Summary Report for Concentrating Solar Power Thermal Storage Workshop

New Concepts and Materials for Thermal Energy Storage and Heat-Transfer Fluids
May 20, 2011

G. Glatzmaier

NREL is a national laboratory of the U.S. Department of Energy, Office of Energy Efficiency & Renewable Energy, operated by the Alliance for Sustainable Energy, LLC.

Technical Report
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Introduction

The U.S. Department of Energy (DOE), National Renewable Energy Laboratory (NREL), and Sandia National Laboratories hosted a workshop on thermal energy storage for concentrating solar power (CSP) on May 20, 2011, at NREL in Golden, Colorado. The objective for this workshop was to engage the university and laboratory research communities to identify and define research directions for developing new high-temperature materials and systems that advance thermal energy storage for CSP technologies. Desired outcomes for the workshop were to 1) inform the workshop participants of CSP technology challenges, specifically with respect to materials, and 2) generate and document new ideas for advancing materials development for CSP thermal energy storage.

The workshop agenda featured introductory presentations by DOE, NREL and Sandia staff that provided overviews of the DOE CSP Program goals and CSP technologies. Emphasis for the presentations was on the role and impact of thermal energy storage when it is incorporated into an operating CSP plant. These were followed by featured presentations given by invited speakers. Topics for these talks were 1) new heat transfer fluids for CSP technologies, 2) sensible thermal energy storage systems, and 3) thermochemical cycles for thermal energy storage. The presentations were followed by three parallel breakout sessions that covered 1) heat transfer fluids, 2) sensible and latent storage, and 3) thermochemical storage. For each session, participants were asked to identify system/material challenges and promising research directions for the topic area. The workshop concluded with summary presentations of the findings from the breakout sessions. All findings from the workshop are documented in this summary report.

SunShot Initiative

This workshop was motivated, in part, by the DOE SunShot Initiative, which was established in 2010.[1] This initiative sets a very aggressive cost goal for CSP technologies. The primary goal is to reach a levelized cost of energy (LCOE) of 6¢/kWh by 2020 with no incentives or credits. Because CSP is the only solar technology that is capable of significant energy storage, this cost goal applies to CSP plants that have several hours of thermal energy storage (TES) included in their design and operation.[2] As such, the cost and performance of the TES system are critical to meeting the overall cost goal for the CSP technology. The target cost for the TES system depends on other cost and performance factors for the power plant, but the initial cost target for TES system components under SunShot has been established at \$15-\$20/kWh$_{th}$. Furthermore, this cost target assumes the TES system integrates with the solar field and power block components in a fashion that does not reduce the efficiency of their operation.

Figure 1 shows qualitatively the collection, conversion, and overall efficiencies for a general CSP plant. The temperature at which the overall efficiency reaches its maximum depends on many factors, including material properties of the CSP plant components. Increasing the operating temperature of the power generation system generally leads to higher thermal-to-electric conversion efficiency. In a CSP system, higher operating temperature leads to greater thermal losses. These two effects combine to give an optimal system-level operating temperature that may be less than the upper operating temperature limit of system components. System-level efficiency may be improved by developing materials, power cycles, and system-integration strategies that enable operation at elevated temperature while limiting thermal losses. This is particularly true for a TES system and its components. Meeting the SunShot cost goal will require new materials for the TES system and heat-transfer fluid (HTF) that allow the CSP power plants to operate at higher temperatures and with greater efficiency than current parabolic trough and power tower plants.

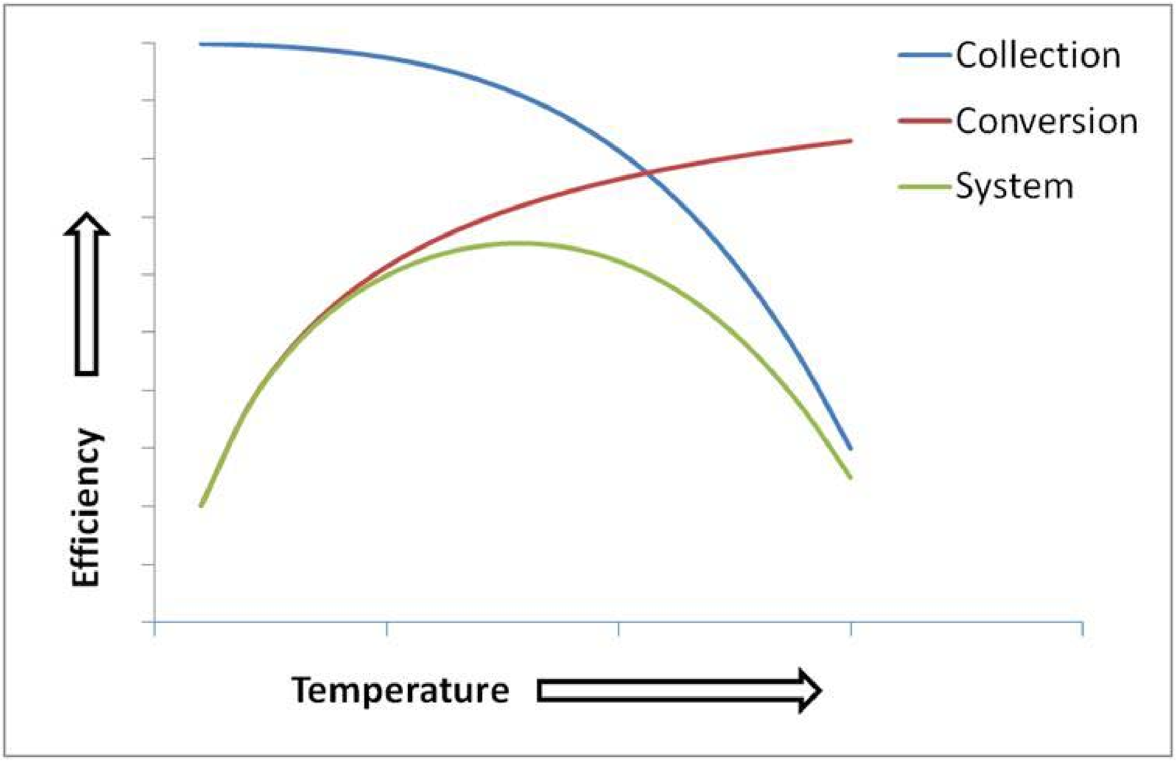

Figure 1. Collection, conversion, and total system efficiencies as functions of temperature.

