Concentrating Solar Power

Concentrating solar power (CSP) technologies use mirrors to focus and concentrate sunlight onto a receiver, from which a heat transfer fluid carries the intense thermal energy to a power block to generate electricity. A distinguishing feature of CSP is its ability to incorporate simple, efficient, and cost-effective thermal energy storage by virtue of converting sunlight to heat as an intermediate step to generating electricity. In addition to providing dispatchable power generation, CSP with thermal energy storage can also enable greater incorporation of other variable generation sources such as PV and wind on the grid. Furthermore, CSP systems can synergistically integrate with fossil-fueled power plants to offset fuel use and reduce carbon footprints. CSP, therefore, presents unique opportunities for the renewable energy space, and is a key enabling technology in the nation's all-of-the-above energy strategy.

The Falling Cost of Concentrating Solar Power

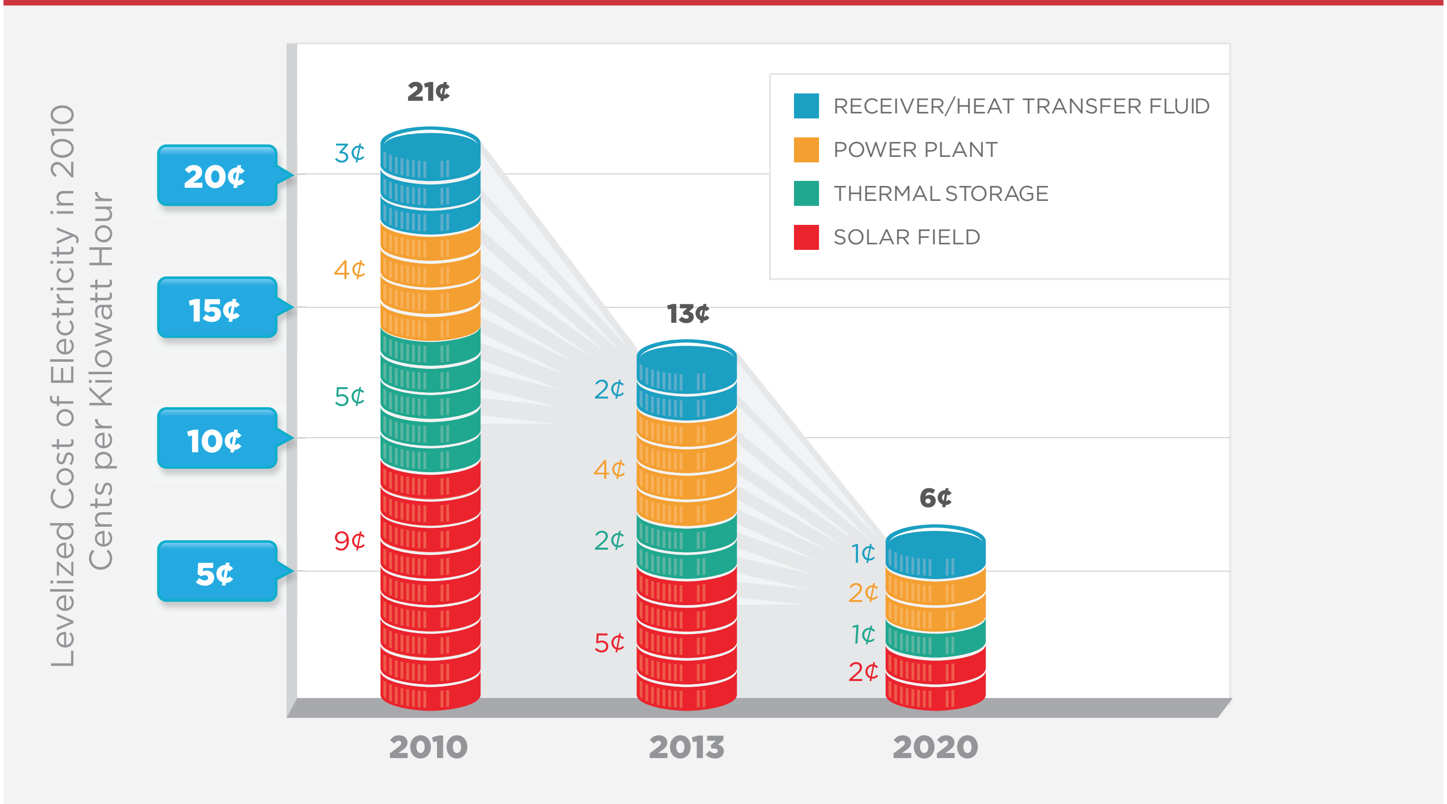

Figure 1. SunShot Initiative 2020 goal for concentrating solar power and the cost reductions achieved from 2010–2013.

