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# Development of a concentrating solar power system using fluidized-bed technology for thermal energy conversion and solid particles for thermal energy storage

Z. Ma[a,] *, M. Mehos[a], G. Glatzmaier[a], and B. B. Sakadjian[b]

[a]National Renewable Energy Laboratory, 15013 Denver West Parkway, Golden, Colorado 80401, USA
[b]Research Engineer, M.S./MBA, Babcock & Wilcox Power Generation Group, Inc.,180 S. Van Buren Ave., Barberton OH 44203, USA

**Abstract**

Concentrating solar power (CSP) is an effective way to convert solar energy into electricity with an economic energy-storage capability for grid-scale, dispatchable renewable power generation. However, CSP plants need to reduce costs to be competitive with other power generation methods. Two ways to reduce CSP cost are to increase solar-to-electric efficiency by supporting a high-efficiency power conversion system, and to use low-cost materials in the system. The current nitrate-based molten-salt systems have limited potential for cost reduction and improved power-conversion efficiency with high operating temperatures. Even with significant improvements in operating performance, these systems face challenges in satisfying the cost and performance targets. This paper introduces a novel CSP system with high-temperature capability that can be integrated into a high-efficiency CSP plant and that meets the low-cost, high-performance CSP targets. Unlike a conventional salt-based CSP plant, this design uses gas/solid, two-phase flow as the heat-transfer fluid (HTF); separated solid particles as storage media; and stable, inexpensive materials for the high-temperature receiver and energy storage containment. We highlight the economic and performance benefits of this innovative CSP system design, which has thermal energy storage capability for base-load power generation.


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*Keywords:* Concentrating Solar Power; Solar Receiver; Heat Transfer Fluid; Gas/Solid Two-Phase Flow.

* Corresponding author. Tel.: +1-303-275-3784; fax: +1-303-384-7495.
*E-mail address:* zhiwen.ma@nrel.gov


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## 1. Introduction

### *1.1. Fluidized-bed CSP system background*

This paper introduces the high-performance, low-cost, solid-particle-based CSP system with economic thermal energy storage (TES) for continuous, dispatchable, grid-scale electricity generation. This design uses gas/solid, two-phase flow as the heat transfer fluid (HTF) and separated solid particles as the storage medium. This novel approach uses stable, inexpensive materials for the high-temperature receiver, energy storage, structure, and containment, to meet the low-cost, high-performance CSP development goal. The system uses fluidized-bed (FB) technology in the heat exchanger for the heat transfer between hot particles and working fluids. The high-temperature capability of the FB-CSP system makes it possible to perform high-efficiency thermal power conversion to create base-load power. We will show the FB-CSP thermal system configuration and its integration with high-efficiency power cycles, and assess the potential for 1) FB-CSP to be competitive in producing baseload power and 2) improving penetration of this renewable energy (solar) into the grid.