CSP Technology Description

CSP plants offer an attractive means for near-term, utility-scale, dispatchable, renewable electricity generation. More than 400 megawatts (MW) of capacity are currently in place in the U.S. southwest.[3] With 650 MW currently under construction in Arizona and California,[4,5] CSP technologies will play an increasingly significant role in providing sustainable power generation. All CSP technologies have similar components – solar collectors, receivers, and thermal power conversion systems. They are grouped into two general types according to their collector/receiver geometries: point-focus and line-focus.

Point-focus geometries are the power tower and parabolic dish. The power tower consists of a single receiver that is located at the top of a tower (Figure 2). The tower is surrounded by a field of two-axis tracking mirrors, or heliostats, that reflect and concentrate sunlight to the receiver. An HTF circulates to the receiver, collects thermal energy contained in the concentrated sunlight, and returns to the power block where it is used to generate steam for the turbine power cycle. Power towers using molten salt HTF normally store the hot and cold salt in tanks that allow for separation of the solar collection and power generation cycles.

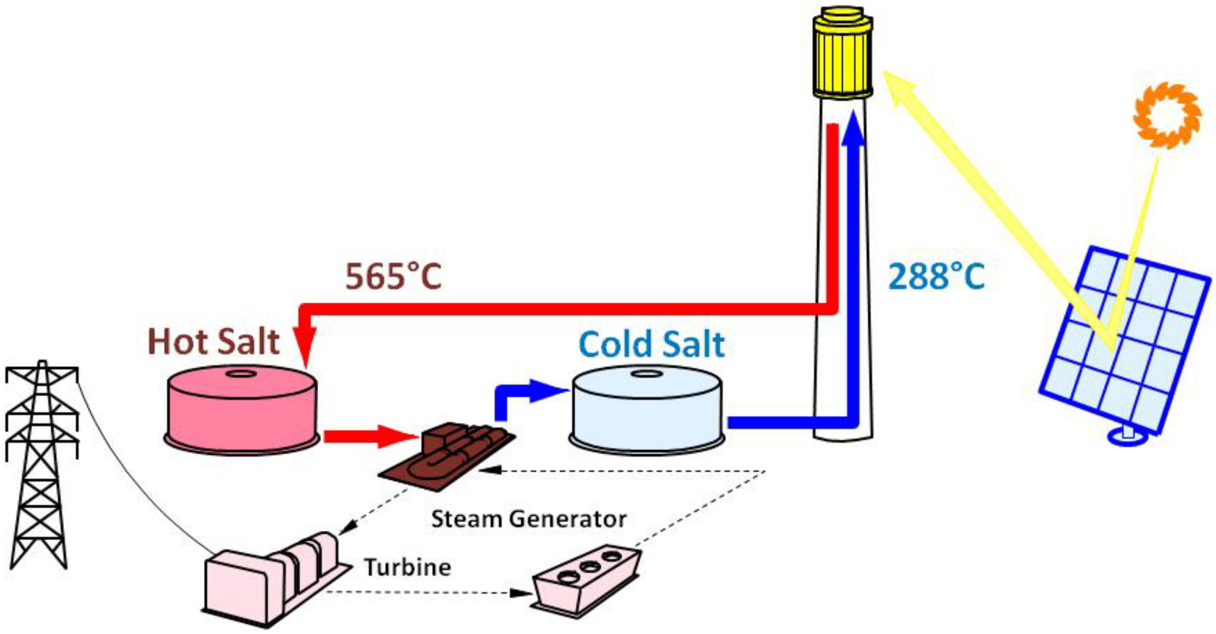

Figure 2. Schematic of power tower with direct, two-tank molten-salt thermal storage.

The most common HTF is molten nitrate salt that is a thermally stable liquid in the temperature range of 220° to 565°C. This type of configuration is a direct system because the HTF and storage fluids are the same. Some power towers send water to the tower, generate steam in the receiver, and send it directly to the turbine.

The parabolic dish is a modular design in which each module consists of a two-axis tracking, point-focus concentrator that has a receiver/engine/generator located at its focal point (Figure 3). A Stirling engine is typically used to convert thermal energy to mechanical power for electricity generation. The working fluid is hydrogen or helium and is heated directly in the receiver. The Stirling engine operates nominally at 800^{o}C and has a high thermal-to-mechanical conversion efficiency. Heat transfer to the working fluid occurs isothermally at the operating temperature of the working fluid.

The most common line-focus geometry is the parabolic trough design. Its collector field consists of single-axis parabolic mirrors that reflect and concentrate sunlight to a focal line (Figure 4). The concentrated sunlight is absorbed by an HTF that flows through receiver tubes located at the focal line. Most trough plants use a synthetic oil for the HTF. Thermal energy within the heated HTF is used to generate steam for the turbine power cycle or can be stored within a separate storage fluid for later use. The storage fluid for this design is molten salt and the storage system is referred to as indirect because the HTF and storage fluids are distinct and require a heat exchanger to transfer thermal energy between them.

