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Impact of Power Block Efficiency on the Prospects of Achieving Significantly Reduced LCOE

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Abstract

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. The fundamental science behind each of these plant items can vary considerably, making the optimization process a complex and multi-disciplinary problem. However, 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. For example, a conventional steam turbine power block is likely to have efficiency below 40% in comparison with a solar collection efficiency of around 55%, receiver efficiency of around 90% and a thermal storage system efficiency of around 98%. It is clearly difficult to continue to improve receiver and storage efficiencies, plus solar collection efficiency has fundamental restrictions due to the range of sun locations, so a key target for reducing the size and cost of CST plants is the introduction of high efficiency power blocks.

One of the challenges in changing the power block used in a CST plant is that it is likely to require different operating conditions than the conventional steam turbine power block, so this will have flow-on impacts on the operating specifications for the other plant components and the technologies that may be appropriate. It is then critical to ensure that the cost and performance of these components is not adversely affected to the extent that the impact on the overall plant cost and performance due to the changes is negative. A methodology is demonstrated that takes realistic ranges for the cost and performance of all plant component, developed from a combination of existing equipment and current research targets, then uses a stochastic analysis to identify the subset of these ranges that achieves a target LCOE of 12c/kWh. This can be used to identify if the new plant design is an improvement over the conventional plant, to highlight areas of the plant which need improvement, and to specify targets that should be applied when researching technologies to meet the requirements of the new plant design.

1. 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 the 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 considerably efficient.

However, the power block technology that is used in existing CST plants is typically a sub-critical steam Rankine cycle with limited superheat and reheat stages that has a net efficiency of 35-38%. There are several reasons for the selection of this power block that include the robust nature of the equipment, availability in a broad range of specifications and plant sizes and limitations to the operating temperature due to the use of molten nitrate salts as a storage medium. Steam turbines are also noted for economies of scale in both cost and performance terms, so it is difficult to develop a cost effective small CST power plant that is based around a steam turbine power block. In practical terms electricity generation on a utility scale would typically use steam turbines that are greater than 200MWe 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 operated in a closed-loop Brayton cycle is an example of a power block that has the potential of equivalent or higher cycle efficiency versus supercritical or superheated steam cycles at temperatures relevant for CSP applications. It also offers a more compact and simpler plant configuration.

In this study, four power block efficiencies which are relevant to existing or under development power blocks for CST applications are considered (i.e. 38%, 42%, 46%, and 50%). Then, the subset of realistic ranges for the cost and performance of all plant components which achieve the Australian Solar Thermal Initiative (ASTRI) target of LCOE of 12 c/kWh are determined using a stochastic approach.

2. Methodology

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.

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 there is currently little published data on the cost and performance of the alternative technologies being developed. However, within ASTRI there are targets that can be used to indicate the expectations of the various research teams for the new technologies under development. This involves quite a broad range of plant areas with different metrics, but can be summarized in generic terms as capital cost (CapEx), operating and maintenance (OpEx) and efficiency for five main plant areas, as provided in Table 1. Some of these values are specific targets for ASTRI projects while others are assumed from a broad literature review of the current status of plant cost and performance relevant to concentrated solar thermal power technologies (Turchi and Heath, 2013; Turchi, 2010; Turchi et al., 2010; Kolb et al., 2011; Kolb et al., 2007; Glatzmaier, 2011; Kelly, 2010; BREE, 2012; CSP Today, 2013; EPRI, 2010; IT Power, 2012).

Table 1 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	$\$/kW_t$
CapEx – Storage	15.5	30.0	50.0	$\$/kW_h$
CapEx - PowerBlock & BOP	800	1100	1670	$\$/kW_e$
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	$\$/kW_t$-y
OpEx – Storage	0.34	0.38	0.41	$\$/kWh_t$-y
OpEx - PowerBlock & BOP	19.91	22.12	24.34	$\$/kW_e$-y
OpEx – Other	5.63	6.25	6.88	$\$/kW_e$-y
Availability	85.0%	90.0%	95.0%	
Annualised Efficiency – Field	55.0%	60.0%	65.0%	
Annualised Efficiency - Receiver & Tower	85.0%	90.0%	95.0%	
Annualised Efficiency – Storage	90.0%	95.0%	99.5%	
Annualised Efficiency - PowerBlock & BOP	Varies by case			
Annualised Efficiency - Gross:Net	85.0%	92.0%	95.0%	

