SAND2021-12620C

Technoeconomic Sensitivities of Horizontal Conveyance Components on LCOE for a Particle-Based CSP Plant

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Abstract. A design study was conducted at the National Solar Thermal Test Facility (NSTTF) at Sandia National Laboratories in Albuquerque, NM with the objective of identifying the technical readiness level, performance limits, capital and O&M costs, and expected thermal losses of particle handling and conveyance components in particle-based CSP plant. Key findings indicated that vertical skips and high temperature horizontal particle conveyance technology is available for moving particles up to 615° ± 25° C. This limits the use of mechanical conveyance above the heat exchanger and suggests vertical integration of the hot storage bin and heat exchanger to facilitate direct gravity fed handling of particles. Skip rails and support structures add significant cost and must be factored into cost analysis. Chutes can be a low cost option for particle handling but uncertainties in tower costs make it difficult to know whether they can be cost effective in areas above the receiver.

BACKGROUND

Particle-based CSP systems have been developed as part of an effort to improve thermoelectric efficiencies by pushing heat transfer media temperatures above 700° C. Prior work by Albrecht, and Gonzàles-Portillo evaluated the levelized cost of electricity (LCOE) for a particle-based CSP plant [1] [2]. Figure 1 shows the flow diagram of the CSP system coded in the Engineering Equation Solver (*EES*) software used to calculate LCOE. Between the labeled major components, there are 7 transitions:

1. Receiver lift to falling particle receiver
2. Falling particle receiver to hot storage
3. Hot storage to heat exchanger lift
4. Heat exchanger lift to heat exchanger
5. Heat exchanger to cold storage lift
6. Cold storage lift to cold storage
7. Cold storage to receiver lift

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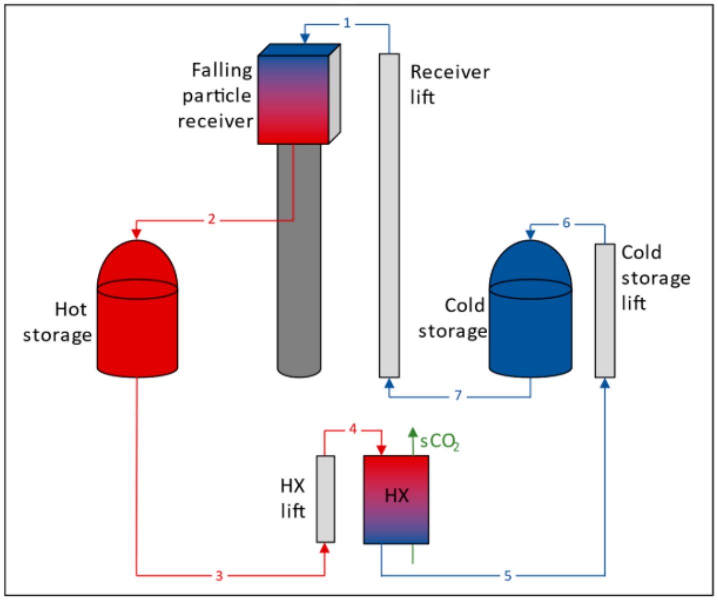

FIGURE 1. Diagram of particle CSP system coded in EES from Gonzàles-Portillo et al. [2]

RECEIVER COSTS

The receiver sub-system includes the cavity, tower, and primary particle lift. Cost considerations for the receiver are discussed in prior work[2]. Only the tower costs and receiver lift costs are discussed herein as they pertain to particle handling.

$$(C_{rec} = C_{fpr} + C_{tower} + C_{lift,rec})$$

Tower

In prior work by Gonzáles-Portillo et al, tower cost models were based on equations given by System Advisor Model (SAM) as an upper bound and by Schlaich Bergermann Partners (SBP) as a lower bound [2, 3]. Both models are considered to be comprehensive in that they account for materials, labor, and disposable assembly assets such as cranes and slip-form molds etc. However, these models were developed around the requirements of molten salt towers. For particle-based CSP systems, tower costs must account for railing and support structures for skips, additional tower height above the receiver to accommodate roof-top particle handling methods, and for systems with tower-integrated storage, material costs must be increased to account for seismic overturning moments. Updated functions are proposed here for both lower and upper bound cost relations to account for three design considerations:

1. Additional height to top of receiver, plus chute height as a function of incline and tower diameter
2. Additional structural materials to support tower-integrated storage in a seismic event

Existing cost models are based on the optical height (h_{opt}) which is the distance from the heliostat's elevation drive to the centroid of the receiver aperture. For towers with external TES the skips may be inside the tower column and could discharge just above the receiver. As a lower bound ($h_{t,ext,lb}$) it can be assumed that the skip rails can extend beyond the roof of the tower. As an upper bound ($h_{t,ext,ub}$) it is assumed that the tower structure must be extended by the length of the skip in addition to the receiver and feed hoppers.

$$h_{t,ext,lb} = h_{opt}$$

$$h_{t,ext,ub} = h_{opt} + h_{skip}$$

For systems with tower-integrated TES, the skips must travel on the rear face of the tower. As a lower ($h_{t,int,lb}$) bound the tower does not need to increase in height, but the capital cost of a rooftop conveyance must be considered.

For capacities ≥ 500 kg/s, horizontal conveyors are estimated at a specific cost of 54 $\left[\frac{\$\cdot\text{hr}}{\text{mton}\cdot\text{m}}\right]$. Smaller conveyors ≤ 100 kg/s are estimated to be 180 $\left[\frac{\$\cdot\text{hr}}{\text{mton}\cdot\text{m}}\right]$.

As an upper bound ($h_{t,int,ub}$), it is assumed that the full cylindrical tower must increase to accommodate a chute leading from the skip discharge point to a feed hopper location above the receiver. If receiver and tower dimensions are not specified, the tower perimeter can be estimated to be the greater of 2x the width of the receiver and the diameter required to maintain stress levels below the strength of the concrete. This relationship can be estimated with a polynomial fit to minimum achievable diameters (D_{tower}) as a function of thermal storage capacity ($Q_{storage}$) in MWh_{th} produced by the tower structural model described in prior work [3]. Towers should be assumed to be no lower than 10 m without expert consultation. Towers with integrated storage are only feasible in regions with minimal seismicity.

$$D\left(Q_{storage}\right)_{lb} = 1.85\left[\frac{m}{MWh_{th}}\right]\cdot Q_{storage} + 5.73\ [\text{m}]$$

$$D\left(Q_{storage}\right)_{ub} = 2.61\left[\frac{m}{MWh_{th}}\right]\cdot Q_{storage} + 6.66\ [\text{m}]$$

$$D_{tower} = \max\left(\frac{2\sqrt{A_{ap}}}{\pi}\ [\text{m}]\,, \text{D}(Q_{storage}) + 5.73\ [\text{m}], 10\ [\text{m}]\right)$$

The repose height (h_{rep}) is defined by the geometry of the receiver plus a contingency reserve volume based on the width and depth (d_{hop}) of the feed hopper and reserve time (t_{res}) at mass flow rate ($\dot{m}_{rec}$).

$$(h_{rep} = \tan\left(\phi_{rep}\right)\frac{\sqrt{A_{ap}}}{2} + \frac{t_{res}\rho_b\dot{m}_{rec}}{w_{hop}d_{hop}}).$$

The required chute height at an incline angle α from the skip is

$$h_{chute,roof} = \tan(\alpha)\left(D_{tower} - \cos(\alpha)\, h_{skip} - \frac{d_{hop}}{2}\right)$$

Where the height of the skip can be derived as a function of height and mass flow. Estimations may assume a fixed cross-sectional area of 9 m^2 and a fixed average velocity of 4 m/s. For the limited purposes of determining the skip height, the rail height can be estimated at 125% of the optical height.