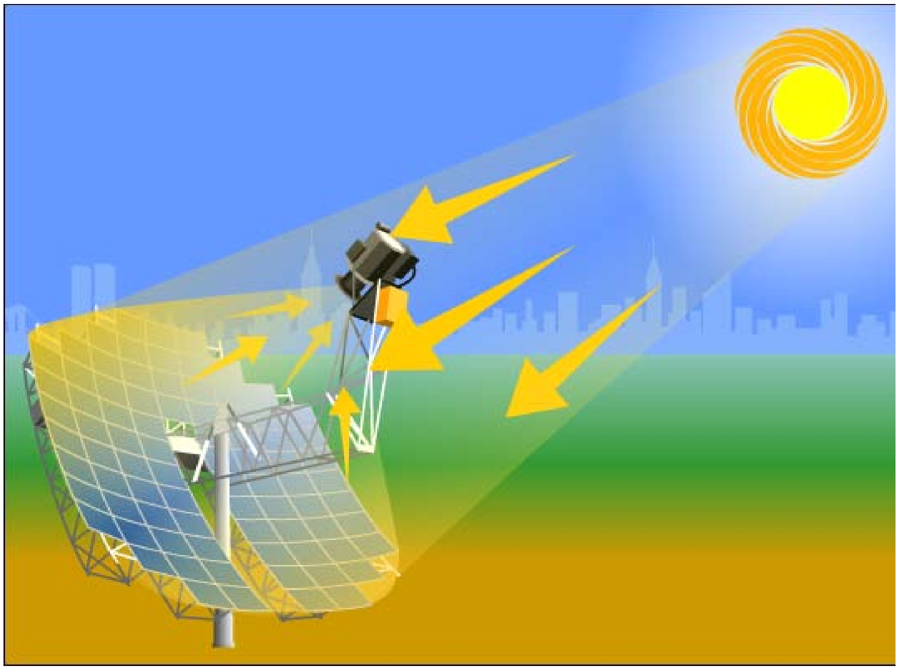

Figure 3. Schematic of parabolic dish with Stirling engine.

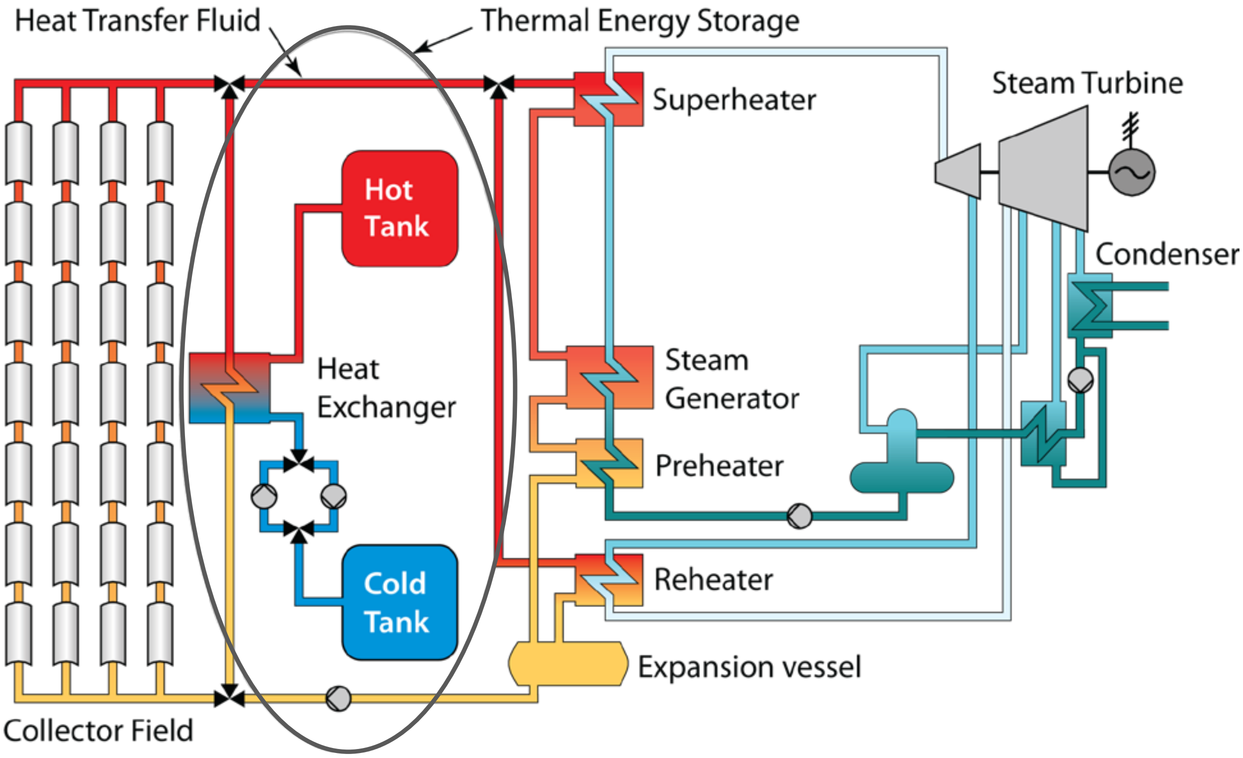

Figure 4. Schematic of parabolic trough power plant with two-tank, molten-salt thermal storage.

Line- and point-focus power plants are currently operating at commercial scale in the U.S. southwest and Spain. Commercial-scale plants of both types are currently under construction in the U.S. and Europe. However, broad implementation of CSP technologies historically has been limited by the cost of electricity produced by these plants, which is greater than electricity costs from conventional power generation. The purpose of the SunShot Initiative is to significantly increase broad-base implementation of solar-to-electricity technologies. Key thrusts of this initiative are dramatic performance improvements and cost reductions in all of the components that make up a CSP plant and the use of TES to increase the plant's capacity factor and dispatchability. Both thrusts will make CSP plants more attractive for utility-scale implementation. Power towers in particular are thought to have greater potential for wide-scale implementation because of their higher thermal conversion efficiency and greater stored energy densities. Both of these features are due to their higher operating temperatures.

