energy, transport and store this energy, and ultimately deliver heat into the high efficiency power cycle.

2 Next generation CSP power cycle

Analysis performed by the Department of Energy and its researchers indicates that CSP LCOE and practical goals require a power cycle with greater than 50% efficiency, a cost under $900/kW, and dry cooling. A comparative analysis of sc-CO_2 Brayton cycles has indicated that a cycle efficiency of 50% with dry cooling can be obtained at a turbine inlet temperature near 720°C for the recompression or partial cooling cycles.[5, 6] The optimal pressure ratio varies from 3.2 (recompression cycle), to 3.4 (simple cycle) and 5 (partial cooling cycle). The primary cycle heat exchanger (for an indirect cycle only) has a temperature rise of 200°C (recompression cycle), 250°C (simple cycle) or275°C (partial cooling cycle). These form the inputs for the components of the power cycle.[6, 7] Dostal and Dyreby analyzed several supercritical CO_2 cycles; they reported that a simple cycle without recuperation led to an efficiency less than 30% making it adequate only for consideration in prototype test projects. Adding only recuperation, a simple supercritical CO_2 cycle efficiency increases with recuperator thermal conductance but peaks well below 50%.[5] In addition, increased compressor inlet temperature (due to dry cooling) reduces the efficiency of the simple cycle with recuperation. To overcome this problem, recompression and partial cooling cycles have been described in the literature.[5, 7] Dyreby reports that optimal thermal efficiency increases with recompression fraction, up to 15% recompression, for a dry cooling case, but higher efficiencies need higher recuperator conductance. In addition, high compressor inlet temperature due to dry cooling also requires high turbine inlet pressures (20-30 MPA) and temperatures (700°C). Partial cooling cycles attain similar efficiencies at the same turbine inlet conditions. Hence, the SunShot program is focused on component development to attain such high turbine inlet pressures and temperatures and compressor inlet temperatures. In addition, to attain cycle efficiencies of 50%, recuperator conductance of 10-15 MW/K with the ability to withstand 550°C temperatures are needed.

For a turbine (or expander) with an inlet temperature $\geq$700°C and optimal pressure ratio of 3-5, the density of sc-CO_2 dictates a multistage radial turbine component operating near 30,000 RPM for a nominal 10-30 MW turbine. Materials for this temperature are currently available but do not have ASME code qualifications for many applications. The high RPM leads to rotor surface speeds beyond the hydrodynamic oil bearing speed limits and necessitates the development of hybrid gas bearings or even magnetic bearings. Similarly, the operating conditions of the expander are outside the limits of labyrinth seals and needs further development of dry gas seals to limit leakage losses of sc-CO_2 and windage losses in the generator. The current evolution is film-riding, non-degrading seals which can have low leakage by operating with 15 micron gaps. These innovations are necessary to enable the high rpm, small diameter sc-CO_2 turbines to achieve high efficiency. Other features such as the alternator and gearbox can be applied from current design.

Significant progress in the design and development of a high temperature sc-CO_2 expander has been demonstrated by General Electric (GE). A net 10 MW expander has demonstrated a successful aeromechanical design and vibration control at ideal operating pressure, temperature, and speed while maintaining the expected efficiency of 87%. GE has also demonstrated a five axis electro discharge milling manufacturing process to create this expander. In principle, the entire expander and shaft will be destructively manufactured. Despite this manufacturing demonstration, challenges still remain before an expander is ready for commercial deployment into a full power cycle, particularly development of dry gas seals and hybrid bearings and the integration of compressor and expander onto single shaft.[8]

For the recompression cycle layout, the main compressor and the recompressor can be mounted on the same shaft as the generator. These two compressors can draw nearly 30% of the power. Each compressor should be multistage in order to operate at the high speeds required ($>$27,000 rpm). If the impeller is unshrouded, seal leakage losses will lead to significant degradation of efficiency. A non-contact seal that maintains a small hydrodynamic film that tracks the rotor is one possible solution to seal performance. High speed rotors need process gas lubricate bearings that are available from aircraft engine applications. Novel hybrid bearings using CO_2 as lubricant need to be developed for high speed compressors with high pressure ratios. In addition, to maintain high efficiency over a range of design inputs would require the development of guide vanes.

Highly recuperated sc-CO_2 cycles need large capacity recuperative heat exchangers. Heat exchangers have been subdivided into shell and tube or compact heat exchangers. Compact heat exchangers have been arbitrarily defined by Shah[9] as having an area density over 700 m^2/m^3, and hydraulic diameter D_h $\leq$6mm. A typical shell and tube heat exchanger has an area density around 100 m^2/m^3. The shell and tube heat exchanger is the most common, versatile design that suffers from lower thermal efficiency, vibration issues, and large footprint. Shell and tube heat exchanger designs are readily available at 10 to 2000 m^2 surface area per shell with a cost less than 50 \$/(W/K) even as they are limited to 50-100 m^2/m^3. In contrast, compact heat exchangers have a smaller footprint, lower initial cost, higher thermal efficiency, and higher thermomechanical strain tolerance. The disadvantages include low mechanical integrity, smaller flow channel diameters, limited manufacturers, and lack of industry experience. Design considerations for sc-CO_2 applications of shell and tube heat exchangers require special attention to high temperature thermal (differential) stress for expansion joints, bellows, floating head and U tube design. Cost curves are available [10, 11] for shell and tube heat exchangers and more compact heat exchangers.

For maximum efficiency of the sc-CO_2 cycle, alloys for piping and pressure vessel that can operate at 720°C are needed. Both, the US DOE and other nations have developed such alloys for use in coal fired boilers. Inconel alloy 740 (ASME code qualified) and Haynes 282 (in process of qualification) have been identified using the criteria of 100,000 hours, strength of 100 MPa (14.5ksi) at 760°C. If the criteria were relaxed for fewer hours of operation at 720°C, Haynes 230 and Alloy 617 can be used. Beyond material strength, other criteria such as fabricability, weldability, weld performance, tensile and fatigue properties, and sc-CO_2 corrosion have to be considered. Inconel 740/740H is an excellent candidate for piping, vessels, whereas Haynes 282 satisfies the requirements for rotor casings and valves. In addition, the use of such materials saves on material costs, due to higher allowable stresses, and reduced pipe diameters and wall thicknesses. Current research is continuing to develop creep data in excess of 45,000 hours, welding technology and weld repair of castings, fabrication processes, turbine component scale-up, and development of a component testing facility under US DOE funding. Fatigue testing of Haynes 282 has been completed to show greater than 100,000 cycles to failure at 50 ksi. In contrast to the steam power plants, the size and length of the piping from the turbine to compressor and recuperators is not expected to be large, and hence, the impact of cost due to high nickel alloys is not expected to be as significant for a sc-CO_2 plant as a steam cycle plant. A significant gap in knowledge pertains to the sc-CO_2 corrosion of high nickel alloys at elevated temperatures.

