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Techno-economic Analysis of Supercritical Carbon Dioxide Power Blocks

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Abstract. Developing highly efficient power blocks holds the key to enhancing the cost competitiveness of Concentration Solar Thermal (CST) technologies. Supercritical CO_2 (sCO_2) Brayton cycles have proved promising in providing equivalent or higher cycle efficiency than supercritical or superheated steam cycles at temperatures and scales relevant for Australian CST applications. In this study, a techno-economic methodology is developed using a stochastic approach to determine the ranges for the cost and performance of different components of central receiver power plants utilizing sCO_2 power blocks that are necessary to meet the Australian Solar Thermal Initiative (ASTRI) final LCOE target of 12 c/kWh.

INTRODUCTION

The overall efficiency of CST power plants is an important factor in reducing the cost of electricity generation, as the technology is capital intensive and improvements in efficiency reduce the overall size of components such as storage, solar field, and receiver. There are limited opportunities for making significant increases in efficiency throughout the plant, as components such as the receiver and storage are already typically in the approximate range of 85-95% and 90-99% thermal efficiency. However, the power block technologies that are typically used in existing CST plants are sub-critical steam Rankine cycles with limited superheat and reheat stages which have a net efficiency of 35-40%. Steam turbines are a robust and well established technology that are noted for having good economies of scale in both cost and performance terms, but are not likely to be cost effective at small scales in CST power plants as they suffer from reduced efficiencies. In practice, electricity generation on a utility scale would typically use steam turbines that are greater than $200MW_e$ output, which would be an impractical size for most potential CST applications in Australia. Therefore, development of alternative power blocks that offer higher efficiency under CST conditions and, preferably, are appropriate for use on a smaller scale is an obvious area for improvement in the next generation of CST power plants.

Supercritical CO_2 (sCO_2) has been proposed as a new working fluid for power blocks, most commonly in closed-loop Brayton cycles, 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. The use of high pressures and only partial expansion in sCO_2 Brayton cycles also promises to offer more compact power blocks. Internationally there is considerable effort being put into development and testing of these new systems, including a project within the Australian Solar Thermal Initiative (ASTRI) that is developing a power block incorporating a radial turbine design. As a new and largely untested technology, it is worthwhile to assess the operating conditions under which the cost and performance of this type of power blocks are optimal when considered the entire CST power plant. In this study a techno-economic analysis of central receiver power plants utilizing sCO_2 power blocks with four different turbine inlet temperatures is conducted to determine the subset of realistic ranges for the cost and performance of the other components of an entire CST plant, such as solar field, receiver and thermal storage, using

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a stochastic approach with the objective of producing a CST plant with an overall LCOE of 12 c/kWh. This value is the ultimate target of the ASTRI research program; therefore, the potential to reach this target determines if the technology selected is appropriate.

POWER BLOCK PERFORMANCE AND COST ANALYSIS

In this analysis, four 25 MW_e power blocks are used in parallel to produce 100 MW_e total electrical power. The recuperated, partial recompression variant of the power block design has been used for all cases operating at a turbine inlet pressure of 20 MPa, but otherwise optimized individually for each case. In order to investigate the effects of higher temperature CST plants, the key parameter is the turbine inlet temperature due to the significant impact on the material cost and performance. Cases are analyzed for power plants with turbine inlet temperatures of 560, 610, 700 and 1000 °C to show system costs over a wide operating range. IPSEpro software package has been used to simulate the four studied cycles. Fig. 1 shows the T-S diagram for the studied cycles and Table 1 provides the estimated cycle efficiencies.