CSP Thermal Energy Storage

CSP plants are unique among renewable technologies in that they provide utility-scale, dispatchable electricity to the power grid. Dispatchable delivery means power is reliably available when it is needed to meet the utility load demand. This feature is due to the incorporation of TES into the power plants. TES allows electricity to be generated consistently at times when sunlight is not available, including momentary cloud transients, which otherwise disrupt electricity generation and cause widely varying power output. For longer time scales, TES allows CSP plants to generate electricity well into the evening hours when electricity is highly valued, making the power plant more cost effective. TES also allows greater use of the turbine and other power-block components. These features provide an economic incentive for the addition of TES. Without TES, CSP solar power is an intermittent power resource that depends on sunlight availability. In addition to enhancing CSP dispatchability, TES enables increased deployment of renewables in general by adding flexibility to a grid with photovoltaic and wind power systems.

Types of Thermal Energy Storage

Figure 5 lists a variety of TES options for CSP plants. They fall into three general categories: sensible, latent, and thermochemical storage. A book published in the mid 1980s provides a comprehensive survey of the fundamentals of the storage options, examples of systems, and the issues that must be addressed for technologies in the range from low to high temperatures.[6] The only TES system that currently operates with multiple hours of storage is the sensible, two-tank, molten-salt system. This system is used because the components associated with molten-salt handling—pumps, valves, tanks, and heat exchangers—have demonstrated reliable operation at commercial scale.

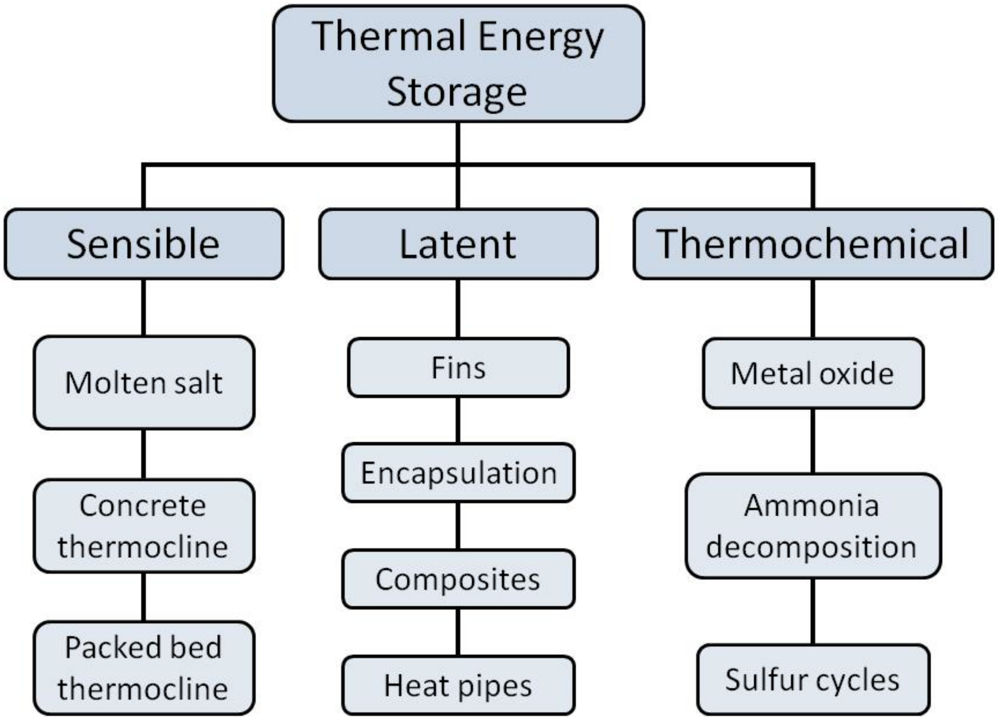

Figure 5. Thermal energy storage options for CSP technologies.

The molten-salt storage fluid is a mixture of $NaNO_3$ and KNO_3. This fluid is liquid in both the charge and discharge states, so there are minimal heat-transfer limitations, making the heat-exchanger design relatively straight-forward. One drawback for this system is the relatively low stored energy density, which results in a large storage medium inventory, requiring large insulated storage vessels. Implementation of this TES system into parabolic trough power plants requires an indirect configuration—distinct heat-transfer and storage fluids—because the storage salt has a high freezing point ($220^{o}C$) and could possibly freeze in the solar collectors if used as the HTF. The indirect system requires a heat exchanger for transferring thermal energy between the HTF and storage fluid (Figure 4). This heat exchanger reduces the performance of the storage system and adds cost to the plant. This approach has been demonstrated commercially in Spain at the Andasol plants.

Implementation of this TES system into power towers can use a direct configuration—common heat-transfer and storage fluids—because steps can be taken to prevent the freezing of molten salt in the receiver and transfer lines within the vertical tower that are not possible in a parabolic trough configuration. This type of system was demonstrated during the Solar Two project in Barstow, California.

The stored energy density of the two-tank system can be increased in two ways. First, increasing the maximum operating temperature of the power plant increases the temperature drop across the turbine. Higher temperature drops increase the efficiency of the turbine power-cycle and the stored energy density of the sensible portion of the TES system. Second, increasing the heat capacity of the storage medium also directly increases the stored energy density. These effects are important to reducing size, and therefore the capital cost of the two-tank TES system.

Thermoclines that use low-cost storage materials offer an opportunity for reducing TES costs. The benefit of thermoclines is significant, especially if the storage material is self-supporting. In this case, the structural requirements of the containment vessel can be reduced. At very high temperatures, the cost of the containment vessel(s) for the storage system may negate the cost benefit from increased temperature drop. Thermoclines have more complex operating requirements than the two-tank, molten-salt system, which creates the potential for utilization and performance losses.