By establishing the general target ranges for the different plant components within ASTRI it is possible to undertake a statistical analysis to determine more specific targets that need to be met if the overall plant performance is to meet the final ASTRI targets. These are summarized in Table 2 for the 8 year ASTRI research program based on a 100MWe net output power plant, showing that the ultimate target is LCOE of 12c/kWh without breaching the individual targets shown. The approach used for this is to conduct a Monte Carlo simulation where a large number of randomized inputs are used within the target ranges to generate plant specifications that meet the ASTRI requirements. The target ranges need to be specified for each plant area (i.e. general site costs, solar field, receiver-tower, storage, power block and balance of plant) and the Monte Carlo analysis performed for each power block design separately to determine if the target KPIs can be met and if this requires more stringent targets for specific various plant sections.

The following equation is used to calculate the levelized cost of electricity (c/kWh):

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

Where CAPEX is 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.

Table 2 Summary of ASTRI targets

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

3. Results and discussion

General range of criteria for cost and performance for components of the systems utilizing 42%, 46%, and 50% efficient power blocks that meets all of the 8th Year ASTRI targets is depicted in Figures 1-3 and listed in Tables 3-5. The constraints imposed are the fixed capacity factor of 46.9% and the acceptable range for LCOE set as 11-12 c/kWh. In addition, the cost values are within the defined ranges in Table 1. 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. It is noted that the system with a 38% efficient power block cannot meet all of the KPIs due to the low power block efficiency which leads to more expensive plant components.

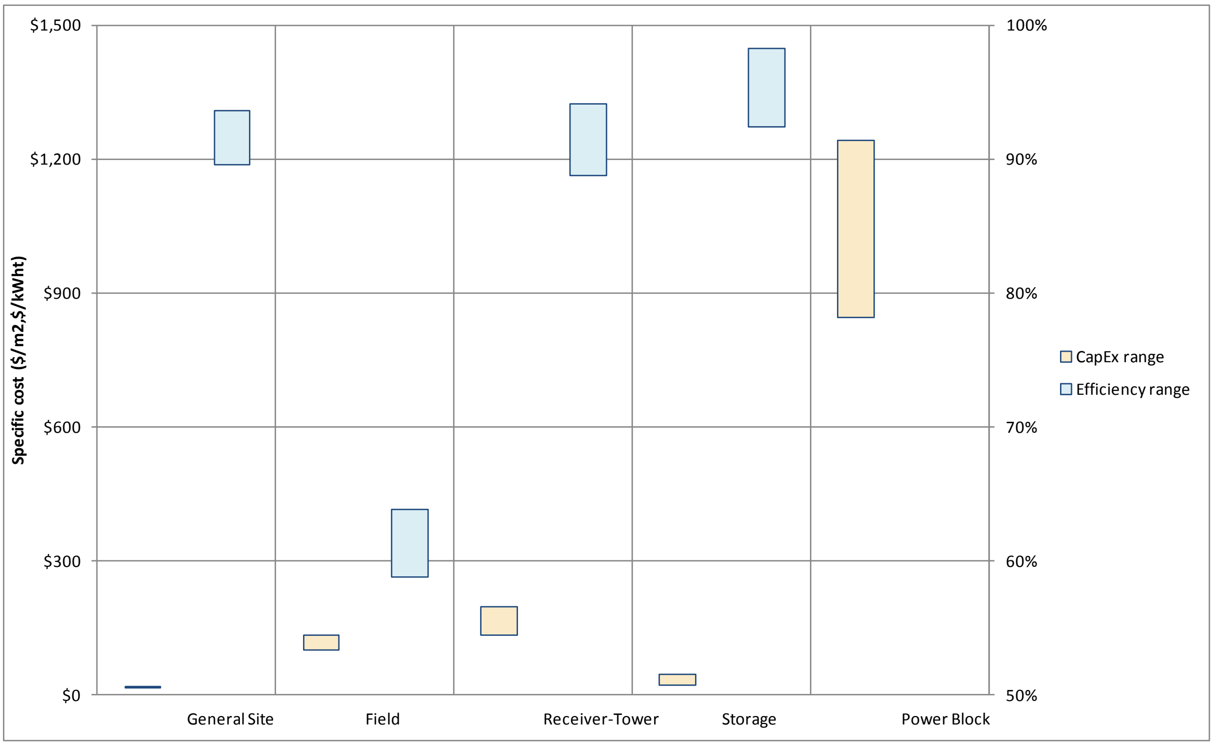

Figure 1. Cost and performance ranges for components of the system with a 42% efficient power block

