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Design Considerations for Commercial Scale Particle-Based Thermal Energy Storage Systems

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Abstract. Particle based heat transfer materials used in concentrating solar power systems benefit from gravity-fed arrangements such as vertically integrated components inside the receiver tower which can eliminate the need for conveyance machinery. However, the amount of particles required for commercial scale systems near 100 MW_e can require towers with very thick walls that must be built with high-strength concrete and heat-resistant concrete formulations. Cost models for particle-based receiver towers with internal particle storage are being developed in this work and compared to well-established cost models that have been used to estimate tower costs for molten salt systems with external storage tanks. For instances where suitable materials are unavailable or do not meet the structural requirements, ground based storage bins must be used in concert with mechanical conveyance systems. Ground based storage vessels have been shown to be consistent with low thermal energy storage cost and heat loss goals. Ground based storage vessels are well-established in industry. New cost models were developed to accommodate the high-temperature applications required for CSP. The results of this study indicate that particle-based tower costs may be more similar to the values used in the System Advisor Model (SAM) than to models developed by Schlaich Bergermann & Partner. Further research is needed to directly compare costs between tower-integrated and external storage and to ensure the use and availability of high-strength and heat resistant concrete (HRC) materials used in these models is feasible.

INTRODUCTION

The peak efficiencies of concentrated solar power (CSP) plants are partly limited by the peak temperatures that can be handled by either the heat transfer medium such as salts, which begin to break down above ~600° C, and the receiver pipes which may become damaged if temperatures exceed material limits. Solid particle receivers provide an opportunity to bypass piping and directly irradiate a curtain of falling ceramic particles. This enables plants to run concentrating solar tower receivers at higher temperatures (~800° C) resulting in increased CSP system efficiencies. Particle based heat transfer media also have beneficial characteristics related to thermal storage as the high specific heat and low conductivity create self-insulating behavior and reduce insulation costs. Particle-based storage containers have weights and volumes similar to molten salts, but the inability to pump particles incentivizes the use

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of gravity-based vertical integration into the receiver tower as is being proposed by the National Solar Thermal Test Facility (NSTTF) at Sandia National Laboratories in Albuquerque, NM, as part of the Generation 3 Particle Pilot Plant (G3P3) project [1]. Previous work has shown the benefits of a flat bottom storage bin design that induces funnel flow in the particle bed to protect the walls from erosion, reduces costs and heat loss associated with a conventional elongated mass flow hopper, and uses stagnant particles on the floor around the outlet as a protective and insulative layer [2]. This study looks at commercial-scale designs and explores the limits of storage capacity that can be practically stored in a tower as well as ground-based storage solutions monolithic concrete domes.

The storage capacity is selected to meet system configurations described in the Gen 3 Pathway and prior technoeconomic analyses by Albrecht et al who propose that levelized cost of electricity (LCOE) approaching $0.06/kWh may be achievable with a 100 MWe system with a particle to sCO2 heat exchanger and ground-based hot and cold bins with 14 hours of thermal energy storage (TES) capacity [3, 4]. The assumed temperature delta across the particle to sCO_2 heat exchanger is based on the most current G3P3 system design at 160° C. The particles are assumed to be CARBO HSP 40/70 which have a specific heat of 1243 $J*g^{-1}*K^{-1}$. The bins are modeled to be external and assume a function for conveyance from the storage bin to the heat exchanger and from the heat exchanger to the cold storage bin. Albrecht acknowledges that there is an unknown breakpoint where the cost of supporting large volumes of particles in the tower exceeds the cost reductions gained by eliminating conveyance machinery between the ground-based components. Albrecht also identifies the need for future studies to evaluate the trade-off in construction cost and heat loss when changing the height to diameter ratio of storage bins and thus the effective surface area of the particle formation. This work does not definitively close those gaps but does present first steps toward the development of a tool that can be used to understand the magnitude of the commercial storage material costs in both tower-integrated and external storage designs. Conveyance costs are not discussed herein.

Tower costs used in the Albrecht model are estimated from the work of Buck [5] who gives a cost function for towers as $C_t = 128H_t^{1.9174}$ and a function for an area-specific and temperature-specific insulated structure cost as $C_{stc} = A_{stc}C_{A,sp,is}(T_{r,ex}) + A_{stc}C_{A,sp,is}(T_{r,in})$. The System Advisor Model (SAM) also provides information on material costs for CSP towers [6]. Actual costs for tower construction are highly dependent on location specific factors such as labor, ground conditions, seismicity, and access to raw materials such as concrete. The International Building Code and American Concrete Institute provide codes and specifications for tower construction and include design factors to accommodate the site specific conditions [7], [8]. This study attempts to illustrate how cost models for receiver towers may need to shift when CSP components are integrated due to the inclusion of refractory insulation, higher strength concrete, and additional wall thicknesses and reinforcing steel required to support the components and heat transfer material.

TOWER-INTEGRATED STORAGE

This study investigates the type and quantity of concrete and reinforcing steel required to support a receiver tower with integrated solar components. Figure 1 illustrates the modeled layout of the tower. The following design parameters were assumed for the components.

Tower Dimensions

Conceptual tower designs have been developed with both the hot material (upper) and the cold material (lower) storage bins enclosed within the tower. This study chose a range of cylindrical tower heights from 50-300 m. The inner tower diameters ranged from 12 m to 50 m at the storage bin walls. The concrete walls of each slip form segment varied in 15 cm (6 inch) increments and were set to be the minimum thickness sustainable for a given height, loading and regional seismicity up to 182 cm (6 feet) which is believed to be the maximum practical thickness for slip form tower construction. The CSP components were arranged as shown in Figure 1 with the cold storage at ground level and turbomachinery, heat exchanger and hot storage bin vertically integrated above. The hot bin used an inverted cone as a floor support [9]. A 100 mm thick layer of particle-contact high-density refractory (1990 kg/m^3) with a 500 mm thick layer of low-density (1110 kg/m^3) refractory insulation was between the particles and the tower walls. Size and weight of the CSP components were considered in determining the heights and thicknesses of the floors, but no considerations were made for component or system integration in this study.

