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Techno-economic analysis of supercritical carbon dioxide power blocks

Mehdi Aghaeimeybodi (CSIRO), Andrew Beath (CSIRO), Stephen Gwynn-Jones (UQ), Anand Veeraragavan (UQ), Hal Gurgenci (UQ) and Kamel Hooman (UQ)

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Delivery of low cost electricity from Concentrated Solar Thermal (CST) power systems relies on reducing the cost and improving the performance of multiple plant items from the solar collection system through to the power block. An overall analysis of the entire system identifies that the power block is typically the lowest efficiency component of the plant and, therefore, has a considerable impact on the size of all other components. Therefore, a key target for reducing the size and cost of CST plants is the introduction of high efficiency power blocks. Supercritical CO2 has been proposed as a new working fluid for power blocks and has been demonstrated to provide equivalent or higher cycle efficiency than supercritical or superheated steam cycles at temperatures and scales relevant for Australian CSP applications.

Power block performance and cost

In this analysis, four 25 MWe power blocks are used in parallel to produce 100 MWe total electrical power. Each analysed power block is a sCO2 Brayton recompression cycle. Cases are analysed for power plants with turbine inlet temperatures of 560, 610, 700 and 1000 °C to show system costs over a wide operating range. Table 1 shows the estimated cycle efficiency for the four studied cycles.

Table 1: sCO2 cycle efficiencies

Turbine inlet temperature	Cycle efficiency
560 °C	45.7%
610 °C	48.0%
700 °C	51.4%
1000 °C	60.4%

Other than the turbine, all major components to be used in the supercritical CO2 power block are currently available in the market in some form. Therefore, the cost estimation methods for the non-turbine components are based on real costs with appropriate scaling or justification for their use as necessary. This leaves only the turbine cost to be estimated solely via the methodology drawing on both industrial and academic knowledge base. Table 2 shows the total power block capital cost.

Table 2: Total power block capital cost

Inlet cycle temperature	560 °C	610 °C	700 °C	1000 °C
Total Power Block Capital Cost ($A million)	37	36	53	109

Monte Carlo simulation

The power block efficiency determines the required thermal input to produce a nominal electricity generation target and the cost of supplying this thermal energy will be a major contributor to the overall cost effectiveness of electricity generation from a CST power plant, typically defined as the levelized cost of electricity (LCOE). In the terms of ASTRI, there is an ultimate target LCOE of 12c/kWh, but there are also a range of other targets that are desirable to achieve for the total capital cost, operating and maintenance, capacity factor and annual plant efficiency. By establishing the general target ranges for the different plant components within ASTRI it is possible to undertake a statistical analysis (Monte Carlo simulation) to determine if the overall plant performance is to meet the final ASTRI targets. Table 3 provides summary of ASTRI target and Table 4 shows the assumed ranges for capital cost (CapEx), operating and maintenance (OpEx) and efficiency for five main plant areas.

Table 3: Summary of ASTRI technical KPIs

ASTRI Year	Capital Expenditure ($m)	Annual Operating & Maintenance ($/kW/y)	Capacity Factor (%)	Annual Efficiency (%)	LCOE (c/kWh)
1	738.0	80.0	36.1	13.0	26.5
2	738.0	80.0	37.9	14.0	25.0
3	664.2	75.0	39.7	15.0	21.5
4	627.3	70.0	41.5	16.0	19.5
5	590.4	65.0	43.3	17.0	17.5
6	553.5	60.0	44.4	17.5	16.0
7	501.9	55.0	45.5	18.0	14.0
8	442.8	50.0	46.9	18.5	12.0

Table 4: Assumed ranges for CapEx, OpEx and Efficiency for different major plant components

Component	Minimum	Likely	Maximum	Units
CapEx – Site	15.0	20.0	21.0	$/m^2$
CapEx – Field	90.0	120.0	150.0	$/m^2$
CapEx – Receiver-Tower	129.6	160.0	284.5	$/kW_{th}$
CapEx – Storage	15.5	30.0	50.0	$/kWh
CapEx – Power Block & BOP	Varies depending on temperature			$/kW_e$
OpEx – Site	0.10	0.11	0.12	$/m^2$-y
OpEx – Field	1.12	1.24	1.37	$/m^2$-y
OpEx – Receiver-Tower	0.40	0.44	0.49	$/kW_{th}$-y
OpEx – Storage	0.34	0.38	0.41	$/kWh-y
OpEx – Power Block & BOP	Varies depending on temperature			$/kW_e$-y
OpEx – Other	5.63	6.25	6.88	$/kW_e$-y
Efficiency – Site	85.0%	90.0%	95.0%	
Efficiency – Field	55.0%	60.0%	65.0%	
Efficiency – Receiver-Tower	85.0%	90.0%	95.0%	
Efficiency – Storage	90.0%	95.0%	99.5%	
Efficiency – Power Block & BOP	Varies depending on temperature			
Efficiency – Gross:Net	85.0%	92.0%	95.0%	

Results

Table 5 shows the proportion of the cases that meet either individual or all technical KPIs. This analysis highlights that the 610°C power block is the most likely to provide an outcome that meets all KPIs, but also that the major source of non-compliance is through failure to meet the capital expenditure target. In terms of achieving the LCOE target only, both the 610°C and 560°C power blocks result in a reasonably high number of cases that meet this target and the 700°C power block provides some cases. Figure 1 depicts the frequency distribution for plant configurations meeting the LCOE KPI. This analysis clearly indicates that the 610°C and 560°C power block systems are expected to be far more likely to deliver lower LCOE electricity at around the 12c/kWh target.