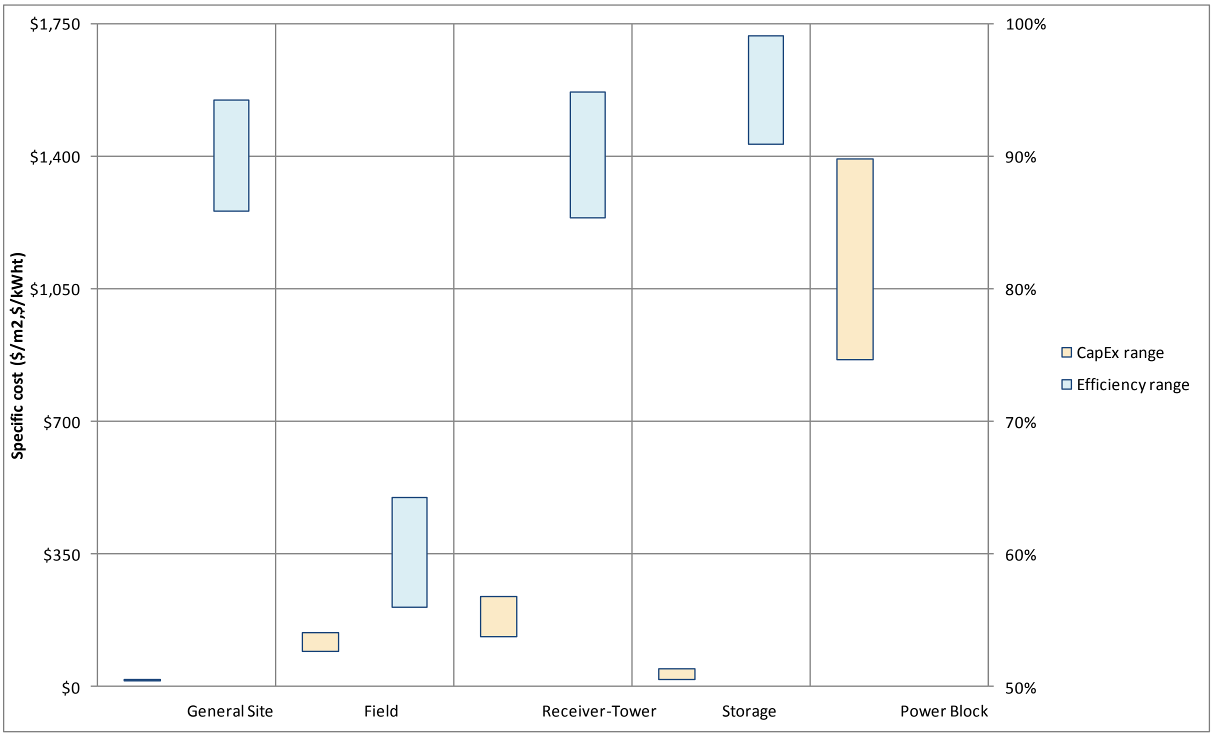

Figure 2. Cost and performance ranges for components of the system with a 46% efficient power block