$$h_{skip} = \frac{\dot{m}_{rec} * h_{rail} * A_{skip}}{v_{lift}\cdot\rho_b}$$

The adjusted height of the tower is then

$$h_{t,int,lb} = h_{opt}$$

$$h_{t,int,ub} = h_{opt} + h_{rec} + h_{rep} + h_{skip} + h_{chute,roof}$$

Towers with integrated storage and components have additional costs associated with thicker walls often at larger diameters required to bear the loads of the storage, fit the particle inventory volume, add floors for components, add steel reinforcement and thicken base foundations. These material costs can be estimated at the lower bound for low seismic regions and the upper bound for regions with medium seismicity as

$$c_{mat,lb} = 1.1\text{E}6\left[\frac{\$}{MWh_{th}}\right]\cdot Q_{storage} - 460000\ [\$]$$

$$c_{mat,ub} = 1.4\text{E}6\left[\frac{\$}{MWh_{th}}\right]\cdot Q_{storage} - 599000\ [\$]$$

Regions with high seismicity such as California are not compatible with tower-integrated storage and external storage bins are necessary. For simplicity a constant height of 250 m was selected as a fixed height that fit all capacities from 0.5 to 10.5 MWh_{th}. Larger storage capacities may not be practical. Lower towers can approximate the material cost factors by scaling proportional to the 250 m tower height as long as heights are selected such that the top of the hot bin is in the lower 2/3 of the tower.

Substituting the specific tower height configuration with h_t, the SBP and SAM tower cost formulas can be applied for particle-based systems as

$$C_{tower,lb} = 4.0\frac{\$}{\text{m}^{2.7}} * {h_t}^{2.7} + 1.3\text{E}6\ [\$] + c_{mat,lb}$$

$$C_{tower,ub} = 0.084\frac{\$}{\text{m}^{3.6}} * {h_t}^{3.6} + 4.59\text{E}6\ [\$] + c_{mat,ub}$$

Receiver Lift

The previous model used a cost relationship derived from Repole et al for a skip-hoist system with linear scaling based on height (h_{lift}) and mass flow rate ($\dot{m}_s$) [4] [1].

$$C_{lift} = 58.37 \left[\frac{\$}{kg\ m\ s^{-1}}\right] * h_{lift}\dot{m}_s$$

The Repole/Jeter models were updated and re-run with costs of rails included. The cost model was refined to have three terms to better differentiate the contributions of height (longer ropes, wider reels) vs capacity (motor power), and the interaction of the two. Total cost for a similar hoist system was found to be

$$C_{lift} = 2.80E4 \left[\frac{\$}{m}\right] * h_{lift} + 265 \left[\frac{\$}{m^2}\right] * h_{lift}{}^2 + 2670\left[\frac{\$}{\text{kg}\cdot\text{s}^{-1}}\right] * \dot{m}_s + 0.51\left[\frac{\$}{kg^2\cdot\text{s}^{-2}}\right] * \dot{m}_s{}^2 - 26.8\left[\frac{\$}{\text{kg}\cdot\text{s}^{-1}\cdot m}\right] * \dot{m}_s h_{lift} - 7.10E5\ \$$$

Ductwork

Ductwork design details are discussed in the companion document[5]. Fabrication and installation costs are taken from cost estimates undertaken in January of 2021 for the G3P3 project execution plan[6]. Refined cost functions are recommended as future work. The material cost per vertical component of the duct segment (h_v) is scaled for required diameter for a given mass flow rate ($\dot{m}_{duct}$) using the equations of Beverloo et al and oversized to limit particle fill to 1/3 of the duct area to facilitate flow [7]. Installation costs are assumed to be the same as the G3P3 estimates. The relationship below accounts for necessary expansion joints and switchbacks to control particle velocity. The lower and upper bound costs reflect independent cost estimates on stainless steel ductwork acquired as part of the G3P3 design phase.

$$C_{duct,lb} = 1160\dot{m}_{duct}^{0.165}\left[\frac{\$}{\text{m}_{vertical}}\right]$$

$$C_{duct,ub} = 1670\dot{m}_{duct}^{0.340}\left[\frac{\$}{\text{m}_{vertical}}\right]$$

Refractory chutes are estimated with different assumptions on process and materials as described in other work. The term chute will refer to an underground refractory pathway in order to avoid confusion with suspended steel ducts throughout the tower. The cost functions are in terms of linear length of duct and include drilling/excavation costs and materials for casing with refractory insulation.

