Techno-economic assessment of the storage value of a novel modular Beam-Down Receiver CSP plant in Australia

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Introduction

CSP has been repeatedly proposed as an interesting addition to the renewable energy mix in countries with high DNI regions, as it can be a reliable dispatchable generator. However, its high generation cost compared with other available alternatives has deterred its deployment. New technologies like supercritical CO_2 power cycle and solid particle heat transfer mediums are lowering these costs. Additionally, Beam Down Receivers (BDR) can be a suitable option to link these two ideas in a simple modular design. To explore this concept, this research is split into four main tasks: characterise the system's optics, propose a novel receiver design and assess its performance, optimise the thermal energy collection subsystem, and analyse the energy dispatch performance for the proposed plant.

In previous works (Saldivia et al., 2021), the optics of the BDR concept were analysed. Additionally, two different concepts for a ground-located solid medium receiver were modelled and assessed: a dual receiver-storage unit (Saldivia and Taylor, 2019) and a horizontal particle receiver (HPR) (Saldivia and Taylor, 2021). The second design was found more suitable for power generation, and its main plant parameters were optimised to minimise the Levelized Cost of Heat (LCOH). Thus, the present work aims to cover the last task of the project: explore and identify the main parameters that affect the economic performance of this proposed plant. Three aspects will be covered: the influence of the power block configuration, the influence of Australian weather and geographic conditions, and the influence of the Australian energy market (NEM).

Methods

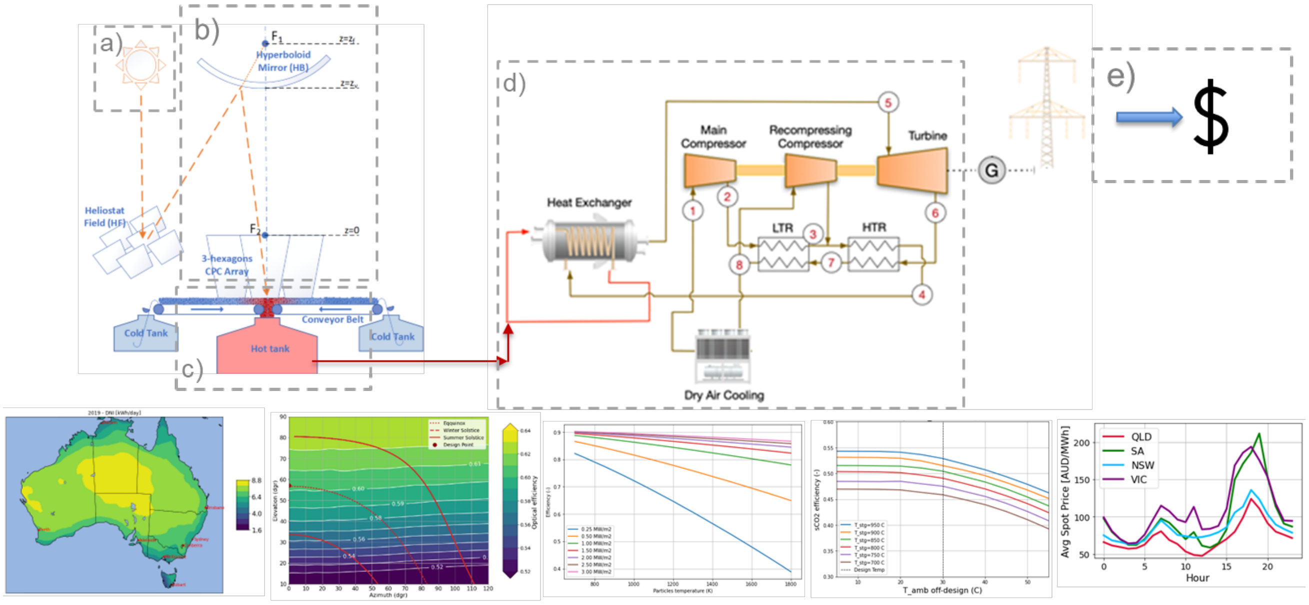
The general scheme of the proposed plant is shown in Figure 1. The main characteristics of the design (Saldivia and Taylor, 2021) are presented in Table 1. The plant performance is assessed throughout the year; therefore, solar field, receiver thermal, and power cycle thermal efficiencies are required for any possible operation state. The solar field optical efficiency is defined as a function of elevation and azimuth angles. The receiver thermal efficiency depends on the average particle temperature, ambient temperature, and radiation flux. The power block cycle efficiency is a function of turbine top temperature and ambient temperature. Solar field and receiver efficiencies are calculated as presented in the authors' previous works (Saldivia et al., 2021; Saldivia and Taylor, 2021), while power block efficiencies are obtained from a python package available in the literature (Neises, 2020). To ensure a quick simulation, efficiencies for the range of possible inputs are calculated initially, and linear interpolation is carried out using these results.