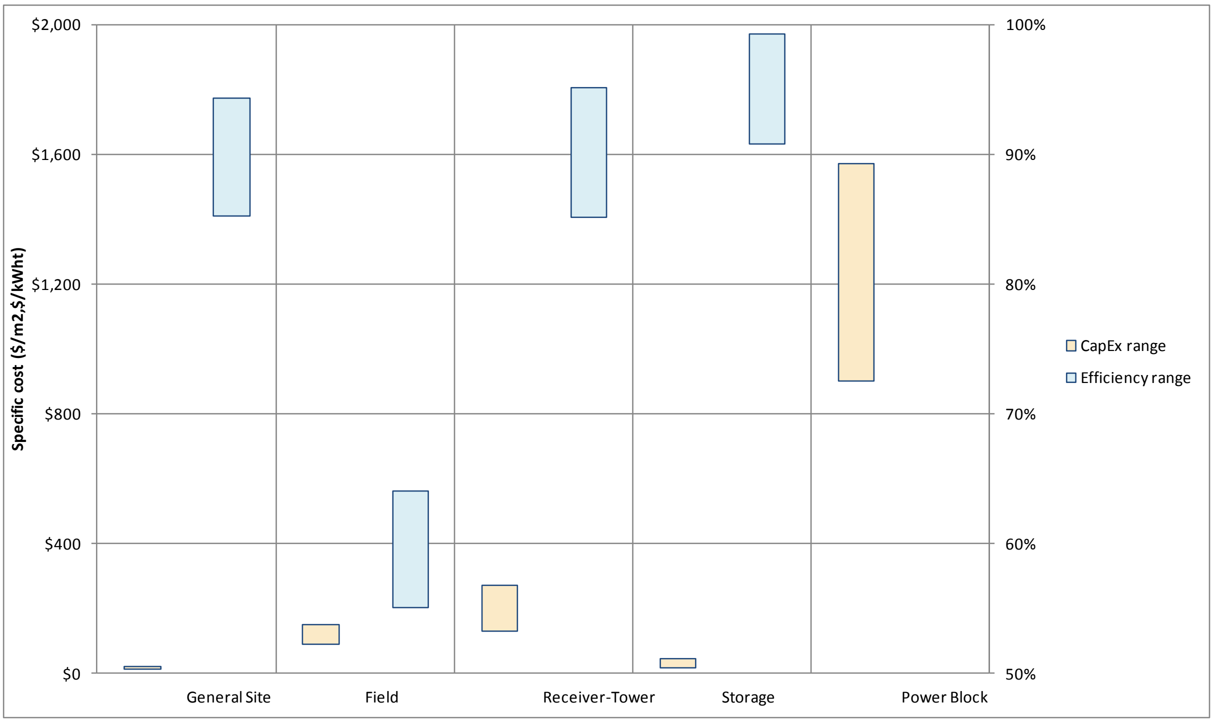

Figure 3. Cost and performance ranges for components of the system with a 50% efficient power block

Table 3 Ranges for cost and performance for the system with a 42% efficient power block to meet ASTRI targets

	General Site	Field	Receiver-Tower	Storage	Power Block& BOP
Minimum cost	$16.30/m^2$	$101.18/m^2$	$134.95/kW_t$	$20.80/kWh_t$	$844.90/kW_e$
Maximum cost	$19.58/m^2$	$133.57/m^2$	$198.73/kW_t$	$47.33/kWh_t$	$1244/kW_e$
Minimum efficiency	90%*	59%	89%	92%	42%
Maximum efficiency	94%*	64%	94%	98%	42%

Table 4 Ranges for cost and performance for the system with a 46% efficient power block to meet ASTRI targets

	General Site	Field	Receiver-Tower	Storage	Power Block& BOP
Minimum cost	$15.64/m^2$	$95.07/m^2$	$132.68/kW_t$	$18.95/kWh_t$	$864.4/kW_e$
Maximum cost	$20.59/m^2$	$144.12/m^2$	$240.72/kW_t$	$47.91/kWh_t$	$1395.23/kW_e$
Minimum efficiency	86%*	56%	85%	91%	46%
Maximum efficiency	94%*	64%	95%	99%	46%

Table 5 Ranges for cost and performance for the system with a 50% efficient power block to meet ASTRI targets

	General Site	Field	Receiver-Tower	Storage	Power Block& BOP
Minimum cost	$15.59/m^2$	$92/m^2$	$130.70/kW$_t$	$17.76/kWh$_t$	$902.02/kW$_e$
Maximum cost	$20.76/m^2$	$149.16/m^2$	$272.44/kW$_t$	$47.92/kWh$_t$	$1571.87/kW$_e$
Minimum efficiency	85%*	55%	85%	91%	50%
Maximum efficiency	94%*	64%	95%	99%	50%