Compared to more studied cycles, high temperature corrosion, particularly above 600°C, is a major risk. The performance and degradation of piping, welds, and components due to corrosive attack in sc-CO_2 cycles is an area of active investigation. DOE has funded several research infinitives with specific focus on CO_2 corrosion for CSP applications at 750°. University of Wisconsin (UW)[12–14] has focused on how contaminants in the fluid influence corrosion rates as well as the formation of chromium oxide protective layers on alloy materials. A recently initiated studied at Oak Ridge National Laboratory will pursue studies controlling for operating condition specific variables such as thermal cycling and pressure effects. Beyond these works, very little data exists in literature at these temperature ranges.

The high temperature heat exchanger (or the heater) bringing thermal energy into the power cycle from a CSP plant's HTF, TESM, or directly from concentrated photons, is particularly technology dependent. To achieve the SunShot power cycle cost target of \$900/kW$_e$, the heater can only consume a fraction of this cost. For the most viable cycles, significant cost allowances must also be made for recuperation. The design of the heater component will be highly dependent on the flavor of CSP technology deployed, as discussed in the following subsections. Successful development of a specific, cost effective, and exegetically efficient solution will directly affect overall plant cost and could influence which technology pathway is technoeconomically superior. However, such a component cannot be developed without a simultaneous understanding technology specific requirements posed by the somewhat defined power cycle as well as the nature of the HTF and TESM and their operating conditions, both of which continue to be developed.

3 CSP technology pathways

For the general CSP plants discussed in this work, the high temperature power cycle defines one boundary condition, thereby setting criteria for technology compatibility: a working fluid turbine inlet temperature of at least 720°C (and at least 20 MPa). All prior subsystems in

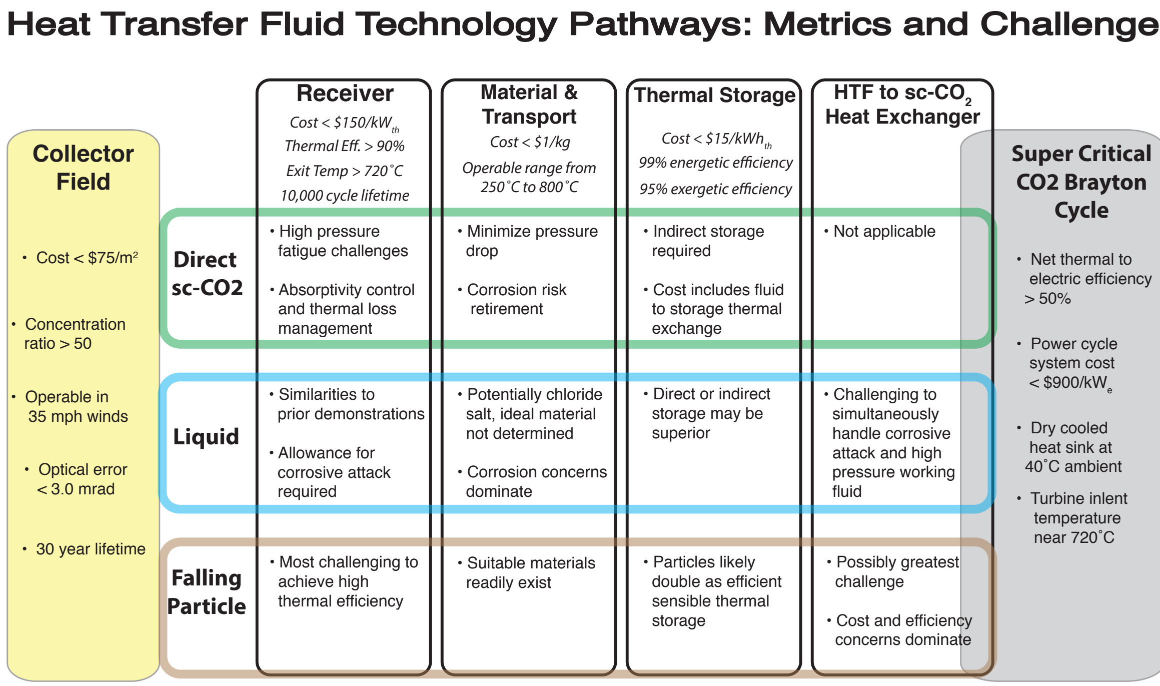

Figure 2: Schematic of SunShot defined subsystem metrics and observed technical challenges in each subsystem depending on the HTF implemented.

the CSP plant must be compatible with this criteria while efficiently interacting with adjacent subsystems. On the other end of the CSP plant, the collector field boundary condition is somewhat agnostic of the subsequent technologies: a high concentration ratio, survivable in high wind speeds, and a low cost. The challenge in developing the technologies between these boundary conditions has two broad facets: the development of the specific subsystem components and the compatibility of the respective emerging technologies. Figure 2 summarizes the areas of focus for promising technology paths. The following subsections describes these emerging technologies by considering the potential HTFs as the focal point of each thermal pathway.

3.1 Direct sc-CO_2 technologies

For a CSP plant operating with a sc-CO_2 Brayton cycle, perhaps the simplest system configuration would be one in which the CO_2 directly receives solar energy, effectively doubling as the HTF. Using CO_2 as the HTF eliminates the need for a heat exchanger between the HTF and power cycle. In this scenario, the receiver portion of the CSP plant also acts as the high temperature heat exchanger to the power cycle. This CSP system configuration is challenged by the impact of transients in solar energy input. Transients impose thermal stress and fatigue on the receiver, piping and turbine. Mitigating the effect of transients on material mechanical strength can hinder the CSP system operational performance and is seen as a disadvantage of the direct sc-CO_2 receiver system concept. Another key technical hurdle of the direct sc-CO_2 concept is the feasibility and cost of piping materials and the resulting necessity to minimize the piping carrying sc-CO_2 temperatures in excess of 700°C and pressures above 200 bar. Finally, a direct sc-CO_2 system requires the development of an economical TESM and associated heat exchanging mechanisms.