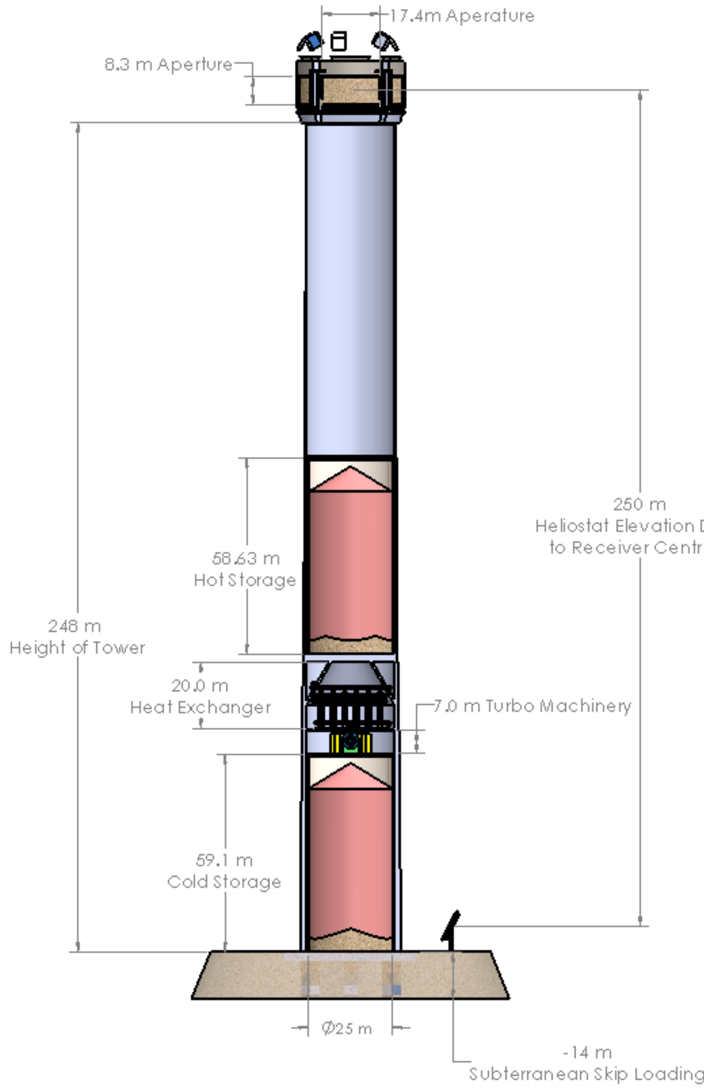


Figure 1. Tower-integrated CSP component dimensions for 25 m diameter 250 m height

Tower Loads

To determine tower loads as a function of tower height, assumptions had to be made as to the implied component mass/volume and storage capacity as a function of tower height. In general, these parameters were interpolated between the dispatch profiles specified in the downselect criteria of the Gen 3 Topic 1 award which defines general criteria baseload and peaker markets [4] with specific cost targets for a 100 MW_e plant. Albrecht et. al. have shown that 14 hours of storage for baseload and 6 hours of storage for peaker plants are one of many possibilities that are consistent with a desirable LCOE [3]. In this study baseload (14 hr storage) plants are >50 MW_e and all others are peaker (6 hr storage). The thermal capacities as a function of tower height were derived from the relationship shown in **Figure 2** which is derived from optical height requirements found in relevant falling particle receiver literature for 1 MW_e [1], 10 MW_e [10], 50 MW_e [11], and 100 MW_e [1] receiver systems. Table 1 summarizes the values derived from selected published and unpublished sources. A thermal to electric conversion of 0.5 is assumed for sizing of all components.

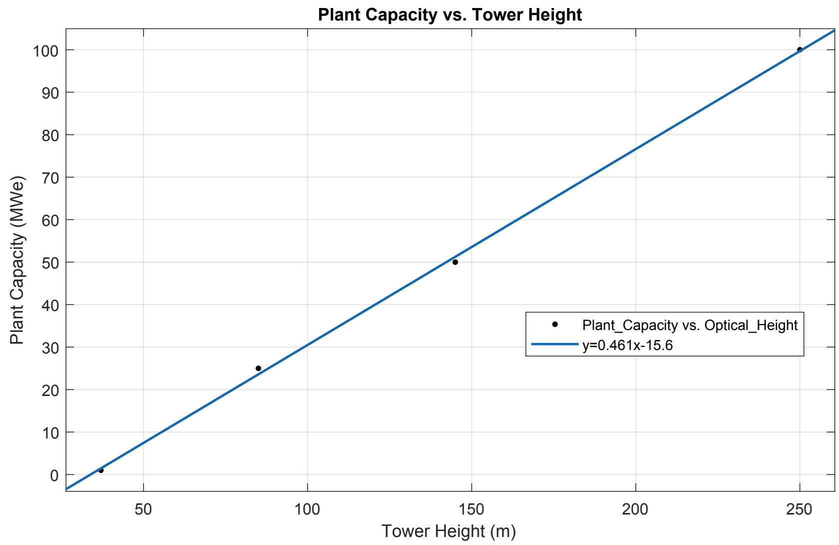


Figure 2. Assumed thermal capacity as a function of tower height

Table 1. Tower Height and Capacity

Source	**Plant Capacity (MW_t)**	**Solar Multiple**	**Receiver Design Point (MWt)**	**Optical Height (m)**
G3P3 [1]	1	2.5	2.5	37
10 MWe [10]	22	1.3	31.2	85
50 MWe [11]	122	1.2	150	145
100 MWe [1]	200	2.75	550	250

The components were sized as follows:

- Receiver: The roofs for baseload plants >50 MWe were loaded with three receivers at 100,000 kg each. Each receiver sub-system included a feed-hopper and weigh-hopper weighing a combined 133,000 kg and three skips on top of the roof with 84,000 kg of particles each and a light rail system weighing 1250 kg. For 33<50 MWe receiver capacities (~100 m towers) 1 receiver sub-system was modeled. And for the 50 m tower, a single 1/10th scale receiver sub-system was modeled.
- Hot Storage: The 100 MW_e system resulted in 23,500 m^3 storage volume with 50.7 million kg of particles [12]. The height of the storage bins varies as a function of bin diameter.
- Heat Exchanger: A bank of 8MW_t heat exchangers weighing ~17,000 kg each designed by *Solex* and *VPE* was located beneath the hot storage support. The weight was scaled to capacity in units of 8 MW_t. An additional 25% weight was assumed for the conveyance system above the heat exchanger. The total load for the 200 MW_t case was of 1.1 million kg. The height including the conveyance system was 13.8 m.
- Power block: The sCO_2 heat exchanger and turbomachinery was modeled on mass estimates for power loops from 25-300 MW_e by Gibbs et. al. (Figure 3) and estimated to be 3,426 kg/MW_e [13]. The height was estimated to be 6.5 m for all instances.
- Cold Storage: The cold storage bin was assumed empty except for the stagnant drawdown region. Three outlets were assumed corresponding to three skip hoists. The hot storage bin assumed five outlets corresponding to the five heat exchanger arrays. The impact of multiple outlets and filler materials on drawdown region mass was evaluated as shown in Figure 4. The filler was assumed to have the cost and density of lava rock and to comprise 90% of the volume with the remaining 10% being comprised of particles. The filler had an assumed density of 1000 kg/m3 vs. the particle density of 2135 kg/m3.