* Plant availability

Consideration of Tables 3 to 5 provides a general observation that the use of a power block with higher efficiency allows for it to be more expensive than less efficient power blocks. As the power block efficiency increases, the cost ranges for all plant areas broaden (i.e. the low end decreases while the high end increases). The variations in the acceptable efficiency ranges are less obvious, but follow the same pattern of increasing flexibility with higher efficiency power blocks. Essentially, this suggests that the inclusion of higher efficiency power blocks allows more flexibility in the provision of the other plant components, while staying within the acceptable limits for the entire plant. One key question is if the higher allowable costs for the high efficiency power blocks are sufficient for the higher temperatures that are expected to be needed to yield the target efficiencies. This assessment is generic and does not specify the working fluids and temperatures necessary to achieve high efficiencies, but it is recognized that power blocks with efficiencies approaching 50% are likely to require high cost materials that will make achievement of the power block cost targets difficult.

Table 6 shows the percentage of the cases generated using the Monte Carlo method which meet the individual ASTRI final KPIs. All the cases meet the LCOE and capacity factor requirements (LCOE <12 c/kWh and capacity factor of 46.9%) as these were the constraints imposed. As the efficiency rises, the number of cases that comply with individual and all objectives increases (e.g. 67% of the cases meet all KPIs for 50% power block in comparison with no compliance for 38% power block). From the results it is evident that in addition to having an efficient power block reducing the capital cost is a crucial step towards developing economically viable CST plants.

Table 6 Percentage of the cases that meet different KPIs

Power Block Efficiency	LCOE	Capacity Factor	Capital Expenditure	Annual Efficiency	Operating & Maintenance	All KPIs
38%	100	100	8	5	2	0
42%	100	100	25	41	46	7
46%	100	100	47	86	91	39
50%	100	100	68	100	100	67

4. Concluding remarks

There is a caveat on this analysis, as the indicative ranges for the cost and performance of the different plant areas that were used in the analysis were based on the targets of the current ASTRI research projects and current commercial best practice. If the findings of any of those projects identify paths to higher achievement for the next phase of ASTRI it could change the analysis outcome significantly and make achievement of the LCOE target more likely.

Alternatively, developments external to ASTRI that significantly reduce costs or improved performance could also be included to potentially reduce the LCOE further. In general, it appears that the current trend of ASTRI projects is capable of achieving the Technical KPIs for the final year of ASTRI with the best option appearing to be to focus on developments around highly efficient power blocks.

References

BREE (The Bureau of Resources and Energy Economics), 2012, 'Australian energy technology assessment'.

CSP Today, 2013, 'CSP solar tower report: cost, performance and key trends'.

EPRI (Electric Power Research Institute), 2010, 'Solar thermocline storage systems'.

Glatzmaier, G., 2011, 'Developing a cost model and methodology to estimate capital costs for thermal energy storage', National Renewable Energy Laboratory, report no. NREL/TP-5500-53066.

IT Power 2012, 'Realizing the potential for concentrating solar power in Australia'.

Kelly, B., 2010, 'Advanced thermal storage for central receivers with supercritical coolants', ABENGOA SOLAR INC., Grant DE-FG36-08GO18149.

Kolb, G.J., Ho, C.K., Mancini, T.R., Gary, J.A., 2011, 'Power tower technology roadmap and cost reduction plan', Sandia National Laboratories, report no. SAND2011-2419.

Kolb, G.J., Jones, S.A., Donnelly, M.W., Gorman, D., Thomas, R., Davenport, R., Lumia, R., 2007, 'Heliostat cost reduction study', Sandia National Laboratories, report no. SAND2007-3293.

Turchi, C.S., 2010, 'Parabolic trough reference plant for cost modeling with the Solar Advisor Model', National Renewable Energy Laboratory, report no. NREL/TP-550-47605.

Turchi, C.S., Heath, G.A.,2013, 'Molten salt power tower cost model for the System Advisor Model', National Renewable Energy Laboratory, report no. NREL/TP-5500-57625.

Turchi, C.S., Mehos, M., Ho, C.K., Kolb, G.J., 2010, 'Current and future costs for parabolic trough and power tower systems in the US market', in: SolarPACES 2010 Perpignan, France, September 21-24.

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