Several research teams are actively pursuing challenges with the direct sc-CO_2 receiver design. The principal goal of a research project with Brayton Energy is to design and demonstrate a low-cost, high efficiency solar receiver that is compatible with sc-CO_2 cycles in utility scale and distributed electrical power generation. A combination of analytical modeling and hardware testing has been performed, culminating in a scaled demonstration of a receiver assembly for thermal performance, and multiple test segments manufactured and tested for mechanical performance at temperature. Brayton Energy has successfully demonstrated fatigue and creep life of the receiver components and the assembly to a header system. Thermal-optical performance has been modeled to exceed the SunShot targeted efficiency and at temperatures greater than 700°C.[15]

The National Renewable Energy Laboratory (NREL) has researched a novel high-temperature receiver technology using sc-CO_2 directly as the HTF, led by Wagner. The SunShot targets at the time of the project start in 2012 guided the design effort toward achieving 90% solar to HTF efficiency at 650°C. Many design decisions and constraints remain applicable at 700° and above. The receiver was designed to withstand 10,000 thermal cycles. The combined creep and fatigue effects (considering daily cycling) when the fluid is pressurized at 20-30 MPa is a regime with many material unknowns. At the heart of this project, a design modeling tool was developed based on first principles multi-physics analysis that incorporated solar field design, ray tracing incident photonic energy, consideration of receiver surface optical properties, CFD for convection and FEA for material mechanical performance. A powerful second order model incorporated these computationally intensive multi-physics modes and enabled rapid multi-variable parametric analysis and optimization.[16, 17]

Common results from both projects include the following generalizations. A cavity receiving surface enables the efficiency and temperature targets to be achieved while staying within material performance limitations with high pressure sc-CO_2. Incident photons must be managed with careful consideration of the optical properties of the receiver surface. For example, high absorptivity can be a detriment causing localized overheating and reducing efficiency because the recessed surfaces are underutilized. Minimizing passive surfaces and maximizing the area that concentrated photons are incident on absorbing surfaces are two key factors in increasing efficiency while staying within material mechanical strength limitations. Flow distribution manifold headers present a challenge in the peak flux regions and likely require the use of thermal-radiative shielding which may require active cooling. The reduction of convective losses is critical to achieving the efficiency target for such large scale (>50 MW_{th}) receivers. Both projects accomplished this with multiple horizontal surfaces that retarded convection. NREL's Wagner developed a 'book shelf' of receiver surfaces while Brayton employed a patent pending concept using quartz tubes. Because the sc-CO_2 HTF is part of the turbine flow, receiver pressure loss is one of the most important design considerations.

Oregon State University (OSU) designed a direct sc-CO_2 receiver and tested proof-of-concept articles employing micro channels within the receiver. This design demonstrated mechanical durability at 100 bar and was was capable of absorbing incident solar flux at a concentration of 100 W/cm^2 while heating the sc-CO_2 with a 150°C temperature rise to 650°C exit temperature. The scaled up receiver concept maintains a pressure drop below 0.35 bar and demonstrates a pathway to $>$90% solar to HTF efficiency.[18, 19] Subsequently this team was awarded funding to advance the design to larger scale demonstration at temperatures above 700°C and pressures up to 250 bar. The follow-on work will look closely at corrosion, fatigue, and creep performance of the microchannel fabrication processed material. The cost and scalability of the microchannel concept, as well as the pressure drop typically associated with microchannel heat exchangers were deemed feasible in the work done and will continue to be validated. A key advantage of the microchannel receiver concept, and similarly the concept used in Brayton's receiver, is the small span between pressure supporting structures of the fluid flow channels, which enables thinner walls between the fluid and solar absorbing surface. This lowers thermo-mechanical stress and reduces the surface temperature and consequently lowers re-radiation losses.

The advances and knowledge gained through research into direct sc-CO_2 receivers gives confidence that the technology can continue to mature to on-sun testing at ever increasing temperatures. As previously discussed, corrosion and piping design for sc-CO_2 remains an important knowledge gap that continues to be pursued with the development of high temperature Brayton cycles. The most critical technology gap for the implementation of a CSP plant with sc-CO_2 as the HTF is proving a cost viable TESM, it's containment material, and it's heat exchanger(s).

3.1.1 Thermal energy storage compatible with direct sc-CO_2

Gases and supercritical fluids in general are a poor choice for a TESM due to their low energy density. For a direct gas receiver to be financially viable, a separate TESM is needed. Since there are no inherit flow requirements on a TESM in a direct receiver design, the primary characteristics of interest for the material are the cost, thermophysical properties, material lifetime, containment material compatibility, and efficiency of heat exchange and storage. While describing the immense range of possible TESM is beyond the scope of this work, other authors have thoroughly reviewed the major technology types: thermal chemical energy storage (TCES), latent energy storage (or phase change storage), and sensible energy storage.[20–27] Of these technologies, sensible storage has the most commercial use and the most known options at high technology readiness levels (TRL). In particular, molten salts have been demonstrated as a TESM in several commercial Spanish and American CSP plants (generally with the salt doubling as the HTF).[25] Few other sensible liquid TESM options exist due in part to the wide temperature range stability required and need for a lower vapor pressure. Conversely high temperature solid, sensible TESM in the forms such as packed beds of alumina particles, or monolithic structures such as concrete and alumina fire bricks have also been considered. However these solutions may suffer from either fatigue with cycling, poor exergetic efficiency or large overall costs.

Alternatively, thermal chemical energy storage (TCES) has the greatest potential upside while requiring the most development effort. The volumetric energy density of TCES options is orders of magnitude greater than sensible or latent storage materials. However, the challenges of incorporating a chemical plant with a CSP plant are not trivial. In 2013, the DOE funded six research initiatives to investigate proposed TCES solutions and accelerate the development effort.[28] While the goal of efficient and dense energy storage is simple, large-scale, long-term operability requires research into efficiency maximization, reactor engineering, chemical engineering innovation, heat transfer investigations, catalysis, system modeling, materials of construction, and on-sun testing. As an example, DOE has funded a research team from Pacific Northwest National Laboratory pursuing metal hydrides for TCES.[29] This research pursues a demonstration of compatible high-temperature and low-temperature metal hydride beds at the 240 kWh scale for 8 hours of storage with minimized capacity decrease over 1,000 cycles. A summary of TCES pursued by DOE intended to integrate with a Brayton cycle are listed in Table 1.

Latent storage via phase change materials (PCM) may offer another viable path to achieving SunShot targets. A unique technology is being developed by Singh's research team at Argonne National Laboratory (ANL). The concept employs a HTF pipe surrounded by a graphite foams. This porous carbon structure is noted for its high thermal conductivity and compliance. The graphite foam is then infiltrated with an appropriate PCM for the designed operating temperatures. Key challenges include preventing oxidation of the graphite, the graphite's interaction with the PCM, and joining the graphite foam to the piping. To date, the research team has shown success overcoming such challenges in the 650-750°C temperature range encapsulating salts as the PCM. This method is viable with any liquid or gas HTF, and shows a promising path to uniquely high exergetic efficiency. Lab scale tests have used air as the HTF with Incoloy 800H as the container material. [30–32] Future work focuses on increasing the maximum operable temperature of the design advancing the concept to to TRL 6.