$$C_{chute,lb} = (69.0\dot{m}_{chute}^{0.400} + 192\,)\left[\frac{\$}{\text{m}_{diag}}\right]$$

$$C_{chute,ub} = (67.1\dot{m}_{chute}^{0.400} + 1490)\left[\frac{\$}{\text{m}_{diag}}\right]$$

STORAGE BIN COSTS

Storage bin designs for mass flow particle-based TES have been proposed by Ma et al using a single bin technique[8]. This study elaborates on a proposed commercial scale plant design that uses two flat-bottomed bins by the Gen3 Particle Pilot Plant team at Sandia National Laboratories[9]. The cost of thermal energy storage bins are describe in prior work [3]. Refinements to the storage bin costs and lift costs are discussed herein.

$$C_{TES} = c_{bin,hot}A_{bin,surf,hot} + c_{bin,cold}A_{bin,surf,cold} + C_{lift,HX} + C_{lift,cold} + C_p + C_{p,loss}$$

Heat Exchanger Lift

Findings in other work indicate a low TRL for horizontal conveyors and skip hoist systems at temperatures greater than 615±25° C. Currently, outlet temperatures at receivers are 800-1000° C [10] and there is interest in pushing temperatures to 1500° C [11]. For these reasons, direct feed from hot storage to the heat exchanger is assumed to be required. The nomenclature $C_{lift,HX}$ will be preserved for consistency, but will indicate the costs of elevating the hot storage bin rather than a skip hoist and conveyor system. Post-heat exchanger, particle temperatures are assumed to be less than 640° C and the utilization of skips and conveyors are assumed. Heat exchanger lift costs as a function of storage capacity ($q_{\text{storage}}[\text{MWh}_\text{t}]$) consider a thick bin floor, pillars, labor, and reinforcement.

$$C_{lift,HX,lb} = 510\left[\frac{\$}{\text{MWh}_\text{t}}\right] \cdot q_{\text{storage}}[\text{MWh}_\text{t}] + 1.292\text{E}5[\$]$$

$$C_{lift,HX,lb} = 850\left[\frac{\$}{\text{MWh}_\text{t}}\right] \cdot q_{\text{storage}}[\text{MWh}_\text{t}] + 2.15\text{E}5[\$]$$

Storage Bin Costs

Refinements in this work divide the area specific bin costs into floor, wall, and ceiling regions. The upper bound insulation design matches G3P3 while the lower bound design only considers heat-resistant concrete. The hot and cold areas are calculated to reflect multiple outlets and asymmetric loading. Distribution over the heat exchanger was found to exceed the temperature limits of conveyance equipment in many systems. It is replaced here by the cost of lifting the hot storage bin above the heat exchanger. The cold lift is broken into the sum of a horizontal conveyor and a hoist system. Particle costs assume an abundant sand such as Saudi red sand and a manufactured bauxite proppant as an upper bound. Particle loss costs are discussed in other work[2].

There is a high degree of variability in the surface area of storage bins that are discussed in other work. Prior studies have shown there is minimal change in heat loss when surface area is varied for a fixed mass of particles. Floor area should be omitted and handled separately for flat-bottom concepts that use a non-flowing region of particles to insulate the bottom of the bin.

For tower-integrated storage bins, the tower diameter defines the geometry. Insulation is required for the floors walls and ceiling. Refractory wall insulation has an area-specific cost of 1280-1920 $\left[\frac{\$}{\text{m}^2}\right]$, roof insulation is 364-546 $\left[\frac{\$}{\text{m}^2}\right]$. Flooring costs $\left(263 - 2210\left[\frac{\$}{\text{m}^3}\right]\right)$ can be estimated as a function of hot storage capacity. The range reflects a modeled range of volume fraction of heat transfer media in the floor region from 50-90% and a range of particle costs from 0.6 to 2 $\left[\frac{\$}{\text{kg}}\right]$. The relationships below reflect a range of bin diameter and number of required outlets from 120 to 4200 MWh_t. A key difference between hot and cold flooring is that the number of outlets in hot bins may be linked to the number of heat exchanger modules while the number of outlets in the cold storage bin is less determinate. The lower and upper bounds reflect the range from center discharge to edge discharge with 1 to 3 outlets.

