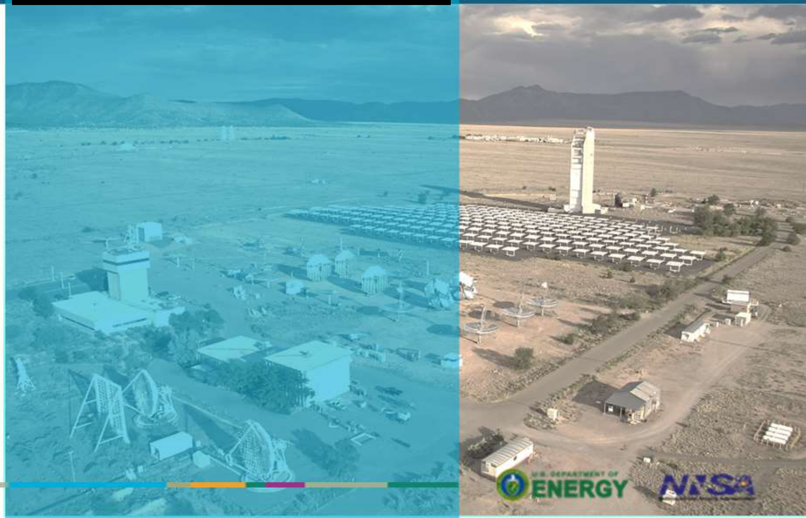
Horizontal High-Temperature Particle Conveyance (HOTPAC) 37368



National Solar Thermal Test Facility

Jeremy Sment, PI

Sandia National Laboratories: Jeremy Sment, PI, Clifford Ho, Nathan Schroeder, Kevin Albrecht, Henk Laubscher, Scott Garcia, Daniel Ray, Matt Carlson (now Heliogen). Magaldi Power S.p.A: Mario Magaldi, Umberto D'Agostino , Davide Concilio, Fulvio Bassetti, Francesco Diniola, Raffaello Magaldi. Onozo Consulting, LLC: Kenzo Repole. University of Madrid: Luis F. González-Portillo.

Project Objectives

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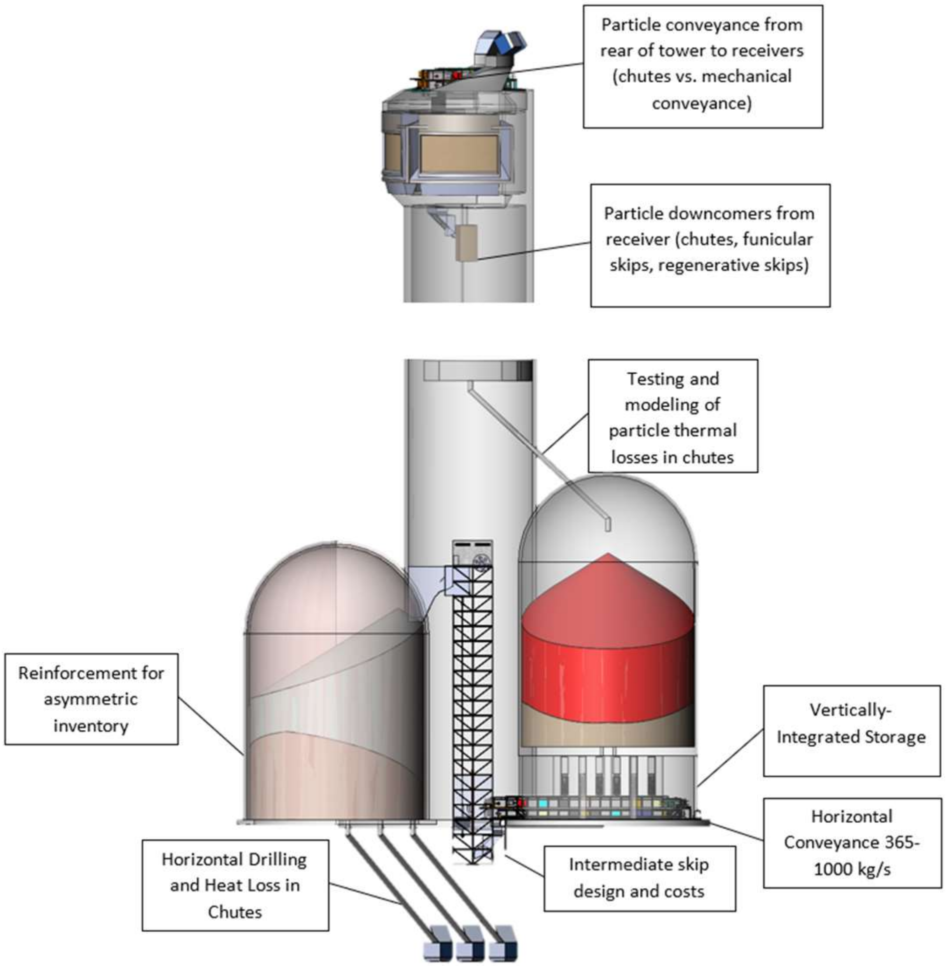
Technoeconomic models were updated with refined information on capital and operating costs of conveyance systems. Increased knowledge base of system design, cost, and heat losses between major CSP components. Vendors of conveyance systems have gained knowledge of key technical requirements of CSP plants.