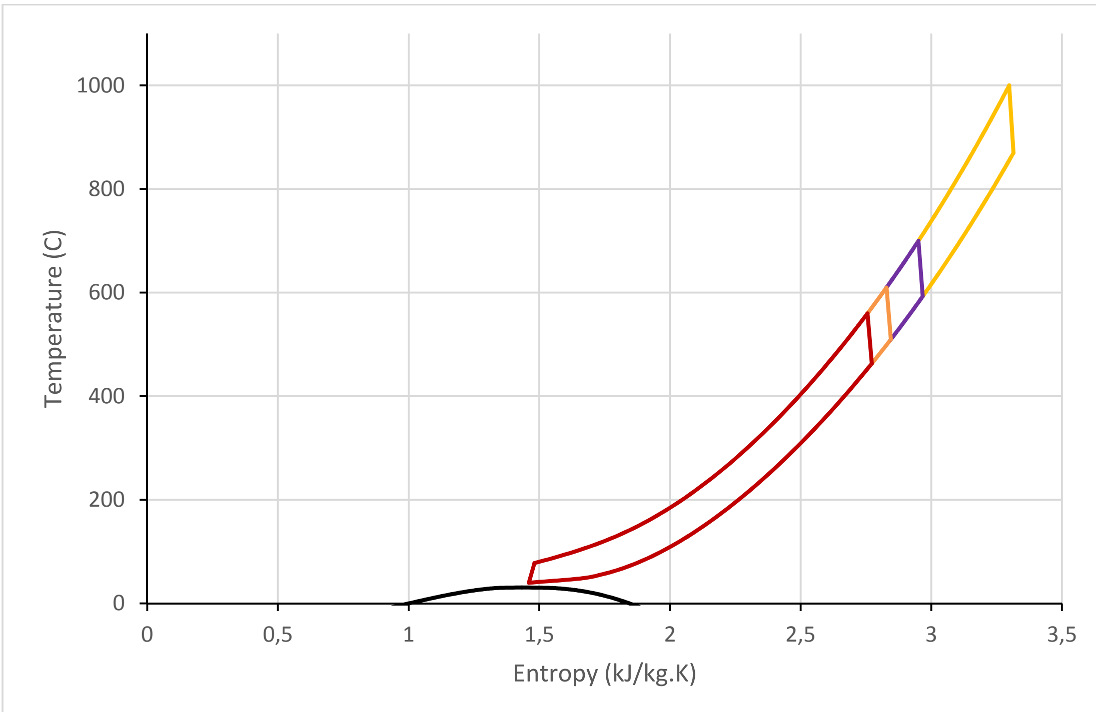

FIGURE 1. Temperature entropy graph showing CO_2 liquid-vapor dome and the four studied sCO_2 cycles

TABLE 1. sCO_2 cycle efficiencies

Turbine Inlet Temperature (°C)	**Cycle Efficiency (%)**
560	45.7
610	48.0
700	51.4
1000	60.4

Other than the turbine, all major components to be used in the supercritical CO_2 power block are currently available in the market in some form (only for low temperature systems). 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 [1,2]. Table 2 shows the total power block capital cost for a 25 MW_e unit.

TABLE 2. Total power block capital cost for a 25 MW_e unit

Turbine Inlet Temperature (°C)	**560 °C**	**610 °C**	**700 °C**	**1000 °C**
Power Block Capital Cost ($A million)	37	36	53	109

STOCHASTIC ANALYSIS

The power block requires thermal input at an appropriate temperature to function effectively, and the cost of supplying this will contribute to the overall cost effectiveness of electricity generation of a CST power plant, typically defined as the levelized cost of electricity (LCOE). For ASTRI, there is an ultimate target LCOE of 12c/kWh, but also a range of other Technical KPIs that should be achieved for the overall capital cost, operating and maintenance, capacity factor and annual overall plant efficiency as shown in Table 3. These constrain the designs so that alternatives can be directly compared.

TABLE 3. ASTRI ultimate targets

ASTRI Year	**Capital Expenditure ($m)**	**Annual Operating & Maintenance ($/kW/y)**	**Capacity Factor (%)**	**Annual Efficiency (%)**	**LCOE (c/kWh)**
8	442.8	50.0	46.9	18.5	12.0

To examine if these can be met using the power blocks specified would formally require the development and simulation of complete solar thermal power plants incorporating all plant items from the solar field through to the power block. This is difficult to achieve, as the current thermal storage technology used in commercial solar thermal power plants involves the use of a molten nitrate salt mixture with a maximum operating temperature below 600°C. To address this, a conceptual plant design was considered that simplifies the plant into five broad areas that each have a capital cost (CapEx), operating and maintenance cost (OpEx) and average annual operating efficiency. The approach used to establish viable combinations of plant characteristics that can achieve the target LCOE and other technical cost and performance criteria is to utilize a Monte Carlo technique where a large number of randomized inputs within the target ranges for each plant characteristic are used. These are used as inputs into a simplified design and costing model to generate an approximate plant design and cost, then to predict the overall performance of the plant.

Table 4 shows the assumed ranges for the cost and performance of the plant. Some of these values are specific targets for ASTRI projects, where these components are being developed, while others are assumed from a broad literature review of the current status of plant cost and performance relevant to CST technologies [3].