3.2 Liquid heat transfer fluid technologies

Traditional CSP plants have overwhelmingly used liquid HTF in the form of thermal oils with a maximum temperature under 400°C or molten salts, generally nitrates, with a maximum operating temperature of 565°C. Molten salt plants using Solar Salt, a nitrate eutectic, have had further success demonstrating the salt as both a HTF and TESM. Due to original demonstrations of Solar Salt in the Solar Two plant and subsequent commercial deployments, implementing higher temperature liquids might be the least radical plant advancement required to support incorporating a high efficiency and high temperature power cycle into a CSP plant. An ideal liquid HTF must have a low freezing point, decomposition temperature above 800°C, a low cost, high heat capacity, and a low corrosion rate with suitable containment materials. Solar Salt was adopted for use because it met these criteria up to its decomposition limit. However, its inability to operate at 800°C makes it incompatible with the SunShot vision. For many other well-known salt eutectics, catastrophic corrosion rates above 700°C prevent their consideration.[33] Many other potentially applicable compositions, such as carbonates, have a freezing temperature that is too high to be technoeconomically feasible in a practical plant design.[34] To overcome these challenges, the DOE has funded several research projects to develop new liquid HTF's or to study and quantify the corrosion rate and lifetime thermophysical properties of promising existing HTF.

The University of Arizona (UA) has led a multidisciplinary university research initiative (MURI) focused on screening possible ternary and quaternary halide eutectics, particularly chloride based compositions, for compatibility with the key HTF metrics listed Figure 1. Following this screening, UA has worked to demonstrate the modeled characteristics and ultimately prove if an adequate material composition exists for high temperature CSP. Rigorous screening has indicated adequate chlorides do exist which could operate from 200°C to 800°C with reasonable thermophysical properties and cost.[35, 36] When screening materials, the cost and intrinsic thermophysical properties of candidate materials are viewed as a combined dynamic technoeconomic variable.[37] For example, a smaller thermal capacity could be acceptable if justified by decreased cost. However the operable temperature range and ability to mitigate corrosion are gating challenges that must directly be overcome. Future endeavors by the team are focused on proving the lifetime stability of screened ternary chloride compositions (with particular attention given to NaCl-KCl-$ZnCl_2$) [38], fully understanding the material corrosion mitigation requirements, and commercializing the most viable candidate. Understanding the operating range in which the material (and containment piping) will not fail, particularly the allowable level of oxygen in the environment, is a point of major emphasis. The tools developed for screening viable materials are being applied to explore quaternary chloride compositions to determine if superior candidates exist.

Aiming for nearly identical material metrics, the University of California, Los Angeles (UCLA) is leading a MURI investigating the feasibility of a liquid metal HTF. They have explored the compositional space of viable liquid metals and utilized a combinatorial sputtering system (through collaborators at Yale University) to precisely control the development of selected binary and ternary eutectics. Despite a very wide material screening, their efforts have identified a more traditional composition, Pb-Bi based alloys, as the most promising candidates. Similar to candidate molten salts, understanding and mitigating corrosion while maintaining a wide operating temperature has proven to be the most technically challenging objective. [39–41] If a compatible liquid metal can be demonstrated, it will likely exhibit lower viscosity and greater thermal conductivity than competing molten salts allowing for more efficient and smaller heat exchangers. This comes with the tradeoff of likely inferior heat capacity and a greater price. However, comparing such tradeoffs is premature until a scenario can be demonstrated in which a liquid metal container will not undergo catastrophic corrosion above 700°C. Lead-bismuth eutectic alloy has shown compatibility with ceramics such as SiC composites, but fracture toughness and other mechanical challenges become a point of concern.[41] UCLA's endeavors have enhanced the knowledge base of liquid metal alloy thermophysical properties and corrosive characteristics in the 700°C to 800°C range, a critical step to understanding the range of viable HTF's.

NREL's Gomez and collaborators have looked at the viability of two corrosion mitigation strategies: alloy coatings and the chemistry of alumina forming alloys such as Haynes 224. Studies at NREL have focused on $MgCl_2$-KCl at temperatures up to 700°C. Due to the incredibly large range of tunable operating conditions, containment materials, and corrosion mitigation strategies to be studied, NREL has implemented an electrochemical impedance spectroscopy experiment to rapidly gain insight into corrosive characteristics within this wide range of scenarios.[42] This tool, used in combination with traditional corrosion immersion tests and scanning electron microscopy with energy dispersive spectroscopy results have enhanced the confidence of the results given to date and helped make authoritative conclusions about the viability of scenarios tested. The prospect of finding an alumina-forming alloy which can self-heal defects is particularly enticing for the 30 year lifetime requirements of CSP plant operation. Corrosion rates significantly less than 100 microns per year are likely required to control the costs associated with increased pipe thickness and heat exchanger tolerances.

Even if corrosion characteristics for an ideal liquid were known and the chemistry understood, specific features of the container would remain a knowledge gap. Pipping welds and bends with unique material properties and which create unique flow profiles would likely show a deviation in properties from standard test coupons. With this gap in mind, Savannah River National Laboratory (SRNL), supported by the University of Alabama and the University of South Carolina, has undertaken a multi-pronged molten salt corrosion study. SRNL has studied the compatibility of $MgCl_2$-KCl with Haynes 230, Inconel 800H, and other alloys while controlling for container properties (weld type, bend type, etc.), salt purity, and isothermal compared to cyclic temperature conditions (at temperatures up to 850°C). Their test campaign also investigates (with promising initial results) the use of Mg additive to serve as a corrosion inhibitor.[43, 44]

In company with the NREL, UA, and UCLA studies, SRNL's work represents some of the only reported corrosion characteristics of high temperature, (above 700°C) liquid heat transfer fluids. These four projects contain much of the earliest research into the field studying high temperature, CSP HTF corrosion. As demonstrated by the path of these teams' research, identifying materials that can function in the appropriate temperature range with adequate thermophysical properties can be limiting, but appropriate fluids do exit. Once identified, quantifying and verifying these values, even in operating conditions, is not unreasonably difficult. On the other hand, the fluids' corrosive behavior at high temperatures in a given environment is a drastically more difficult phenomena to articulate in a simple variable. The chemistry is complex, and hypotheses are still being developed and tested to accurately and precisely predict what will happen in a given scenario over a 30 year lifetime. The degree of variability in these high temperature corrosion experiments has put a greater burden on developing screening models and rapid characterization tests that provide realistic results, a point of emphasis in each research endeavor. Finally, once corrosive behavior is fully understood in a repeatable format, its impact on the mechanical properties of the containment material must be accounted for, and adequately considered in plant design and economic analysis.

Once these technical considerations relating directly to the HTF are accomplished, advanced TRL designs can be developed for a high temperature fluid receiver, thermal storage container, and heat exchanger to the power cycle working fluid. Design and optimization processes for high temperature sc-CO_2 receivers, discussed in Section 3.1, are applicable to high temperature liquid HTFs with the following tradeoffs are considered. Receivers designed for liquid HTFs much account for more aggressive material corrosion that super critical fluids, however liquids' superior thermophysical properties and operation at atmospheric pressure relax receiver design requirements. Despite a lack of commercial deployment above 700°C, recent receiver development and proven lower temperature commercial demonstration make this challenge appear solvable.