Goal: Identify the technical readiness, performance limits, capital and installation costs, and expected thermal and parasitic losses of one or more horizontal particle conveyance designs in commercial-scale CSP systems.



Hot Particle Skips

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Ducts and skips were considered as pathways for lowering particles to hot storage bins in Tower-Integrated TES configuration.

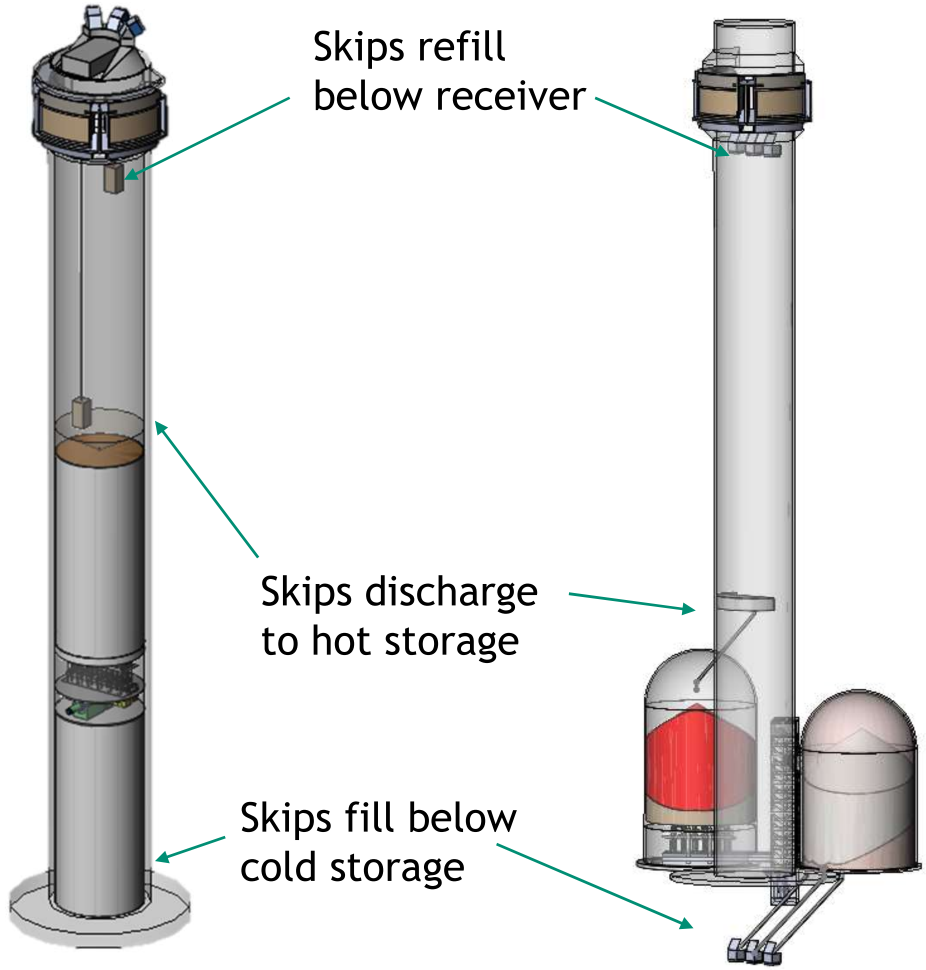
- Ducts require frequent expansion joints and valves to control particle momentum. Distances are ~100 m from receiver to hot storage.
- Hot particle ducts were costed at $2500/m length + $7,500/m for rail support ($1.0M)
- Internal skip cost was $15M including railing but can generate ~$770k/yr using regenerative braking (assumes 68% alternator efficiency) and may be <5% of the heat loss

External TES configuration can easily increase skip size for a second stop to refill below receiver

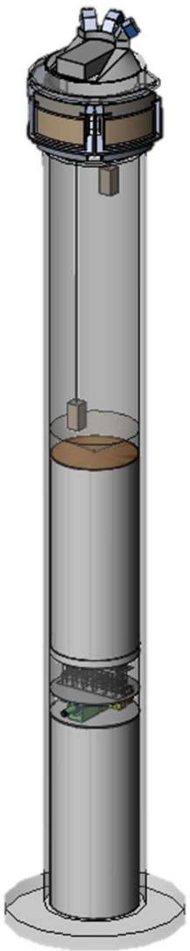
- Skips have been sized for additional time for multiple charges and discharges.
- Motor can be downsized due to the funicular weight offset on the downcoming skip