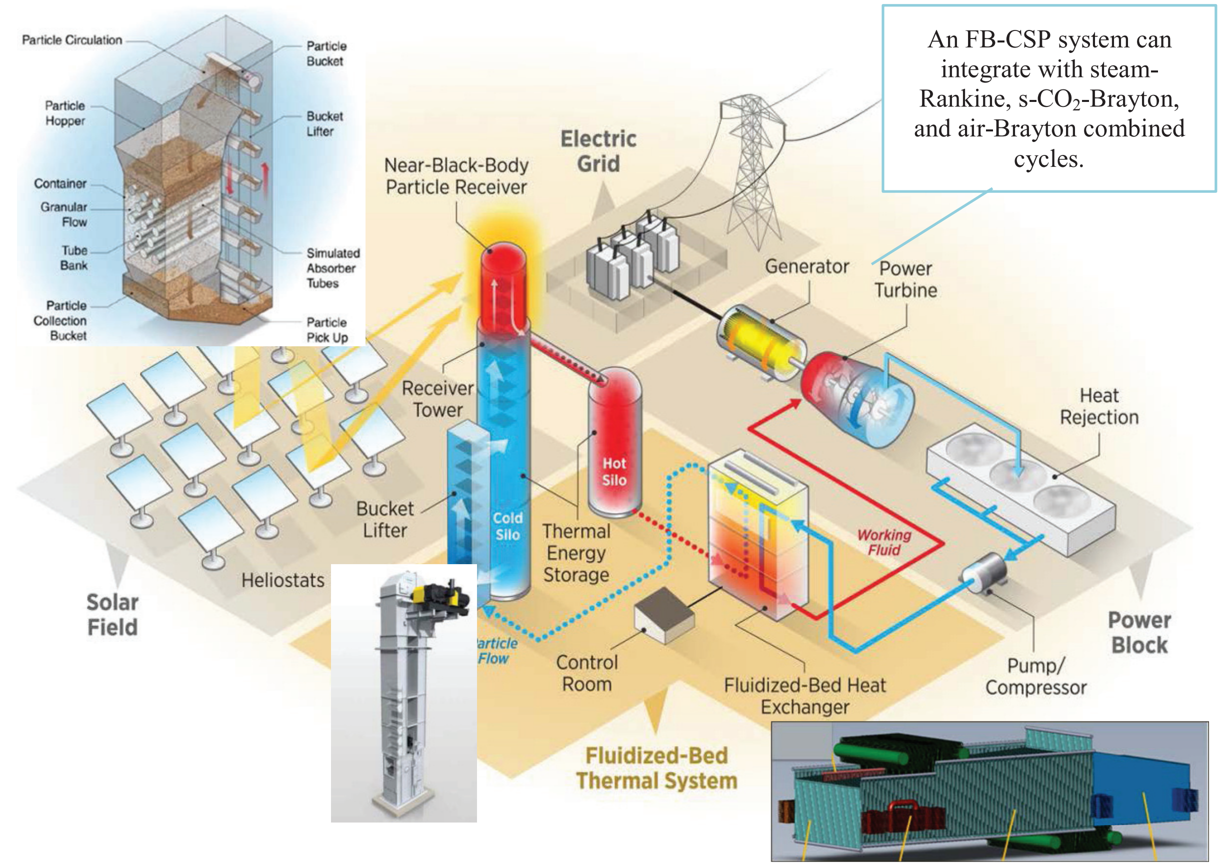



Figure 1. Schematic of a fluidized-bed CSP system with a near-blackbody enclosed particle receiver integrated with a fluidized-bed heat exchanger and solid-particle thermal energy storage. (Illustrations by Alfred Hicks, NREL)

Figure 1 shows the FB-CSP thermal system integrated into a power tower solar field. The major components include an enclosed particle receiver; an FB-heat exchanger; low-cost, high-temperature solid-particle containment consisting of a cold silo (integrated inside the tower) and a hot silo for TES [1]; and ancillary equipment (a bucket lifter and particle distribution system). The particles are heated by concentrated solar flux inside a solid-particle receiver. The particles exit the receiver, fall into a hot silo, and are subsequently used as the storage medium. High-temperature particles discharged from thermal storage pass through an FB-heat exchanger and heat the working fluid for the power cycle.

The FB-CSP technology is suitable for a point-focus tower system, which heats particles in a central receiver. The solid particles flow among silos and the heat exchanger can use conventional particle transportation methods, such as pneumatic transport or a conveyor, and are lifted to the receiver on the tower top by a bucket lifter. The FB-heat exchanger can heat several types of media: steam for a conventional steam-Rankine cycle, supercritical $CO_2$ (s-$CO_2$) for an s-$CO_2$ Brayton power cycle, or air for an air-Brayton combined cycle (ABCC). This development will leverage existing technology and manufacturing capabilities for the FB thermal system, accelerate technology realization, and minimize technical risk.

The use of fluidized particles as the HTF in CSP plants offers many benefits relative to conventional liquid HTFs. Fluidized particles are thermally stable at temperatures well above 1,000°C and eliminate the risk of the fluid freezing. In addition, the cost of particles that are used for heat transfer and TES offer a significant cost benefit relative to state-of-the-art fluids. The very high temperature that can be achieved using fluidized-particle heat transfer in CSP plants creates the opportunity to integrate power generation with very high thermodynamic conversion efficiencies. Low-cost, stable particles are readily available that can work at temperatures above 1,000°C. Power tower solar fields with proper heliostat optics and layout can deliver high solar fluxes to the particle receiver to achieve these temperatures. Using these design features and materials gives the FB-CSP system the potential to drive a high-efficiency thermal power cycle, and to achieve high solar-electric conversion efficiency. The challenge, and focus of the technology development, is to design and fabricate a particle receiver that can operate with desirable performance and reliability at or close to these high temperatures.

### *1.2. Advantages of the FB-CSP system compared to a state-of-the-art nitrate-salt CSP system*

Current molten-salt receiver designs are limited by an upper operating temperature of 600°C due to the use of nitrate-salt HTF, and the cost and corrosion of containment materials needed for use with temperatures above the 600°C. High-temperature receiver performance is also constrained by an available high-temperature coating that is needed to achieve high receiver efficiency. The FB-CSP system is aimed at removing technical and economic barriers in today's nitrate-salt-based CSP system. Table 1 benchmarks the FB-CSP system against the state-of-the-art nitrate-salt system.

Table 1. Benchmark of the FB-CSP system to current state-of-the-art salt systems (100-$MW_e$ scale)

| HTF / Storage Media | State-of-the-Art: Nitrate Salt ($1.00 /kg) | Our Approach: Solid Particle (e.g., ash, sand) ($0.01–0.1/kg) | Benefits of Our Approach |
|---|---|---|---|
| **Precondition time** | Conditioning, 3 months | None | Early revenue |
| **Salt freezing protection** | Required | None | Low O&M |
| **Stability** | <600°C | >1000°C | High efficiency |
| **Corrosion** | High with chloride impurity | No | Long life |
| **Structure materials** | Steel, stainless steel, or alloy | Ceramic/refractory/concrete | Low cost |
| **TES cost estimation** | 30–75 $/$kWh_{th}$ | <10 $/$kWh_{th}$ | Lower LCOE |
| **Supporting power cycles** | Super-heated steam/s-$CO_2$ | Steam-Rankine/s-$CO_2$/air-Brayton | Efficiency |
| **Receiver cost estimation** | Salt: ~$100s of millions | SPR, ~$10s of millions | Cost reduction |
| **Estimated LCOE** | ~14¢/kWh | About 2.5¢/kWh reduction | |

The cost and performance benefits of the FB-CSP system over a salt system come from using low-cost, stable ceramic/refractory materials instead of an expensive high-temperature alloy for HTF containment. The FB thermal system, including the high-temperature, particle storage silos and FB-heat exchanger, is based to some extent on existing commercial technologies [2]. The storage silo design is derived from commercial concrete silos that are currently used to temporarily store flue ash in a coal-fired plant. The FB-heat exchanger design originates from FB boilers that are used for coal-fired electric generation and presents minimum technical risk. The falling-particle, solar receiver is the most important component for determining the performance and commercial viability of a CSP plant that uses flowing particles as the heat transfer fluid and static particles as the thermal energy storage medium.