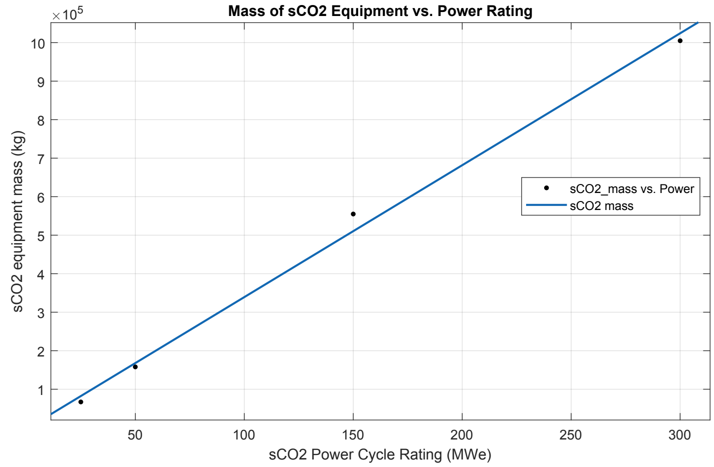
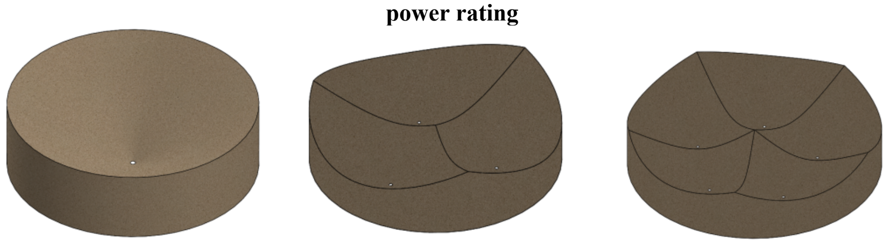


Figure 3: **Estimated mass of sCO_2 loop including heat exchangers, turbomachinery, pipes and valves as a function of power rating**



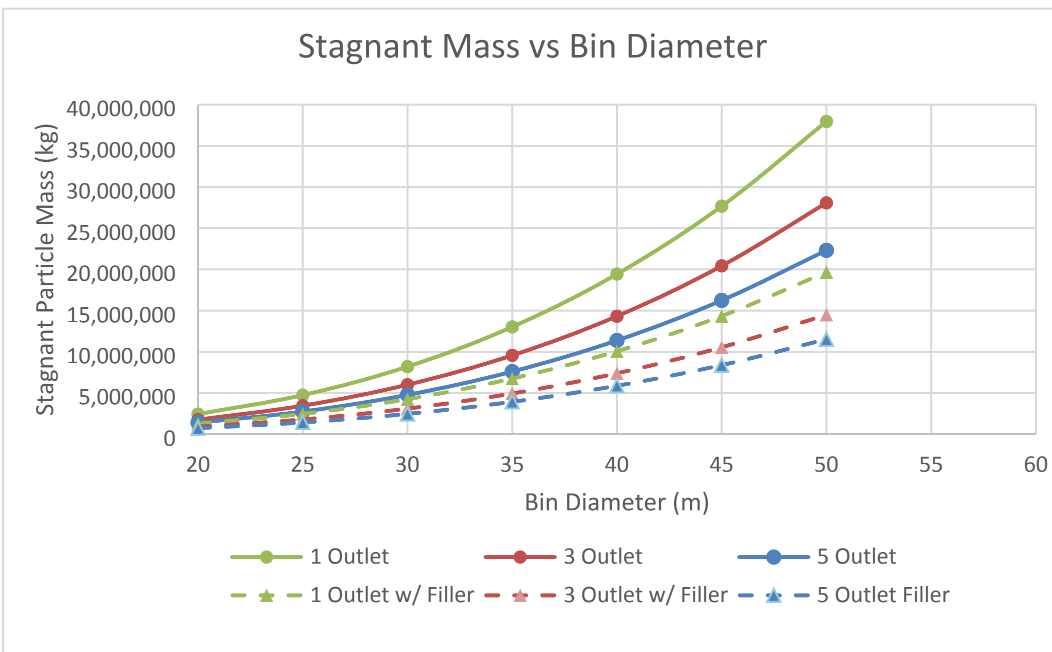


Figure 4: (above) Modeled drawdown regions with 1, 3, and 5 outlets. (below) Overlay of mass of drawdown region as a function of bin diameter for 1, 3, and 5 outlets with all particles and with a lightweight filler

TOWER STRUCTURE REQUIREMENTS

Tower Structure Model

A tower model was developed to evaluate the feasibility of tower construction with and without integrated CSP components [9]. The particle receiver tower is proposed to be of reinforced concrete design. The conceptual design of the tower has been performed using the requirements of the International Building Code (IBC) [7], the American Concrete Institute (ACI) 318-14 Building Code Requirements for Structural Concrete and the ACI 313-16 Design Specifications for Concrete Silos and Stacking Tubes for Storing Granular Materials [8].

The extreme height and mass of the resulting tower structure result in a structure that is sensitive to seismic action. The lateral shear and overturning moment of the tower structures have been estimated per the requirements of the IBC, given the proposed locale of the structure. The fundamental period of vibration of the tower used in the overturning analysis has been estimated using a numerical integration technique developed by C.E. Freese for vertical pressure vessels [14]. It is desired to place both the hot and cold materials in the tower in order to reduce the amount of mechanical equipment necessary to transport the material and to minimize heat loss. However, the large seismic overturning moments estimated in areas of high seismic risk may preclude placing both storage bins in the tower.

The towers are conceived as vertical reinforced concrete cylinders. It is envisioned that the tower shell construction will be performed using slipform construction techniques, often utilized in the construction of reinforced concrete silos. The thickness of the tower shell and the vertical reinforcement in the wall are a maximum at the base of the tower, and may be reduced as the height of the tower increases. The circumferential reinforcement in the shell wall is a maximum in the bin storage regions, where the shell is designed per the ACI 313-16 requirements.

The lower storage bin is located at grade and may be supported directly on the tower foundation or on columns from a lower structural level. In towers with both the hot and cold materials enclosed in the tower, the presence of the lower bin precludes the use of supporting interior columns that would penetrate the lower storage bin. The bottom floor of the upper storage bin must be entirely supported by the exterior tower cylindrical shell. In towers with diameters > 25 m, an inverted conical support structure is proposed to provide interior support for the bin floor.

The large tower loads and potentially large seismic overturning moments result in significant foundation loads. Site specific geotechnical investigations will be required to determine the optimal foundation support system for the proposed towers. Should large at-grade soil bearing pressures not be achievable, deep foundations utilizing piles or caissons are anticipated.