Alternatives to the two-tank, molten-salt storage system are being considered to increase the stored energy density and, ultimately, to reduce the cost of the TES system. The most developed alternative is the use of phase-change materials (PCMs) to increase stored energy density. PCMs have both latent and sensible enthalpies that contribute to the stored energy density, providing a benefit over purely sensible systems. PCM systems suffer from a limitation in heat transfer during the discharge process due to the generally low thermal conductivity of the solid phase. This limitation results in low power density for PCM systems and will need to be overcome if PCM storage is to become a viable alternative. PCM storage is the most compatible storage system for the parabolic dish/Stirling concentrator because thermal energy delivery to the engine is isothermal.

The third option, thermochemical storage offers perhaps the greatest benefit due to the large quantity of stored energy associated with the heat of reaction. Practical implementation of these systems is often limited by the loss of system performance as it is put through many charge/discharge cycles. System performance depends on maintaining consistent physical and chemical properties of the chemical components and of any solid-phase materials used in the system over many cycles. Over time, degradation of these material properties may result in reducing both the system heat-transfer rate and storage capacity. In addition, some cycles require the handling of gas-phase reactants that may require compression or corrosive substances that require special materials of construction. The benefits of very high energy densities and the possibility of storing reaction products at ambient temperature keep thermochemical storage under consideration for CSP technologies.

System and Material Challenges for Thermal Energy Storage

Meeting the SunShot cost target will require cost and performance improvements in all systems and components within a CSP plant. Solar collector field hardware will need to decrease significantly in cost with no loss in performance and possibly with performance improvements. As higher temperatures are considered for the power block, new working fluids, heat-transfer fluids, and storage fluids will all need to be identified to meet these new operating conditions. Figure 6 shows thermodynamic conversion efficiency as a function of temperature for the ideal Carnot cycle and 75% Carnot, which is considered to be the practical efficiency attainable by current power cycles. Current conversion efficiencies for the parabolic trough steam cycle, power tower steam cycle, parabolic dish/Stirling, Ericsson, and combined air-Brayton cycles are shown at their corresponding operating temperatures. Efficiencies for supercritical steam and CO_2 are also shown for their operating temperature ranges.

Figure 6 makes clear the benefit of increased power-cycle operating temperature. Moving in this direction requires the use of working fluids other than subcritical steam for parabolic troughs and power towers. Supercritical steam and CO_2 are options that correspond to power cycles in the 600° to 800°C range. Air is being considered for air-Brayton cycles operating above 1,200°C. These working fluids will impact the requirements for the heat-transfer fluid. In some cases, the HTF and working fluid may by the same, as in the case of a supercritical CO_2 power cycle that uses a supercritical CO_2 receiver or an air-Brayton cycle that uses an air receiver. These cycles also dictate the requirements for the heat exchanger and TES system that will couple to the power cycle and receiver. A temperature greater than 565°C will be required, and whether that temperature falls into the 565°–800°C range or is closer to 1,300°C will depend, to a large extent, on the feasibility of developing a TES system able to operate at the corresponding temperature while keeping to a minimum the system losses associated with high-temperature operation (Figure 1).

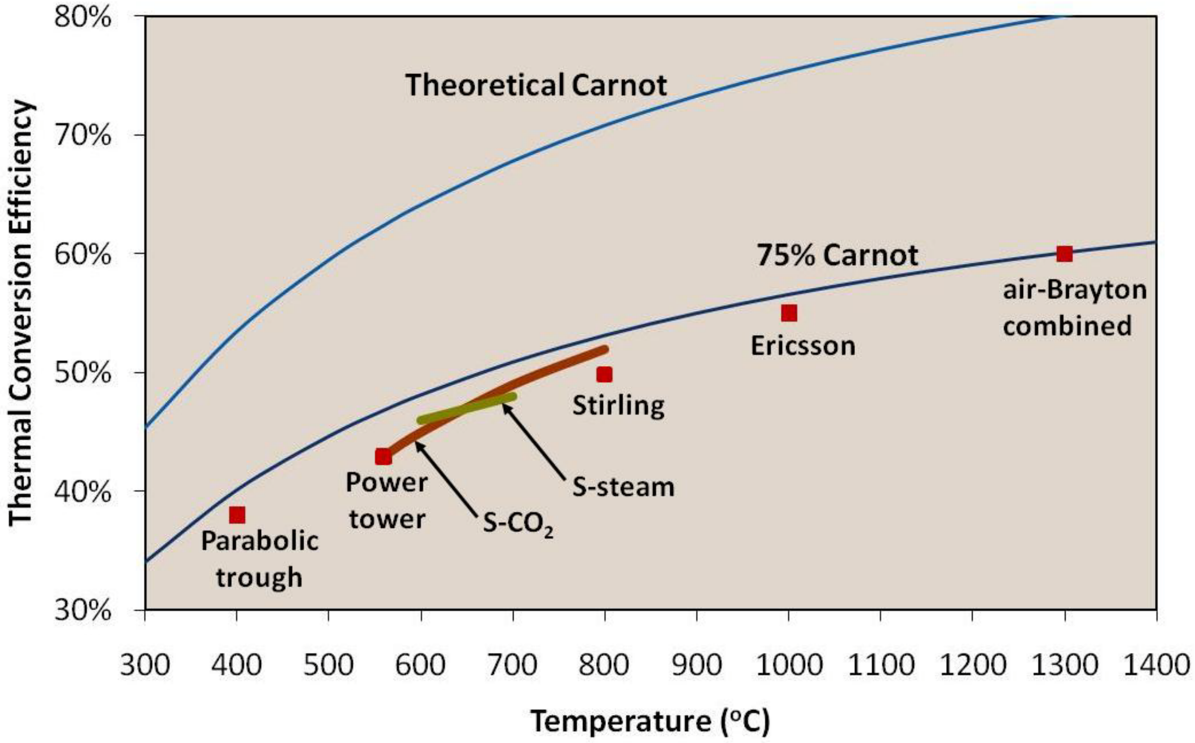

Figure 6. Power-cycle efficiencies for CSP technologies.