$$c_{ext,floor,hot,lb} = 767\left[\frac{\$}{\text{MWh}_\text{t}}\right] \cdot q_{\text{storage}}[\text{MWh}_\text{t}] - 1.03\text{E}5[\$]$$

$$c_{ext,floor,hot,ub} = 3120\left[\frac{\$}{\text{MWh}_\text{t}}\right] \cdot q_{\text{storage}}[\text{MWh}_\text{t}] - 4.78\text{E}5[\$]$$

$$c_{ext,floor,cold,lb} = 1640\left[\frac{\$}{\text{MWh}_\text{t}}\right] \cdot q_{\text{storage}}[\text{MWh}_\text{t}] - 2.20\text{E}5[\$]$$

$$c_{ext,floor,cold,ub} = 9990\left[\frac{\$}{\text{MWh}_\text{t}}\right] \cdot q_{\text{storage}}[\text{MWh}_\text{t}] - 1.58\text{E}5[\$]$$

Cold Storage Lift

The route from the heat exchanger to the cold storage bin considers a horizontal (d_{hori}) and vertical (d_{vert}) component that over a range of bin sizes, mass flow rates, and spacing of storage bins derived in the companion study[5].

$$C_{lift,cold} = c_{hori} + c_{vert}$$

where the horizontal component can be costed as a fixed cost for the head and tail of the conveyor that include the motor and drive system and a cost/length for the more passive middle portions. Cost information is only known at two capacities that can be combined and scaled.

$$c_{hori,@100\frac{\text{kg}}{\text{s}}} = \frac{\dot{m}}{100}\left[\frac{\text{kg}}{\text{s}}\right]\left(610\text{E}3[\$] + 5.73\text{E}4\left[\frac{\$}{\text{m}}\right]d_{hori}\right)$$

$$c_{hori,@500\frac{\text{kg}}{\text{s}}} = \frac{\dot{m}}{500}\left[\frac{\text{kg}}{\text{s}}\right]\left(920\text{E}3[\$] + 8.71\text{E}4\left[\frac{\$}{\text{m}}\right]d_{hori}\right)$$

The vertical component is a skip and is estimated using the same relationship above, $c_{vert} = C_{lift}(d_{vert}, \dot{m}_{HX})$

For tower-integrated configurations, there is no cold storage lift.

LEVELIZED COST OF ELECTRICITY

The model was updated with the refined cost relationships for the receiver and storage components. Figure 2 shows the relative increase. The costs of particle handling amount to 0.012 $/kWh in external systems and 0.011 $/kWh in tower-integrated systems. The quantity of hoist systems used was the most impactful assumption. Single-hoist lift systems are likely feasible but become more uncertain at capacities suitable for systems > 100 MW_e due to the skip size requirements. For these systems, two-hoist systems that utilize skip sizes that are much more common with demonstrated overturning capabilities may be necessary. The cost comparison is shown in Figure 3.

Electricity losses due to conveyance systems were found to be less than previously estimated. Designs with funicular downcoming skips and internal skips with regenerative braking were shown to improve LCOE. Heat losses were not significant in tower-integrated systems but were more pronounced in systems with external TES. Heat losses were not factored in previous analyses.

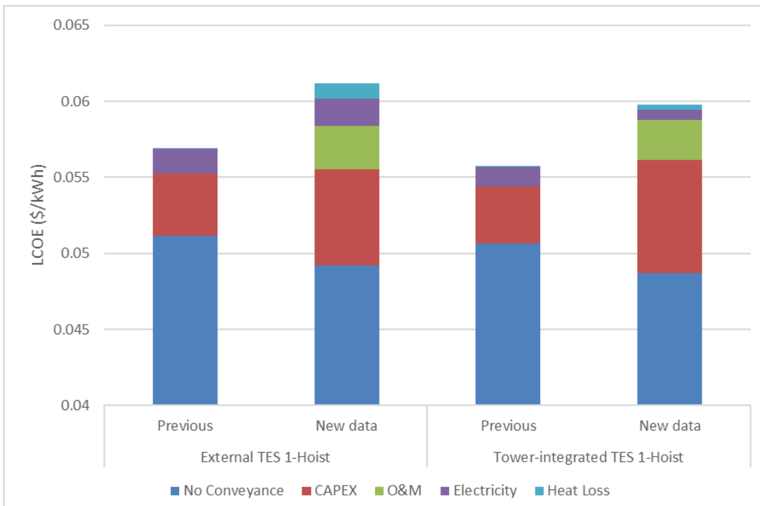

FIGURE 2. Levelized cost of electricity with previous and new component cost assumptions.

