CSP integration for high temperature processing with heat storage and its techno-economic assessment

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We present a novel approach for estimating the minimal levelised cost of heat (LCOH) required to continuously provide hot air, at temperatures exceeding 1000°C, to an industrial process. This approach involves a sophisticated solar thermal plant with a packed bed thermal storage system. A dynamic model, employing 10-minute time intervals solar input data over a full year, is utilised to optimize this process. The model encompasses various sub-models that account for the entire solar plant, including seamless integration with the industrial process. This entails the incorporation of the heliostat field, solar receiver, storage system, heat recovery mechanism, and thermal transmission system. Notably, the simulation captures not just thermal power, but also comprehensively monitors the temperature and mass flow rate of the heat transfer medium at each time-step. While individual sub-systems are simulated independently, they remain interconnected, exchanging information at each time-step. To ensure uninterrupted heat supply to the industrial process, a contingency plan is integrated in the form of a backup heater. The backup heater is also modelled to be directly after the storage before the thermal transmission system. Therefore, the discharging cycle can be maintained at a constant temperature without experiencing the thermal cycle and hence its related issues, discussed by Nathan,et al. [1]. On the other hand, both of the thermal storage and transmission are operated for 24 hours a day, hence more sub-systems for the heat losses. The effect of the design and performance of these 2 systems on CSP system with this configuration were not known, and hence it is addressed in this work.

Figure 1 presents a diagram of the entire system that was modelled. The heliostat field was modelled with the CSIRO's Heliosim and it provided a transient concentrated solar input to the open solar cavity receiver. The details of each subsystem can be found in a previous study [2, 3]. Instead of using a regular mid temperature reciver [4], a Solar Expanding-Vortex Particle Receiver (SEVR) [5] was used. It converts the solar into thermal energy to charge the storage system to above 1000 °C. However, this type of system requied to operater around atmosphere pressure. Therefore, instead of directly pumping the return air back to the receiver, to balance the pressure, the air discharged from the system is used to heat the fresh air in the heat recovery system, which is then sent back to the solar receiver. The receiver, heat recovery, and storage systems form the charging cycle of this system. On the discharge cycle, the heated air from the storage is heated by the backup combustion heater to ensure uninterrupted supply to the process demand after the thermal transmission system.

A case study for targeting retrofit into an existing bayer alumina process which required at 1100 °C of hot air and return air at 600 °C. There are six 20MW requirements for the demand, hence 20 to 120MW of thermal power is used for the assessment with a 150 MW of solar input to the solar receiver, hence it simulates a range of solar multiples from 1.25 - 7.5. The effect of the storage capacity and effectiveness of the thermal storage on the overall solar share SS and levelised cost of heat (LCOH) are also assessed.