The receiver development will aim to achieve both the technical and economic targets of an operating temperature > 650°C, receiver thermal efficiency, $\eta_{thermal}$, > 90%, life cycles >10,000, and cost < \$150/kW$_{thermal}$. The operating condition enables high-efficiency power cycles, can directly integrate with steam power generation, and easily extend to use in an s-$CO_2$ Brayton power system. We also studied the economic outcome of a pressurized fluidized-bed [3, 4] to heat air and drive a gas turbine or ABCC power generation. We focused on the development of a novel receiver design to collect concentrated solar heat and to indirectly heat flowing particles by using the blackbody-furnace working mechanism. We intend to resolve the performance and scale-up issues in other types of particle receiver designs.

## 2. System configuration and major components

### *2.1. Development of the particle receiver*

A solar receiver must possess high thermal collection efficiency for the entire plant to obtain high performance and attractive economics. In addition, the receiver must collect and transfer thermal energy to the falling particles effectively to reach the desired temperature. Previous receiver designs, such as the centrifugal falling particle receiver and the open-cavity free-falling particle receiver, used a curtain of ceramic particles dropping through an open cavity that are directly radiated by concentrated sunlight [5-7]. This open-cavity solid-particle-receiver (SPR) design has several potential drawbacks: (1) particle flow is affected by wind, (2) falling particles can entrain cold air through the cavity receiver opening, (3) solar flux passes particles and heats up the receiver's back wall, and (4) the speed of freely falling particles may not allow adequate heating. As such, it may be necessary to recirculate the particles to heat them adequately. Particle recirculation, however, introduces cyclic thermal losses and additional particle-lifting parasitic power consumption in the particle free-falling receivers. The open-cavity SPR designs, such as the rotating cavity receiver, rotary kiln receiver, and free-falling particle receiver, have limited heating rate for high particle flow rate when scaling up to above 100MW$_t$ receiver thermal rating. In those receiver designs, particles directly exposed to the ambient condition add IR radiation and force convection losses for high-temperature applications [8-10].

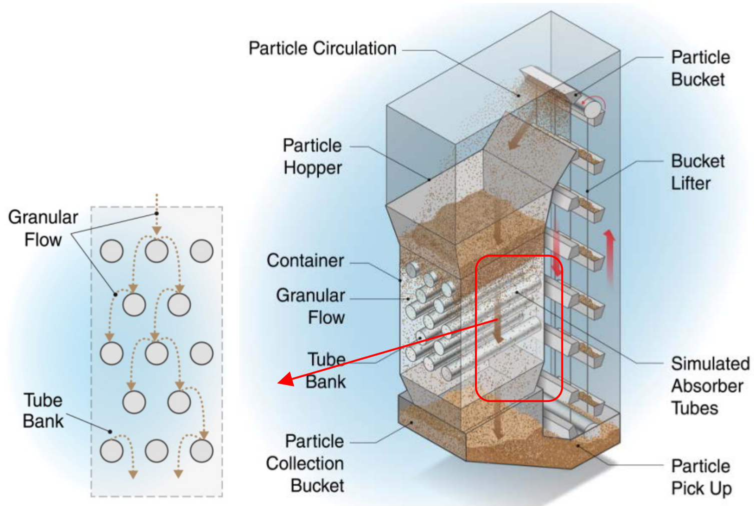



Figure 2. Schematic of the enclosed particle receiver module that features highly effective solar heat collection. (Illustrations by Alfred Hicks, NREL)

To improve the particle receiver performance and to resolve the primary issues associated with the open-cavity particle receiver designs, we developed the enclosed particle receiver concept that is depicted in Figure 2. It contains an array of absorber tubes that separate flowing particles from the external environment. The concentrated solar flux heats the particles in the absorber tubes. Heat transfer is extended along the length of the tubes from a two-dimensional planar state to a three-dimensional state, significantly increasing the heat transfer effectiveness. Figure

3 shows the effective absorptivity with respect to the material emissivity and the cylinder aspect ratio; Siegel and Howell ([11], p.295) show a similar chart. The tube-shaped absorber can achieve an effective absorptivity of 0.99 for a length-to-diameter ratio of 3, with material emissivity of 0.9; therefore, we call it a near-blackbody (NBB) receiver. The NBB receiver design reduces reflection and convection losses by shielding the absorber tube from the ambient air, and the design approach is suitable for the receiver to reach high thermal efficiency for high-temperature applications.