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%	

The following equation is used to calculate LCOE (c/kWh) [3]:

$$LCOE = \frac{\sum_{t=1}^{n} \frac{CAPEX_t + OPEX_t + F_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+r)^t}} \tag{1}$$

Where CAPEX is the total capital cost ($), OPEX is the operational and maintenance cost ($/y), F is fuel cost ($/y), n is life of project (3 years of construction and 27 years of operation), r is the discount factor (0.07), E is the energy output (kWh/y), and t is the year of the project.

RESULTS AND DISCUSSION

The general range of criteria for cost and performance for components of systems using 560°C and 610°C power blocks that meets all of the 8th Year ASTRI Technical KPIs is given in Figs. 2-3 and Tables 5-6. Total capital cost is the dominant cost in the LCOE calculation and therefore only CapEx ranges are shown. The constraints imposed are the fixed capacity factor of 46.9% and the acceptable range for LCOE of 11-12 c/kWh. With the 560 °C system, the ranges appear to be realistically achievable for all areas of plant, but for any specific plant design it will be necessary to balance the various costs and efficiencies to achieve the overall plant requirements. For example, an individual component cost can only be high if it is matched by lower costs for other components and likewise the efficiency can have an impact on what is acceptable elsewhere. In the simplest interpretation, there will be a reciprocal relationship between cost and performance within each section, but also an overarching limit for the combined values for the whole plant.

There is very little difference between the requirements for the 560 °C and 610 °C systems, although it could generally be stated that there is a slight relaxing of the cost limits. The efficiency improvement over the 560 °C power block is accompanied by a slight cost decrease, so there is essentially a double effect on the other plant components where they are both reducing in size and can have slightly higher costs. As the changes are quite small and there is some randomness in the analysis technique this does not have a major impact on the results.

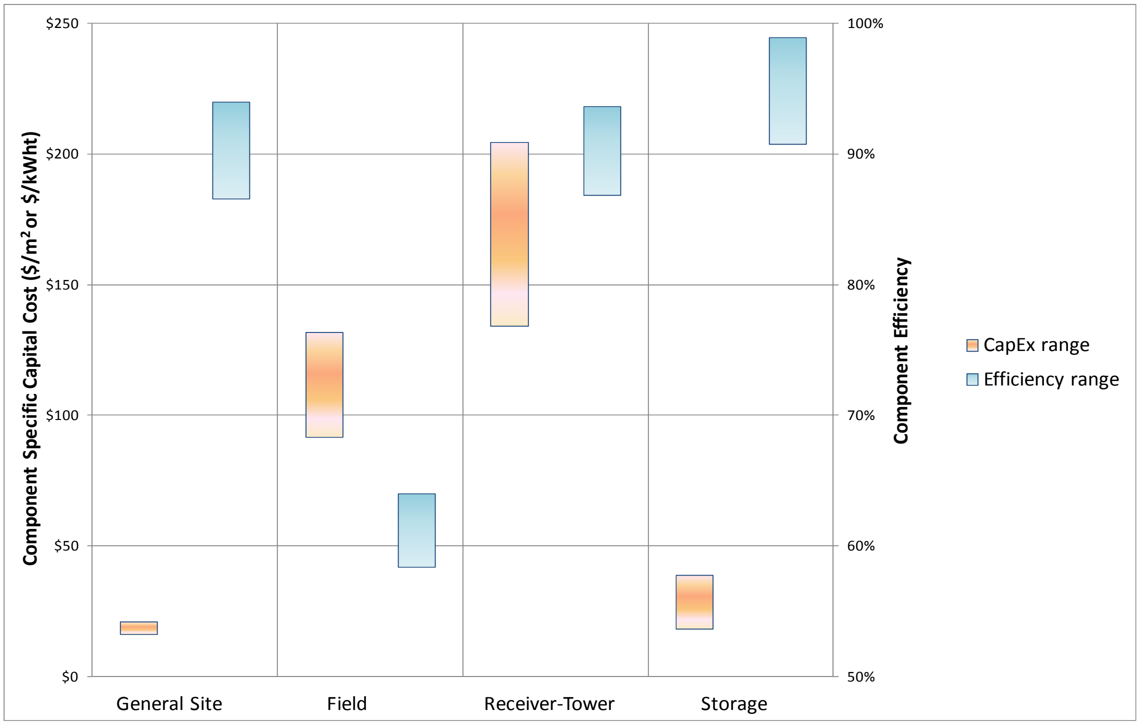

FIGURE 2. Cost and performance ranges for components of a 560°C power block system

