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# Advanced power cycles for concentrated solar power

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ABSTRACT

This paper provides a review of advanced power cycles under consideration for CSP. As variable renewables make rapid commercial progress, CSP with thermal energy storage is in an excellent position to provide low cost stability and reliability to the grid, however higher efficiency and lower costs are critical. Steam turbines provide a robust commercial option for today but more advanced power cycles offering greater agility and flexibility are needed. Supercritical steam turbines are attractive at large scale but presently commercial products are too large for today's solar towers, unless multiple towers with an aggregating heat transfer fluid is used. CSP/PV hybrids combine benefits of PV's and low cost thermal storage. Supercritical $CO_2$ closed loop Brayton cycles are early in their development but promise high efficiency at reasonable temperatures across a range of capacities, with the prospect of significantly lowering costs. The next few years building knowledge on materials and components cost and performance along with demonstration is crucial. Gas turbine combined cycles driven by CSP are one of the highest efficiency options available, though other bottoming and topping cycle configurations should be progressed also. Again, component demonstration at the required high temperatures is critical.

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## 1. Introduction

This paper reviews some of the most promising power cycle options for concentrating solar power (CSP) in the present to medium term future. The heat engine is one of the most critical components in a CSP plant. The heat engine, usually some form of turbine cycle when generating electricity, dictates the temperature that the solar concentrator, receiver and storage must provide. It is the component that has the single most impact on overall system efficiency and thus a significant effect on cost of electricity. Heat engines are the generic thermodynamic conversion device for thermoelectric or thermochemical systems. This paper considers CSP applications for electricity production and thus turbine cycles will be assumed unless otherwise mentioned. The discussion concentrates on cycles beyond conventional subcritical steam Rankine cycles.

CSP plants have always built upon heat engines used in other sectors of the power industry. All commercial CSP plants in operation today use a sub-critical steam turbine Rankine cycle, common to the coal-fired power industry, with some minor refinements to suit the diurnal nature of solar operation. Thus the heat engine operating conditions are usually well-established and the front-end of the CSP system (concentrator, receiver and storage) must meet these conditions. This is both an advantage (in that part of the system is already commercially available) and a drawback in that efficiency limits are already in place and an even greater cost reduction burden is then placed on the collector and storage components. Thus the possibility of more advanced thermodynamic cycles and machinery is of immense potential benefit to the CSP industry. This is particularly so as, even though the solar photons are free, the cost of generating heat from these photons is relatively expensive compared to fossil fuels today – the more expensive the heat source the greater the importance of efficiency in the cost of electricity calculation (Fig. 1).

Cycle efficiency increases with turbine inlet temperature, all other parameters remaining constant. Thus one of the key technological targets for CSP is in the production of higher temperatures to match the most efficient cycles. The solar concentrator itself (ie the mirrors) can, in principle, produce the flux necessary to generate the highest temperatures used by the power industry today.

*Abbreviations:* BCSS, Bottoming Cycle Storage Systems; CC, Combined Cycle system; CIT, compressor inlet temperature; ISCCS, Integrated Solar Combined Cycle Systems; LCOE, levelized cost of electricity; ORC, organic Rankine cycle; PCHE, Printed circuit heat exchangers; $sCO_2$, supercritical carbon dioxide; SGT, solar gas turbine; TES, Thermal energy storage; TET, turbine exit temperature; TIT, turbine inlet temperature.

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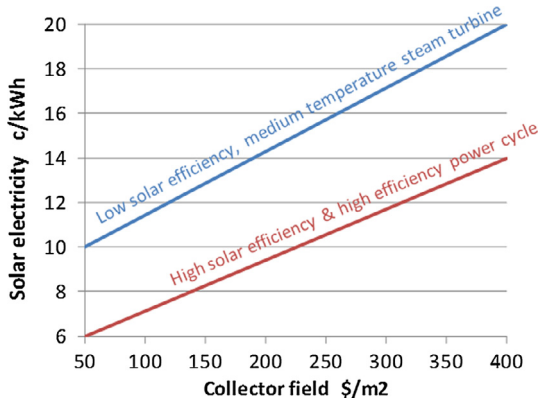


**Fig. 1.** The effect of efficiency and collector cost on LCOE. The blue line shows a conventional CSP system with 38% efficiency steam turbine. The red line shows an advanced CSP system using a $sCO_2$ cycle with TIT of 700 °C. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

For example at a solar concentration ratio of 1000 times which is relatively easily achieved by dish and tower concentrators, stagnation temperature is >1500 °C (Winter et al., 1991). The upper temperature limits are usually imposed by the properties of available materials and heat transfer fluids in the receiver and/or storage that can deliver suitable life expectancy. Temperatures of about 1000 °C out of the receiver are reasonably achievable today in pilot plants, though not yet for commercial scale.

Fig. 2 shows the relationship between turbine cycle efficiency and turbine inlet temperature for some of the main power cycles that have or are being considered for application in CSP systems.