The NBB receiver consists of an array of absorber tubes. Each absorber tube works as a cavity receiver and uses a blackbody approach in the radiation design. Incident flux enters the absorber tube through the aperture in the tube front, and heats up the tube wall. The adjacent tubes are joined in the aperture front by hexagonal openings and form a sealed space to enclose particles inside the array of absorber tubes. Solid particles flow around the external sides of the absorbers and transfer heat from the incoming solar flux to the particles, as shown in Figure 3. Computational analysis of convection and thermal emission losses, coupled with ray-trace modeling of the flux distribution along absorber tubes, has indicated that the thermal efficiency of the preliminary design is on track to meet the > 90% goal. The absorber-cavity flux absorption reduces thermal losses, resulting in high receiver thermal efficiency and high operating temperatures (> 800°C) that can drive a variety of high-efficiency power cycles, including the sub-critical or super-critical steam-Rankine cycle, the s-$CO_2$ Brayton cycle, or the ABCC power cycle.

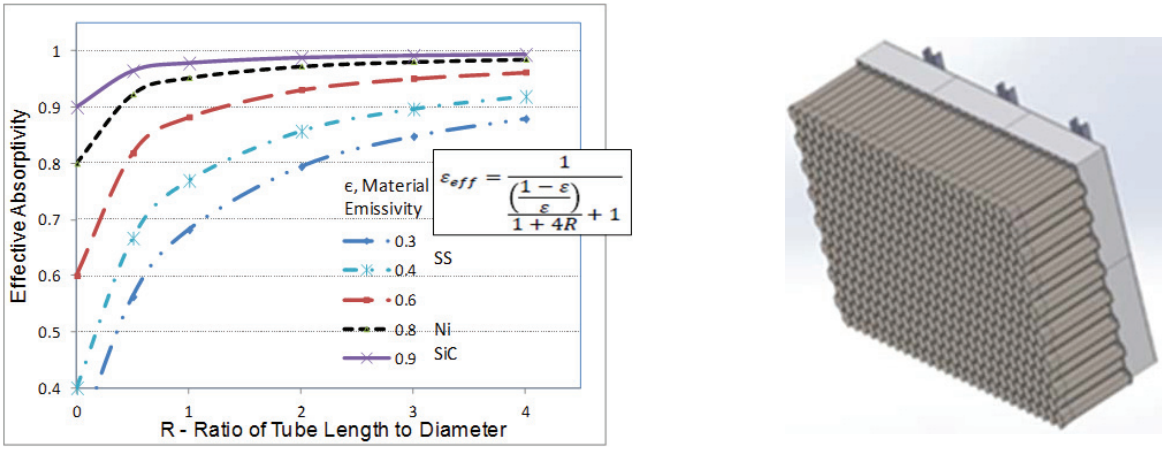



Figure 3. Effective absorptivity to material emissivity and tube aspect ratio *produces near-blackbody absorption.*

Significant efforts have been devoted to the NBB enclosed particle receiver development within the U.S. Department of Energy (DOE) SunShot CSP project, and progress has been made towards a prototype design. Modeling and testing tools have been developed to simulate the receiver performance and the design parameters. Successful development of the receiver necessitates detailed study and understanding of particle flow patterns, particle velocity, and heat transfer coefficients. These factors must be understood to ensure adequate spacing between tubes and suitable absorber tube design. To provide initial guidance for the receiver-module design and performance analysis, the current study focuses on theoretical simulation and analysis of granular flow patterns, and the resulting convective and conductive heat transfer to the particulate phase.

### *2.2. Development of the FB-heat exchanger*

The design of the FB-heat exchanger is informed by substantial commercial experience in FB boiler production and operation. In addition, the heat exchanger design used for steam generating systems is also transferrable to heat exchangers for any of the power cycles mentioned previously (steam-Rankine, s-$CO_2$-Brayton, air-Brayton, and ABCC cycles). To use solid particles or a gas/solid two-phase flow as an HTF, the heat exchanger must be designed to maximize the heat-transfer coefficient between the solids and the heating surface. Existing mature technology in the field of FB-boilers is useful for this purpose. The design for the FB-CSP system with sensible heat only is straightforward due to the absence of combustion within an FB-boiler and is advantageous for reconfiguring heat-transfer surfaces from existing commercial fluidized-bed designs. The heat exchanger can therefore be optimized for size and cost.

Virtually any stable particles with good fluidization ability can be used in the particle FB TES. In practice, when selecting particles, one must consider the particle stability, cost, heat transfer and fluidization characteristics, flowability, material handling and equipment compatibility. In addition, the following factors are also considered in selecting solid particles for the particle FB-TES system:

i. Particle properties affecting the overall FB-CSP thermal system performance should be considered. These include energy storage density, material composition, softening temperature, density, and heat capacity.
ii. Particle size is not a factor in particle storage, but it is important for heat transfer, i.e., particle receiver and heat exchanger performance. Heat transfer coefficients are high for small particles.
iii. Particle size and density together determine the FB-boiler manufacturer's gas/solid separator performance and fluidization design.

Particle erosion on the heat-transfer tubes has been a concern in FB-boiler development process. Nowadays, the FB-boiler manufacturers have accumulated significant experience in mechanical design of pipes and in applying a refractory lining to eliminate localized erosion issues. Manufacturers have improved tube-erosion protection with smooth and strategic tube-bend design to eliminate the abrupt flow disturbance where the refractory begins, weld overlay that is ground smooth, and plasma spray weld coatings. Other coatings have been developed for the bare tube water walls to protect them from erosion. With the design experience in FB boilers established, the development can focus more on selecting particle materials. Table 2 shows a few particle materials, their thermal properties, and their potential usage in the FB-CSP application.