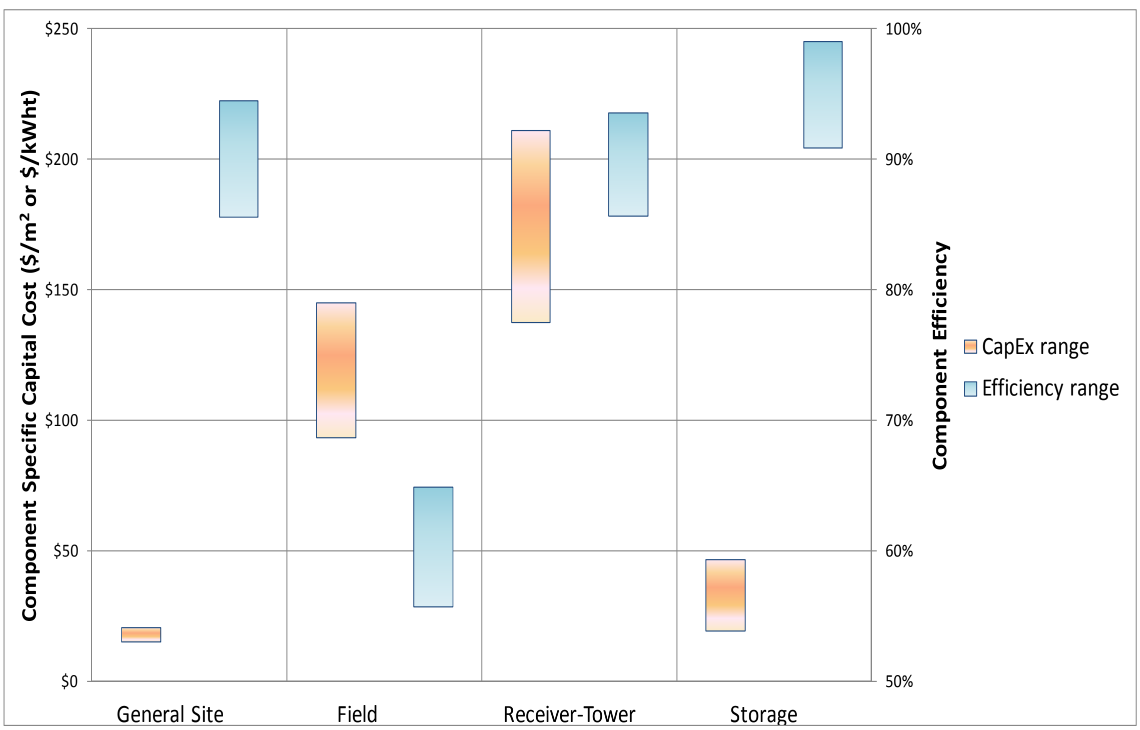

FIGURE 3. Cost and performance ranges for components of a 610°C power block system

TABLE 5. Ranges for cost and performance for a 560°C system to meet ASTRI targets

	General Site	Field	Receiver-Tower	Thermal Storage
Minimum cost	$16.09/m^2$	$91.69/m^2$	$134.35/kW_{th}$	$18.26/kWh
Maximum cost	$20.86/m^2$	$131.73/m^2$	$204.61/kW_{th}$	$38.78/kWh
Minimum efficiency	87%	58%	87%	91%
Maximum efficiency	94%	64%	94%	99%

TABLE 6. Ranges for cost and performance for a 610°C system to meet ASTRI targets

	General Site	Field	Receiver-Tower	Thermal Storage
Minimum cost	$15.31/m^2$	$93.44/m^2$	$137.68/kW_{th}$	$19.31/kWh
Maximum cost	$20.49/m^2$	$145.33/m^2$	$211.14/kW_{th}$	$46.93/kWh
Minimum efficiency	86%	56%	86%	91%
Maximum efficiency	95%	65%	94%	99%

Increasing the inlet temperature for the power block to 700°C offers an additional gain in efficiency over the lower temperature power blocks, but at the addition of significant cost. This is broad agreement with studies performed previously where it has been noted that above 650°C it is necessary to use high nickel alloys that add significant cost [4]. This added significantly to the cost of the power block, but this will also be expected to affect the cost of storage and receiver components that are also exposed to higher temperature duties. The analysis in this case found that the LCOE target can be met under some scenarios, but it was not possible to meet the total capital expenditure target for the plant. Under the assumption that this situation may be improved by research to identify more cost effective construction materials, the capital expenditure target was relaxed with a 5% increase to approximately identify the ranges for other plant areas. The results for this analysis are shown in Fig. 4 and Table 7, but are quite similar to those identified for the lower temperature cases.