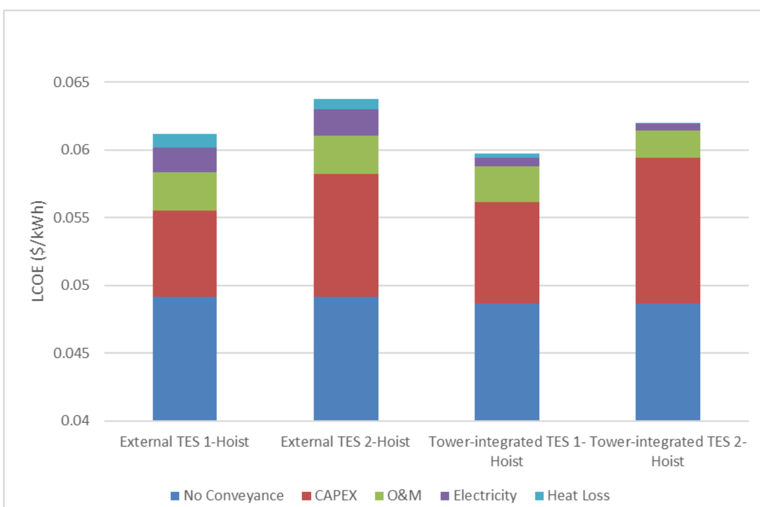

FIGURE 3. New LCOE results with single and two-hoist particle lift systems

Figure 4 shows the relative specific costs for each method of conveyance. The assumed cost for vertical lifts was 58.37 $-s/m-kg. Primary skips were found to be close to this value but smaller components such as horizontal conveyors or intermediate skip may be more costly. Chutes have the lowest specific cost but can increase costs dramatically if tower height must be raised to accommodate inclines above the receiver.

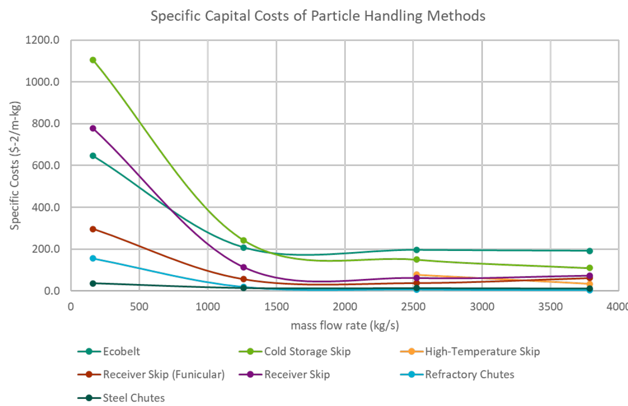

FIGURE 4. Comparison of specific costs of various particle handling methods.

CONCLUSIONS

This study found that particle handling components can amount to as much as 0.012 $/kWh toward the total system LCOE. Reductions in handling components costs will likely have a significant impact in the LCOE pathway from 0.06 to 0.05 $/kWh. Preferring the use of steel ducts and refractory chutes over other options may reduce specific costs, but chutes have design limitations related to erosion, momentum, and increase costs dramatically if tower height must be raised to accommodate inclines above the receiver. Thermal losses in horizontal sections were ignored in previous analyses but may be more significant in external systems with several transitions or unconsolidated mass such as conveyors and chutes. Preliminary designs for capturing energy with downcoming skips appear to be beneficial and should be explored. Particle-based tower designs should be costed by contractors as part of future work.

ACKNOWLEDGMENTS

Sandia National Laboratories is a mulitmission laboratory managed and operated by National Technology & Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International Inc., for the US Department of Energy's National Nuclear Security Administration under contract DE-NA0003525. SAND No.

This material is based upon work supported by the U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy (EERE) under the Solar Energy Technologies Office Award Number DE-37368.

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