Table 2 shows no significant difference in heat capacity among different solid particles. Weighing cost and properties, commonly available particle materials, sand or ash, can be chosen as storage media. Ash may perform better than silicon sand if it has alumina ($Al_2O_3$) as a component because the alumina contributes to higher thermal conductivity. Ash and sand are abundant, low-cost, and stable. In addition, FB boilers and material-handling equipment makers are familiar with ash and have readily available experience in and equipment for ash containment and handling. Ash-handling technologies and ash equipment are ready for the TES application. A concern about using ash is its mineral content, which may cause corrosion to some steel or ceramic components.

All components of the system shown in the figure are mature technologies, other than the solid-particle receiver being developed. Thus, the design of the heat exchanger involves minimal risk. The same technologies can be applied with some rearrangement to the single-phase s-$CO_2$ power system. If the heat exchanger design uses a pressurized fluidized-bed (PFB) to heat air directly, then the heated air can drive an ABCC system to generate electricity.

Table 2. Some Solid Particle Material Properties

| Material | Composition | Properties[a] | | Advantage | Disadvantage |
|---|---|---|---|---|---|
| | | Density(kg/m3) | Capacity(J/kg°C) | | |
| **Silica Sand** | *$SiO_2$* | 2610 | 710 | Stable, abundant, low cost | Low conductivity |
| **Quartz Sand** | *$SiO_2$* | 2650 | 755 | Stable | Medium |
| **Alumina** | *$Al_2O_3$* | 3960 | 880 | Stable | High cost |
| **Ash** | *$SiO_2$, $Al_2O_3$, +* minerals | 2100 | 720 | Stable, abundant, No/low cost | Identifying suitable ash |
| **Silicon Carbide** | *SiC* | 3210 | 670 | High conductivity | High erosion, high cost |
| **Graphite Pebble** | *C* | 2250 | 710 | High conductivity | Oxidization, attrition |

Note a: Data source: www.matweb.com or www.wikipedia.org.

Design of the FB-CSP thermal system used to drive an ABCC power cycle may benefit from the experience gained from PFB combustion technology development. The PFB originated from the combustion boiler and is a variation of the FB-boiler. PFB technology is the product of a multi-year research and development effort to develop low-emission and high-efficiency coal power plants. It was in the proven commercialization stage for converting coal efficiently into power through a pressurized, fluidized-bed, gas-turbine combined cycle (GTCC) process. The process yields a higher thermal power efficiency of 40%–45% at a combustion temperature of 850°C [12]. We can assume the thermal efficiency for CSP is in the range of 44%–50%, because the closed-particle-loop in FB-CSP incurs no exhausting-heat loss from hot bottom ash and unburned carbon. The use of PFB with ABCC has fewer challenges compared to the coal combustion process, and can be implemented quickly for high-efficiency and economic CSP plants. Direct and intimate contact between gas and particles eliminates the need for a structured heat exchanger, reduces heat exchanger cost, and improves performance by eliminating the exergy losses associated with the heat transfer through a heat exchanger.

Figure 4 shows the concept of integrating the PFB-heat exchanger for ABCC power generation in a PFB-ABCC-CSP system. Because of the high gas density under pressure, the PFB heat exchanger uses low fluidization speed. The hot particles may be injected from the top and move to the bottom through different stages of the heat exchanger, and be discharged from the bed bottom, where a lift device is used to feed cold particles to top of the cold silo. From the silo top, cold particles will be sent to the receiver when solar heat is available, or they will be stored in the cold silo when solar heat is unavailable.

The fluidized particles are removed by the gas/solid separator, and flow to a gas turbine that is close to the hot-particle temperature needed for power extraction. Erosion on gas turbines has been studied by Japan Hitachi [3] and may be prevented by either filtering the air further after cyclone gas/particle separation, or by enhancing the turbine blade with an erosion-resistive coating. The hot gas from the turbine exhaust will go through a heat recovery heat exchanger. So in the PFB process, the waste heat is used for preheating the water. Water is evaporated and superheated by extracting particle heat. The cooled air is further cooled and intercooled for stage compression, which improves compressor efficiency. Figure 4 shows air in the closed-loop configuration, which may be designed as an open-loop operation for air discharged after the heat recovery heat exchanger, and the air compressor takes ambient air directly. Heated steam is used in steam-turbine power generation. Based on the experience gained from PFB combustion technology, this system may achieve 44%–50% cycle efficiency, and cost around \$1,000/kW$_e$.