Particle-based towers must be higher for particle handling

- Receiver height + Feed Hopper + Chutes > 3% higher or $6-$20M



Hot Particle Skips Cost Data



Tower-Integrated TES Configuration

CAPEX

- Primary Skips(2 pairs) = $73 M
- Internal Skips (1 pair) = $15 M

O&M

- Primary Skips (2 pairs) = $0.68 M/yr
- Internal Skips = $0.69 M/yr

Power Consumption

- Primary Skip (2 pairs)
  - Motor Capacity = 13 MW_e
  - Annual Energy = 17,700 MWh_e
  - Annual Cost = $1.24 M
- Internal Skip
  - Motor Capacity = 3.37MW_e
  - Annual Energy Consumed = 0.917 MWh_e
  - Annual Energy Generated = -16.1 MWh
  - Annual Cost = -$0.77 M

Heat Loss

- Primary Skips (2 pair) = 135 kW
- Internal Skip (1 pair) = 70 kW

External TES Configuration

CAPEX

- Primary Skips (2 pairs) = $51.67 M
- Intermediate Skips (1 pair) = $14 M

O&M

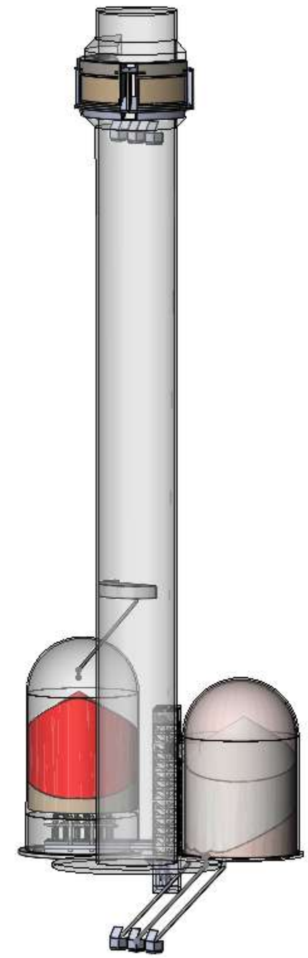
- Primary (2 pairs) = $ 1.5 M/yr
- Intermediate = 0.33 M/yr

Power Consumption

- Primary Skips (2 pairs)
  - Motor Capacity = 13 MW
  - Annual Energy = 12,700 MWhe
  - Annual Cost = $0.888M
- Intermediate Skip (1 pair)
  - Motor Capacity = 3.3 MW
  - Annual Energy Consumed = 8,260 Mwh_e
  - Annual Energy Generated = 0
  - Annual Cost = $0.58

Heat Loss

- Primary Skips (2 pair) = 88 kW
- Intermediate Skip = 23 kW



Storage Bin Modifications

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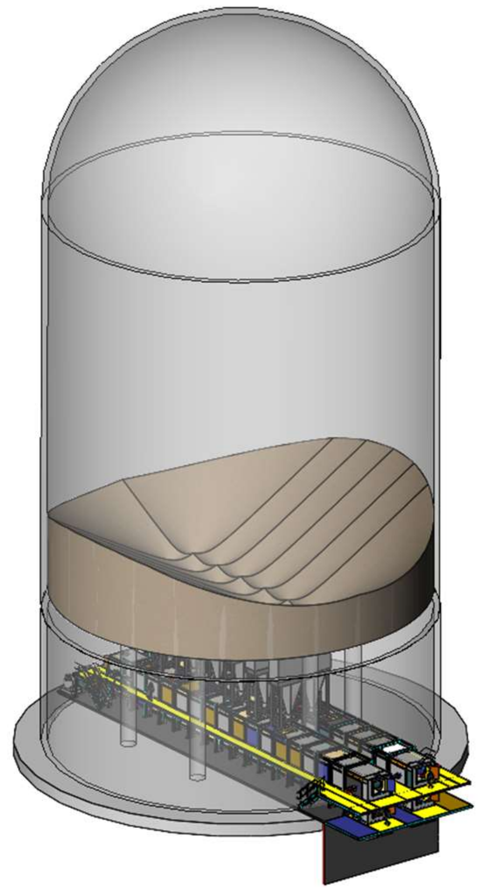
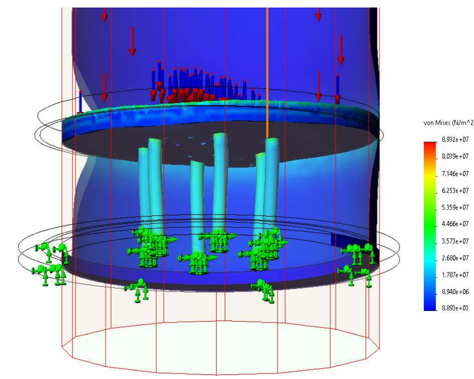
Conveyance Over Heat Exchanger