Participants in the breakout sessions identified the following needs and challenges for thermal energy storage.

Heat-Transfer Fluids

Reaching the higher temperatures required for the SunShot goal will require new HTFs that possess a very wide liquid temperature range. In the extreme, new HTFs could be identified that have liquid temperatures in the range of 0° to 1,300°C. Practically, the temperature range will be narrower, depending on the power cycle. In addition to having a wide liquid temperature range, a suitable fluid will require combination of the following properties, depending on heat-transfer and storage media: 1) low cost, 2) environmentally safe, 3) compatible with piping and tank wall materials, and 4) high-temperature stability, possibly in air. Preferred properties that will make any new HTF more attractive for particular systems are 1) high heat capacity, 2) high thermal conductivity, 3) low viscosity, 4) high fluid density, 5) low thermal expansion coefficient, 6) high extinction coefficient, 7) high heat-transfer coefficient, and 8) low vapor pressure over the operating range.

Needs and Challenges

When considering a fully integrated power plant, use of a single fluid for heat transfer and storage is preferred because the heat exchanger and associated thermodynamic penalties can be eliminated. This arrangement results in lower power-plant capital costs and greater thermodynamic efficiency. Developing a low-cost fluid that meets all the technical requirements for both functions may not be possible, in which case the use of two distinct fluids may be the only practical configuration for a plant.

There is a need to develop guidelines and standards for high-temperature thermophysical properties measurements and a figure of merit for high-temperature performance of new heat-transfer fluids. High-temperature measurements were recognized as being very difficult to make, and a large amount of high-temperature data already exist in the literature. There is a need to better characterize the structure of nanofluids and identify the role of radiative heat transfer in high-temperature systems. Additionally, hysteresis of the melting and freezing points can generate uncertainty in the behavior of the fluid at low temperatures where freezing in the plant piping may occur; this effect needs to be better understood. Compatibility with materials of construction must also be determined. The measurement of properties requires very careful analysis of the chemical composition of the samples tested and documentation of the methods of measurement.

Sensible Energy Storage

The effectiveness of TES systems depends critically on the thermophysical properties of the storage materials. Thermal conductivity, density, viscosity, melting and freezing points, and enthalpies of fusion or reaction all impact the design, performance, and cost of the TES system, as well as the fully integrated power plant. Part of current work is to identify the impact of these properties, along with operating conditions, on TES system performance. The following analysis for storage-fluid heat capacity is given as an example of the analyses that will help define new research directions.

Cost Benefit from Improved Heat Capacity of Sensible Storage Fluids

The simplicity and efficiency of direct two-tank storage makes it an appealing approach to TES. A relatively easy way to improve the economics of this system is to improve the heat capacity of the storage fluid. The minimum required heat capacity for a sensible storage material is a function of the temperature drop across the turbine. The heat capacity and temperature drop together determine the stored energy density of the TES system. Other factors are the costs of the storage material, tank, and piping materials that are required for the TES system. For the two-tank storage system, the low-temperature tank is normally at 300^{o}C (as specified by the steam-cycle pinch point), so the temperature drop across the power block is determined by the maximum operating temperature.

Analysis was performed in which the cost of TES was estimated as a function of the maximum operating temperature from 400°C to 1,100°C. Heat capacities for the storage fluid varied from 1.5 J/g-K, which is the heat capacity of the binary $NaNO_3/KNO_3$ mixture that is currently used in the two-tank storage system, to 4.5 J/g-K or a factor of 3 greater than the binary salt. The cost of the tank wall material varies with temperature. From 400°C to 450°C, carbon steel can be used as the wall material for the hot tank. From 450°C to 650°C, stainless steel is required and above 650°C, a nickel-based alloy is required. The cost difference between these materials significantly impacts the cost of the TES system as a function of operating temperature. The analysis determined the cost of the TES system in the temperature range accounting for the increased cost of the tank wall material as temperature increases. Results of the analysis indicate that the TES cost goal of \$15–\$20/kWh_{th} can be reached at temperatures in the range of 450°C and at 650°C if the heat capacity of the storage fluid is between 3–4.5 J/g-K. For temperatures greater than 650°C, the high cost of nickel-based alloys makes it difficult to meet the cost target using this type of storage system.

This analysis assumes that the storage medium needs to be contained in a two-tank type storage system. If thermochemical TES is used, the high-energy products from the charging process may be stored at low temperature. The stored energy in the products can then be released at high temperature. Also, if the storage medium is self supporting, such as a ceramic matrix material in a thermocline, then the requirements for the high-temperature tank material may not be as strict and its associated cost may be less. In both of these cases, operating temperatures well above 650°C still offer performance and cost benefits.

Similar analyses have been performed for the other thermophysical properties including conductivity, density, and viscosity. The impacts of these properties on the performance of TES systems and the complete plant have been characterized. High viscosities for either the HTF or storage fluid lead to unacceptably high pumping power within the plant. This power requirement is subtracted from the total generated power to get the net power produced. Limits for viscosity have been established to minimize this parameter. Increasing HTF and storage-fluid densities actually improve plant performance and cost. Higher storage-fluid density decreases the required storage volume and decreases tank costs. Higher HTF density reduces HTF velocities in the piping, thereby reducing frictional losses and pumping power. Minimum values for storage fluid and HTF thermal conductivities have also been established to ensure adequate heat transfer within the receiver and heat exchangers.

Needs and Challenges

There is significant overlap of needs in sensible-heat storage materials and heat-transfer fluids. These include the need for integrated systems modeling to determine costs, requirements, and relative needs for various fluids and components within an operating power plant. The point was made that the requirements for the HTF vary depending on the specifications and performance of other components within the plant. Fully integrated system models are able to determine the dependence and trade-offs between these factors and set bounds of the properties that are required for the HTF and other components.