COST ANALYSIS

Particles

The cost of the particles has the largest impact on storage costs when gravity-based particle handling is possible. The same information in Figure 4 was evaluated in terms of cost of the material and shows the relative cost savings as a function of bin diameter (Figure 5) and number of outlets of the non-moving drawdown region when a filler is used as opposed to simply allowing the particles themselves to occupy the volume. The cost of the filler is notionally assumed to be \$150/m^3 vs. \$2000/m^3 for particles based on quotes obtained from CARBO Ceramics.

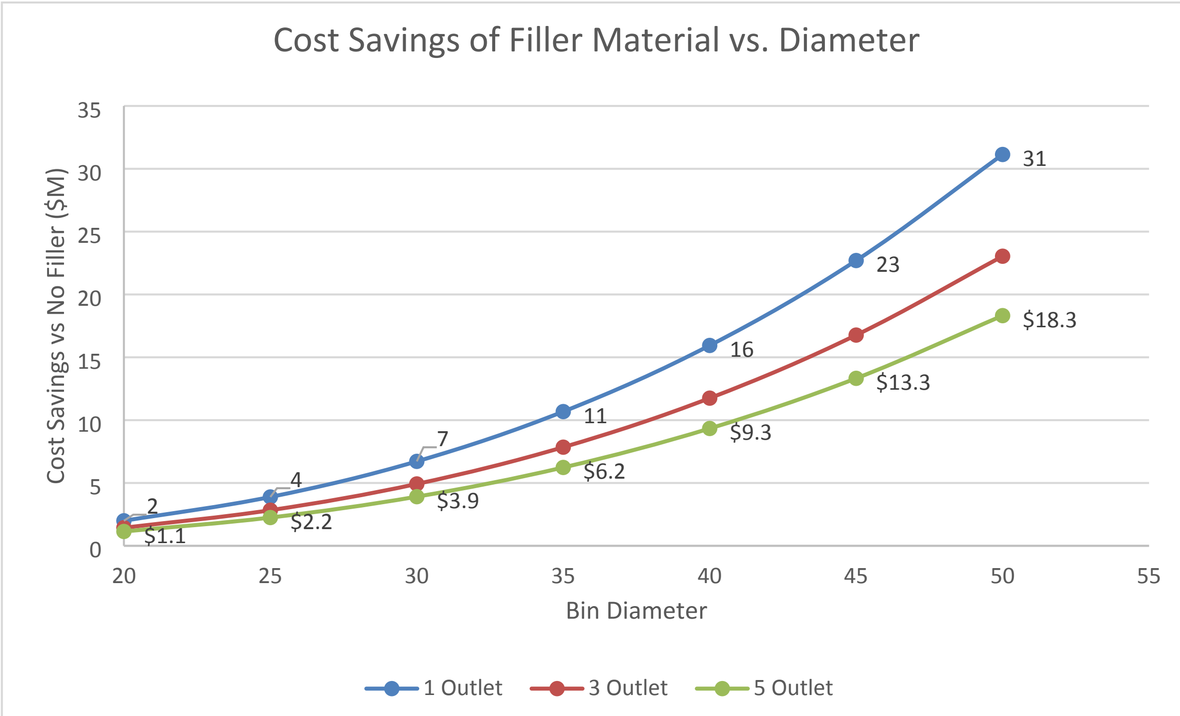


Figure 5: The difference in cost with particles only and with 90% filler vs. bin diameter for 1, 3, and 5 outlet bins

Tower

The estimated costs for concrete and reinforcement for tower-integrated systems were compared to established cost models for molten salt systems with external subsystems produced for Schlaich Bergermann & Partner (SBP) [5, 15], and the System Advisor Model (SAM) [6]. The required material volumes derived with the Harvey model used a constant value of $163.50/m^3 for concrete and $2,200/tonne for reinforcing steel. The storage bins included a volume of high-density refractory and low-density refractory both assumed to be $2700/m^3. In regions where particles touch the walls a heat-resistant Calcium Aluminate concrete formulation was assumed at $850/m^3. It is noted that the engineering required to incorporate heat-resistant concrete with the high-strength concrete is outside the scope of this study.

Throughout the tower, high-strength concrete is used to minimize wall thickness and cost. A cost correlation for high-strength concrete is given by the US Department of Transportation [16]. The use of this correlation should be evaluated by professionals with current knowledge of concrete availability and distribution as well as the appropriateness of using high-strength concrete in slipform tower construction methodology.

Figure 6 shows a cost comparison of tower-integrated particle-based CSP sub-systems with cost models of receiver towers used in molten salt systems with externally located sub-systems. As a baseline, SBP provided the assumed wall thicknesses over the height of two towers. When the tower geometry was replicated in the Harvey model with no extra loading, costs were ±30% of the SBP model. The SBP model is shown in dashed orange. Data points for material costs for the tower were extracted from the SAM model documentation and are shown in dashed black in Figure 6 [6]. When the concrete wall thicknesses and strengths are increased to handle the loads for the tower-integrated storage and components, the cost curves resemble the SAM.

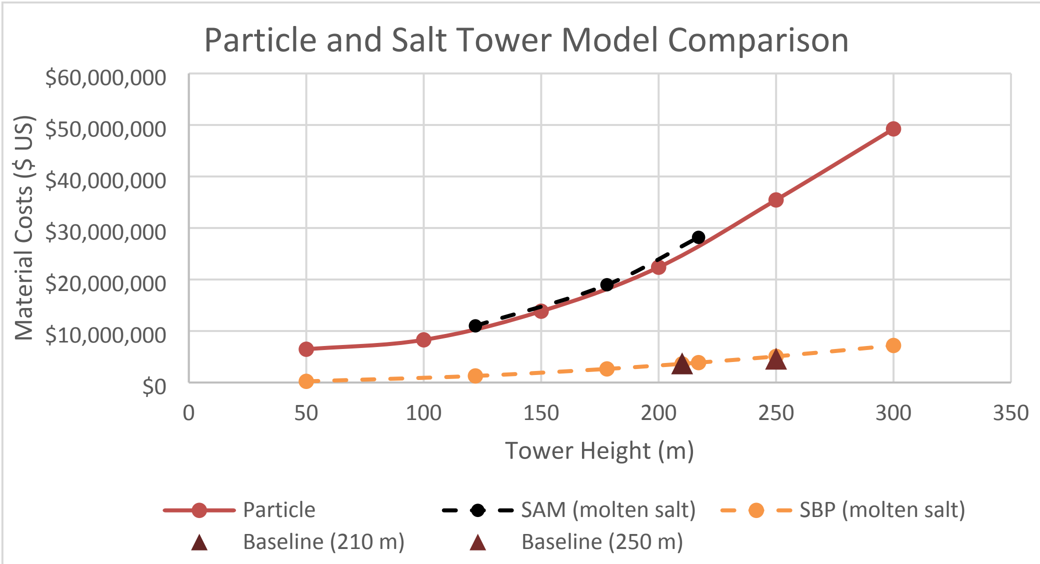


Figure 6: **Tower material costs vs. height for two salt-based system models with external storage and a particle-based system with tower-integrated thermal components and storage**

Seismic shear and overturning were the primary limitations in the tower design. The SAM model literature used Tucson, Arizona as the location for the tower, which is a region of low seismicity. The SBP model was based in Tabernas Desert in Spain with medium seismicity. The effects of increased seismicity are also reflected in Figure 7 which shows the particle tower model costs in Tucson (low), Tabernas (med) and Daggett (high).