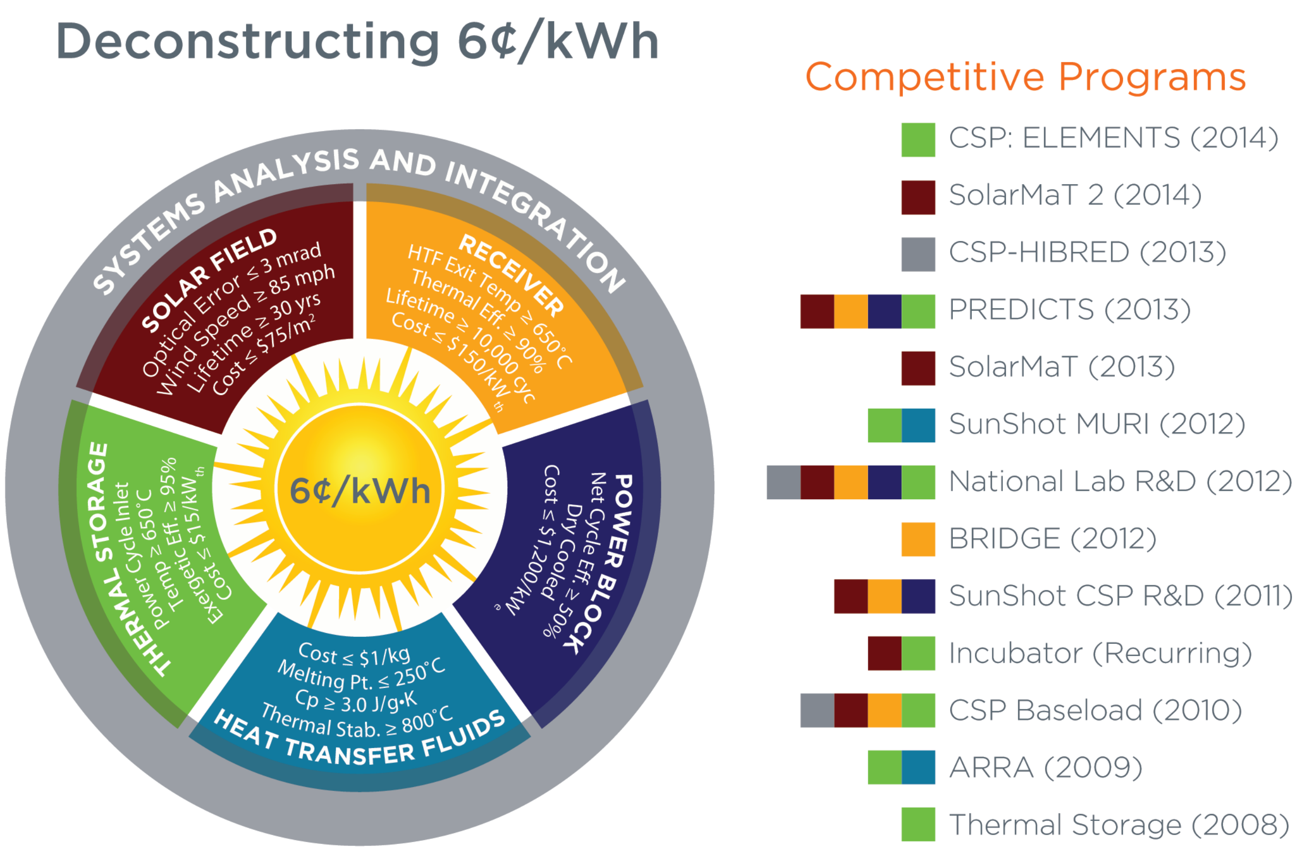

Figure 2. Technical metrics and cost targets for CSP subsystems to achieve an LCOE of $0.06/kWh, and the subsytems addressed by the funding opportunity announcements released.

CSP technologies are deployed primarily in four system configurations: parabolic trough, linear Fresnel, dish engine, and power tower. Parabolic trough and linear Fresnel systems focus sunlight onto a linear receiver whereas dish engine and power towers focus sunlight onto a single central receiver. These system configurations include collectors (solar field), receivers, power block (power plant) and thermal energy storage subsystems. The SunShot Initiative goal for CSP translates to achieving a subsidy-free levelized cost of energy (LCOE) of $0.06/kWh or less by the end of the decade. Toward this objective, Fig. 1 shows the cost reductions that are targeted in the various subsystems relative to their costs at the beginning of the decade. It is evident that these reductions represent an aggressive challenge that calls for significant technical advancements in performance and efficiency.

The LCOE target of $0.06/kWh may be mapped using a technoeconomic analysis to the performance and cost targets for each of the subsystems, as depicted in Fig. 2. In general, the targets require higher temperature operation at higher efficiency, longer lifetime, and lower cost. These target metrics are the basis for the competitive funding opportunity announcements of the SunShot CSP subprogram. The program provides funding—all through competitive awards—to industry, national laboratories and universities (Fig. 3) to develop component technologies and systems solutions to achieve the technoeconomic goals of the SunShot Initiative. Since the launch of the Initiative in 2011, about $145M has been committed for developing CSP technologies to meet SunShot goals.

CSP R&D portfolio funding distribution

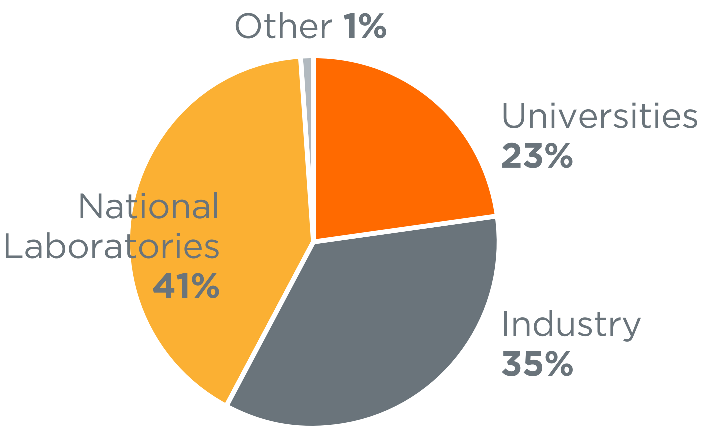

Figure 3. CSP R&D portfolio funding distribution among industry, national laboratories and universities in FY13.

Awarded projects are selected through a rigorous peer review process, and are actively managed with defined quantitative and measurable milestones, deliverables, and periodic stage gates with go/no-go criteria. Much emphasis is placed on understanding the fundamentals to drive innovation and technological advances at the component and system levels, with a steadfast focus on driving down costs.

The current portfolio of projects includes investments with near-term to long-term horizons that span all of the various CSP technologies. Ongoing R&D efforts aim to deliver transformative technologies within the next three to five years. These include highly efficient reflector materials integrated with low-cost collector structures, lean solar field manufacturing and assembly approaches, self-aligning and tracking controls, self-cleaning mirrors, novel receiver designs, solar selective coatings for enhanced collection efficiency, corrosion-resistant materials and coatings, viable heat transfer fluids to carry the heat from the receivers for high temperature operation, and cost-effective thermal energy and thermochemical energy storage technologies. High-temperature, higher-efficiency power cycles such as the supercritical carbon dioxide Brayton cycle demonstrated at the 1–10 MW scales, and the solar-integrated air Brayton cycle, will also be very significant. These next-generation power cycle technologies have broader relevance beyond the solar industry to the nuclear, fossil and geothermal industries, among others. In addition, an award as part of the CSP-HIBRED (Heat Integration for Baseload Renewable Energy Development) funding opportunity seeks to catalyze near-term demonstration of hybrid power systems that integrate CSP with fossil-powered plants.

Just two years into the SunShot Initiative, DOE's investments at the national laboratories, industry, and universities are beginning to pay off. Based on 2013 figures, the LCOE for CSP is $0.08/kWh less than what it was in 2010 (Fig. 1)—that's over the halfway mark in the reductions needed toward the SunShot target. While the initial reduction is impressive, much remains to be done as we continue to work towards the goal of subsidy-free cost parity of CSP-generated electricity on the grid.

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Collecting the Sun

The solar field comprises up to 40% of the total system costs for CSP technologies. The SunShot CSP subprogram seeks to dramatically reduce the cost of the solar field while improving optical accuracy and ensuring durability. In order to accomplish these goals, SunShot supports R&D efforts to develop high optical accuracy reflectors, reduce collector structure weight and material, develop lean and rapid methods for manufacturing, assembly and installation, develop highly efficient tracking and control methods as well as accurate metrology tools, and reduce collector soiling and the water required for operations and maintenance.