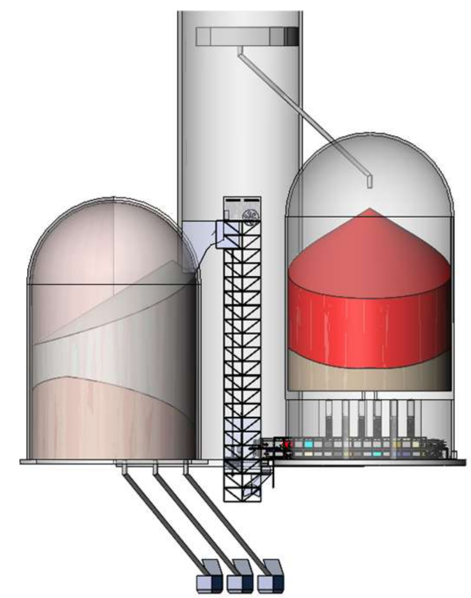
- Belt, pan, and drag conveyors were investigated
- Technologies with steel parts in contact with particles have very low TRL at temperatures >500 °C
- Bypassing the hottest portion by elevating hot storage bin better utilizes existing technologies and is priced similarly to conveyors at the same scale.
- FEA studies show high temperatures dramatically reduce strength. Twenty-one 1.5 m pillars and a 1.8 m thick bin floor may be sufficient to support a 2800 MWh_{th} load.
- Bunker cost $7.3M for 100 MW_e configuration

Formation of stored material

- The system layout lends itself to side loading and unloading.
- Additional materials are needed for increased surface area and for increased stresses







Storage Bin Modifications vs. Chutes

Asymmetric Bin Load Considerations

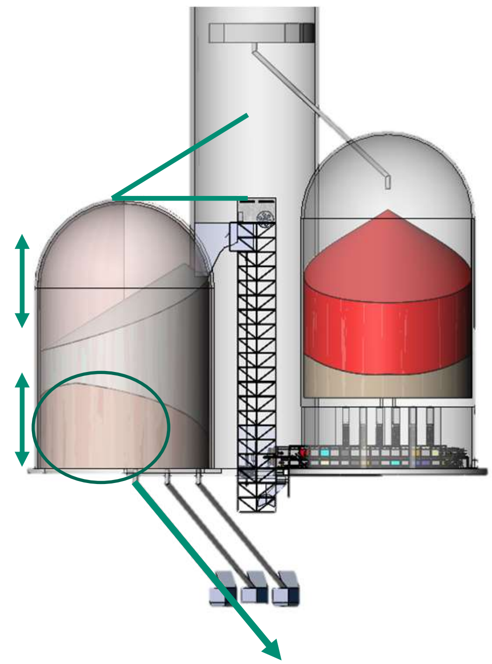
Cost Factors

- Nominal dome cost = $\$861.11/m^2$
- Refractory insulation (material + labor) = $(\$2700 + \$17)/m^3$
- Compensation for asymmetric load
  - 4% increase in concrete + 10 kg/m^3 of additional steel

Symmetric Bin Load Considerations

Cost Factors

- Skip cost for additional height = $64,200/m
- Chute cost per vertical meter = $15,000/m



Case Study A: Asymmetric Cold Bin (100 MW_e) $2.35 M

- Additional height for asymmetric inlet $400k
- Additional height for asymmetric outlet (cold only) = $650k
- Additional flooring material for asymmetric outlet (cold only) = $1.3M

Case Study B: Symmetric Cold Bin with Higher Skips and Ducts (100 MW_e) $3.3 M

- Additional 20m skip height for center inlet $1.58M
- Additional drilling for center outlet = $116k
- Additional cost of refractory chutes for center outlet = $1.6M

Chutes: Testing

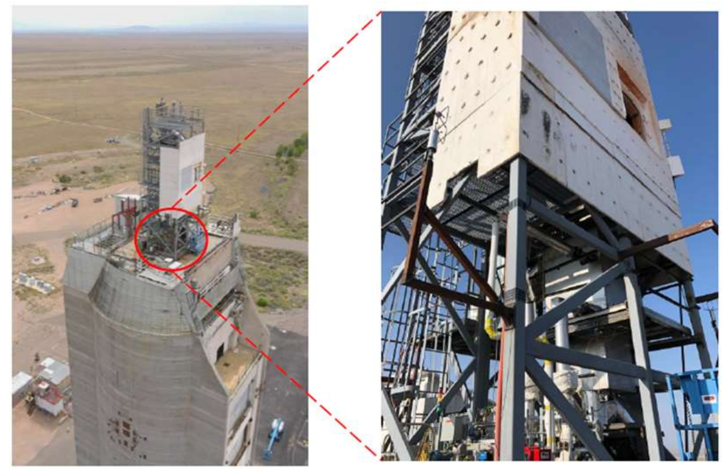
Funded by:

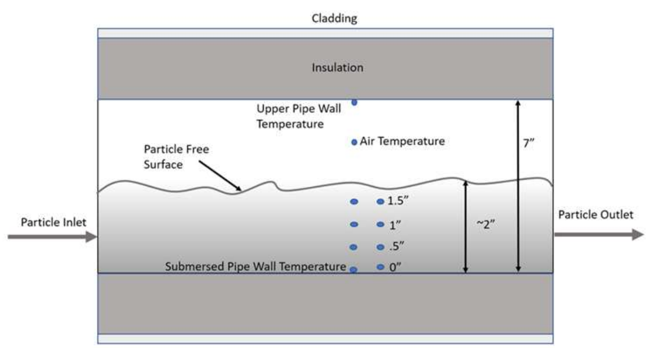
Chutes may be an effective means of handling particles between components. Some uncertainties remain:

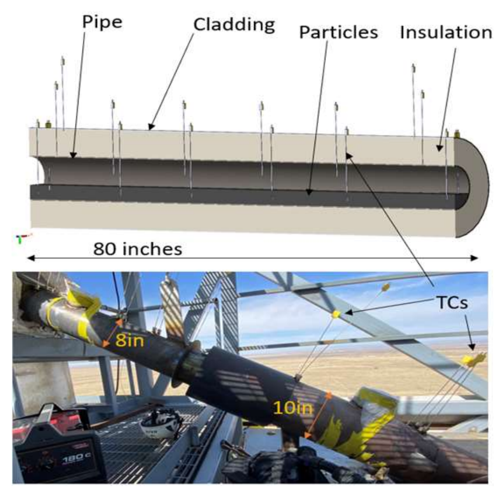
- Large flow rates (2800 kg/s) that must descend over 100 m distances may gain substantial momentum that could impact structures or increase abrasion of ductwork and valves.
- Thermal losses in pipes are difficult to model due to the stratification of temperatures over the flowing bed.
- Particle mixing within pipe may be highly variable

Thermal testing was performed at the NSTTF to evaluate

- average temperature drop over a 2 m length of pipe
- stratification of particle temperatures from the duct surface to top of particle bed.







Test Results

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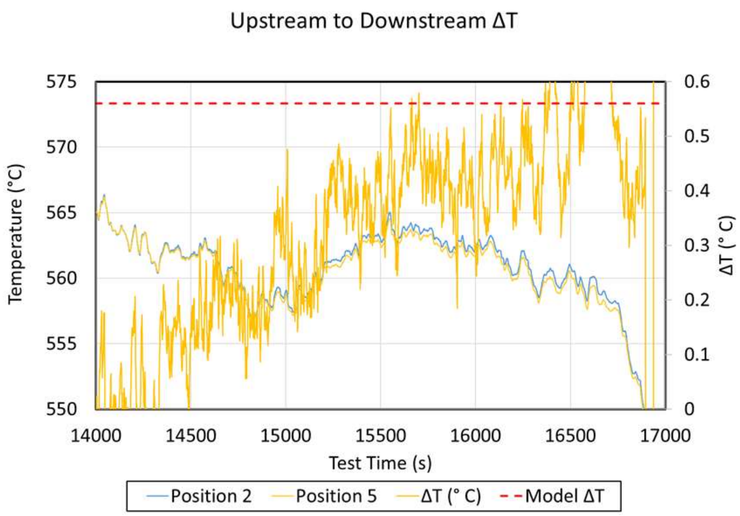
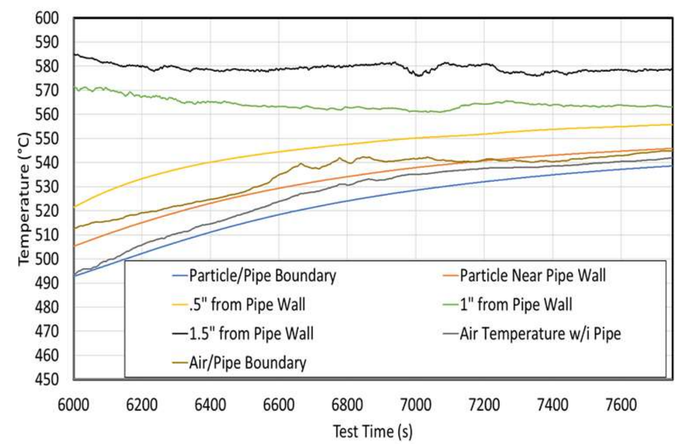
Test 1: Drop in temperature over linear pipe distance

- ~0.4 °C drop over 2m which is less than the 0.75% error associated with K-type TCs

Test 2: Vertical stratification of temperatures in flowing bed.