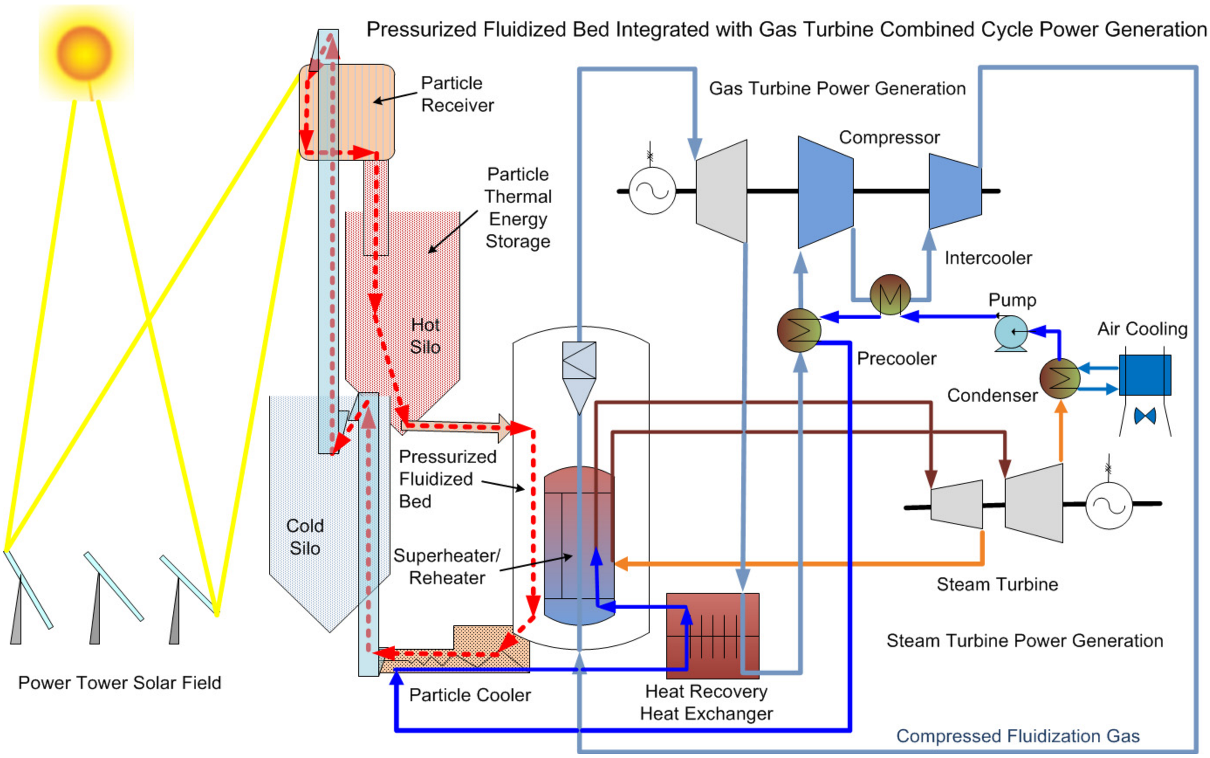


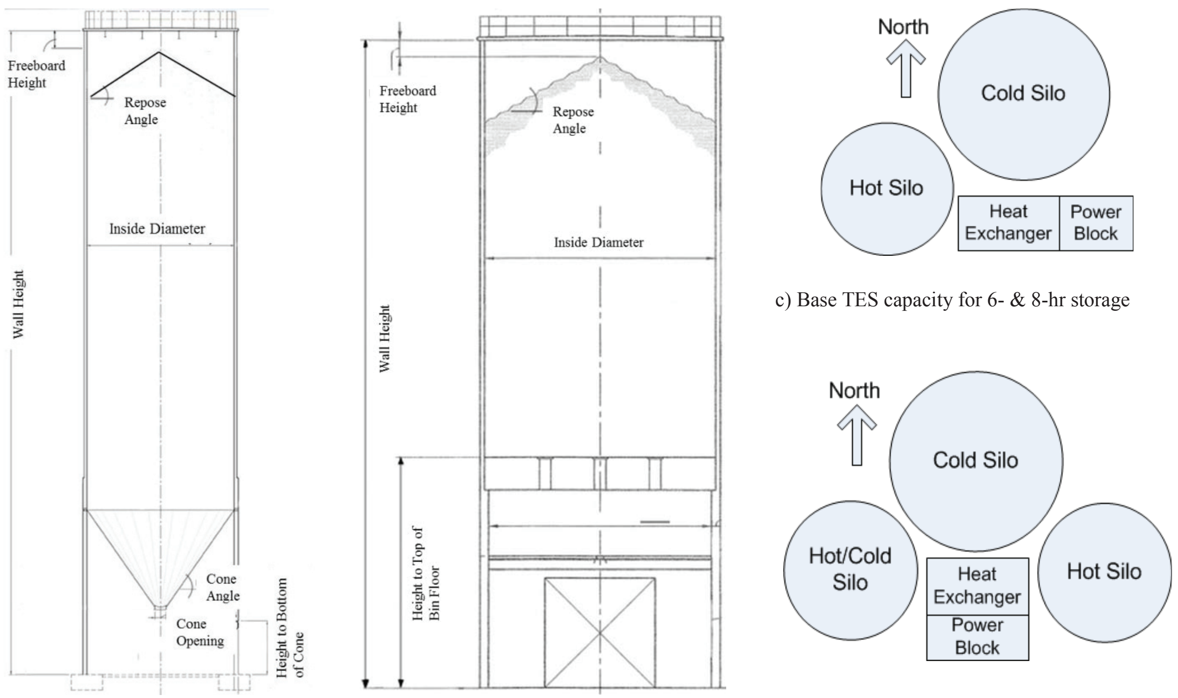

Figure 4. Pressurized fluidized bed for an air-Brayton gas-turbine combined cycle CSP system (NREL PFB-ABCC-CSP Configuration).

A significant performance advantage of the PFB-ABCC-CSP system is the direct contact between air and hot particles in PFB, which minimizes exergy loss due to the heat transfer. Air can exit with a maximum particle temperature to drive the turbine in a high gas-turbine inlet temperature for possible high thermal efficiency without the cost and loss of heat transfer surfaces. Although the technology has not been noticed by the current CSP developers yet, this study indicates that FB-CSP development could make it a suitable and near-term solution to CSP power-cycle cost and performance goals.