SunShot technical targets for the solar field:

- Cost <$75/m^2
- Optical error <3 mrad
- Sustain wind speed >85 mph
- Lifetime >30 years

SELF-CLEANING CSP COLLECTORS

Boston University | Boston, MA | $0.7M | SunShot CSP R&D | 08/2012–01/2015

Boston University is developing a new method to keep solar collectors dirt- and dust-free to help maintain high optical efficiency. This project aims to develop large-scale prototypes, cost-effective manufacturing processes, and commercialize the technology in large-scale CSP devices for applications in semi-arid and desert climates. Specific objectives include establishing proof-of-concept of the application of the electrodynamic screen (EDS) for self-cleaning solar concentrators, producing and evaluating laboratory-scale prototypes of self-cleaning solar collectors, including flat mirrors and curved mirrors, and testing the EDS-incorporated collectors for optical efficiency of sunlight, dust removal efficiency, power requirements, and durability.

FLEXIBLE ASSEMBLY SOLAR TECHNOLOGY

BrightSource Energy | Oakland, CA | $4.8M | SunShot CSP R&D | 08/2012–04/2014

BrightSource Energy is designing and deploying an automated collector-assembly platform and a more efficient installation process that has the potential to drastically reduce construction time and cost for utility-scale CSP facilities. This Flexible Assembly Solar Technology (FAST) system accelerates the heliostat assembly and field installation processes by combining elements of both on a single platform with direct access to the solar collector field. The system incorporates preliminary, partial assembly of the mirror units at a centralized offsite facility capable of supplying multiple CSP projects, an automated, transportable FAST platform for assembly completion, and delivery of the fully completed assemblies into the solar field for final installation.

LOW-COST, LIGHTWEIGHT SOLAR CONCENTRATORS

Jet Propulsion Laboratory | Pasadena, CA | $2.3M | SunShot CSP R&D | 10/2012–09/2015

JPL is designing an optimized solar thermal collector structure using a lightweight collector capable of lowering structural costs and simplifying installation to reach mass manufacture. The specific project objectives are to design and develop a mirror module using an inexpensive reflective film bonded onto a lightweight structural rigid foam support; design and develop a low-cost, non-traditional mirror-module support structure; select low-cost drive components and associated control system; design, integrate, and test a low-cost concentrator; and analyze the system's cost to demonstrate achievement of the $\$75/m^2$ collector system target.

SCATTERING SOLAR THERMAL CONCENTRATORS

Pennsylvania State University | State College, PA | $0.2M | SunShot CSP R&D | 08/2012–10/2014

Penn State is designing and testing a novel solar collector system that relies on stationary optics and avoids the need for mirror movement. The system is capable of achieving optical performance equal to state-of-the-art parabolic trough systems, but at a lower cost. The research team is working to demonstrate a scattering solar concentrator with optical performance equal to existing designs of state-of-the-art parabolic troughs, but with the added benefits of immunity to wind load tracking error, more efficient land use, and elimination of movable heat transfer elements. The goals of the project are to demonstrate a small-scale, fully functioning prototype and test its performance outdoors, attain break-even optical performance compared against existing parabolic troughs, and improve the overall performance and reliability of the collector field.

ADVANCED MANUFACTURE OF REFLECTORS

University of Arizona | Tucson, AZ | $1.5M | SunShot CSP R&D | 08/2012–04/2014

UA is developing technology to improve the optical accuracy and reflectivity of the self-supporting glass mirrors used in CSP collectors. The research team is working to optimize and validate a novel glass-molding technique that creates very precise mirrors in a variety of shapes. The focus is on developing a novel hot glass molding process that could be used for high-speed production at low cost and be easily integrated into a production line. In parallel, the research team is developing a novel way to boost second-surface silver reflectivity and inhibit soiling. The goals of the project are to develop new methods for rapidly shaping glass mirrors and coating them for higher reflectivity and soil resistance, include both point-focus and line-focus mirror designs, improve mirror optical accuracy, and reduce the cost of the solar trough mirrors made in very high volume by about 40%.

LOW-COST HELIOSTAT FOR MODULAR SYSTEMS

National Renewable Energy Laboratory | Golden, CO | $2.2M | National Laboratory R&D | 10/2012–06/2014

NREL seeks to develop a novel collector design and heliostat field technologies that reach the SunShot Initiative cost and performance targets. This includes optimization of an efficient low-profile rigid collector design, implementation of inexpensive wireless communication and control devices to reduce field wiring, and development of an automated optical tracking/calibration technique that enables the use of lower-cost motor and drive components through improved error correction. This design will be optimized, prototyped, tested, and transferred to industry during the three year period of performance.

LOW-COST SELF-CLEANING REFLECTOR COATINGS FOR CSP COLLECTORS

Oak Ridge National Laboratory | Oak Ridge, TN | $2.3M | National Laboratory R&D | 10/2012–09/2014

ORNL is developing self-cleaning, optically transparent coatings that can be applied to the surfaces of heliostats and collector mirrors in CSP systems. The goal is to reduce the time and costs associated with cleaning collector and heliostat mirror surfaces and increase the reliability and efficiency of CSP systems. The research team has developed optically transparent superhydrophobic (SH) materials and coatings based on nanostructured silica surfaces that can address soiling and maintenance issues associated with CSP systems. The team is investigating and optimizing the adhesion, transmittance, and water- and dirt-repellent properties of these multifunctional, nanostructured surface coatings, and using a suspension of SH silica nanoparticles, polymeric binders, and solvents that can be applied to large area surfaces using simple, low-cost spray coating techniques developed by the commercial paint industry.

PREDICTIVE PHYSICO-CHEMICAL MODELING OF INTRINSIC DEGRADATION MECHANISMS FOR ADVANCED REFLECTOR MATERIALS

National Renewable Energy Laboratory | Golden, CO | $2.1M | PREDICTS | 01/2014–12/2016

NREL seeks to develop the capability to predict measurable characteristics from models of fundamental physico-chemical processes driving intrinsic degradation and failure mechanisms of advanced materials and coatings targeted for use in CSP systems. The team will use novel physics- and chemistry-based modeling techniques to predict the time evolution of reflector properties under both controlled and real world conditions. This prediction will be possible through the creation and application of validated, predictive models that use the measured behavior of individual materials to provide predictions for lifetimes of complete multi-layer reflectors.

Receivers and Heat Transfer Fluids

The SunShot CSP subprogram aims to significantly increase the operating temperatures, efficiency, and lifetime of solar receivers while lowering costs. The SunShot Initiative funds R&D on receiver systems, heat transfer fluids (HTFs), and related aspects within the industry, national laboratories and universities. This funding is intended to support the development of fundamentally new receiver designs and novel solar selective coatings, and to explore high temperature receiver corrosion and heat transfer fluid stability.