- 32 °C difference in reading between TCs 38 mm (1.5") apart compared to 3 mm accuracy in TC placement
- System takes about 2 hours to reach equilibrium with duct





Conveyors: Magaldi Ecobelt

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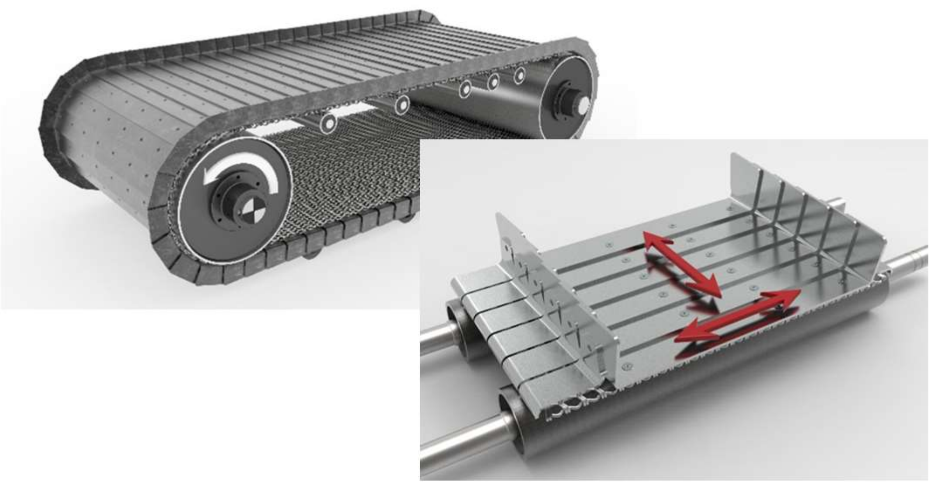
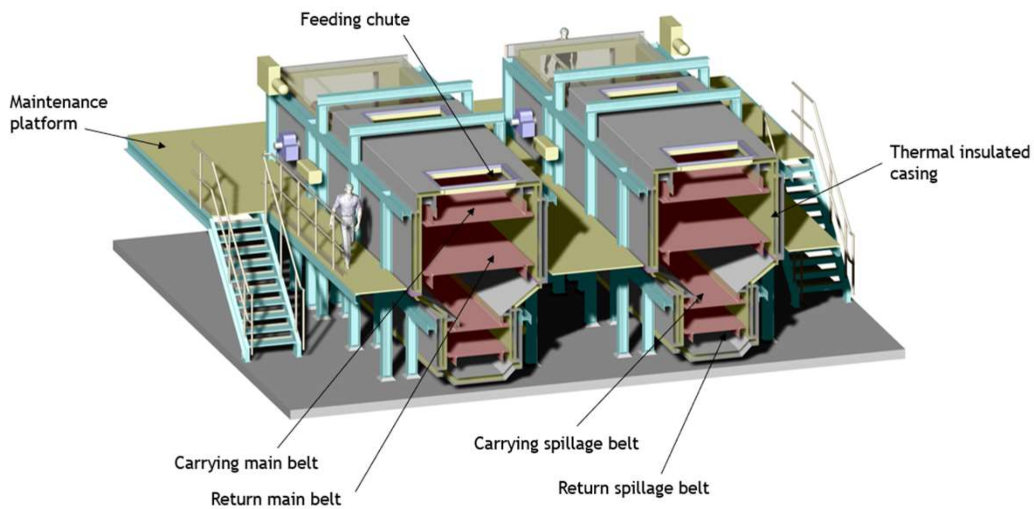
Mechanical conveyance downselect

- Bucket conveyor manufacturers asserted that scaling to 1000 kg/s would be a significant technical leap
- Drag conveyors were not considered due to the single point of failure of the chain linkages immersed in particles at temperatures above the softening point of steel
- Pan conveyors were considered but manufacturers asserted that mechanical cooling would be necessary on surfaces that interacted with particles and could not be insulated with existing designs
- Magaldi Power provides a belt conveyor with overlapping pans (Ecobelt) that can allow bulk particle temperatures up to 640° C
  - Pans float on a metal and ceramic mesh providing for thermal expansion in all directions
  - Cooled rollers, rather than metal pans, carry the load and are thermally isolated from particles by mesh





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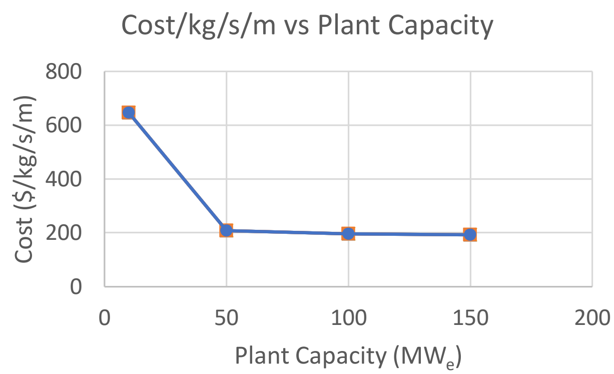
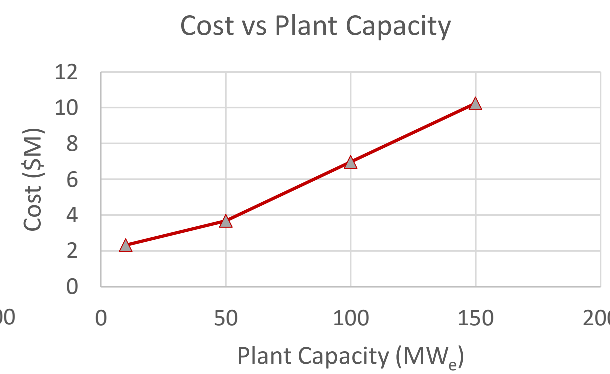
Conveyor Economic Data

Magaldi Power provided design details for the largest Ecobelt at 1800 t/h (500 kg/s) and a small design at 365 t/h (100 kg/s). The design and costs can be numbered up to provide parametric data.