In summary, the performance of the heat exchanger in the balance of plant for CSP power generation depends on power cycle options. The FB-CSP system overcomes the limitation of other HTFs and TES capability and can drive high-efficiency power cycles with high exergetic efficiency. The ability for FB-CSP to support the three power cycles provides near-term implementation opportunities and long-term system-improvement capabilities that may offer significant technical and economic benefits for solar energy conversion.

## *2.3. TES particle containment*

The TES design assumes a steam power cycle. The cold-particle temperature is about 240°C and the hot particle temperature is 800°C. A temperature difference of 560°C is used for sensible-heat storage. In the FB-CSP thermal system, storage silos and ducts that operate at high temperatures are composed of a concrete structure insulated by a refractory-lining layer to protect the concrete from overheating. The particle TES performance assessment was analyzed in references based on general TES performance metrics. This section illustrates the storage containment consideration, and layout.




a) Cone bottom silo b) Flat floor silo d) Double TES capacity for 12- & 16-hr storage

Figure 5. Storage silo layout in a CSP plant. (Drawings of a) and b) were based on the Marietta Silo web tool: www.mariettasilos.com)

Heated particles from a solar receiver drop into the hot silos by gravity through a duct. The hot-silo dispenses the hot particles, as needed, from a cone-shaped bottom and are controlled by a particle-flow valve. Therefore, all hot particles can drain from the hot silo, transfer heat to the power generation, and get 100% storage effectiveness. The hot particles circulate through an FB-heat exchanger and the separated cold particles are sent to the cold silo. In the double-capacity design, once the cold silo is full, the cold particles can be contained in the hot/cold dual-purpose silo, and only one cold silo needed. Because of low TES-particle cost, using one additional hot/cold silo to double the TES capacity increases the CSP plant capacity factor and lowers the plant levelized cost of electricity (LCOE) with less TES cost.

Two ash-silo sizes have been considered that can fit in the silo layout for four storage capacities: a single 12,500-ton silo and a 17,000-ton hot and cold silo for 6-hr and 8-hr TES capacity, respectively. The silo manufacturer indicates it has the ability to build silos holding the particle weight and volume for 6-8 hr of TES. Figure 5 shows particle-silo layouts for two TES capacities, the base capacity of 6-hr and 8-hr silos (shown in Figure 5.c), and the double capacity of 12-hr and 16-hr storage, obtained by adding one hot/cold silo (shown in Figure 5.d), respectively. Figures 5.a and 5.b show typical silo shapes from a calculator available from Marietta Silos (http://www.mariettasilos.com/). This company specializes in ash silo design, construction, and repair. Figure 5.a has a cone-shaped bottom for particle dispensing, which is a design for a hot-particle silo. Hot particles will flow from the bottom by gravity force and be controlled by a pneumatic particle-flow valve, which was developed for and used in commercial circulating fluidized-bed (CFB) boilers. The cold particles will be stored in the flat-floor silo shown in Figure 5.b, and transported by a bucket lifter from the cold silo to the receiver tower. The cold-particle silo will be part of the receiver tower because of operating and cost benefits.

## 3. System techno-economic analysis

The FB-CSP power plant subsystems—including the high-temperature, particle storage silos and FB steam generator—are based, to some extent, on existing commercial technologies. The storage-silo design is derived from commercial concrete silos currently used to store ash for a coal-fired power plant or other particulate materials, but is modified to accommodate high-temperature particles. The FB steam-generator design is derived from particulate-coal FB boilers used for electricity generation from fossil fuels. The NBB particle-receiver design is not related to any existing commercial application for flowing particle handling or heat transfer. The ongoing development of the NBB-particle receiver is aimed at achieving the technical and economic goals for a CSP receiver. The solid-particle receiver is important for the performance and commercial viability of an FB-CSP plant. Other flowing-particle receivers under development in parallel can be implemented in the FB-CSP system if they are successful.

In the past few years, with the deployment of several CSP plants in the southwest United States, the CSP plant LCOE has dropped significantly from ~18¢/kWh$_e$ to ~13.3¢/kWh$_e$, without the investment tax credit (ITC) incentive. Much of the LCOE reduction is attributed to higher production volumes and more efficient manufacturing and business processes. Figure 6 illustrates the economic benefits of the FB-CSP system compared to a salt-based CSP plant. Techno-economic analysis indicates that the system can achieve about a 20% cost reduction over a molten-salt CSP plant, assuming identical operating conditions for a traditional steam-Rankine cycle. The FB-CSP system can further reduce the CSP power generation cost when the system drives a high-efficiency power cycle such as an s-$CO_2$-Brayton power cycle or an ABCC power generation. Advanced power cycles with 47% thermal efficiency and near-term, low-cost solar collector systems (priced at \$100/m$^2$) are expected to reduce the LCOE for CSP to below 9¢/kWh$_e$. Further reduction in LCOE of CSP requires a lower solar-field cost (\$75/m$^2$) and an increased power-cycle efficiency (>50%) based on the U.S. Department of Energy SunShot targets. Those targets can be realistic. For example, one approach of using thermochemical energy storage (TCES) to achieve > 900°C heat-release temperatures may get > 50% power-cycle efficiency. Together with the cost reduction of the solar field, the FB-CSP system can facilitate the future CSP plant to reach the SunShot goal of LCOE that is equal to conventional power generation. In addition, several factors may impact the potential for future CSP competitiveness:

i. Improving renewable grid penetration: CSP with TES provides dispatchable power generation, which supplies electricity on demand, or stores solar-thermal energy economically for peak power production. CSP TES also has potential to serve as an electric energy storage method that can be integrated with wind or PV to avoid curtailing wind power or shifting PV generation to peak-demanding period.