SunShot technical targets for receiver subsystems:

- Heat transfer fluid exit temperature from the receiver >650°C
- Thermal efficiency >90%
- Lifetime >10,000 cycles
- Cost <\$150/kW_t

HIGH-EFFICIENCY RECEIVERS FOR SUPERCRITICAL CARBON DIOXIDE CYCLES

Brayton Energy | Hampton, NH | \$1.6M | SunShot CSP R&D | 09/2012–08/2015

Brayton is building and testing a new solar receiver that uses supercritical carbon dioxide (s-CO_2) as the heat transfer fluid. The research team is designing the receiver to withstand higher operating temperatures and pressures than state-of-the art technology so that the device can enable higher efficiency systems. The primary objectives of this project include achieving an outlet temperature for the receiver working fluid (s-CO_2) that is greater than or equal to 750°C, maintaining high receiver efficiency, retaining durability over the lifetime of the CSP plant, and significantly reducing the cost as compared to baseline receivers. To satisfy these objectives, the team is performing a combination of analytical modeling and hardware testing. The use of s-CO_2 in the power cycle is also being explored.

ADVANCED LOW-COST RECEIVERS FOR PARABOLIC TROUGHS

Norwich Technologies | White River Junction, VT | \$0.3M | SunShot CSP R&D | 08/2012–09/2013

Norwich has developed and validated optical and thermal models and completed optimization analysis to identify key performance characteristics for a first-generation laboratory prototype design of a unique vacuum-free receiver for parabolic troughs. The team built fully functioning optical and thermal laboratory prototypes using accurate, validated models that captured important underlying physical mechanisms. The test results from these prototypes establish performance exceeding the FOA requirement of thermal efficiency >90% for a CSP receiver while delivering an exit fluid temperature of >650° C and a cost <\$150/kWth. The team's vacuum-free SunTrap receiver design promises improvements over conventional vacuum-tube collectors, allowing dramatic reductions in thermal losses at high operating temperatures.

NEAR-BLACKBODY, ENCLOSED PARTICLE RECEIVER INTEGRATED WITH FLUIDIZED-BED HEAT EXCHANGER

National Renewable Energy Laboratory | Golden, CO | $3.7M | SunShot CSP R&D | 10/2012–08/2015

NREL will design, develop, and test a prototype high-temperature particle receiver and heat exchanger system. Many existing receiver designs are limited by an upper operating temperature of 650°C due to the use of nitrate salt as the heat transfer fluid and the limitation of available high-temperature coatings for high receiver efficiency. To overcome these limitations, NREL will develop an innovative receiver design with near-blackbody (NBB) absorptive performance, and select materials that can withstand temperatures of >1000°C. The concept uses low-cost stable materials, a ceramic solar receiver, and storage containers with refractory liners. These liners can accommodate temperatures much higher than oil/salt and ordinary metals or metal alloys at a fraction of the cost, thereby resulting in a low-cost, high-performance CSP system with TES capability for baseload solar power.

USING SOLID PARTICLES AS HEAT TRANSFER FLUID FOR USE IN CSP PLANTS

University of Colorado | Boulder, CO | $0.5M | BRIDGE | 02/2013–01/2016

As part of an ultimate goal of developing a commercially-viable, transformative method for the design of next generation of CSP plants based on granular media as the heat transfer fluid, the objective of this project is to develop, verify and validate a first-principles modeling tool for use in the optimization, scale-up, and design of a near-blackbody (NBB) receiver. The continuum model will be implemented into the Multiphase Flow with Interphase eXchanges software framework, which is an open-source, cost-free computational fluid dynamics solver for multiphase systems. It will be validated using existing experimental data and discrete-element-method simulations carried out as part of the current effort. Once validated, the model will be used to assist in designing the NBB receiver to achieve the SunShot goal of $0.06/kWh.

HIGH FLUX MICROCHANNEL RECEIVER DEVELOPMENT WITH ADAPTIVE FLOW CONTROL

Oregon State University | Corvallis, OR | $0.8M | SunShot CSP R&D | 08/2012–02/2015

OSU seeks to reduce the size, weight and thermal losses from high temperature solar receivers by applying microchannel heat transfer technology to solar receiver design. Their objective is to design a supercritical CO_2 microchannel receiver operating at a fluid exit temperature of 650°C and absorbing an average flux of 100 W/cm^2 with a receiver efficiency of 90% or greater. OSU plans to develop two microchannel solar receiver designs, one for liquid cooled microchannel receivers and one for gas cooling. Metrics were determined using one-dimensional heat transfer calculations to estimate the maximum flux that could be absorbed on a microchannel solar receiver as a function of channel characteristics. Metrics for the supercritical CO_2 receiver will be based on "on sun" experimental results. Metrics for the other design will be based on laboratory test results, modeling, and simulation.

A SMALL PARTICLE SOLAR RECEIVER FOR HIGH TEMPERATURE BRAYTON POWER CYCLES

San Diego State University | San Diego, CA | $3.1M | SunShot CSP R&D | 09/2012–08/2016

The objective of this project is to design, construct, and test a revolutionary high-temperature solar receiver in the multi-megawatt range that can be used to drive a gas turbine to generate low-cost electricity. A secondary goal is demonstrating, for the first time, a pressurized solar receiver with a window greater than 1 m in diameter. The proposed use for the receiver is to drive a gas turbine, but such a receiver can also be used for process heat applications and solar processing of fuels and chemicals. The capability of the receiver to generate pressurized (0.5 MPa) and high temperature (~1000 C) air at high efficiency (~90%) will be demonstrated at the multi-megawatt level via prototype testing at the National Solar Thermal Test Facility at Sandia National Laboratories.

HIGH TEMPERATURE FALLING PARTICLE RECEIVER

Sandia National Laboratories | Albuquerque, NM | $4.5M | SunShot CSP R&D | 10/2012–09/2015

The objective of this project is to make revolutionary advancements in falling particle receivers for CSP applications that will enable higher temperatures and greater efficiencies at lower cost. Technical innovations will be pursued through a combination of modeling, systems analysis, design, testing, and optimization. These include: **1)** advances in receiver design with consideration of particle recirculation, air recirculation, and interconnected porous structures; **2)** advances in particle materials to increase solar absorptivity, energy storage, and durability; and **3)** advances in other areas, such as thermal storage, heat exchange, and particle conveyance.

LOW COST HIGH PERFORMANCE NANOSTRUCTURED SPECTRALLY SELECTIVE COATING

University of California | La Jolla, CA | $0.9M | SunShot CSP R&D | 08/2012–03/2015

UCSD will employ a highly scalable process to fabricate and coat nanoparticles onto solar absorber surfaces to achieve ultra-high spectral selectivity. Refractory protected and unprotected semiconductor nanoparticles will be fabricated by spark erosion and coated onto absorber metal surfaces by spray coating. The material composition, size distribution, and morphology of the nanoparticles will be guided by numeric modeling as well as optimized by design of experiment tests. Optical and thermal properties, such as solar absorptance and infrared emittance will be modeled and measured. High temperature durability will be achieved by using modified semiconductors, refractory nanoparticles, ceramic matrix nanocomposites, and high temperature annealing. The proposed SSCs will achieve solar absorptance of greater than 94% and infrared emittance of lower than 7% at 750°C. This will enable higher thermal conversion efficiency (≥90%) and operating temperature of heat transfer fluids (≥650°C) in order to achieve lower operations and maintenance costs.