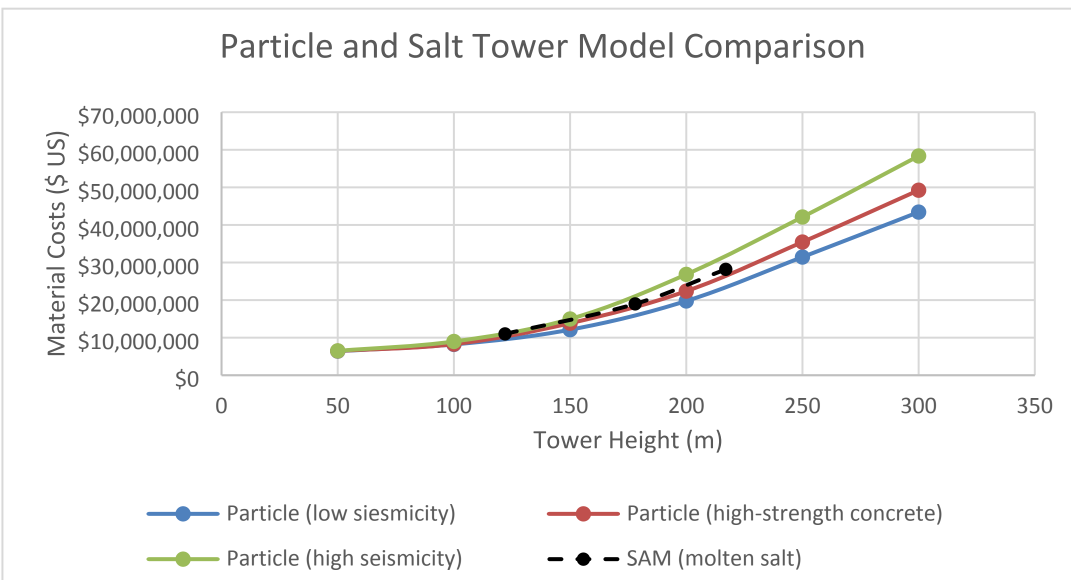


Figure 7. Costs of towers in three seismic regions

The use of high-strength concrete with compressive strength up to 83 MPa (12,000 psi) is required for many designs. Experts in the field of tower construction warned that in some regions, high-strength concrete >45 MPa (6,000 psi) may be difficult to obtain, and shipping and delivery costs may make their use prohibitive. The particle tower model was run with a 45 MPa strength limit. Table 2 shows the height limitations in various regions given the assumed storage capacities above. The study assumes that the maximum wall thickness for a slip-form construction method is 1.8 m (6 ft). When a solution could not be found (i.e. required strength ≥ concrete strength) at that thickness, the diameter was increased. For towers above 200 m, 30 and 40 m diameter towers were required which quickly become cost prohibitive. Furthermore, in areas of medium and high seismicity, no solution (N/A) could be found ≤ 40 m in diameter implying there is a limit to the thermal capacity of tower integrated plants in places like Daggett [9] unless high-strength concrete at 83 MPa (12,000 psi) can be used throughout height of the tower.

Table 2: Maximum height achievable with ≤45 MPa (6000 psi) concrete

Tower Height / Seismicity	50 m	100 m	150 m	200 m	250 m	300 m
Low	$6,982,490	$10,208,130	$18,452,158	$33,274,273	$50,499,789	$84,753,689
Medium	$7,427,080	$11,534,873	$21,822,307	$38,631,074	N/A	N/A
High	$8,040,519	$13,720,305	$29,288,533	N/A	N/A	N/A
Diameter Color Code (m)	18	20	25	30	40	N/A

The cost of the tower integrated solutions is also largely impacted by the insulation requirements of the storage bins. The lowest cost solutions were found to have tower diameters of 18 m. For a 2800 MWh_t capacity (100 MW_e baseload), the resulting bin size would need to be 100 m in height. This requires a large area of refractory to insulate the particles and to protect the structural concrete from over heating. A temperature of 100° C was considered to be the maximum temperature that could be sustained by the structural concrete. The limits to how much insulation can be applied to the walls of the silo were not evaluated in this work, but are asserted to be 500 mm. Results from a cyclic steady state model for a bin with a 100 m height and 18 m diameter [17]. The increase in heat loss for the 100 m high bin relative to a bin with minimal surface area (30 m high) is less than 1%.

A model was developed to evaluate the relationship between insulation layer thicknesses and wall temperatures consisting of a parametrized, one dimensional thermal resistance analyses. This allowed for adjusting of insulating and structural layer thicknesses and environmental parameters. The model accounts for both the cylindrical and spherical roof of the proposed bins. The model conservatively assumes a direct hot-face condition of the entry temperature of the particles and assumes steady state conditions. A more sophisticated transient model or cyclic steady state model may show reduced concrete temperatures and heat loss as the particles in contact with the bin cool and self-insulate. The model only includes heat loss to the environment through convection (radiation terms are neglected), and uses approximate, non-temperature dependent material properties.

With an assumed 800° C inner face temperature, a 100 mm high-density liner, and a 500 mm low-density refractory liner, the interior face temperature of the structural concrete would be approximately 280° C. A high-strength heat-resistant concrete made with Calcium Aluminate was identified that has strengths up to 62 MPa (9,000 psi) at cyclic temperatures up to 1100° C [18]. The costs were estimated to be about 5.2 times the cost of standard Portland cement-based concrete (herein referred to as "cement"). In a scenario where the structural wall thickness surrounding the hot storage bin is 60 cm, there would need to be a 5:1 ratio of HRC to cement to protect the concrete layer to <100° C. The actual design requirements to join layers of multiple materials is not in the scope of this study. For the purposes of cost modeling, the sections of the tower materials surrounding the hot and cold storage bins was assumed to be 5.2 times higher.

Figure 8 illustrates the relative cost contributions from the storage walls. The baseline case (also shown in Figure 6, and Figure 7) is with high-strength concrete throughout the tower height. At the slipform sections around the storage bins, HRC walls are assumed along with 600 mm of refractory insulation. Alternative designs are shown to illustrate the relative importance of the storage bin materials. The cost curve without HRC or insulation is shown in purple. The upper curve (blue) shows the costs when concrete strength is limited to 45 MPa. The discontinuities reflect the jumps in diameter of the bin that are required to achieve the upper heights.