Table 1. Main parameters of the optimised thermal subsystem of BDR CSP plant

Tower height	35m	Receiver Area	11.8 m^2
Receiver Thermal Power	10.0 MW_{th}	sCO_2 top temperature	900°C
Receiver Avg. Rad. Flux	1.0 MW/m^2	Total mirror surface	22 220 m^2

The weather data is extracted from MERRA2 reanalysis datasets for Australia (Global Modeling And Assimilation Office and Pawson, Steven, 2015, p. 2). The main parameters required as DNI and ambient temperature. DNI is estimated from GHI values using DISC method from PVlib library

(F. Holmgren et al., 2018). The spot prices from NEM are obtained using Nemosis package (Gorman et al., 2018). The analysis in this work is done using 2019 data, as this is the last full year pre-pandemic. A simplified dispatch strategy for the plant is developed to capture the storage value of CSP. It is modelled assuming perfect weather and spot price forecasts for the next 24 hours. For each day (starting at sunrise), the expected collected thermal energy for the sun hours is calculated, and then the most profitable dispatch periods are selected, to maximise the revenue. Physical constraints such as storage capacity are imposed at any time. For simplicity, it is assumed that the plant sells 100% of the energy in the spot market (no PPA involved), it is considered a price-taker, and no other revenue streams -such as LGCs or FCAS- are included.



a) Weather data b) $\eta_{SF} = \eta(\alpha, z)$ c) $\eta_{rcv} = \eta(T_p, T_{amb}, Q_{in})$ d) $\eta_{PB} = \eta(T_{hot}, T_{amb})$ e) Spot Prices

Figure 1. Schematic of the CSP plant and its main subsystems and input data. a) Weather data, b) solar field optical efficiency, c) receiver thermal efficiency, d) power cycle efficiency, and e) spot prices in NEM.

Results and Discussion

The first parameters to analyse are the storage capacity (T_{stg}, in hours of nominal power cycle operation) and the solar multiple (SM), which measure the relative size between thermal and power generation subsystems. Figure 2 shows the financial results for the selected design in a high-DNI location in South Australia (SA, lat=-27°;lon=132.5°). The levelized cost of electricity (left) and Payback period (right) are selected as performance parameters. Both curves follow similar trends, with an optimal SM for each T_{stg}; however, using LCOE tends to identify larger plants (bigger storage size and SM). The main difference is that LCOE does not depend on spot price values but only on the generation capacity. The minimum payback period is around 14 years for a solar multiple between 2.0 and 2.5 and a storage capacity between 10 to 12 hours. SM=2.0 and T_{stg}=10hrs will be used for the upcoming analysis, although it is important to note that these values might change if a different location is selected.

The influence of weather conditions and spot market prices is assessed in Australia. Each location is assigned to its respective spot market region with available transmission lines to the main grid. Additionally, the Northern Territory (NT) location uses the SA prices, while Western Australia is not included in this analysis. Figure 3 shows the results for power generation (left), revenue (centre) and payback period (right). In the simplified dispatch model, generation depends only on weather conditions, so the central part of Australia has better results, as expected. If the different spot markets are included, the revenue and payback period differences between regions become more relevant. South Australia and Victoria markets are more favourable for CSP plants because of their steeper curves in evening and morning peaks (effect known as the "duck curve", as shown in Figure 1.e)), while Queensland and NSW hardly make the plan profitable (PB<30yrs). It is well known that steeper curves (like SA and VIC ones) are expected in the future if the energy mix is transitioning towards a high-penetration renewable mix.

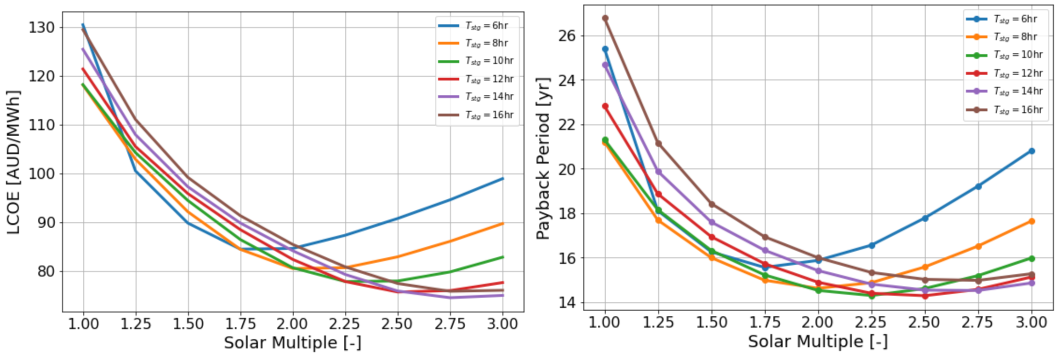


Figure 2. LCOE (left) and Payback period (right) for different solar multiple and thermal storage capacities.