HIGH-TEMPERATURE THERMAL ARRAY FOR NEXT-GENERATION SOLAR THERMAL POWER PRODUCTION

Los Alamos National Laboratory | Los Alamos, NM | $2.0M | National Laboratory R&D | 12/2012–11/2015

LANL is developing a MW-scale heat pipe-based technology designed to bridge the heliostat reflector field and the power cycle by replacing both the solar receiver and the heat transfer fluid system used in existing CSP systems. Major technical aspects of this work are focused on cost-effective wick composition, thermal array fabrication methods, countergravity physics, heat pipe start-up and thermal cycling protocols, and system testing and scaling for large-scale deployment.

DEGRADATION MECHANISMS AND DEVELOPMENT OF PROTECTIVE COATINGS FOR TES AND HTF CONTAINMENT MATERIALS

National Renewable Energy Laboratory | Golden, CO | $3.2M | National Laboratory R&D | 10/2012–12/2015

NREL is working to extend the lifetime of containment materials and reduce the capital and maintenance costs of future solar power plants. Advanced protective coatings and surface modification techniques will be developed and evaluated to yield degradation rates lower than 30 microns/year. The objective is to develop and validate material systems and protective conditions that increase the lifetime of HTF and TES containing materials at temperatures of 600 to 900°C. For molten salts, electrochemical techniques will be employed to understand and control the corrosion mechanisms; while for liquid metal alloys, immersion degradation will be evaluated. For supercritical CO_2 attack, autoclave and flow tests will be used. Coatings containing nanomaterials like graphite and alumina will be evaluated for this purpose.

DIRECT S-CO_2 RECEIVER DEVELOPMENT

National Renewable Energy Laboratory | Golden, CO | $2.6M | National Laboratory R&D | 10/2012–8/2015

NREL seeks to develop, characterize, and experimentally demonstrate a novel high-temperature receiver technology using supercritical CO_2 (s-CO_2) directly as the heat transfer fluid. To be considered successful, the commercial technology must achieve the SunShot receiver targets of greater than 90% thermal efficiency while heating the CO_2 to 650°C. The commercial receiver will also be able to withstand 10,000 thermal cycles before mean-time-to-failure and have an expected commercial cost of less than $150/kWt. A prototype receiver system will be constructed and tested to validate the performance model that will be used to develop the commercial receiver design. They will also characterize multiple direct receiver concepts, disseminate the results to industry, and produce a set of modeling tools and methodologies that can be used by other parties to deploy direct receiver technologies for s-CO_2 systems.

HIGH-TEMPERATURE SOLAR SELECTIVE COATING DEVELOPMENT FOR POWER TOWER RECEIVERS

Sandia National Laboratories | Albuquerque, NM | $2.6M | National Laboratory R&D | 10/2012–11/2015

Sandia will develop solar selective coatings for next-generation power tower applications that exhibit high absorptance with low thermal emittance, surpassing the performance of the current benchmark material, Pyromark. These materials will be stable at high temperature (≥700°C) in air, have high thermal conductivity, and be nonvolatile. The team will develop deposition methods that can be scaled up to practical sizes. The team will also conduct durability testing of promising materials deposited on receiver metal substrates in conventional thermal furnaces, solar simulators, and on-sun to understand the degradation mechanisms and improve stability under realistic simulated environments.

FUNDAMENTAL CORROSION STUDIES IN HIGH-TEMPERATURE MOLTEN SALT SYSTEMS FOR NEXT GENERATION CSP SYSTEMS

Savannah River National Laboratory | Aiken, SC | $3.8M | National Laboratory R&D | 10/2012–09/2015

SRNL seeks to improve materials durability in CSP systems in the presence of high operating temperature (HOT) heat transfer fluids (HTFs) for use in advanced power production processes. Improvements in materials durability will be achieved via an integrated experimental and numerical approach that will identify optimal combinations of HOT HTFs with materials of construction and corrosion protection schemes that maintain the HTFs good heat transfer properties, achieve low corrosion rates, and indicate good performance in CSP system simulations. This objective will be achieved by combining: **1)** experimental determination of corrosion rates in model HOT HTF systems and identification of critical parameters of corrosion mechanisms, **2)** thermodynamic property modeling for HOT HTFs, **3)** risk mitigation methods for the identified corrosion mechanisms, **4)** demonstration of the effectiveness of corrosion mitigation methods and **5)** modeling of corrosion in heat transfer systems.

HALIDE AND OXY-HALIDE EUTECTIC SYSTEMS FOR HIGH PERFORMANCE HIGH TEMPERATURE HEAT TRANSFER FLUIDS

University of Arizona | Tucson, AZ | $5.5M | MURI | 10/2012–09/2017

This project seeks to optimize the ternary and quaternary compositions of alkali halides (ionic salts) and metal halides (covalent salts) in a eutectic system in order to develop a high temperature heat transfer fluid that has low melting point (250°C), high temperature (800°C) thermal stability, as well as favorable thermal and transport properties. Oxy-Lewis acid/base and network-forming additives will be added into the system to reduce the vapor pressure and corrosion, and also to fine tune the thermal and transport properties.

HIGH-OPERATING TEMPERATURE HEAT TRANSFER FLUIDS FOR SOLAR THERMAL POWER GENERATION

University of California | Los Angeles, CA | $5.0M | MURI | 10/2012–12/2017

The goal of this project is to develop liquid metals with thermophysical and corrosion properties suitable for use as heat transfer fluids at temperatures above 800°C. The team will employ combinatorial material synthesis and high-throughput characterization techniques together with advanced thermochemical modeling to efficiently identify compositions that are intrinsically less corrosive or where corrosion can be mitigated through the formation of passivation layers. Scaled flow loop tests will be performed to confirm the effective prevention or mitigation of corrosion. Heat transfer experiments will also be conducted to directly determine the convective heat transfer coefficients as a function of flow parameters and develop engineering models to facilitate optimal design of compact heat exchangers.