Finally, the 1000°C inlet temperature power block has a high efficiency, which reduces the size and cost of other plant components, but this does not compensate effectively for the high power block expense. No scenarios were identified where this power block could produce systems that were even close to the targets for LCOE or capital expenditure and it would take a considerable innovation in materials to expect that this system in current form would meet the ultimate ASTRI targets.

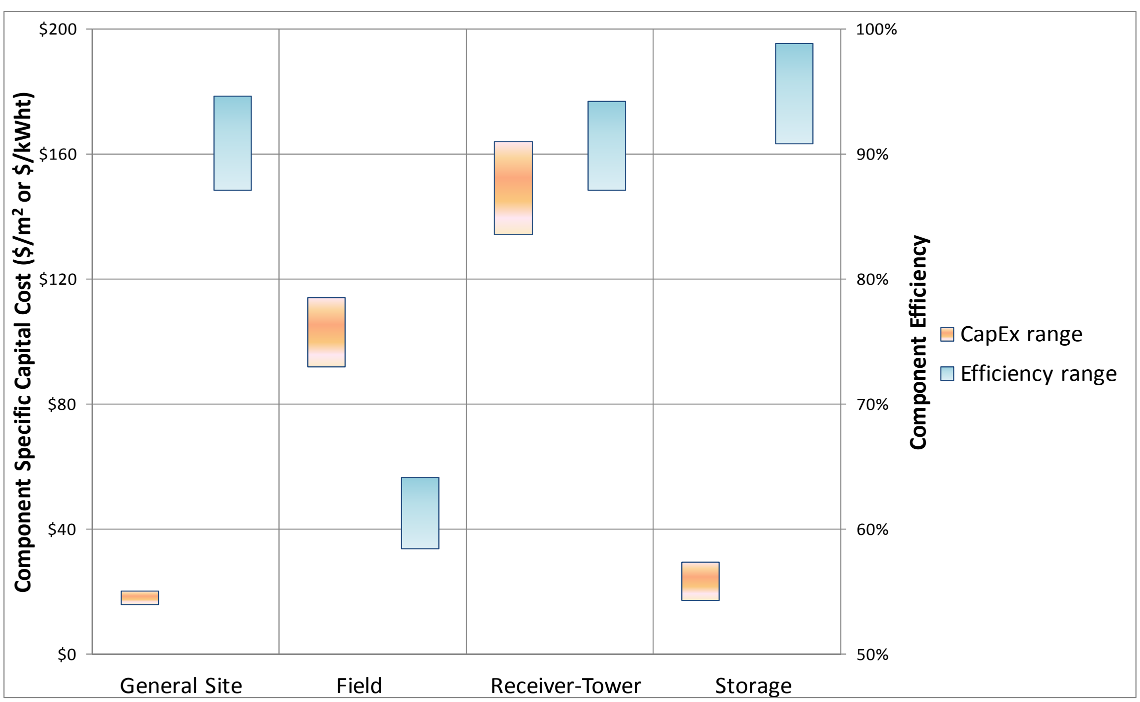

FIGURE 4. Cost and performance ranges for components of a 700°C power block system

TABLE 7. Ranges for cost and performance for a 700°C system to meet ASTRI targets

	General Site	Field	Receiver-Tower	Thermal Storage
Minimum cost	$16.13/m^2$	$92.22/m^2$	$134.50/kW_{th}$	$17.41/kWh
Maximum cost	$20.48/m^2$	$114.31/m^2$	$164.10/kW_{th}$	$29.71/kWh
Minimum efficiency	87%	58%	87%	91%
Maximum efficiency	95%	64%	94%	99%

An alternate analysis is to consider the full range of scenarios provided in Table 4 to identify the proportion that meets the final target. As reduction in LCOE is ASTRI's main technical goal, the outcome frequency distribution for plant configurations regarding the LCOE achieved was determined using the Monte Carlo method. This is shown in Fig. 5, with solid lines indicating the frequency and dotted lines the cumulative frequency. The black line and arrow 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, but there remains a significant probability of failure. The 700°C power block has some probability of also achieving this target, noting the earlier observations on capital cost overruns. Even though they have high calculated cycle efficiencies, it appears unrealistic to expect that 1000°C power block systems can achieve anything near the 12c/kWh target due primarily to the high material costs.