The influence of spot price curves and the "duck curve" phenomenon is explored in more detail. The 2019 data for four states (SA, QLD, NSW, VIC) is split into quarters and between weekdays and weekends to reflect the variability of price profiles. The resulting 32 subsets are averaged hourly, and a Fourier series curve fitting is done for each case. It is found that the curve can be characterised by the 0th, 1st, and 2nd harmonic amplitudes (called A_0, A_1, and A_2, respectively). Three quantities that represent the average value ($P_0=A_0$), evening peak ($P_1=A_0+A_1+A_2$), and morning peak ($P_2= A_0+A_1-A_2$) are then defined. For each of these subsets, the daily average revenue is calculated, and the results are presented in Figure 4. As expected, a linear trend is found for each parameter. However, surprisingly, a more substantial relationship is found for the morning peak than the evening one. A possible explanation for this is because the evening peak will be chosen nevertheless, as it is the most profitable period. In contrast, the morning peak would only be chosen if it is high enough and there is enough stored energy in the previous night. Further exploration of these results for different combinations of storage capacities and solar multiples would be of interest too.

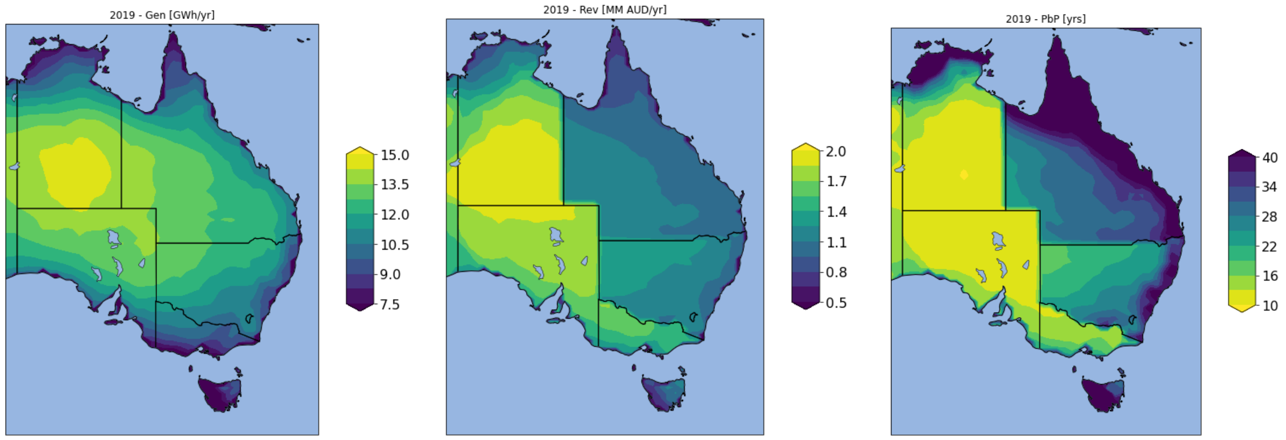


Figure 3. Performance results for the proposed plant in Australia. (left) Annual generation (in GWh); (centre) annual revenue (in MM AUD); (right) Payback period (in years)

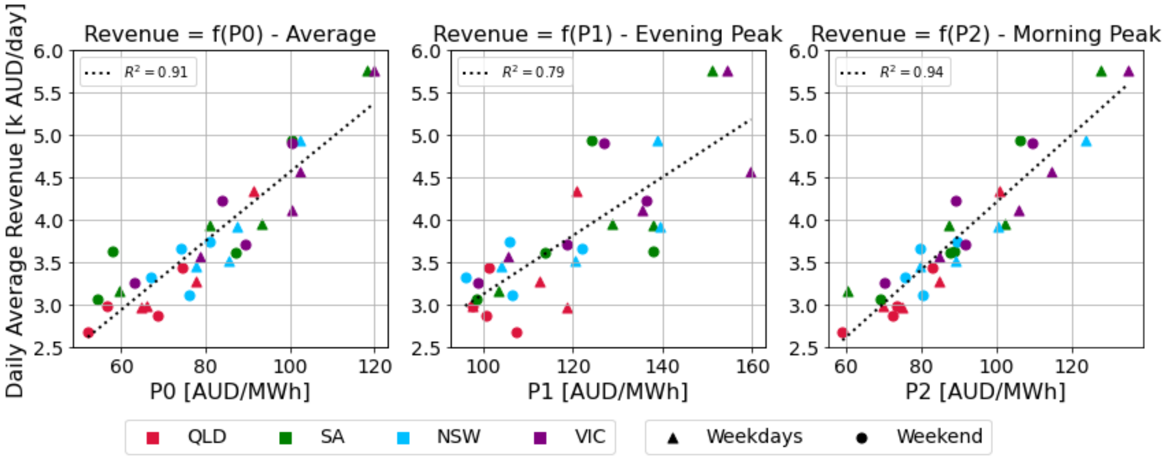


Figure 4. Daily Average revenue for price subsets as functions of average (P_0, left), evening peak (P_1, centre), and morning peak (P_2, evening).

Conclusion

A design for a small modular CSP plant using BDR is proposed. The performance of this design under real weather and energy market conditions is assessed. The main power block parameters are studied (storage capacity and solar multiple), and an optimal case is found. The influence of weather and spot markets is then evaluated. A strong relationship between potential revenue and the shape of spot curves is found, which might strongly affect the plant revenue sufficiency of potential projects. Future works include additional physical constraints to the geographic analysis, such as transmission line proximity, topography, and protected areas. Finally, the relation between the price curve shape and the renewable penetration in the energy mix will be studied, and therefore the impact of different energy mix scenarios on CSP economic performance.

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