Present day commercial heat exchanges transfer energy from molten nitrates at 565°C to water using shell and tube heat exchangers or reboilers, As such, the Solar Two test facility and the Tonopah Dunes made use of heat exchangers for saturation, evaporation and superheating of steam. The design of a heater coupling with a sc-CO_2 Brayton cycle does not need to account for interaction with a fluid as it transitions through distinct phases which simplifies one design aspect. However, molten salt to working fluid heat exchangers operating above 700°C have not been demonstrated. The heat exchangers are dependent on the development of heat transfer fluids and materials for shell and tubes. Recently initiated research at Purdue University aims to solve this challenge by designing and developing a novel millichannel, ceramic metal composite that can operate at 800°C and cost less than $100/kW.

Molten salts have been commercially demonstrated for direct use as a TESM. For example, the Solana Generating Station outside of Phoenix, AZ is a 250 MW plant with 6 hours of direct TES. In a high temperature molten salt CSP plant, it is reasonable to assume directly using the

HTF for a TESM would be the baseline case. The challenges of designing a direct thermal storage system, such as a two tank design, are likely small compared the fluid, receiver, and heater designs. It is also reasonable to envision a secondary material with superior heat storage properties could be proven technoeconomically advantageous enough to overcome efficiency losses in heat exchanger and serve as an indirect form of thermal energy storage. The general classes of sensible, latent, and thermal chemical energy storage are each worth consideration. If an indirect route is to be pursued, optimized fluid to TESM heat exchangers must be developed in addition the material itself.

3.3 Falling particle technology

The desire for operating temperatures in excess of 700°C and the challenges associated with finding suitable materials to contain fluids for 30 years or more at these temperatures has driven interest from the SunShot Initiative in solid particle technology for heat collection and transport (see Figure 2). This concept, commonly referred to as falling particle technology, utilizes small, sand-like particles to receive solar flux from the collector field, potentially store the collected heat for several hours, and ultimately deliver thermal energy to a high-efficiency power cycle. Using sub-millimeter sized solids to deliver thermal energy, as opposed to a fluid, provides a viable path to avoid the significant challenges associated with high temperature fluids such as freezing, high temperature corrosion, and high temperature material break down. Initial concerns regarding particle induced erosion have not been observed after tests of significant duration.[45, 46] The particles under research have shown the ability to achieve temperatures approaching 1,000°C without material degradation or particle sintering. As an additional benefit, using particles such as silica and/or alumina as a TESM holds the strong potential to be more cost effective than current molten salt technologies while also allowing for an increased turbine inlet temperature. For falling particle technology to achieve commercial viability, the design, development, and testing of a particle based receiver must be completed under relevant operating conditions. Other significant challenges include resolving appropriate methods for particle movement while minimizing parasitic losses, selecting or developing an optimized particle material, and transfer of thermal energy from the particles to the power cycle working fluid. SunShot has funded three separate research initiatives, led by Sandia National Laboratory (SNL) the National Renewable Energy Laboratory (NREL), and the University of Colorado Boulder (CU), to explore various subsystem designs, enhance the understanding of each challenge, and to move falling particle technology towards cost competitive commercial deployment.

One of the first steps in commercializing falling particle technology is finding an appropriate material to serve as the particle. The thermophysical properties, material cost, the effect of thermal cycling, and sintering should be considered when selecting a material for CSP applications. Additionally, for an open cavity receiver, optical properties greatly influence the system's overall performance. SNL, in collaboration with researchers at Bucknell University, Georgia Tech, and King Saud University have systematically reviewed the properties of commercially available particles.[47] This team has also worked to enhance existing particles by chemically treating them in a manner that provides the particle with superior optical properties and has demonstrated long term material handling methods to maintain these properties. While storage of the particles is not considered a major challenge, the SNL team has measured thermal losses of only 4-5% per day when particles are stored in a relatively small but well-insulated storage tank. These losses are expected to match those of traditional molten-salt storage technology (1-2% per day) when the storage vessels are moved to commercial sizes. Independent from SNL, NREL has also reviewed and analyzed suitable particle materials by prioritizing the cost efficiency of using the material in a fluidized bed to remove heat from the particles. [45, 48] NREL settled on a readily abundant material composed primarily of silica and alumina for their application.

In concert with particle selection, receiver design is also an important consideration when configuring a CSP system that can integrate with an sc-CO_2 cycle. Similar to its efforts in alternative high temperature receiver designs, SunShot funding has pursued falling particle receiver designs capable of operating above 720°C while achieving thermal efficiencies greater than 90% and maintaining a cost under \$150/kW$_{th}$. NREL and SNL have taken two separate approaches to achieving these targets with a falling particle receiver design. SNL's design is an open cavity receiver that avoids thermal flux limitations of traditional tubular receivers, thereby allowing for increased solar concentration ratios. By optimizing air recirculation and material insulation to minimize thermal losses, SNL has proven the concept's ability to reach the aforementioned SunShot receiver targets at lab scale.[46, 49, 50] Future work on this design by SNL includes continuation of on-sun testing at the National Solar Thermal Test Facility (NSTTF) with a 1 MW$_{th}$ receiver. As an alternative to SNL's open cavity design, the NREL led research initiative into falling particle receivers developed an enclosed particle receiver design with arrayed absorber tubes that optically distribute the solar flux to the falling particles, which cascade down over the tubes inside the enclosure (the design looks similar to a pachinko board). One of the keys to the success of this enclosed receiver design has been the development of a multi-stage optical coating that serves to distribute the flux as desired and avoid the creation of hot spots.[45, 48, 51, 52] Modeling of this design has shown challenges with hot spot creation, and associated material limitations, and has required a significant redesign of the NREL concept and therefore no on-sun testing of the concept is planned at this time.

Supporting the work of these design and demonstration research projects, CU has developed a first principles continuum model to describe thermal interaction between flowing particles and the surfaces they encounter in a falling particle receiver design.[53] This work has made significant improvements in the understanding of particle thermal effects in realistic receiver designs as well as improved the understanding of local heat transfer coefficients within the system. This has been accomplished through accurate incorporation of microscale effects into larger 2-D heat transfer models. Ultimately this work seeks to accurately predict thermal transfer in the particle environment allowing for more robust predictive capabilities in the design of falling particle receivers.

A final key piece of technology development required to realize falling particle receiver technology is an efficient and cost effective particle to sc-CO_2 heat exchanger. Particle to sc-CO_2 heat exchanger options can be roughly classified into fluidized bed and moving packed bed heat exchangers. Research into particle to sc-CO_2 moving packed bed heat exchangers have typically looked at two traditional heat exchanger designs, the shell and tube heat exchanger and the shell and plate heat exchanger. Commercial manufacturers such as Solex have proposed a very simple shell and tube configuration with a vertical casing and horizontal tubes carrying the sc-CO_2. A holding tank for the particles provides a head that is maintained above the tubes and ensures that all tubes are filled with particles and also prevents the addition of particles from impinging or eroding the tubes. The shell casing in this design is at atmospheric pressure, and tube selection for high pressure and temperature is a key cost consideration in the design. The heat transfer coefficient of the particles is relatively low, and therefore solid flow past the tubes must be slow and channel lengths must be relatively long. This leads to challenges in the achievement of necessary heat transfer coefficient and associated cost concerns.