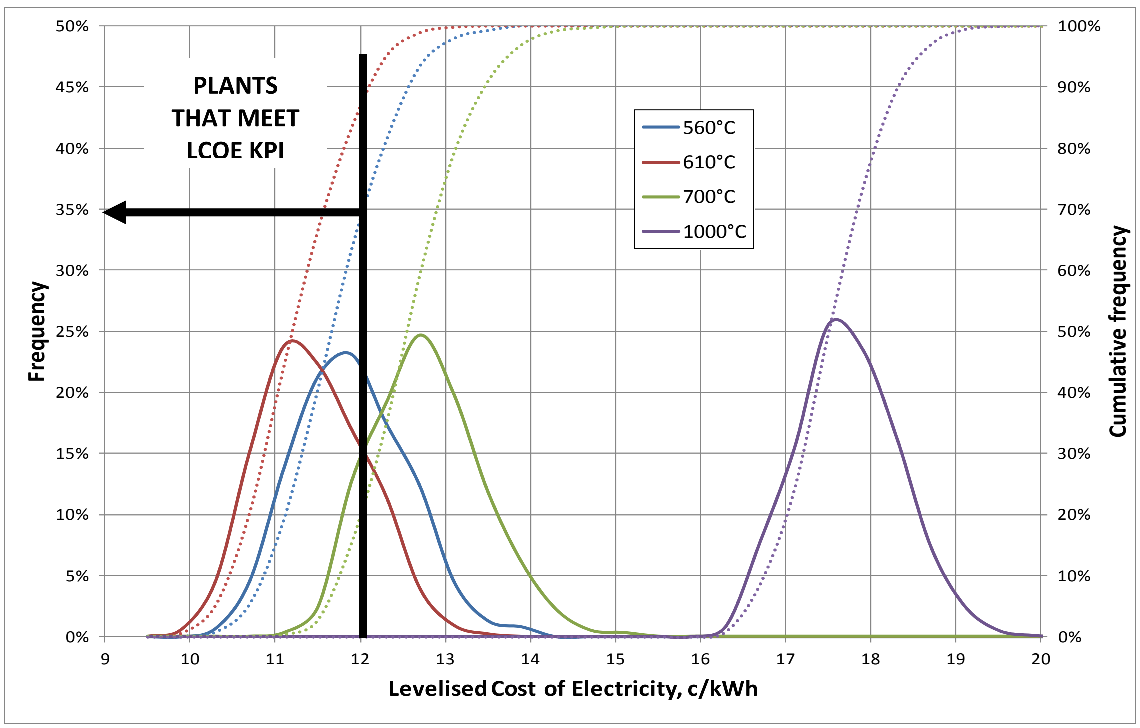

FIGURE 5. Frequency distribution for LCOE of CST systems showing percentage of systems achieving 12c/kWh

CONCLUSIONS

This techno-economic analysis considered entire CST power plants that were based around the specific sCO_2 power blocks operating at the four inlet temperatures of 560°C, 610°C, 700°C and 1000°C. The cost and performance of the power blocks produced in this analysis were based on real cost estimates where possible, sophisticated academic estimation methods and detailed cycle analysis, but the remaining plant sections (field, tower-receiver and storage) were considered to be within target ranges derived from a combination of current ASTRI project activities and current commercial best practice. These cost and performances estimations were used to establish complete power plants that meet all of the ultimate (year 8) ASTRI Technical KPIs, with some additional allowance for situations where the LCOE KPI is met without achieving all other KPIs for capital expenditure, operating and maintenance costs, capacity factor and annual efficiency.

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. The plants based on the 700°C power block plants had some probability of achieving the LCOE KPI of 12c/kWh, but were likely to fail to achieve other KPIs with the major problem appearing to be excessive capital expenditure. Plants based on the 1000°C power block have high capital cost and this appears to provide no opportunity for achieving the LCOE target.

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