There is a need to learn more from members of the nuclear community because they have been working in this area of high-temperature HTFs for many years and have accumulated much information on this topic. The laboratories need to develop high-temperature materials characterization methods so new fluids can be accurately characterized. These methods include high-temperature materials compatibility testing and properties measurements.

Several needs were identified relating to systems and components for the heat-transfer fluid. Eliminating the heat exchanger between either the HTF and storage fluid or HTF and working fluid reduces capital cost and exergy losses. For the air-Brayton power cycle, means for efficient heat transfer between the air and storage medium need to be modeled and developed. New alloys need to be developed that are inexpensive, strong at high temperatures, and compatible with potential heat-transfer fluids.

Phase-Change Storage

Needs and Challenges

The same capability needs that were identified for sensible storage are applicable to phase-change storage, as well. For phase-change storage, it is particularly important to develop new materials with high thermal conductivity to improve heat-transfer rates upon discharging (freezing) of the PCM. Fully integrated systems modeling is essential to determine the specifications and performance for PCM storage because its behavior is more complex than that of sensible-storage systems. Of specific interest is the need to better model heat transfer between the heat transfer fluid and PCM in complex geometries. New approaches must be found to overcome the losses due to build up of solid phase at heat-exchange surfaces. Encapsulation of phase-change media at scales from nano to macro must be developed to improve heat transfer and construction of a cascade of PCMs that cover the operating range of the power cycle. High-temperature materials characterization is also essential for PCM storage.

PCM storage matches well to Stirling engines because energy transfer to the Stirling engine is isothermal. There is a need to develop PCMs that are specific to this application. Also, the need for high heat-transfer rates and adequate power density is required and may be met by the use of heat pipes integrated with the receiver and Stirling engine components.

Thermochemical Storage

Thermochemical storage offers the greatest volumetric stored energy density of any of the thermal energy storage options.[7, 8, 9] In some cases, the stored energy density may be an order of magnitude greater than that available from sensible or phase-change storage systems. In thermochemical storage systems, thermal energy from sunlight is absorbed by a forward reaction, A → B (Figure 8). The reaction product, B, preheats the reactant, A, and is stored at ambient temperature. To recover thermal energy, the reverse reaction generates product A and is used to preheat the reactant B for this reaction. Because A and B can be stored at ambient temperature, this approach creates the potential for long-term storage.

For any thermochemical cycle, design considerations must include the minimization of exergy losses. For the general storage system in Figure 7, the heat exchangers should be designed to have minimal temperature drop. The reverse reaction, B →A, should occur at a temperature as close as practical to the temperature of the forward reaction, A → B. Parasitic losses due to pumping and/or compressing reactants and/or products also need to be minimized.

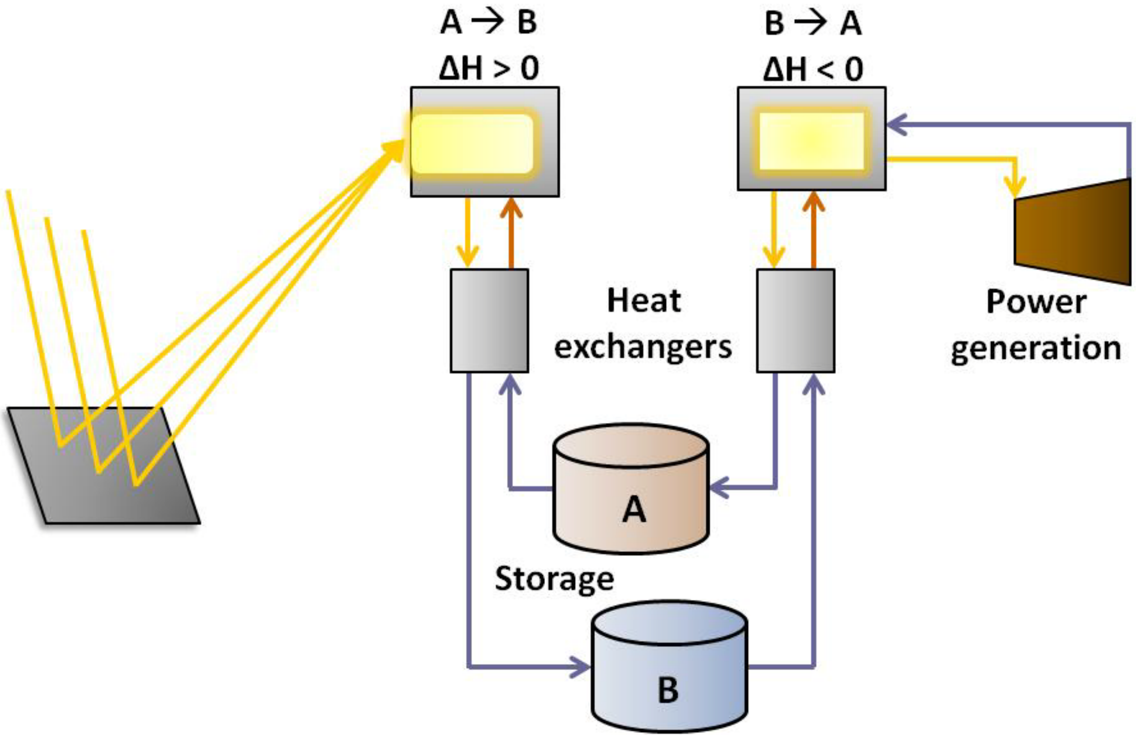

Figure 7. Schematic of generalized thermochemical storage cycle for CSP technologies.[10]

Needs and Challenges

Comparisons were made to the development of thermochemical cycles for the nuclear industry and high-temperature solar fuels applications. These are predominantly directed to water splitting to produce hydrogen as an energy carrier.[11, 12] The multi-step thermochemical cycles proposed in the temperature range of 600° to >1,000°C will present a challenge to integrate into CSP technologies where operation may be subject to repeated start up and shut down. Further, integration of thermochemical reactions into CSP systems will require receivers that are quite different compared to current receiver designs, which have HTF flowing through them. Systems will have to be designed that can meet the requirements for both generating electricity and charging the storage system with high efficiency. Thermochemical cycles will need to be simpler and unaffected by the variable energy input that is characteristic of solar power generation.