ii. Wide technology deployment potential: Only low-cost, conventional materials are used in the solid-particle thermal system. Well-known engineering principles are used in technology development and component design. Conventional manufacturing procedures are considered in all component fabrications and constructions.

iii. Overall cost of the particle-TES for CSP is a fraction of the competing TES methods such as that for nitrate salt. The particle-TES uses a concrete container integrated with a tower, which reduces the cost of TES containment significantly, especially for very high-temperature storage that tends to use containers made with expensive alloys. The FB-CSP system has the ability to reduce the capital cost and to support a high-temperature, high-efficiency power cycle. These characteristics are expected to yield high plant capacity and reduce the solar field size, both of which should improve performance.

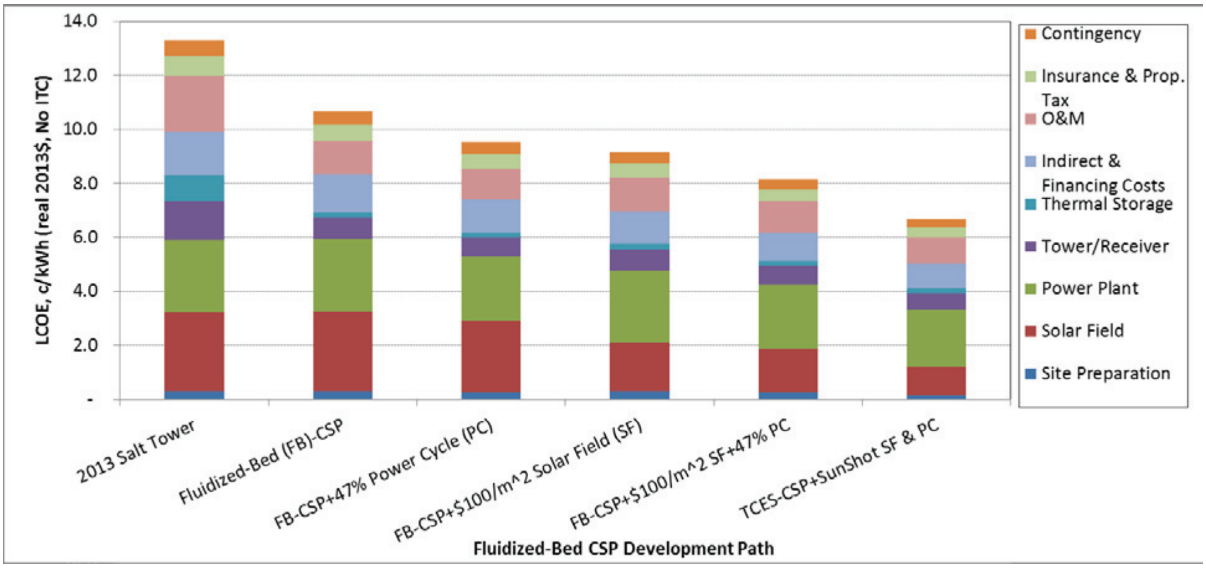



Figure 6. Techno-economic path of FB-CSP to SunShot goal with improved solar field and power cycle.

The FB-CSP technology is aimed at eliminating technical and economic barriers in today's salt-based CSP thermal systems. The development of the FB-CSP system will significantly leverage the existing power technology and manufacturing capabilities, including material suppliers, manufacturers, constructors, and academic research, to accelerate realization of the technology and deployment opportunities.

## 4. Conclusions

This novel thermal system for a low-cost, high performance CSP plant uses gas-solid fluidization to replace liquid salt or oil as the HTF and a solid as the storage medium. The materials used (solid particles, refractory brick, and concrete) are stable, abundant, and low cost, enabling CSP to be more competitive with conventional power generation. The TES can integrate with mature FB-technology used with a solar-tower system. By leveraging the FB-power plant design, the FB-CSP system can reduce the development cycle and mitigate the technology risk. The success of the technology will be accelerated with integration of commercial fluidization technology, continued development and improvement of the solid-particle receiver, and FB-CSP system development. The FB-CSP thermal system will be compatible with high-efficiency power cycles and improve the overall CSP plant efficiency, yielding a lower LCOE.

The FB-CSP system with TES can operate at high temperatures because of stable materials and minimized thermal losses due to thermal self-insulation of particles in the storage mode. The TES system can hold large-capacity thermal energy for a longer period without the need for expensive metal alloys and insulation. The FB-TES system costs in the range of \$5–\$6/kWh$_{th}$, and can achieve a 75% cost reduction over current TES systems (less than a quarter of current TES cost estimated at \$30/kWh$_{th}$). These costs meet the SunShot cost target on TES development. The FB-TES has the potential to support different types of power cycles, and high-temperature (> 800°C) needs.

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