Optimizing the Supercritical CO_2 Brayton Cycle for Concentrating Solar Power Application

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Abstract

The supercritical CO_2 (sCO_2) cycle provides unique benefits to Concentrating Solar Power (CSP) power plants, and has been extensively investigated by the US Department of Energy Solar Energy Technologies Office (SETO) based on its potential to help meet the program's 2030 CSP levelized cost of electricity (LCOE) targets: 5 ¢/kWh for baseload power plants (with ≥ 12 hours of thermal energy storage) and 10¢/kWh for peaker units (≤ 6 hours of thermal energy storage). The sCO_2 cycle is a uniquely well suited match for the CSP application due to the following advantages:

- Higher cycle efficiency than the Rankine Cycle for a given heat transfer fluid (HTF) outlet temperature
- Ability to incorporate air cooling as ultimate heat sink, with minor impacts on cycle efficiency
- Compactness of turbomachinery and ease of build, installation, and operation
- Ability to interface well with high temperature heat transfer media (HTM) at smaller scale
- Scalability to the 10-100 MW regime while maintaining high efficiency

This manuscript reviews state-of-the-art sCO_2 research and development within the CSP context. The value proposition of six R&D focus areas, for CSP, are described and quantified. The focus areas are:

1. power block efficiency
2. power block cost
3. primary heater temperature change (ΔT)
4. CSP HTM-to-sCO_2 heat exchanger
5. dry cooling
6. Operation and maintenance (O&M), including consideration of autonomous CSP power cycle operation.

In several areas, specific future technology improvement concepts are described. These development opportunities are shown to be consistent with the power block needs of CSP to become an impactful source of electricity in US markets and ultimately support SETO's 2030 technoeconomic targets.

1 Background and Motivation

The U.S. Department of Energy (DOE) has set targets for the levelized cost of electricity (LCOE) from solar photovoltaic (PV) and concentrating solar power (CSP) systems to enable wide deployment of both technologies in the US. Unlike PV systems, CSP technology captures and stores the sun's energy in the form of heat, using materials that are low cost and materially stable for decades. This allows CSP with thermal energy storage (TES) to deliver dispatchable renewable energy while providing important capacity, reliability and stability attributes to the grid, thereby enabling increased penetration of variable renewable electricity technologies.

Today's most advanced CSP systems are towers integrated with a two tank, molten-salt thermal energy storage (TES), delivering thermal energy at 565 °C for integration with conventional steam-Rankine power cycles. They make use of a nitrate eutectic salt with a melting point of 222 °C as heat transfer fluid, and with a ΔT of 270°C between the two tanks. These power towers trace their lineage to the 10-MW_e pilot demonstration of Solar Two [1] in the 1990's. This design has lowered the cost of CSP electricity by approximately 50% over the prior generation of parabolic trough systems [2].

While recent advances in CSP deployment and cost reduction are both rapid and significant [3], the technology remains at a cost disadvantage compared to other forms of large scale power generation within the U.S. Recently, DOE's Solar Energy Technologies Office (SETO) announced 2030 LCOE goals for CSP of 5 ¢/kWh goal for baseload plants (≥ 12 hours of TES), and 10 ¢/kWh for peaker plants (≤ 6 hours of TES), without subsidies [4]. If achieved, these cost targets would enable significant deployment of CSP in the US in the absence of any policy influence. In 2010, a new CSP plant was estimated to be capable of generating electricity at an LCOE of 21 ¢/kWh; by 2017 that cost is estimated to have already fallen to 10 ¢/kWh for a baseload plant [2]. A key part of the strategy to enable further cost reductions is to reduce the cost and increase the efficiency of CSP power cycles; sCO_2-based turbomachinery is a promising approach.

The design of a supercritical sCO_2 cycle power block for a CSP plant, must be developed in parallel to the CSP plant that can deliver adequate temperatures to the power block to attain the SETO goals. In August of 2016, DOE hosted a workshop of CSP stakeholders that defined three potential pathways for the next generation CSP plant (Gen3 CSP) based on the form of the thermal carrier in the receiver [5]: molten salt, particle, or gaseous fluid. That August, 2016 meeting initiated a collaborative process that generated a "Gen3 CSP Roadmap" that addresses and prioritizes research and development (R&D) gaps and lays out the potential technology development pathways. Technology gaps for each of the technology pathways were identified, together with research priorities designed to address them.

Molten-Salt Pathway. Of the three pathways presented in this roadmap, molten-salt systems represent the most familiar approach. Conceptually there is no change from current state-of-the-art power tower design; however, the increase in hot-salt system temperature from 565°C to approximately 720°C brings significant material challenges. Although the engineering challenges associated with achieving the high receiver outlet temperature required to drive a sCO_2 turbine at > 700°C are relatively well understood, knowledge about the selection of a high-temperature molten salt is needed, especially with regard to its impact on containment materials that can achieve acceptable strength, durability, and cost targets at these high temperatures.