EXAMINATION OF CERIUM OXIDE DOPANTS FOR THE SOLAR-DRIVEN THERMOCHEMICAL GENERATION OF HYDROGEN

California Institute of Technology | Pasadena, CA | $0.2M | SunShot Postdoctoral Research Awards | 10/2013–09/2015

This project concerns the conversion of solar energy to chemical fuels with the recently demonstrated CSP-driven thermochemical generation of fuels from CeO_2. The goal of this project is to assess the effect of modification of CeO_2 with the targeted dopants Pr, Tb, Nb, Ta, and Sn on hydrogen production efficiency at reduced operating temperatures. Based on the material properties of CeO_2, a thermodynamic efficiency of up to 16% may be attainable even without sensible heat recovery, making CSP-driven thermochemical generation of fuels a promising CSP system for economical CSP energy storage.

Power Conversion and Systems

Power plant components and systems for CSP benefit from mature and well-understood technology found elsewhere in the power generation industry. The most common cycles employed by conventional CSP plants include subcritical Rankine and Stirling. Gross thermal-to-electric conversion efficiencies are typically 35%–45%, and working fluids include steam, hydrogen, and helium. The primary driver for improving CSP power cycles is to increase solar-to-electricity conversion efficiency. Because CSP facilities are typically located in desert areas where water is a scarce resource, high efficiency cycles utilizing dry cooling are needed, which may include systems that use topping and bottoming cycles, augmentation, or other hybrid options. The SunShot Initiative funds R&D on the power block and related aspects of power conversion within the industry, national laboratories and universities. This funding is intended to support the development of high temperature power cycles, such as supercritical-CO_2 (s-CO_2) and solar integration to Brayton cycles, solid state power conversion techniques as topping cycles, and to investigate hybrid power systems.

SunShot technical targets for power block subsystems:

- High temperature power cycles
- Net cycle efficiency >50%
- Dry cooled
- Cost <1,200/kW_e

CONCENTRATED SOLAR THERMOELECTRIC POWER

Massachusetts Institute of Technology | Cambridge, MA | $1.0M | SunShot CSP R&D | 09/2012–02/2015

The objectives of this project are to demonstrate concentrating solar thermoelectric generators (CSTEGs) with >10% solar-to-electrical energy conversion efficiency that are capable of 24-hour operation. These objectives will be achieved through developing and demonstrating key components of the envisioned system, including **1)** achieving a >10% solar-to-electricity energy conversion efficiency, **2)** limiting optical concentration to <10x and potentially <4x, and **3)** demonstrating 24-hour potential through use of phase-change materials. This project builds on existing thermoelectric materials, leverages work conducted through an Advanced Research Projects Agency-Energy (ARPA-E) program on thermal storage materials, and focuses on system demonstration.

INTEGRATED SOLAR THERMOCHEMICAL REACTION SYSTEM FOR THE HIGH EFFICIENCY PRODUCTION OF ELECTRICITY

Pacific Northwest National Laboratory | Golden, CO | $3.5M | SunShot CSP R&D | 10/2012–09/2015

PNNL seeks to advance the technology of solar thermochemical reaction systems from Technology Readiness Level (TRL) 3 to TRL 6. To accomplish this, we will improve the performance of the system and establish the design and manufacturing methods that enable solar power generation at a Levelized Cost of Energy (LCOE) of no more than $0.06/kWh by 2020. Specific project goals include improving the performance of the solar thermochemical reaction system, improving the solar-to-chemical energy conversion efficiency from 63% to about 75%, increasing the solar thermochemical augment from about 20% to as much as 28%, reducing the manufacturing costs, and establishing a validated baseline for capital costs of solar thermochemical systems.

Nx-TEC: NEXT-GENERATION THERMIONIC SOLAR ENERGY CONVERSION

SLAC National Accelerator Laboratory | Stanford, CA | $0.8M | SunShot CSP R&D | 10/2012–12/2014

This research will create a new solid state energy conversion technology based on microfabricated and photon-enhanced thermionic energy converters (PTECs) which, when used as a topping cycle in CSP systems, will enable system efficiencies in excess of 50%. Using device and system modeling, the team will design thermally-isolated, thermionic arrays and microelectromechanical-based wafer-stack technologies for their fabrication, culminating in the demonstration of devices with >5% power conversion efficiency. In parallel, the team will fabricate heterostructure semiconductor cathodes based on active layer absorbers such as GaAs and similar materials with the addition of band engineered passivating layers such as GaN to demonstrate high quantum efficiency Photon Enhanced Thermionic Emitters. The resulting Nx-TEC device will achieve a stand-alone laboratory efficiency of >15%; a significant intermediate step towards a stand-alone goal of >30%, which is needed to achieve the >50% system efficiency target.

DEVELOPMENT OF A HIGH EFFICIENCY HOT GAS TURBO-EXPANDER AND LOW COST HEAT EXCHANGERS FOR OPTIMIZED CSP SUPERCRITICAL CO_2 OPERATION

Southwest Research Institute | San Antonio, TX | $6.8M | SunShot CSP R&D | 09/2012–07/2015

SwRI aims to develop a novel, high-efficiency supercritical CO_2 (s-CO_2) hot gas turbo-expander optimized for CSP applications, which have highly transient duty cycles. A secondary objective is to optimize novel printed circuit heat exchangers for s-CO_2 applications to drastically reduce their manufacturing costs. The s-CO_2 turboexpander and novel s-CO_2 heat exchanger will be tested in a 1-MWe s-CO_2 test loop and fabricated to demonstrate performance of the components and the optimized s-CO_2 Brayton cycle over a wide range of part load conditions and during representative transient operations. The scalable s-CO_2 expander design and improved heat exchanger address and close two critical technology gaps required for an optimized CSP s-CO_2 power plant.

OPTIMIZING THE CSP TOWER AIR BRAYTON CYCLE SYSTEM

Southwest Research Institute | San Antonio, TX | $3.1M | SunShot CSP R&D | 09/2012–01/2015

The objective of the project is to increase the CSP tower air receiver and gas turbine temperature capabilities to 1,000°C by the development of a novel combustor, which can eventually be integrated into a commonly used gas turbine. The 1,000°C temperature target significantly exceeds the 650°C combustor inlet temperatures demonstrated in current Air Brayton CSP projects. The team proposes to achieve this at a reduced scale with emphasis on effects of thermal cycling on hardware and with extremely low emissions.

PHYSICS-BASED RELIABILITY MODELS FOR SUPERCRITICAL CO_2 TURBOMACHINERY COMPONENTS

GE Global Research | Niskayuna, NY | $1.9M | PREDICTS | 10/2013–09/2016

GE seeks to develop a physics-based life prediction and reliability model for hybrid gas bearing (HGB) and dry gas seal (DGS) components. Coupled multi-physics models for performance prediction of these components during a typical supercritical CO_2 (s-CO_2) cycle will be developed in order to generate a loading history that serves as an input to the physics-based lifing model. The coupon level fatigue and corrosion experiments under a controlled CO_2 environment will be carried out and will provide critical validation of the performance prediction models and provide data that serves as input to the life prediction model. DGS test in a 1 MWe s-CO_2 loop will validate the performance prediction models and provide key data that serves as input to the life prediction model. A probabilistic framework will be developed to quantify statistical uncertainty and to calibrate and validate the physics-based life model.