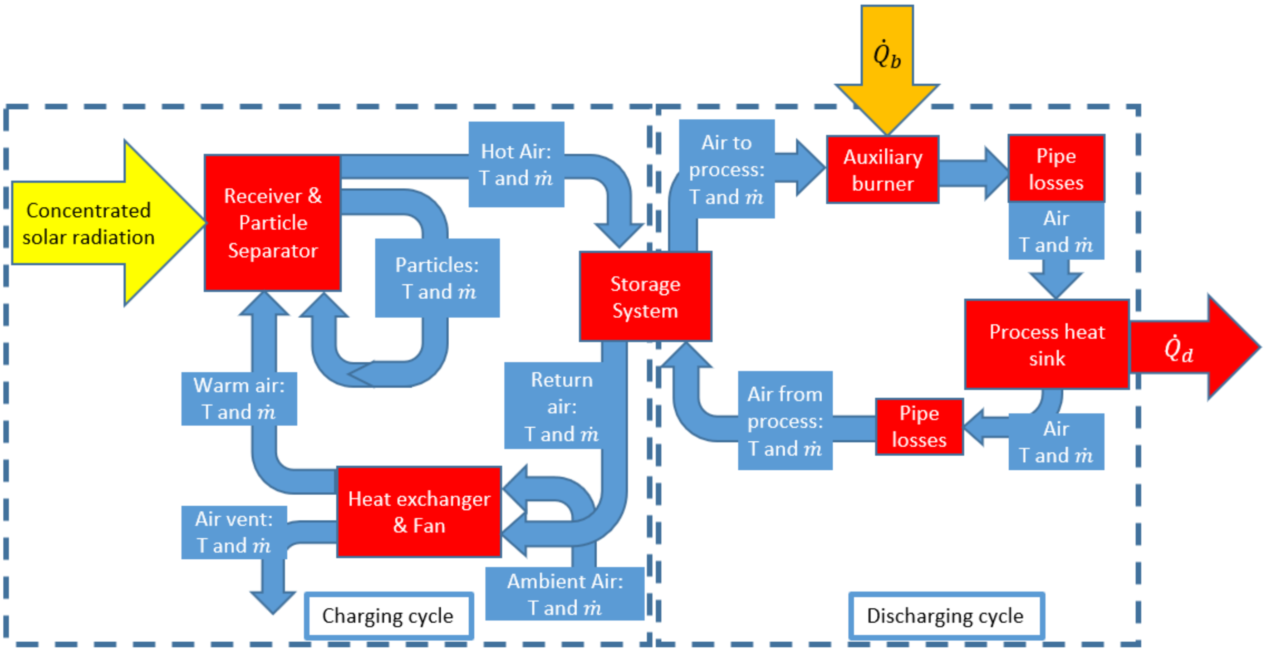

Figure 1. Schematic diagram of the CSP model and the interactions between the sub-models.

The levelised cost of heat could be increased a lot if the effectiveness of the transmission η_{tr} is too high (too much thermal insulation is used). For a 60 MW transmission system with 1100 °C, the lowest LCOH is observed for a transmission system with 98% effectiveness, shown in Figure 2.

Figure 3 shows that, increasing the effectiveness of the thermal storage SOC_{24} increase the annual solar share, due to higher overall effiency of the system. The effectiveness of the thermal storage is affected by the design, hence the cost (size and material/ insulation used). For a given solar scale of 150 MW and solar multiple 2.5, the optimised normalised 24 hours effectiveness of the thermal storage is 60% with 4 hours of thermal storage capacity of the demand.

The study shows that for a 150MW solar input system, the annual solar share is reduced by about 30% for the solar multiples reduced from 2.5 to 1.25 (50%). Similar behaviors can be observed for the LCOH, shown in Table 1.

It suggested the LCOH for retrofitting CSP into an existing 60MW process providing hot temperatures air at 1100 °C with 1km apart to be ~35 USD/GJ with solar share of 35% and solar multiple of 2.5 based on current manufacturing costs in Australia. Even lower LCOH can also be done with a lower solar multiple system, however, the solar share is reduced.

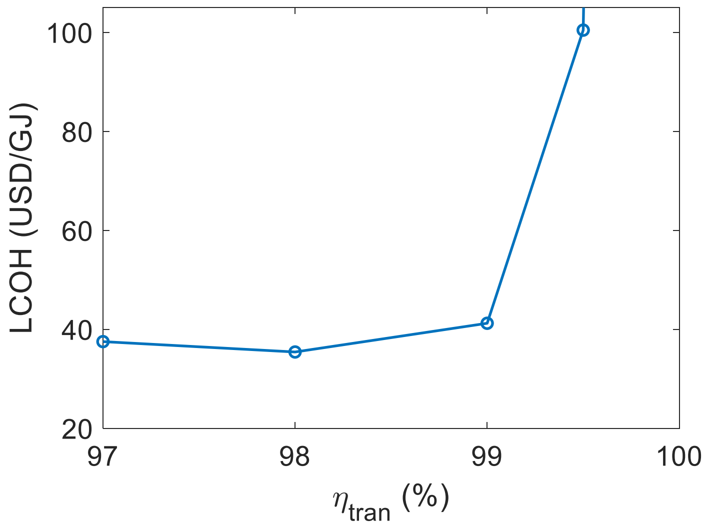

Figure 2. The dependence on effectiveness of the thermal transmission system on the Levelised Cost of Heat (LCOH) for a 150MW thermal input to the receiver CSP system with 4 hours of storage capacity for the demand of 60 MW.