Conveyors on roof may be economical depending on the true cost of the additional tower height.





CAPEX (100 MW_e Baseline)

- 2 1800 t/h Ecobelts $6.97 M

O&M

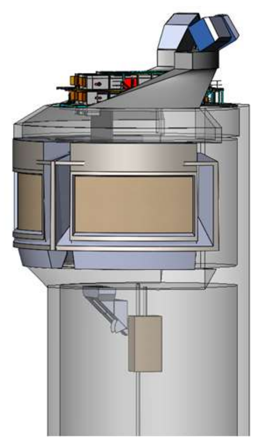
- Spare parts = 2% of CAPEX/yr
- Downtime = 28 hr/yr
- Reliability = 99.5%

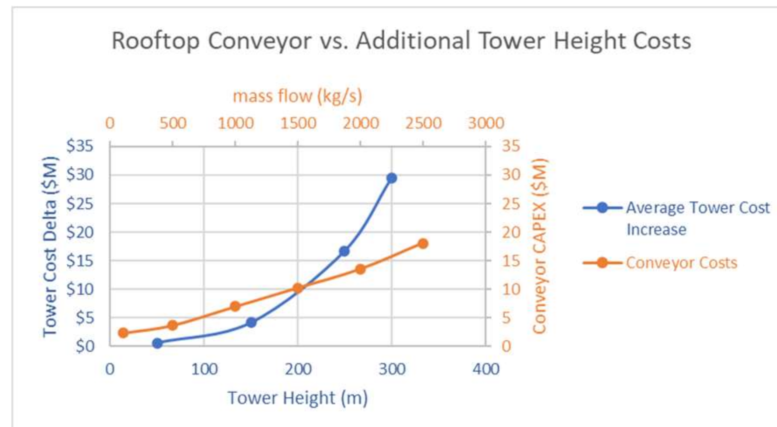
Power Consumption

- Conveyor = 110 kW
- Spillage Conveyor = 15 kW
- Lubrication System = 6 kW
- Belt take-up system = 11 kW

Heat Loss

- Conveyor = 1358 kW
- Vent air = 830 kW
- Material temperature drop under hot storage = 1.8° C





MAGALDI POWER – DOUBLE DECK ECOBELT

Cost Summary

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Additional refinement of cost models is necessary to find cost range but initial point estimates for a 100 MW_e system shows:

- Conveyance capital costs may be on the order of $125M at the lower bound
- Both system configurations have similar costs

	External TES Configuration						Tower-Integrated TES Configuration					
Pathway	CAPEX ($M)	O&M/yr ($M)	Electricity/yr ($M)	Peak Electrical Power (kW)	ΔT (° C)	Heat Loss (kW)	CAPEX ($M)	O&M ($M/yr)	Electricity ($M/yr)	Peak Electrical Power (kW)	ΔT (° C)	Heat Loss (kW)
Chutes from Primary Skip to Receiver (+tower height)	$8.27	$0.00	$0.00	0	0.5	757	$6.92	$0.00	$0.00	0	1.1	
Skips to Receiver	$51.7	$1.49	$0.89	13	3	88.2	$73.3	$0.68	$1.24	13	2.3	135
Hot Storage Bin Modifications	$2.87	$0.00	$0.00	0	30	1280	$0.00	$0.00	$0.00	0	30	1280
Ecobelt	$6.97	$0.14	$0.09	142	1.8	2.19	$0.00	$0.00	$0.00	0	0	
Auxilliary Skip (Intermediate or Internal)	$13.7	$0.33	$0.58	3300	1.1	23.1	$15.08	$0.69	($0.77)	1745	1.07	69.6
Cold Storage Bin Modifications	$1.92	$0.00	$0.00	0	20	886	$0.00	$0.00	$0.00	0	20	886
Chutes from Cold Storage to Primary Skip	$6.31	$0.00	$0.00	0	0.5	757	$0.09	$0.00	$0.00	0	0	
Total ($M)	$91.7	$1.97	$1.55	3460	56.90	3790 kW	$95.40	$1.37	$0.46	1760	54.47	2370 kW
Grand Total ($M)	$91.65 + $3.52 * yr						$95.41 + $1.84 * yr					