Much discussion related to the need to always evaluate any thermochemical system from the standpoint of exergy losses. On an energy basis, TES efficiency may be very high, but if the thermal energy ultimately is delivered to the power block at a low temperature, then the exergy efficiency will be unacceptably low. Exergy losses can be minimized by minimizing heat-exchange steps in the system and operating the reverse chemical process at the highest possible temperature.

Other practical challenges are the need to minimize loss of surface area or activity for catalysts or solid-phase reactants, if present, over many thermal cycles due to sintering or poisoning. Reaction kinetics are proportional to these properties, so they need to be preserved to maintain adequate power densities. There is a need to identify chemical reaction rates that are fast enough to match the solar or heat flux that is supplied to the chemical reactors—

whether the chemical reactor is directly driven by the solar heat in a dedicated receiver designed for the chemical process (direct solar thermal chemistry) or is driven by some fraction of heat from the same HTF stream used for driving the power cycle (an indirect solar thermal process). Gas-phase reactants or products from the chemical system may require compression for storage and contribute to parasitic losses. For example, identifying chemical cycles in which gas-phase reactants are oxygen or water would be advantageous because the system could be open and not require compression for storage of these gases.

Research Directions for Thermal Energy Storage

Participants in the breakout sessions identified the following research directions for thermal energy storage.

Heat-Transfer Fluids

1. Develop advanced capabilities in modeling of mechanistic, multi-physics systems and new standards for high-temperature stability and properties measurements. Both of these efforts will help define the requirements for performance and reliability for HTFs in fully integrated power plants.

2. Develop single heat-transfer/storage fluid, preferably a fluid that has improved radiative properties. Possible fluid types include liquid metals (Na, Al/Sn), gases (nitrogen), nanofluids, high-temperature non-nitrate salts, ionic liquids, or sulfur. Liquid Na has already been studied for use in nuclear power plants, so there are existing data that may be applicable to CSP.

3. Explore surface modification for improved heat transfer to fluids . Characterization of the structure of nanofluids is important for understanding enhancements due to adding nanoparticles to fluids.

4. Examine the use of particles for direct absorption of solar radiation. Such systems could use the same particles for TES.

5. Develop barrier coatings to prevent hydrogen permeation for Stirling engines and evaluate variations of the HTF for Brayton systems that include particles, air, liquid, or helium.

Sensible Storage

New directions for sensible storage include:

1. Additives that will lower the freezing point of molten salts to near-ambient temperature.

2. Lower-cost containment materials for high-temperature storage. One approach is to develop protective coatings that allow containment of potentially corrosive storage fluids with lower-cost wall materials.

3. Consideration of materials that have not previously been considered for storage applications. These materials include inter-metallic materials, nanofluids, and high-temperature storage materials derived from natural sources such as lava, rocks, sand, and cements.

Phase-Change Storage

New directions in phase-change storage materials include:

1. Investigation of metal alloy PCMs. There is also a need to fully characterize chlorates, sulfates, and carbonates for high-temperature storage and to develop materials or composites with higher thermal conductivity, particularly in the solid state.

2. Methods to encapsulate micro- or nano-sized PCMs that may be integrated into an HTF. Encapsulation of PCMs is needed to reduce heat-transfer losses are encountered in the charging and discharging of the storage material.

3. The development of PCMs specific to dish/Stirling applications. Also, the development of heat pipes integrated with the receiver and Stirling engine components will increase the high heat-transfer rate and power density required for this system.

Thermochemical Storage

Many thermochemical cycles were discussed and identified as potential candidates for solar thermochemical storage. These cycles include the following:

1. Solid-based reactant plus a gas-phase reactant: $MO + CO_2 = MCO_3$

2. Reactions that use other gases: SO_2, SO_3, H_2O

3. Systems that have liquid reactant(s) and liquid product(s)

4. Organic reactions that could be possible below 400^oC, e.g., depolymerization = polymerization conversion

5. Inorganic reactants possible at higher temperatures: polymerization/depolymerization reactions based on siloxane chemistry $[-S(CH_3)_2O-]_n$

6. Polymerization/depolymerization of sulfur

7. Metallurgical conversions involving molten metals and metal oxides

8. Gas reactants to liquid or gas products

9. Reforming reactions and the corresponding reverse

10. Methanation with catalysts from $600^o–700^oC$

11. Gas reactants to gas products:

$$SO_2 + \frac{1}{2}O_2 = SO_3$$

$$CO + \frac{1}{2}O_2 = CO_2$$

Identifying and screening new cycles for solar thermal energy storage will require a general capability that 1) uses high-level chemical process modeling software for screening chemical storage cycles and 2) takes into account thermodynamics, kinetics, by-products, heat recovery, separations, and more.

Summary

CSP technologies need to make significant cost and performance improvements to meet the SunShot Initiative cost target of 6¢/kWh LCOE. In addition, thermal energy storage will be an essential component of next-generation power plants because these plants will need to deliver reliable, consistent power during daylight hours and into the evening. Meeting the cost target will require significant performance improvements and cost reductions for all components and subsystems that make up a CSP plant. With respect to TES, new heat-transfer fluids and storage materials will be required that are stable at high temperature and have high stored energy density due to high heat capacities and/or multiple phase changes. Thermochemical storage may provide the ultimate solution to the TES challenge if a suitable system can be identified and developed for high-temperature CSP applications.

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