In contrast to the shell and tube heat exchangers, shell and plate designs involve vertical flow with heat transfer to diffusion bonded coolant plates. Diffusion bonding allows for the bulk material strength to be ‘maintained while utilizing small channel sizes, created through chemical etching, to achieve high effective heat transfer rates. The plate assemblies and header manifolds for particle transport can be brazed or bonded to an integral sc-CO_2 manifold in this design. Diffusion bonded shell and plate heat exchangers have been demonstrated to operate at conditions of up to 20 MPa and 500°C. The size of the shell and plate design can be much more compact than shell and tube designs, which gives hope for significant cost reduction. Shell and plate heat exchangers capable of reaching temperatures up to 800°C are being currently studied under the SunShot Initiative.

The final alternative being explored for particle to power cycle working fluid heat exchanger is fluidized beds. Air-fluidized beds have been shown to be capable of high temperature operation in several industrial applications, one example being fluidized bed ash coolers. Ash cooler efficiency have been shown to be as high as 95% and the current cost is estimated to be $1,000/kW. Additionally, heat transfer coefficients greater than 500 W/m^{2}K have been demonstrated in submerged tube designs.[54] Babcock and Wilcox (B&W) has taken a fluidized bed design based on the ash cooler and modified it for falling particle applications under the aforementioned NREL project.[55] This design utilizes a serpentine path for the flow of particles fluidized by air from below, with sc-CO_2 flowing in tubes suspended in the flowing particle path. The air flow is vented from the bed and used for additional heat recuperation in the power cycle. Significant risk remains to achieving the necessary technoeconomic metric for particle to sc-CO_2 heat exchanger. With this in mind SNL has recently began a broad study to consider potential heater designs from a variety of venders and work on down selection and testing of potential solutions.

For the falling particle technology path to be viable, four general areas of concern must be proven at an advanced technology readiness level: the material and transport capabilities, the receiver, thermal storage, and the particle to working fluid heat exchanger. At the onset of the SunShot initiative, particle receiver technology was likely the least developed and represented the greatest risk. Advances in this subsystem have paved the way for eminent on-sun testing of a MW scale receiver. Key remaining concerns include proving a receiver optical coating viable well above 700°C and operable for the plant’s lifetime as well as proving receiver designs which can transition from 650°C to 750°C. The particle material, and the handling of the materials, does hold inherit risk, particularly when considering flow and thermal cycling for 30 years. However, screening of materials and plant designs indicate that viable materials exist and thoughtful design can account for particle handling and ’flow’ challenges as evidenced by SNL’s work. Particles use as direct storage is a unique advantage of the falling particle HTF design and is not viewed to be a significant source of risk. The most critical challenge for the falling particle technology path is the cost per energetic efficiency of transferring heat from the particles to the working fluid. If controlling corrosion in a cost effective manner is the most dire risk to molten salt HTFs, then analogously, cost effective heat transfer into and particularly out of the particles matches this level of concern.

Table 1: Select SunShot funded research supporting next generation high temperature CSP[28]

Tech Path / Component	Lead Institution	Specific Technology	Notes
Direct sc-CO_2			
Receiver	NREL	Book shelf cavity	650°C, high efficiency
Receiver	Brayton	Mesh with quartz window	750°C, long term creep
Receiver	Oregon State	Microchannel design	650°C, low pressure drop
Corrosion	ORNL	sc-CO_2 containment alloys	Isolate operating parameters
Corrosion	NREL/WU	sc-CO_2 containment alloys	Protective layer formation
Liquid HTF			
HTF	UCLA	Liquid metals	Fluid development
HTF	UA	Chloride salt eutectics	Fluid development
Corrosion	SRNL	Corrosion inhibitors	Salts in CSP conditions
Corrosion	NREL	Coating and additives	Rapid screening methods
Heater	Purdue	Millichannel heat exchanger	Stable ceramic composite
Falling Particle			
Entire System	SNL	Direct open cavity rec.	NSTTF
Receiver	NREL	Optical flux distribution	Optical coating focus
Heater	SNL	Comparative Study	720°C, 20 MPa
Receiver	CU	Heat exchange	First principles modeling
Brayton Power Cycle			
'Compander'	SwRI	Compressor and expander	Integrally geared
Turbo expander	GE	Bearings and seals	Failure modes
Compressor	GE	Compression Train	Operation during transients
Regenerator	UW	Recuperation cycle	
SAM Software	NREL	LCOE Modeling	
Energy Storage			
PCM	ANL	Graphite foam container	Salt phase change
TCES	LANL	Binary Metals	
TCES	SRI	Carbonate/Silicate	
TCES	UF	Strontium Carbonates	
TCES	PNNL	Metal Hydride	
TCES	UCLA	Anhydrous Ammonia	
TCES	SNL	Metal Oxides	
TCES	CO Mines	Perovskites	
Other			
Heat Pipe	LANL		Trough Design
O&M	NREL		
Optical coatings	ANL		

4 Conlcusions

The DOE has aided in pioneering CSP technology to its current status, through both commercial demonstrations and research and development initiatives. The SunShot Initiative's primary goal is to complete the final push to cost competitive commercial deployment (see Table 1). Developing concentrated solar power plants competitive with traditional energy sources will require step-function advancements in each subsystem. Using a high efficiency Brayton cycle makes such cost advancements possible while necessitating nearly every prior subsystem be redesigned for high temperature compatibility. The DOE has invested in developing competing technologies to support the cost reduction of CSP compatible with high temperature cycles. While significant advancements have already been achieved, the final steps will require a new generation of CSP plants. Analysis has indicated the efficiency and cost targets that must be achieved in each subsystem to achieve SunShot success.

This work has presented three heat transfer fluid centric technology paths that may achieve technoeconomic viability and become the next generation of commercial CSP: direct sc-CO_2, falling particle, and liquid technologies. Each path comes with distinct advantages and disadvantages. Primary concerns center around material stability, corrosion, efficient energy transfer, and the cost to achieve required performance. Additionally, continued development of the sc-CO_2 Brayton cycle must occur concurrently if modular CSP plants are to be deployed in the near term. Despite the broad array of challenges, the DOE continues to view the development of a third generation of CSP as a realistic pathway to achieving SunShot.

References

[1] M Ragheb. Solar thermal power and energy storage historical perspective. *University of Illinois at Urbana-Champaign*, 2011.

[2] NREL: National Renewable Energy Laboratory. CSP Projects. `http://www.nrel.gov/csp/solarpaces/by_project.cfm`, 01/01/2015.

[3] US DOE. Sunshot vision study. `http://energy.gov/eere/sunshot/sunshot-vision-study`, 2012.

[4] DOE Solar Energy Technology Office. CSP: APOLLO funding opportunity announcement. 2015.