Solid Particle Pathway. The solid particle pathway consists of heating particles either directly, falling as a curtain in concentrated sunlight, or indirectly through a solar flux to particle heat exchanger. These hot particles can be stored and delivered to heat sCO_2. Many of the thermal and material transport components for this pathway are mature and have been developed by the industry, including particle heat exchangers, storage bins, particle feeders, hoppers and lifts. Heating the particles with concentrated sunlight poses additional challenges with efficient particle heating, flow control and containment, erosion and attrition, and conveyance.

Gas-Phase Pathway. The gas-phase technology pathway relies on an inert, stable gas-phase heat transfer fluid (HTF), such as carbon dioxide or helium, operating within a high-pressure receiver. Unlike the other two pathways, this pathway relies on indirect TES options such as a phase-change material or particle storage.

Independent of the developed pathway, the sCO_2 power cycle is an enabling technology that can support the CSP LCOE targets for any thermal transport system. The specific thermal transport pathway defines the input boundary conditions for the cycle. The subsequent section describes the cost and thermodynamic requirements of a compatible Brayton cycle as well as recent technical advances in its components. In a similar manner, Section 3 describes the competing research priorities that can be further developed to make the sCO_2 cycle compatible and acceptable to the CSP plant.

2 Next generation CSP power cycle

As a part of the SunShot initiative, the Department of Energy and its researchers had earlier conducted analyses of subsystem technoeconomic metrics compatible with the original LCOE goal of 6¢/kWh [6]. One viable solution requires a power cycle with greater than 50% efficiency, a cost under \$900/kW$_e$, and dry cooling. Very large solar fields in a CSP system have diminishing optical efficiencies, necessitating power cycles viable at a smaller scale than supercritical steam. Developing power cycles, such as sCO_2 Brayton cycles, have the best chance of attaining these goals. Analysis indicates that a cycle efficiency of 50% with dry cooling can be obtained at a turbine inlet temperature near 715°C for the recompression or partial cooling cycles [7, 8]. However, high compressor inlet temperatures due to dry cooling also require high turbine inlet pressures (20-30 MPa) and temperatures (700°C). Hence, SETO is focused on component development to attain such high turbine inlet pressures and temperatures and compressor inlet temperatures. In addition, to attain cycle efficiencies of 50%, recuperator conductance of 10-15 MW/K with the ability to withstand 550°C temperatures are needed.

Many combinations of technical and cost metrics exist which would obtain the SETO LCOE targets. Two crucial power cycle related input that can significantly help control the LCOE are shown in Figure 1, namely, power cycle efficiency and capital cost per kW$_e$. The results shown in Figure 1 were obtained by National Renewable Energy Laboratory (NREL) analysts using Solar Advisor Model (SAM), for the DOE. For the example shown in Figure 1, the baseline pathway to LCOE of 5 ¢/kWh requires a solar field cost of 50 \$/m^2, power cycle efficiency of 50%, and power cycle cost of 900 \$/kW$_e$, while maintaining all other target costs; reducing the power cycle cost to 700 \$/kW$_e$ results in relaxation of solar field cost to 70 \$/m^2 at a power cycle efficiency of 50%; further relaxing power cycle efficiency to 47% requires reduction of solar field cost to 60 \$/m^2. This figure describes optimization that can be performed by integral changes to component costs that can lead to the achievement of the LCOE of 5¢/kWh. Similar analysis can be performed for the 10 ¢/kWh peaker target. Such analysis indicates much greater priority should be placed on power cycle cost and O&M targets rather than solar field cost and power cycle efficiency for the peaker scenario.

3 sCO_2 Cycle Technology Improvement Focus Areas

Highlighted here are six significant technology improvement focus areas for the CSP application. Each of the focus areas provide an opportunity for CSP; however the value of that opportunity needs to be quantified in cost, performance, or LCOE terms. Each focus area is then be expanded in discuss future research opportunities. The focus areas discussed are:

1. Power block efficiency
2. Power block cost
3. Primary Heater Temperature Change (ΔT)
4. CSP HTF-to-sCO_2 heat exchanger
5. Dry cooling
6. Operation and Maintenance (including consideration of autonomous CSP power cycle operation)