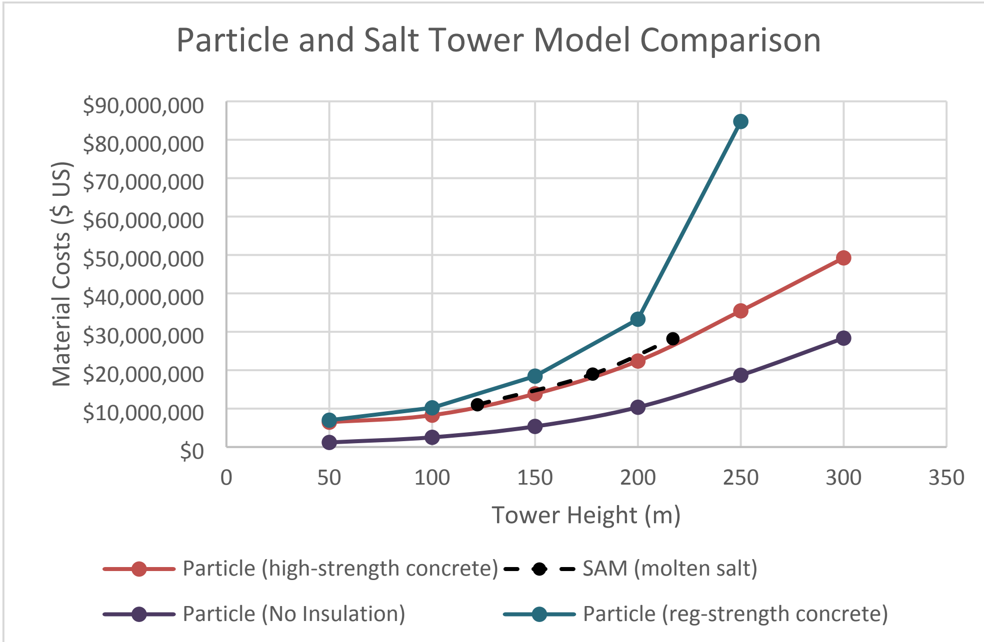


Figure 8. Tower costs comparisons by material

External Storage

For towers that are too short and narrow to fit all the CSP components, or too narrow and tall to survive in areas of high seismic activity, or too remote to acquire an adequate supply of high-strength concrete at an acceptable cost, external storage may be necessary. Monolithic concrete domes may be a low-cost alternative to tower-integrated storage. Hundreds of domes have been used across several industries since the 1970s providing a significant body of evidence for reliability over life-cycles approaching 30 years. These domes have been used in high-temperature applications such as clinker storage which may initially reach over 1000° C. However, the cyclic use of particle-based heat transfer material >800° C may be novel to the industry. The cyclic thermal cycling during charging, storing, and discharging will push the limits of thermal interactions in the materials. Elements to be explored include effective heat transfer of steel reinforced walls and shotcrete anchors, ground effects, and particle penetration into joints and cracks in the shotcrete walls.

Figure 9 shows the results from a cyclic steady state thermal model used to determine whether the dome storage could meet heat loss goals of <1% and if the concrete temperatures would be too hot to remain structurally reliable. The results show the daily heat loss to be <1% in the nominal design scenario which includes 600 mm of refractory insulation and cement. Dome and foundation temperatures however are far beyond the 100° C maximum temperature requirement so a HRC must be used in tandem with the standard concrete.

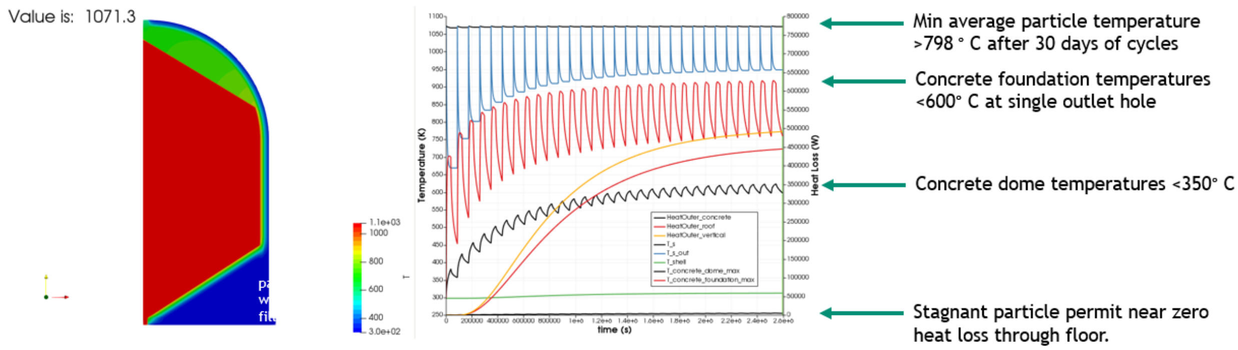


Figure 9. Results from cyclic steady state model of concrete monolithic dome.

Unlike the towers, domes do not require high-strength concrete. There are several heat-resistant concretes that also meet the strength requirements of the dome [19]. The same 1D thermal resistance model was used to determine the required amount of heat-resistant concrete needed to protect the structural concrete to <100° C.

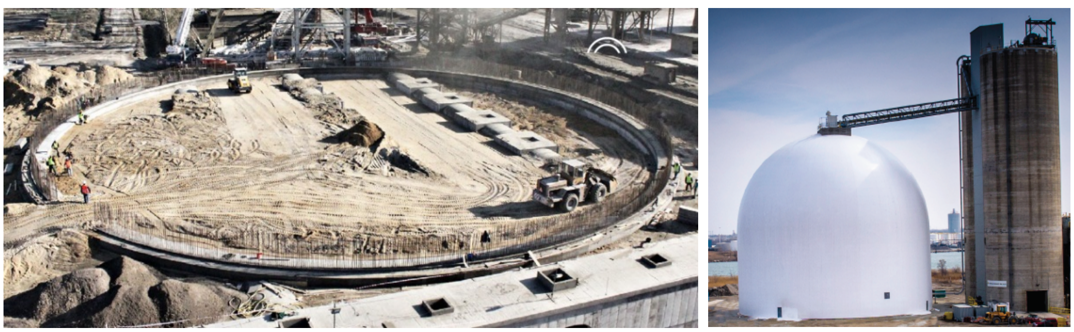


Figure 10. Monolithic concrete dome storage vessels. (Left) foundation construction of a large concrete dome with discharge tunnel. (Right) Dome with charging chute. Images are property of Dome Technology and are used with permission.