[5] T Neises and C Turchi. A comparison of supercritical carbon dioxide power cycle configurations with an emphasis on csp applications. *Energy Procedia*, 49:1187–1196, 2014.

[6] John Dyreby, Sanford Klein, Gregory Nellis, and Douglas Reindl. Design considerations for supercritical carbon dioxide brayton cycles with recompression. *Journal of Engineering for Gas Turbines and Power*, 136(10):101701, 2014.

[7] M Kulhánek and V Dostal. Thermodynamic analysis and comparison of supercritical carbon dioxide cycles. In *Proceedings of Supercritical CO2 Power Cycle Symposium*, pages 24–25, 2011.

[8] Azam Thatte and Xiaoqing Zheng. Hydrodynamics and sonic flow transition in dry gas seals. In *ASME Turbo Expo 2014: Turbine Technical Conference and Exposition*, pages V07BT32A020–V07BT32A020. American Society of Mechanical Engineers, 2014.

[9] Ramesh K Shah, Allan D Kraus, and DC Metzger. *Compact heat exchangers*. New York, NY (United States); Hemisphere Publishing, 1990.

[10] Geoff F Hewitt and Simon J Pugh. Approximate design and costing methods for heat exchangers. *Heat transfer engineering*, 28(2):76–86, 2007.

[11] Clifford K Ho, Matthew Carlson, Pardeep Garg, and Pramod Kumar. Cost and performance tradeoffs of alternative solar-driven s-co2 brayton cycle configurations. In *ASME 2015 9th International Conference on Energy Sustainability collocated with the ASME 2015 Power Conference, the ASME 2015 13th International Conference on Fuel Cell Science, Engineering and Technology, and the ASME 2015 Nuclear Forum*, pages V001T05A016–V001T05A016. American Society of Mechanical Engineers, 2015.

[12] Ling-Feng He, Paul Roman, Bin Leng, Kumar Sridharan, Mark Anderson, and Todd R Allen. Corrosion behavior of an alumina forming austenitic steel exposed to supercritical carbon dioxide. *Corrosion Science*, 82:67–76, 2014.

[13] Paul J Roman, Kumar Sridharan, Todd R Allen, Jacob J Jelinek, Guoping Cao, and Mark Anderson. Corrosion study of candidate alloys in high temperature, high pressure supercritical carbon dioxide for brayton cycle applications. In *CORROSION 2013*. NACE International, 2013.

[14] V Firouzdor, K Sridharan, G Cao, M Anderson, and TR Allen. Corrosion of a stainless steel and nickel-based alloys in high temperature supercritical carbon dioxide environment. *Corrosion Science*, 69:281–291, 2013.

[15] S Sullivan, E Vollnogle, J Kesseli, and J Nash. High-efficiency low-cost solar receiver for use in a supercritical-co2 recompression cycle. *CONCENTRATING SOLAR POWER PROGRAM REVIEW 2013*, page 15, 2013.

[16] Ty W Neises, Michael J Wagner, and Allison K Gray. Structural design considerations for tubular power tower receivers operating at 650° c. In *ASME 2014 8th International Conference on Energy Sustainability collocated with the ASME 2014 12th International Conference on Fuel Cell Science, Engineering and Technology*, pages V001T02A045–V001T02A045. American Society of Mechanical Engineers, 2014.

[17] Michael Wagner, Zhiwen MA, Janna Martinek, Ty Neises, and Craig Turchi. Systems and methods for direct thermal receivers using near blackbody configurations, November 19 2015. US Patent 20,150,330,668.

[18] Thomas L'Estrange, Eric Truong, Charles Rymal, Erfan Rasouli, Vinod Narayanan, Sourabh Apte, and Kevin Drost. High flux microscale solar thermal receiver for supercritical carbon dioxide cycles. In *ASME 2015 13th International Conference on Nanochannels, Microchannels, and Minichannels collocated with the ASME 2015 International Technical Conference and Exhibition on Packaging and Integration of Electronic and Photonic Microsystems*, pages V001T03A009–V001T03A009. American Society of Mechanical Engineers, 2015.

[19] Charles J Rymal, Sourabh V Apte, Vinod Narayanan, and Kevin Drost. Numerical design of a high-flux microchannel solar receiver. In *ASME 2013 7th International Conference on Energy Sustainability collocated with the ASME 2013 Heat Transfer Summer Conference and the ASME 2013 11th International Conference on Fuel Cell Science, Engineering and Technology*, pages V001T11A012–V001T11A012. American Society of Mechanical Engineers, 2013.

[20] Antoni Gil, Marc Medrano, Ingrid Martorell, Ana Lazaro, Pablo Dolado, Belen Zalba, and Luisa F Cabeza. State of the art on high temperature thermal energy storage for power

generation. part 1—concepts, materials and modellization. *Renewable and Sustainable Energy Reviews*, 14(1):31–55, 2010.

[21] Marc Medrano, Antoni Gil, Ingrid Martorell, Xavi Potau, and Luisa F Cabeza. State of the art on high-temperature thermal energy storage for power generation. part 2—case studies. *Renewable and Sustainable Energy Reviews*, 14(1):56–72, 2010.

[22] Sarada Kuravi, Jamie Trahan, D Yogi Goswami, Muhammad M Rahman, and Elias K Stefanakos. Thermal energy storage technologies and systems for concentrating solar power plants. *Progress in Energy and Combustion Science*, 39(4):285–319, 2013.

[23] Ming Liu, Wasim Saman, and Frank Bruno. Review on storage materials and thermal performance enhancement techniques for high temperature phase change thermal storage systems. *Renewable and Sustainable Energy Reviews*, 16(4):2118–2132, 2012.

[24] Joseph Stekli, Levi Irwin, and Ranga Pitchumani. Technical challenges and opportunities for concentrating solar power with thermal energy storage. *Journal of Thermal Science and Engineering Applications*, 5(2):021011, 2013.

[25] Yuan Tian and Chang-Ying Zhao. A review of solar collectors and thermal energy storage in solar thermal applications. *Applied Energy*, 104:538–553, 2013.

[26] K Nithyanandam and R Pitchumani. Cost and performance analysis of concentrating solar power systems with integrated latent thermal energy storage. *Energy*, 64:793–810, 2014.

[27] Dan Nchelatebe Nkwetta and Fariborz Haghighat. Thermal energy storage with phase change material—a state-of-the art review. *Sustainable Cities and Society*, 10:87–100, 2014.

[28] Deparment of Energy; CSP: Competitve Awards. `http://energy.gov/eere/sunshot/concentrating-solar-power-competitive-awards`, 2013.

[29] Ewa CE Rönnebro, Greg Whyatt, Michael Powell, Matthew Westman, Feng Richard Zheng, and Zhigang Zak Fang. Metal hydrides for high-temperature power generation. *Energies*, 8(8):8406–8430, 2015.

[30] Taeil Kim, David M France, Wenhua Yu, Weihuan Zhao, and Dileep Singh. Heat transfer analysis of a latent heat thermal energy storage system using graphite foam for concentrated solar power. *Solar Energy*, 103:438–447, 2014.