ADVANCED NITRATE SALT CENTRAL RECEIVER POWER PLANT

Abengoa Solar | Lakewood, CO | $4.5M | CSP Baseload | 09/2010–06/2014

Abengoa will demonstrate a 100 MW central receiver plant using nitrate salt as the receiver coolant, thermal storage medium, and heat transport fluid in the steam generator. The plan is to operate the plant at full load for 6,400 hours each year using only solar energy. Key components include a new high-temperature molten salt receiver based on a fossil boiler and heat exchanger design that will be more robust and more manufacturable; a cermet, high-temperature, low-emissivity selective coating for central receivers that is stable when exposed to air; an optimized surround heliostat field; and an optimized thermal storage, steam generator, and power cycle configuration based on dry cooling.

SAM ENHANCEMENTS FOR CSP

National Renewable Energy Laboratory | Richland, WA | $0.6M | SunShot CSP R&D | 10/2012–09/2015

This project will leverage recent System Advisor Model (SAM) kernel improvements by developing a robust tool specifically designed for CSP systems. This work will enable simulations of more complex plant control algorithms and receiver, field, and storage models optimization codes while providing a standardized interface to streamline modeling efforts. The team will also develop and validate detailed high-temporal-resolution models. These models will support CSP grid integration simulation and analysis efforts performed by other centers at NREL. They will also help inform optimal plant-operation strategies and aid in the analysis of material thermal cycling. Finally, the team will develop models for advanced power cycles and hybrid plant designs that have been proposed for CSP systems. These innovative power cycles are potentially higher efficiency and lower cost alternatives to current CSP cycles.

THE DOE NATIONAL SOLAR THERMAL TEST FACILITY (NSTTF)

Sandia National Laboratories | Albuquerque, NM | $2.5M | National Laboratory R&D | 10/2012–09/2015

This funding ensures that capabilities at the NSTTF are maintained, operational, and safe for researchers and industrial partners to utilize to achieve their scientific and business goals. The facility enables researchers in their study and benchmarking of subsystem performance on-sun at high flux, power, and thermal levels in the pursuit of DOE SunShot goals. Activities at the

NSTTF includes the testing of novel, high-temperature solar receivers up to 6 MWth using the newly refurbished heliostat field; testing of prototype solar central receivers and associated components such as heat shields; evaluation of individual heliostat reflected beams with a Beam Characterization System (BCS); and evaluation of low-flux beams from customer provided heliostats, which will help reduce the cost of the heliostats, the most expensive part of a CSP plant.

SMUD CSP HIBRED PROJECT

Sacramento Municipal Utility District | Sacramento, CA | $10.0M | HIBRED | 10/2012–12/2014

SMUD will design, develop, and demonstrate through commercial operation an advanced hybrid CSP technology that will be integrated at an existing natural gas-fueled combined cycle power plant at SMUD. The CSP system will provide 45 MW_t peak solar collection and 32 MW_t extended on-peak delivery to the power plant using stored energy for a net minimum reliable capacity increase of >10 MW_e solar generating capacity. The thermal energy input temperature to the thermal-to-electric conversion system's working fluid will be at or above 500°C. The CSP system will include high temperature thermal energy storage that will optimize reliable hybrid plant production during the summer afternoon peak and super peak dispatch hours.

Thermal Energy Storage

A distinguishing feature of CSP among other renewable technologies is its ability to include thermal energy storage at the point of power generation to handle the intermittencies of solar availability. The SunShot Initiative funds R&D on sensible, latent, and thermochemical energy storage and related aspects within the industry, national laboratories and universities. This funding is intended to help engineer heat transfer fluids for high temperature stability and thermophysical properties and develop novel thermal energy storage methods to meet technical and cost targets. The CSP subprogram is funding the following projects to achieve these DOE Sunshot goals. The first two projects involve Sensible Heat, the second two Phase Change Materials (PCMs), and the final eight Thermochemical.

SunShot technical targets for thermal energy storage subsystems:

- Improve heat transfer and thermal energy storage media
- Thermal energy storage cost <$15/kWh$_{th}$ (kilowatt hours thermal)
- Exergetic efficiency >95%
- Material degradation due to corrosion <15 μm/year.

HIGH EFFICIENCY THERMAL ENERGY STORAGE SYSTEM FOR CSP

Argonne National Laboratory | Argonne, IL | $2.2M | National Laboratory R&D | 10/2012–09/2015

The goal of this proof-of-concept project is to develop an efficient high-temperature, lab-scale TES prototype by utilizing advanced phase change materials (PCMs) in combination with new, high-conductivity, graphite foams. The laboratory scale prototype TES system will be built and tested with the purpose of gathering performance data (e.g., transport properties, system durability, and thermal cycling) regarding a combination of PCM mixtures and foam types and densities. In addition, associated technologies needed for scale-up and practical implementation will also be developed. These include the process to infiltrate the foams, coating the foams for strength and environmental (oxidation/corrosion) durability enhancements, and joining techniques for system integration.

DISH STIRLING HIGH PERFORMANCE THERMAL STORAGE

Sandia National Laboratories | Albuquerque, NM | $2.4M | National Laboratory R&D | 10/2012–09/2015

This objective of this project is to demonstrate the key components of a thermal storage system for dish Stirling power generation. The thermal storage system features latent heat transport and latent heat storage which is an optimal combination with the isothermal input of Stirling engines. This combination minimizes thermodynamic energy and exergy losses. The resulting subscale demonstration should be sufficient to interest partners in the manufacture of dish Stirling systems with storage. This system will provide up to six hours of storage on a 25 kWe Stirling system. The storage and the engine are both moved to the rear of the dish. This placement provides an optimum balance of the dish system, reduces cantilevered weight, and allows closing of the "pedestal gap," leading to efficient structural designs. The size and duration of the proposed embodiment will enable sufficient storage on utility-scale dish Stirling deployments.

SULFUR BASED THERMOCHEMICAL HEAT STORAGE FOR BASED LOAD CONCENTRATED SOLAR POWER GENERATION

General Atomics | San Diego, CA | $2.0M | Baseload | 09/2010–11/2014

The goal of the project is to demonstrate the engineering feasibility of using a sulfur-based thermochemical cycle to store heat from a CSP plant and support baseload power generation. The team will study the sulfur-generating disproportionation reaction and develop it into a practical engineering process step. The team will also carry out preliminary process components design and experimental validation. The engineering data will be used for process integration between the CSP plant, the sulfur processing and storage plant and the electricity generation unit. Through this project, the team will demonstrate the economics and safety of a CSP plant integrated with sulfur storage.