Table 3 shows the basic geometric considerations for the plant capacities used in this study. The 200 and 300 MW_t capacities are likely choices for external storage when a single tower is selected. The nominal configuration was sized with a height to diameter aspect ratio that would minimize the particle-contact surface area. The flooring material is assumed to be particles with no filler material. The refractory walls had a fixed design with 100 cm of high-density shotcrete applied refractory and 500 cm of low-density shotcrete applied refractory. A heat-resistant concrete was used behind the refractory layers and set to a proportion of the required structural wall thickness that kept the cement below 100° C. Table 4 summarizes the costs of the storage bins. The 200 MW_t (100 MW_e) storage bin with 14 hours of thermal storage has a unit cost of ~$40/$kWh_t$.

Table 3. Basic geometry considerations for concrete monolithic dome storage.

Plant Capacity (MW_t)	Storage Capacity (hr)	Heat Transfer Material Mass (kg)	Heat Transfer Material Volume (m^3)	Inner Diameter (m)	Ceiling Height (m)	Structural Wall Thickness (m)
20	6	2.2M	1000	12	14	0.25
100	6	11M	5000	20	24	0.4
100	14	25M	12000	27	32	0.5
200	14	51M	24000	34	41	0.6
300	14	76M	36,000	39	47	0.7

Table 4. Cost considerations for insulated hot and cold concrete monolithic domes

Plant Capacity (MW_t)	Storage Capacity (hr)	Heat Transfer Material (million $US)	Refractory installed (million $US)	Nominal Dome as Built (million $US)	Additional Cost for HRC (million $US)	Total Cost (million $US)	Unit Cost ($US/kWht)
20	6	$3.1 M	$4.24 M	$1.40	$0.669	$9.44 M	78.6
100	6	$15.6 M	$8.38 M	$3.00	$2.69	$29.7 M	49.5
100	14	$36.5 M	$13.2 M	$5.00	$5.98	$60.7 M	43.4
200	14	$72.9 M	$19.6 M	$7.60	$11.5	$112 M	39.9
300	14	$109 M	$24.1 M	$9.28	$17.7	$161 M	38.2

A low-cost scenario was investigated that used lower cost filler material at the base of the flat-bottomed bin and used heat-resistant concrete in lieu of any cement in the dome structure. In all cases, above, the proportion of HRC to cement was ~5:1. Given the cost of HRC is ~5 times that of cement, it was hypothesized that there is no need for any insulative refractories since the structure temperatures do not need to be restricted, and most of the thermal resistance in the heat transfer material comes from the particles themselves and not the insulation. Figure 11 shows the results of a cyclic steady-state model ([17]) that shows the volumetric average temperature of particles in an uninsulated bin are 4.1° C cooler than a similarly shaped bin with 600 mm of insulation and a microporous insulation layer. This is 3 times the relative heat loss but amounts to 2% of the total required heat.

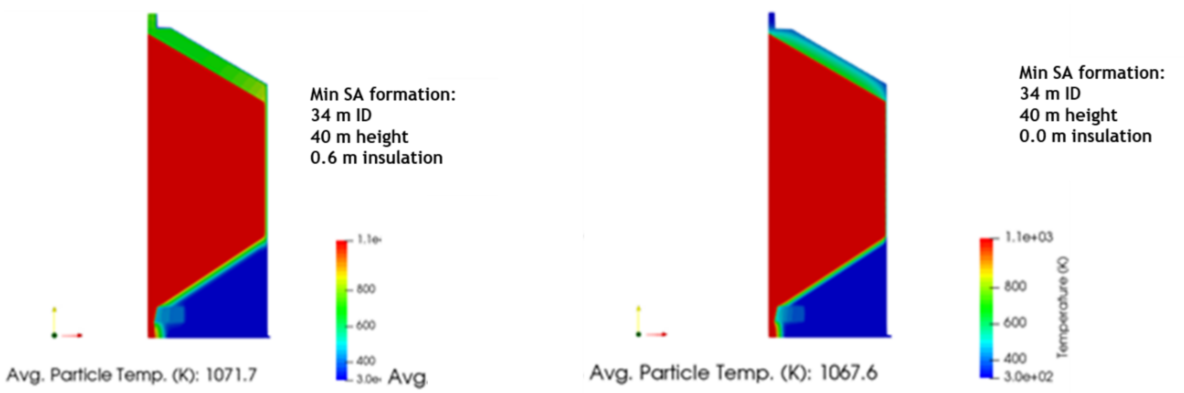


Figure 11. A comparison of particle bins with 600 mm of insulation (left), and no insulation (right).

The DOE SunSHOT 2030 goal is to develop a storage system for $15/kWh$_t$. This may be achievable with concrete domes if the conveyance costs are not considered to be part of the storage system. Figure 12 shows a waterfall chart on the effects of each design considerations on the nominal unit cost for three baseload capacities. One possible scenario takes advantage of cost-saving measures discussed above including five-outlet designs with low cost filler material (Base Filler), elimination of refractory layers and cement by using only heat-resistant concrete in the structure (All HRC). Storage costs could approach the SunSHOT goal while retaining the quoted costs of domes and heat-resistant concrete if particles could be found for 25% less than the currently assumed price of CARBO HSP 40/70 (0.75 $/kg particles) and required mass of heat transfer material could be reduced by developing heat exchangers where the approach temperatures could be lowered to provide for a 200° C ΔT.

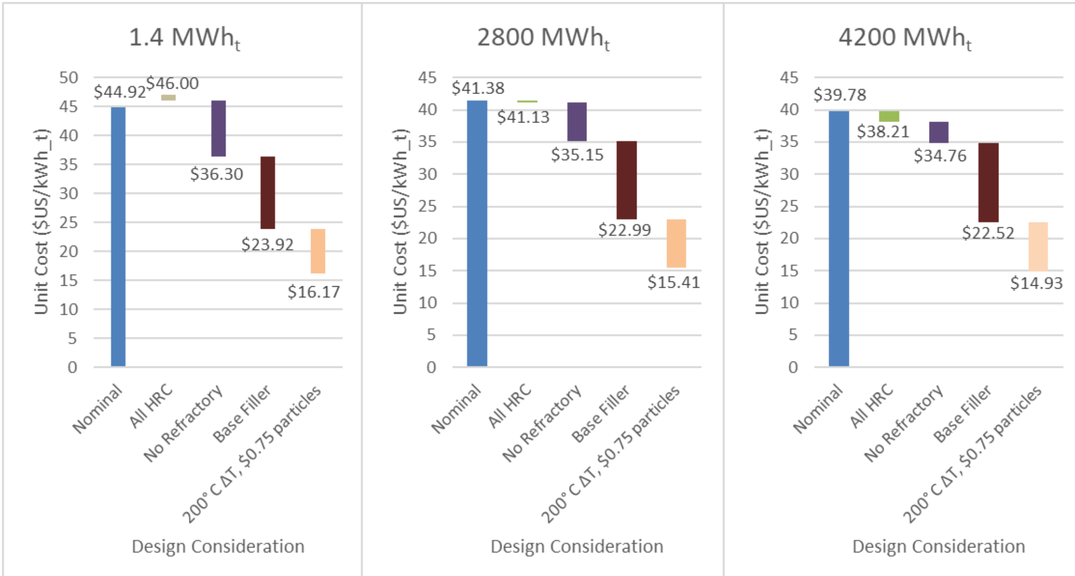


Figure 12. Waterfall chart showing impact of design considerations on thermal energy unit cost by capacity