[31] Weihuan Zhao, David M France, Wenhua Yu, Taeil Kim, and Dileep Singh. Phase change material with graphite foam for applications in high-temperature latent heat storage systems of concentrated solar power plants. *Renewable Energy*, 69:134–146, 2014.

[32] Dileep Singh, Weihuan Zhao, Wenhua Yu, David M France, and Taeil Kim. Analysis of a graphite foam–nacl latent heat storage system for supercritical co 2 power cycles for concentrated solar power. *Solar Energy*, 118:232–242, 2015.

[33] K Vignarooban, Xinhai Xu, A Arvay, K Hsu, and AM Kannan. Heat transfer fluids for concentrating solar power systems–a review. *Applied Energy*, 146:383–396, 2015.

[34] Tao Wang, Divakar Mantha, and Ramana G Reddy. Novel low melting point quaternary eutectic system for solar thermal energy storage. *Applied Energy*, 102:1422–1429, 2013.

[35] K Vignarooban, P Pugazhendhi, C Tucker, D Gervasio, and AM Kannan. Corrosion resistance of hastelloys in molten metal-chloride heat-transfer fluids for concentrating solar power applications. *Solar Energy*, 103:62–69, 2014.

[36] K Vignarooban, Xinhai Xu, K Wang, EE Molina, P Li, D Gervasio, and AM Kannan. Vapor pressure and corrosivity of ternary metal-chloride molten-salt based heat transfer fluids for use in concentrating solar power systems. *Applied Energy*, 159:206–213, 2015.

[37] Peiwen Li and Ye Zhang. Minimum system entropy production for the figure of merit of high temperature heat transfer fluid properties. *Energy Technology 2015: Carbon Dioxide Management and Other Technologies*, pages 355–372, 2015.

[38] Venkateswara Rao Manga, Stefan Bringuier, Joshua Paul, Saivenkataraman Jayaraman, Pierre Lucas, Pierre Deymier, and Krishna Muralidharan. Molecular dynamics simulations and thermodynamic modeling of nacl–kcl–zncl 2 ternary system. *Calphad*, 46:176–183, 2014.

[39] C Cionea, MD Abad, Y Aussat, D Frazer, AJ Gubser, and P Hosemann. Oxide scale formation on 316l and fecral steels exposed to oxygen controlled static lbe at temperatures up to 800 $^{\circ}$c. *Solar Energy Materials and Solar Cells*, 144:235–246, 2016.

[40] Miroslav P Popović, Alan M Bolind, Cristian Cionea, and Peter Hosemann. Liquid lead-bismuth eutectic as a coolant in generation iv nuclear reactors and in high temperature solar concentrator applications: Characteristics, challenges, issues. *Contemporary Materials*, 1(6):20–34, 2015.

[41] D Frazer, Erich Stergar, C Cionea, and P Hosemann. Liquid metal as a heat transport fluid for thermal solar power applications. *Energy Procedia*, 49:627–636, 2014.

[42] Judith C Gomez, Robert Tirawat, and Edgar E Vidal. Hot corrosion studies using electrochemical techniques of alloys in a chloride molten salt (nacl-licl) at 650 c. In *ASME 2014 8th International Conference on Energy Sustainability collocated with the ASME 2014 12th International Conference on Fuel Cell Science, Engineering and Technology*, pages V001T02A057–V001T02A057. American Society of Mechanical Engineers, 2014.

[43] Roderick Eliel Fuentes, Luke Christopher Olson, Michael Joe Martinez-Rodriguez, Joshua R Gray, and Brenda Lee Garcia-Diaz. Corrosion of high temperature materials in fluoride and chloride molten salts. In *Meeting Abstracts*, pages 743–743. The Electrochemical Society, 2014.

[44] Brenda L Garcia-Diaz, Luke Christopher Olson, Michael J Martinez-Rodriguez, Roderick Eliel Fuentes, and Joshua R Gray. Electrochemical study of corrosion in high temperature molten salts. In *Meeting Abstracts*, pages 741–741. The Electrochemical Society, 2014.

[45] Z Ma, M Mehos, G Glatzmaier, and BB Sakadjian. Development of a concentrating solar power system using fluidized-bed technology for thermal energy conversion and solid particles for thermal energy storage. *Energy Procedia*, 69:1349–1359, 2015.

[46] C Ho, J Christian, D Gill, A Moya, S Jeter, S Abdel-Khalik, D Sadowski, N Siegel, H Al-Ansary, L Amsbeck, et al. Technology advancements for next generation falling particle receivers. *Energy Procedia*, 49:398–407, 2014.

[47] N Siegel, M Gross, C Ho, T Phan, and J Yuan. Physical properties of solid particle thermal energy storage media for concentrating solar power applications. *Energy Procedia*, 49:1015–1023, 2014.

[48] Z Ma, GC Glatzmaier, and M Mehos. Development of solid particle thermal energy storage for concentrating solar power plants that use fluidized bed technology. *Energy Procedia*, 49:898–907, 2014.

[49] Clifford K Ho, Joshua M Christian, David Romano, Julius Yellowhair, and Nathan Siegel. Characterization of particle flow in a free-falling solar particle receiver. In *ASME 2015 9th International Conference on Energy Sustainability collocated with the ASME 2015 Power Conference, the ASME 2015 13th International Conference on Fuel Cell Science, Engineering and Technology, and the ASME 2015 Nuclear Forum*, pages V001T05A013–V001T05A013. American Society of Mechanical Engineers, 2015.

[50] J Christian and C Ho. System design of a 1 mw north-facing, solid particle receiver. *Energy Procedia*, 69:340–349, 2015.

[51] Janna Martinek and Zhiwen Ma. Granular flow and heat transfer study in a near-blackbody enclosed particle receiver. In *ASME 2014 8th International Conference on Energy Sustainability collocated with the ASME 2014 12th International Conference on Fuel Cell Science, Engineering and Technology*, pages V001T02A012–V001T02A012. American Society of Mechanical Engineers, 2014.

[52] Zhiwen Ma, Greg Glatzmaier, and Mark Mehos. Fluidized bed technology for concentrating solar power with thermal energy storage. *Journal of Solar Energy Engineering*, 136(3):031014, 2014.

[53] AB Morris, S Pannala, Zhiwen Ma, and CM Hrenya. A conductive heat transfer model for particle flows over immersed surfaces. *International Journal of Heat and Mass Transfer*, 89:1277–1289, 2015.

[54] Daizo Kunii and Octave Levenspiel. *Fluidization engineering*. Elsevier, 2013.

[55] B Sakadjian, S Hu, M Maryamchik, T Flynn, K Santelmann, and Z Ma. Fluidized-bed technology enabling the integration of high temperature solar receiver csp systems with steam and advanced power cycles. *Energy Procedia*, 69:1404–1411, 2015.