Table 5: Frequency of compliance with the ultimate ASTRI technical KPIs

Power block	Capital Expenditure	Capacity Factor	Annual Efficiency	Operating & Maintenance	LCOE	All KPIs
560°C	9%	100%	91%	83%	68%	8%
610°C	31%	100%	99%	95%	86%	29%
700°C	0%	100%	100%	100%	18%	0%
1000°C	0%	100%	100%	100%	0%	0%

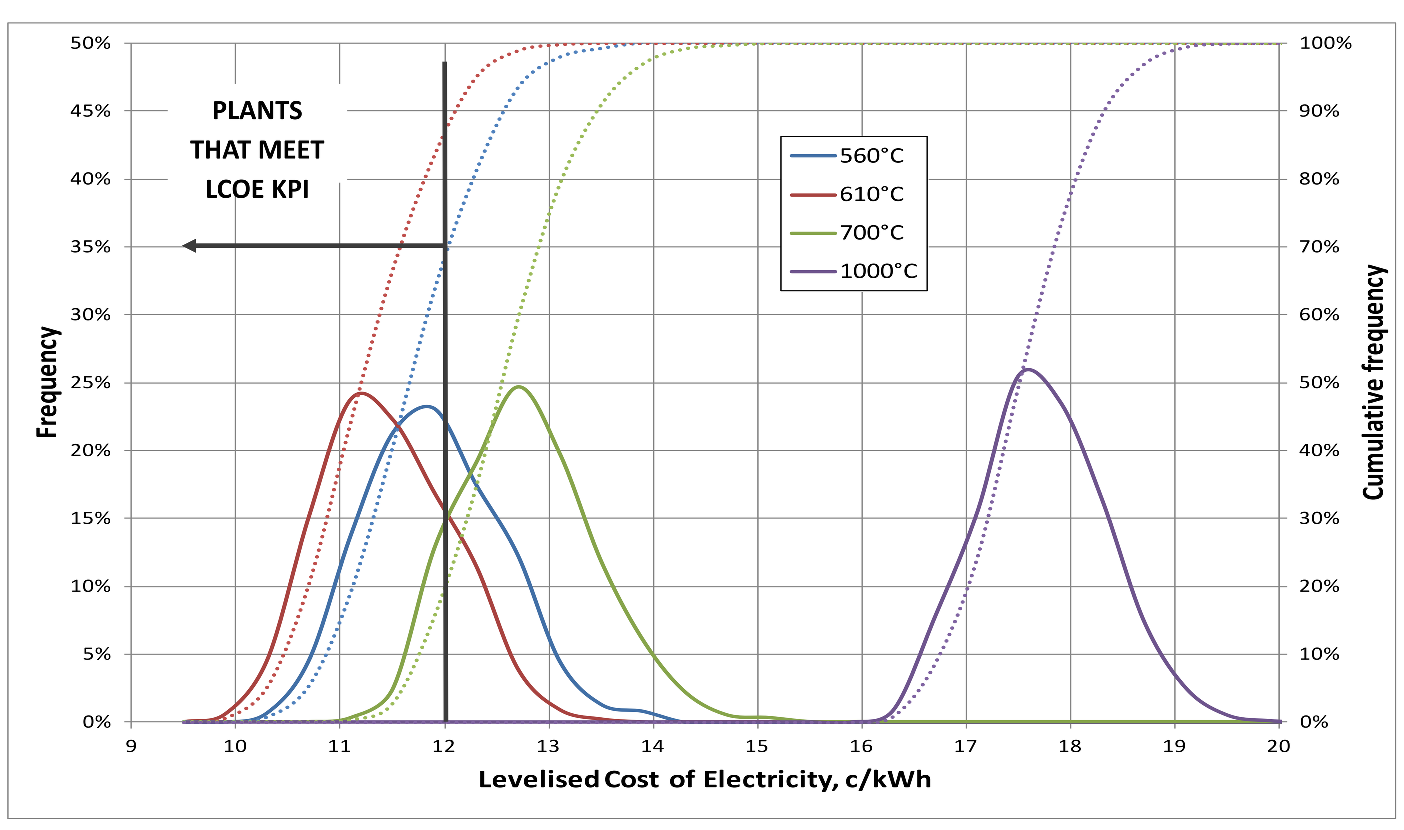

Figure 1: Frequency distribution for LCOE of CSP systems

Summary

This analysis suggests that it is more likely for the plants based on the 610°C power block to achieve all ASTRI KPIs, with the plants based on the 560°C power block having a lower probability, but still potentially being successful.

CSIRO

THE UNIVERSITY OF QUEENSLAND AUSTRALIA

AUTHOR CONTACT
Mehdi Aghaeimeybodi
e mehdi.aghaeimeybodi@csiro.au
w www.astri.org.au

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