CONCLUSIONS AND NEXT STEPS

Material costs for particle towers with integrated TES may be higher than some salt-based tower models due to the required wall thickness, higher strength sections of concrete, and insulation. Particles have the largest impact of overall TES costs followed by the heat exchanger ΔT. Narrow towers (<20 m) can reduce materials but may not be an option in areas of high seismicity or for towers with large capacities. Bin designs that are taller and narrower than those with minimum surface area cause ~0.2% increase in heat loss. It is costly and structurally difficult to add sufficient refractory insulation to maintain surface temperatures of concrete <100° C. Calcium aluminate-based HRC can survive up to 1100° C with compressive strengths > 65 MPa (9000 psi), but HRC has a higher thermal conductivity than cement. As a boundary condition, models without any insulation show particles only lost 3.4% of their heat after 14 hours of storage. A $15/kWh TES goal may be feasible if particle inventory could be reduced by increasing achievable ΔTs in the heat exchanger and modest reductions in material costs across the board. This will also require several modes of horizontal particle conveyance not included in these models. While it is subjective whether the costs of conveyance are attributed to the storage goals or not, there will be an impact to the LCOE. Tower integrated storage is limited by tower height and diameter as well as the seismicity of the region.

Direct cost comparison of particle-based towers and salt-based towers (SAM, SBP) remains ambiguous. Tower construction experts may be able to provide complete cost models which refine existing design assumptions and incorporate labor and other site costs. The assumed use and costs of high-strength concrete should be verified by experts. The regions around the tower-integrated storage bins will require heat-resistant and high-strength concrete interfaces. Cost offsets from the elimination of external storage bins remains to be factored into the overall tower-integrated TES system cost models. Integration of heat exchanger and turbomachinery inside the tower has not yet been evaluated other than in terms of volume and weight. Particle conveyance costs must be integrated into system technoeconomic analyses in order to fully assess the value of external storage options.

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REFERENCES

1. Clifford K. Ho, K.J.A., Lindsey Yue, Brantley Mills, Jeremy Sment, Joshua Christian, Matthew Carlson, *Overview and Design Basis for the Gen 3 Particle Pilot Plant (G3P3)*, in *SolarPACES 2019 Conference Proceedings*. 2019: Daegu, South Korea.
2. Jeremy N. Sment, M.J.M., Kevin J. Albrecht, Clifford K. Ho. *TESTING AND SIMULATIONS OF SPATIAL AND TEMPORAL TEMPERATURE VARIATIONS IN A PARTICLE-BASED THERMAL ENERGY STORAGE BIN*. in *ASME 2020 14th International Conference on Energy Sustainability*. 2020. Denver, CO: ASME.
3. Kevin J. Albrecht, M.L.B., Clifford K. Ho. *Parametric Analysis of Particle CSP System Performance and Cost to Intrinsic Particle Properties and Operating Conditions*. in *ASME 2019 13th International Conference on Energy and Sustainability*. 2019. Bellevue, WA: ASME.
4. Powers, S., *Gen 3 CSP Topic 1 - Phase 3 Test Facility Down-Selection Criteria*. 2019, United States Departmente of Energy Office of Energy Efficiency and Renewable Energy.
5. Reiner Buck, S.G. *Impact of Solar Tower Design Parameters on sCO2-Based Solar Tower Plants*. in *2nd European Supercritical CO2 Conference*. 2018. Essen, Germany.
6. Craig S. Turchi, G.A.H., *Molten Salt Power Tower Cost Model for the System Advisor Model*. 2013: NREL.
7. Council, I.C., *International Building Code (IBC)*, in *IBC2018*. 2018.
8. ACI_Committee_313, *Design Specification for Concrete Silos and Stacking Tubes for Storing Granular Materials*, in *ACI 313-16*, A.C. Institute, Editor. 2016.
9. Timothy A. Harvey, P.E., *100 MW Storage Options Report*. October 13, 2019, Matrix PDM, Engineering.
10. Brantley Mills, C.K.H., *Proposed 10 MWe North-Facing Falling Particle Receiver Design*. 2016, Sandia National Laboratories, U.S. Department of Energy.
11. Brantley Mills, C.K.H. *Annualized Thermal Performance of Intermediate-Scale Falling Particle Receivers*. in *SolarPACES 2017*. 2017. Santiago de Chile.
12. Kevin J. Albrecht, L.Y., Brantley Mills, Jeremy N. Sment, Hendrik F. Laubscher, Joshua M. Christian, Matthew D. Carlson, Clifford K. Ho, *Design Features and System Integration of a Next-Generation Concentrating SOlar Power Particle Pilot Plant*, in *14th International Conference on Energy and Sustainability*. ASME: Denver, CO.
13. J.P. Gibbs, P.H., M.J. Driscoll, *Applicability of Supercritical CO2 Power Conversion Systems to GEN IV Reactors*. 2006, Center for Advanced Nuclear Energy Systems.
14. Freese, C.E., *Vibrations of Vertical Pressure Vessels.* Journal of Engineering for Industry, 1959: p. 77.
15. Gerhard Weinrebe, S.G., Reiner Buck, Ansgar Macke, Anne Burghartz, Daniel Nieffer, Fabian Gross, Amadeus Rong, Tim Schlichting, Kristina Blume, *Kostensenkung bei Solarturmkraftwerken durch optimeierte Heliostatkonturen plus angepasstes Turm-und Felddesign*. 2019, Schlaich Bergermann Partner (sbp), Deutsches Zentrum Fur Luft- und Raumfahrt (DLR), Concentrating Solar Power (CSP) Services: HELIKONTURplus. p. 110.
16. DOT, U.S., *Optimized Sections for High-Strength Concrete Bridge Girders--Effect of Deck Concrete Strength*. 2006, U.S. Department of Transportation Federal Highway Administration.
17. Jeremy N. Sment, K.J.A., Mario J. Martinez, Clifford K. Ho. *Design Considerations for a High-Temperature Particle Storage Bin*. in *SolarPACES*. 2020. Degu, South Korea: SolarPACES.

18. *Fondag Product Properties*, K. Inc., Editor., Kernius Inc. https://www.imerysaluminates.com/content/en/Our-solutions/Products/FONDAG/
19. Kerneos_Aluminate_Technologies, *Fondag*. 2010. https://www.imerysaluminates.com/content/en/Our-solutions/Products/FONDAG/