Levelized Cost of Electricity

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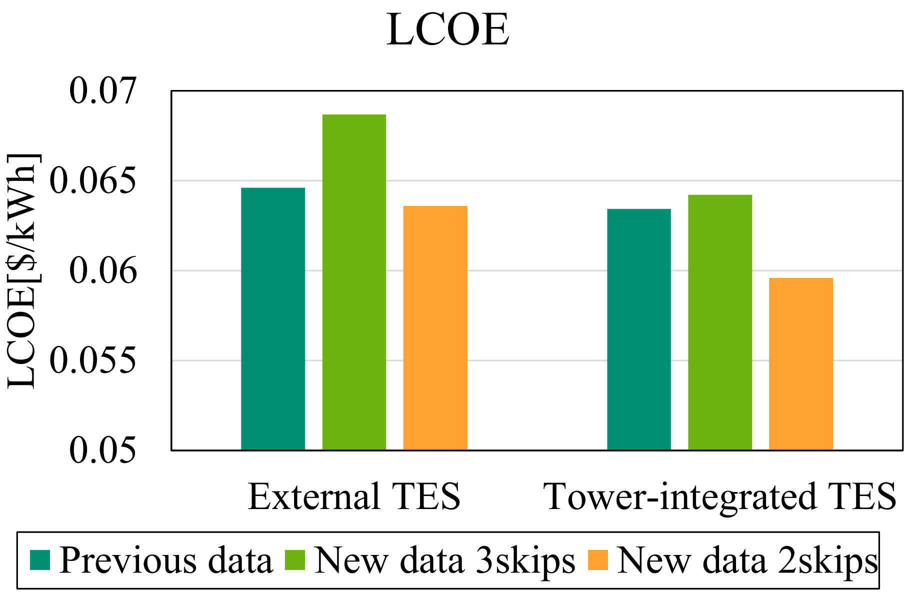
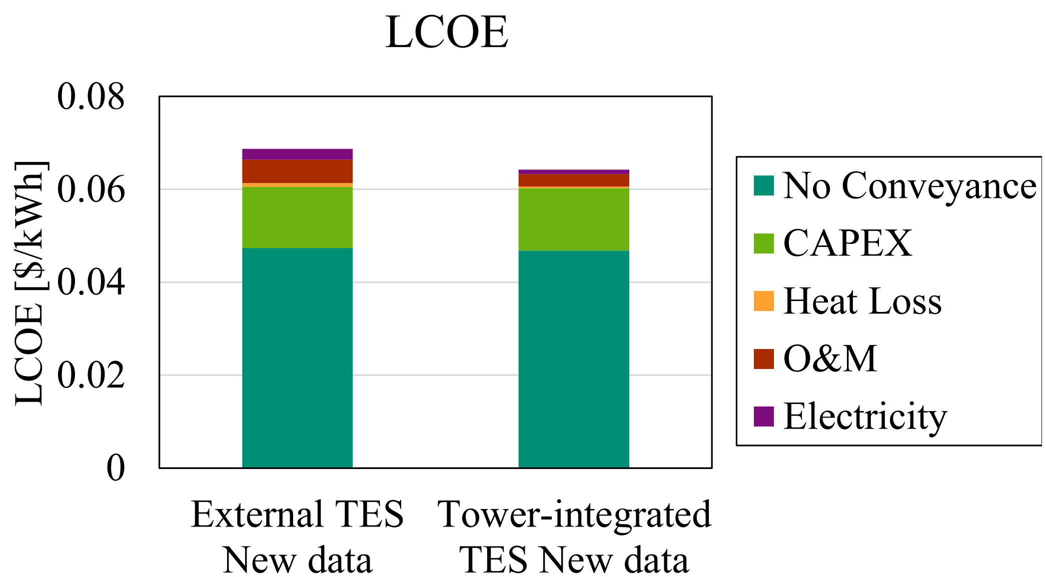
LCOE Analysis from previous work (González-Portillo, Albrecht) was re-run with new cost data for inter-component conveyance.

- Preliminary results show LCOE may be slightly higher than previously assumed, but design details revealed the mass flow could be handled by two skip pairs vs. three as had been assumed.
- Preliminary results show that LCOE is sensitive to conveyance cost factors
- Future work will refine the cost data and thermal losses and inform most cost-effective design choices





Summary and Conclusions

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SETO Lab Call explored costs and feasibility of many common options for particle handling including skips, conveyors, and chutes.

LCOE may be sensitive to costs associated with particle handling systems.

Mechanical conveyance options were found to be limited to <640° C

- Vertically integrated hot storage and HX may be feasible
- Ecobelt is viable after the heat exchanger and potentially on roof of tower

Funicular and regenerative skip designs may reduce electricity consumption and thermal losses that pay for the increased capital costs after several operational years

Thermal losses in chutes have high uncertainty. Testing shows a qualitative drop over 2 m length but drop is small relative to measurement uncertainty.

Acknowledgments

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Thank you