LOW-COST METAL HYDRIDE THERMAL ENERGY STORAGE SYSTEM FOR CSP SYSTEMS

Savannah River National Laboratory | Aiken, SC | $2.5M | National Laboratory R&D | 10/2012–09/2015

The objective of this research is to evaluate and demonstrate a metal hydride-based TES system for use with a CSP system. The team's unique approach makes use of a hierarchal modeling methodology that combines modeling experience and material knowledge to screen several promising metal hydride candidate materials and select the best candidates for more thorough evaluation through experiments and more detailed models. During the second year, material optimization, bench-scale testing and more detailed component and system models will lead to a proof-of-concept demonstration and a preliminary system design. The culmination of this proposed research will be the design, fabrication and evaluation of a prototype metal hydride energy storage system that aims to meet SunShot cost and performance targets for thermal energy storage systems.

HIGH-TEMPERATURE THERMOCHEMICAL STORAGE WITH REDOX-STABLE PEROVSKITES

Colorado School of Mines | Golden, CO | $1.0M | ELEMENTS | 05/2014–04/2017

This project will explore the techno-economic feasibility of redox cycles with low-cost, perovskite oxides for high-temperature thermochemical energy storage (TCES) in a concentrating solar plant. Perovskites (chemical structure ABO3-δ) can undergo endothermic reduction to store energy at temperatures as high as 900°C. The stored energy can be released by exothermic re-oxidation to provide high-temperature heat exchange to drive high-efficiency power cycles, such as supercritical CO_2. Combined thermochemical and sensible energy in the partially reduced perovskites already identified can provide storage of 750 kJ/kg or more (with 60% coming from TCES) such that less than 1.5 m^3 of particles can be re-oxidized to produce a MWh of electricity for a 50% power cycle.

ENGINEERING A NOVEL HIGH TEMPERATURE METAL HYDRIDE THERMOCHEMICAL STORAGE

Pacific Northwest National Laboratory | Richland, WA | $3.5M | ELEMENTS | 05/2014–04/2017

The team will develop a concept for high-energy density thermochemical energy storage for CSP which is projected to meet SunShot energy and exergy efficiency targets. The full system will be designed, fabricated, and evaluated, to culminate in on-sun testing with a solar dish to validate the projected efficiencies and full-scale performance. The technical concept is based on a system that consists of a high-temperature metal hydride bed for heat storage operating at ≥650°C and 2.4 bar pressure connected to a second metal hydride bed operating at low temperature which is used to store H_2 near ambient temperature.

HIGH PERFORMANCE REDUCTION/OXIDATION METAL OXIDES FOR THERMOCHEMICAL ENERGY STORAGE

Sandia National Laboratories | Albuquerque, NM | $3.0M | ELEMENTS | 05/2014–04/2017

Sandia will systematically design, develop, characterize, and demonstrate a robust and innovative storage cycle based on novel metal oxides with mixed ionic-electronic conductivity (MIEC). Thermal energy is stored as chemical potential in these materials through a reversible reduction-oxidation reaction; thermal energy from concentrated sunlight drives a highly endothermic reduction reaction that liberates lattice oxygen from the oxide to form O_2 gas, leaving an energy-rich oxygen-depleted solid. When desired, the heat is recovered as the MIEC is re-oxidized in an exothermic reaction upon exposure to air. The system is highly integrated with an air Brayton power cycle. The compressor of the Brayton engine delivers the heated, compressed air to the re-oxidizer reactor, which then drives the turbine of the Brayton engine; expansion of the air turns the turbine and generator thus efficiently producing electric power.

REGENERATIVE CARBONATE- AND SILICATE-BASED THERMOCHEMICAL ENERGY STORAGE SYSTEM FOR CSP

Southern Research Institute | Birmingham, AL | $0.9M | ELEMENTS | 05/2014–04/2017

This project seeks to develop thermochemical energy storage (TCES) systems for CSP based on endothermic-exothermic gas-solid reaction cycles at temperatures >650°C. The 24-month project will develop and demonstrate regenerative carbonate and silicate sorbent-based process in a simulated TCES system at bench scale. The project will advance the proposed TCES system from technology readiness level (TRL) 2 to 4 by demonstrating the system's key advantages, its high exergetic and energetic efficiencies, and its potential to meet a cost target of $15/kWhth.

CARBON DIOXIDE SHUTTLING THERMOCHEMICAL STORAGE USING STRONTIUM CARBONATE

University of Florida | Gainesville, FL | $1.0M | ELEMENTS | 05/2014–04/2017

The objective of this project is to find an economical thermochemical storage solution for CSP by means of inexpensive, safe, and non-corrosive chemicals. Using a previously unconsidered reaction, chemical bonds are broken using high temperature, concentrated sunlight. During off-sun periods, the reaction is reversed to release heat at temperatures previously unachievable in other thermochemical, latent, or sensible energy storage schemes. The energy is absorbed by a working fluid such as air and sent to a combine cycle power plant. The laws of thermodynamics dictate that the greater the temperature of a working fluid in a power block, the greater the efficiency of the cycle, making this technology a prime candidate for transformative change.

THERMOCHEMICAL STORAGE WITH ANHYDROUS AMMONIA: OPTIMIZING THE SYNTHESIS REACTOR FOR DIRECT PRODUCTION OF SUPERCRITICAL STEAM

University of California | Los Angeles, CA | TBD | ELEMENTS | 05/2014–04/2017

The team will design and build an ammonia synthesis reactor that is optimized for the direct production of supercritical steam and perform analysis that shows that storage of the energy rich gas mixture in adapted gas well systems can deliver the target cost of $15/kWht. The proposed research will make significant contributions toward the viability of the ammonia TCES storage concept and solar thermochemical storage more broadly. By careful optimization of the synthesis reactor and associated heat exchanger, it will demonstrate supercritical steam production at 650°C, a feat which has not yet been achieved for ammonia synthesis. In addition, a cost-effective storage solution for gaseous components will be investigated that could have far reaching impact for other candidate reactions given the importance of gas storage for a multitude of applications.

COMPUTATIONAL ANALYSIS OF NANOPARTICLES-MOLTEN SALT THERMAL ENERGY STORAGE FOR CONCENTRATED SOLAR POWER SYSTEMS

University of Texas | El Paso, TX | $0.27M | MURA | 09/2010–09/2014

The research goal of this project is to perform computational analysis for designing anefficient and cost-effective thermal energy storage (TES) system for CSP using nano-fluidized molten salt as the storage medium. An efficient TES system contributes to reaching the SunShot goal of making solar electricity cost competitive with conventional sources. The educational efforts include an interdisciplinary course designed specifically for students with different backgrounds who share a common interest in renewable energy, a targeted solar energy workshop at the University of Texas at El Paso, and student and faculty visits and summer research at the National Renewable Energy Laboratory and Sandia National Laboratories.