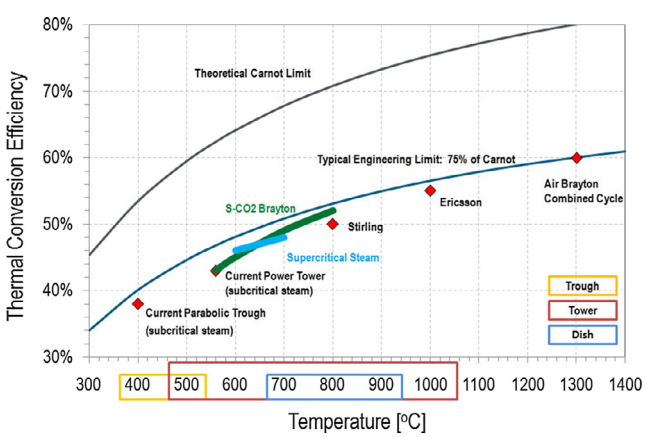


**Fig. 2.** Turbine cycles with potential application for CSP (Siegel et al., 2014).

The current parabolic trough plants, based on oil as the receiver heat transfer fluid with a maximum oil temperature of 395 °C and a sub-critical steam turbine with 380 °C/100 bar steam (single reheat) have a net efficiency of about 37.5% (39% gross) (Hirsch and Khenissi, 2014). The solar towers today using molten salt or water/steam as the receiver heat transfer fluid are able to achieve higher steam turbine inlet conditions (550 °C/120 bar) and have a net turbine efficiency of about 41.5% (43% gross). These efficiencies are simply a reflection of the steam turbine – troughs or linear Fresnel using salt or direct steam generation and producing the same temperature as the molten salt towers would still benefit from these higher turbine efficiencies. These efficiencies will change slightly depending on factors such as condenser pressure (dictated by ambient temperature and cooling technology), level of regenerative feedwater heating and pressure. The use of reheat in a steam Rankine cycle allows higher turbine inlet pressures to effect higher efficiency without the detrimental effect of lower steam quality (higher moisture) on the last stage blades.

The efficiency of rotating machines typically improves with increasing capacity, due to both leakage (between the blade periphery and the turbine casing) and windage losses. The specific capital cost ($/kWe) also tends to improve with increasing capacity as rotating machines are volumetric. Typically the greater the capacity the higher the efficiency and/or the lower the specific capital cost (Fig. 3). This is a well-documented phenomena in steam turbines and has had a significant effect on where the commercial CSP industry is today, seen in the push for larger plant capacities by commercial developers. Though the commercial reasons for this are understandable, the downside is that it has been a struggle for small steam turbine-based systems and new developers to enter the market.

Another important consideration is the turbine cycle part load performance. Steam turbines typically exhibit a relatively flat part load performance curve compared to the much peakier part load curves of open cycle combustion gas turbines. Fig. 4 shows an operating range (turn-down) of 75% and only a 5% increase in heat rate at 50% load (Denholm and Mehos, 2011). Part of the value of CSP to the grid in the future is likely to be the flexibility it affords. Flexibility, that is the ability to respond quickly and "in-fill" for variable renewables or when ramp rates demand means that, storage notwithstanding, there will be times when the turbine needs to operate at part load, and thus any new thermodynamic cycles should also offer good part load performance and turn-down ratio.

## 2. Power cycles for CSP applications

There are a number of technically feasible options for converting concentrated solar energy to electricity. This paper will discuss two that are receiving the most development attention at present –

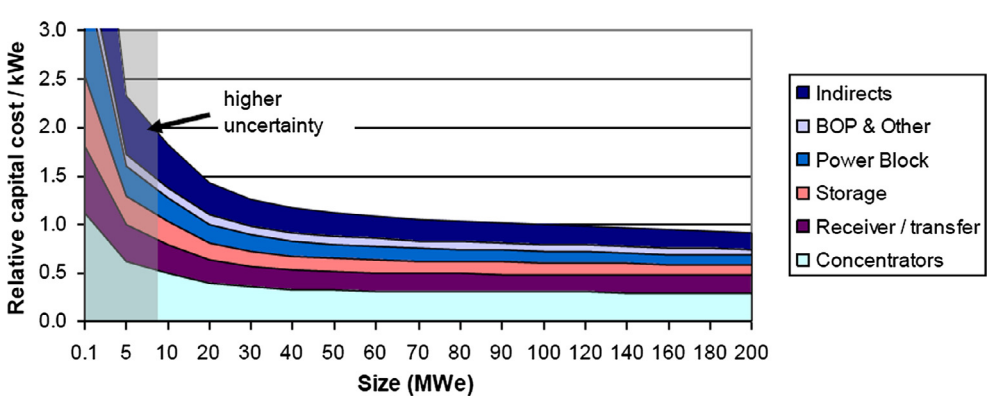


**Fig. 3.** The effect of plant capacity on capital cost. Note this is for a complete CSP plant with 5hrs storage Component break-ups are shown (Lovegrove et al., 2012).

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