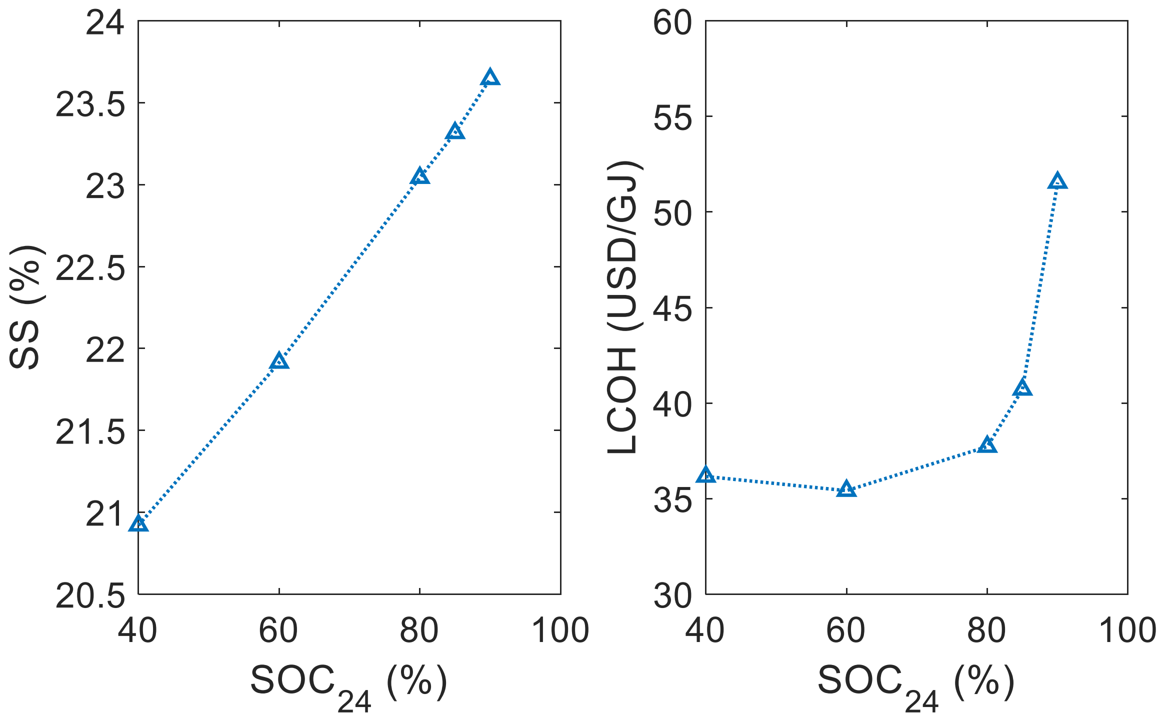

Figure 3. The dependence on normalised 24 hours effectiveness of the thermal storage of the solar share (left) and Levelised Cost of Heat (LCOH) (right) for a 150MW thermal input to the receiver CSP system with 4 hours of storage capacity for the demand of 60 MW.

Table 1 Effect of solar multiple on the solar share and LCOH.

$Q_{solar,DP}$ (MW)	150	150	150	150
$Q_{demand,out}$ (MW)	60	80	100	120
Solar multiples $Q_{solar,DP}/Q_{demand,out}$	2.5	1.875	1.5	1.25
Annual solar share (%)	35	29	25	23
LCOH (USD/GJ)	35	29.5	27.5	25

Table 2 List of key variables

SS	$Solar\ Share\ (\%)$ $$SS = \frac{E_{ann,CST}}{E_{ann,d}} = \frac{\int \dot{Q}_d - \dot{Q}_b dt}{\int \dot{Q}_d dt}$$
η_{tr}	Design effectiveness of the thermal energy transmission system. (%) $$\eta_{tr} = \frac{\dot{Q}_{pipe,out}}{\dot{Q}_{pipe,in}}$$
SOC_{24}	Effectiveness of storage at design point, calculated as the state of charge (%) of the storage after idle for 24 hours (effected by the insulation thickness) $$\mathrm{SOC}_{24} = \frac{\dot{E}_{stor,24}}{\dot{E}_{stor,full}}$$

References

1. Nathan, G.J.G., L. Lee, P. Ingenhoven, Z. Tian, Z. Sun, A. Chinnici, M. Jafarian, P. Ashman, D. Potter, and W. Saw, "*Pathways to the use of concentrated solar heat to drive high temperature industrial processes". *Solar Compass: p. 100036, 2023.

2. Ingenhoven, P., L. Lee, W. Saw, M.M. Rafique, D. Potter, and G.J. Nathan, "*Techno-economic assessment from a transient simulation of a concentrated solar thermal plant to deliver high-temperature industrial process heat". *Renewable and Sustainable Energy Reviews, **185 (2023): 113626**, 2023.

3. Ingenhoven, P., W. Saw, M.M. Rafique, D. Potter, A. Chinnici, M. Jafarian, K.L. Lee, and G.J.G. Nathan. *Energetic Assessment of a High Temperature Packed Bed Storage System in Combination with a Solar Expanding-Vortex Particle Receiver*. in *Solar World Congress 2021*. 2021. International Solar Energy Society.

4. Lee, K.L., A. Chinnici, M. Jafarian, M. Arjomandi, B. Dally, and G. Nathan, "*The influence of wind speed, aperture ratio and tilt angle on the heat losses from a finely controlled heated cavity for a solar receiver". *Renewable Energy, **143**: p. 1544-1553, 2019.

5. Ang, D., A. Chinnici, Z.F. Tian, W.L. Saw, and G.J. Nathan, "*Influence of particle loading, Froude and Stokes number on the global thermal performance of a vortex-based solar particle receiver". *Renewable Energy, **184**: p. 201-214, 2022.DOI: https://doi.org/10.1016/j.renene.2021.11.042.