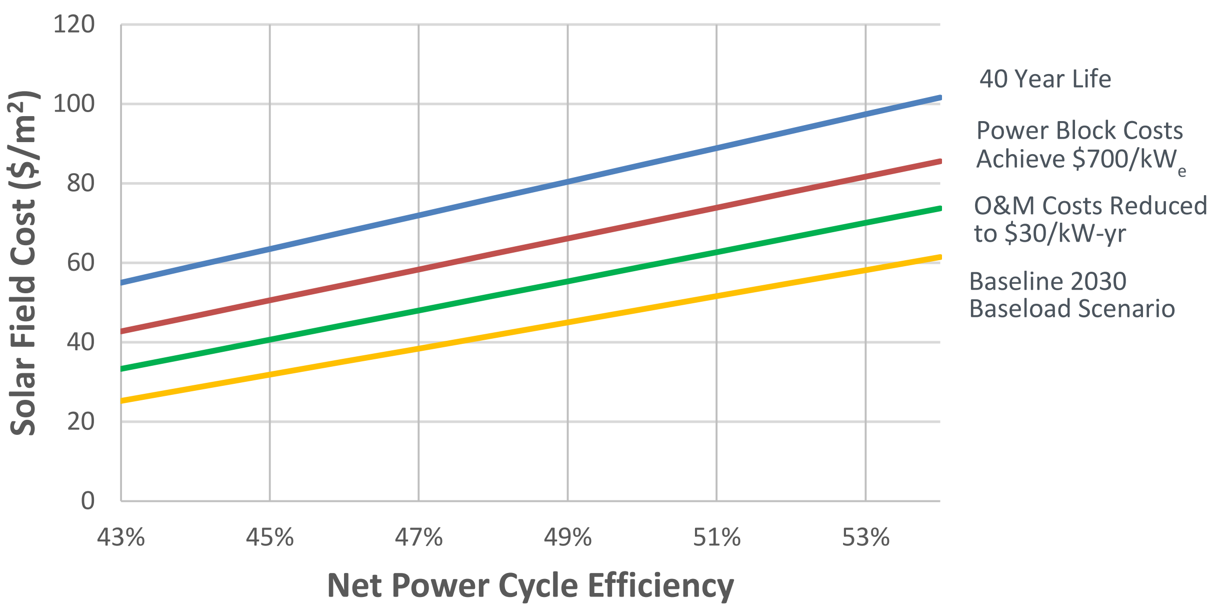

Figure 1: Solution Space for 5¢/kWh LCOE. Space below each line represents an LCOE <5¢/kWh for the specified scenario. Inputs include a plant designed for 115 MW_e case, 14 hour TES, solar multiple of 2.7; receiver cost of $120/$kW_{th}$ and 90% thermal efficiency; TES cost target of $15 /kWh; 30 year life. For the baseload scenario, the LCOE is most sensitive to solar field cost and net power cycle efficiency. If more aggressive metrics can be achieved in other areas, the solution space for these parameters is expanded.

3.1 Power Block Efficiency

3.1.1 Current Research

The sCO_2 power cycle target efficiency for application to CSP is 50% net efficiency at turbine inlet temperature (TIT) of 715°C with dry cooling. Focusing on these needs, SETO embarked on the following research and development areas:

1. A 10 MW_e expander development program in a 5.4 MW_{th} natural gas heater-based sCO_2 simple cycle loop with a 4 MW_{th} printed circuit heat exchanger (PCHE) [9]
2. A 4 MW_e compressor development program for the design, development and testing of main compressor and recompressor [10]
3. An integral geared compressor-expander development program for testing in sCO_2 loop [11]
4. A particle bed, switched valve, regenerator as a less costly replacement for recuperators [12]
5. Fundamental research on sCO_2 corrosion mechanism on materials and weldments at high temperature and pressure [13].

Some of this research is being further developed in DOE's Supercritical Transformational Electric Power (STEP) initiative [14] at the 10 MWe power level. It is clarified that the present day research has not attained the goals of 50% efficiency at turbine inlet temperature of 715°C, nor is this target expected to be experimentally obtained by the STEP initiative. Further turbomachinery design improvements (beyond those funded by SETO and STEP) may be needed to attain the 50% target, and are discussed further in Section 3.1.3.

In order to attain the target TIT, molten salt must be supplied at temperatures of the order of 750°C or solid particles at temperatures around 775°C. These design temperatures will lead to selection of piping and containment materials that may greatly increase the capital cost of CSP plants. This opens an avenue for research into increased sCO_2 power cycle efficiency for all turbine inlet temperatures. For a CSP plant operating with a recuperated sCO_2 Brayton cycle, the dependence of overall power cycle efficiency upon the component efficiencies (main compressor, recompressor, and expander), recuperator UA, TIT, and compressor inlet temperature are well known [8]. For a given TIT, compressor inlet temperature, and fixed recuperator total UA, the largest impact on cycle efficiency is from turbine efficiency improvements (0.5 %/%) followed by compressor efficiency (0.12 %/%) and recompressor efficiency (0.1 %/%) (Figure 2). Improvement to TIT approximately result in 0.5% efficiency increment for every 10°C increment in TIT (Figure 3). Improvement in compressor inlet temperature results in 0.4% efficiency improvement in every degree reduction in compressor inlet temperature (example for a TIT of 700°C, compressor inlet temperature varying from 45 to 31°C). The impact of recuperator UA is nonlinear as shown in Figure 4 (from [7], with results provided by T. Neises as personal correspondence), and levels off as the total recuperator conductance approaches 30 (MW/K).

3.1.2 *Value to CSP*

From the above discussion, it appears that there exists scope for optimum design that will focus on lower cycle costs (driven by turbomachinery costs, primary heat exchanger costs, recuperator costs and precooler costs). Figure 5 breaks down the cost reduction to LCOE attained via power block efficiency and cost. However, designing the power block to a TIT of 715°C, increases the cost of thermal energy storage and salt piping. It also appears that designing for a slightly lower turbine inlet temperature (625-650°C versus 715°C) can lead to significant reductions in piping cost and storage tank cost reduction for the CSP plant; reduce the cost of thermal energy storage tank; reduce the cost of HTF fluid-to-sCO_2 heat exchanger; reduce turbomachinery casing costs; and reduce recuperator costs (making use of stainless steel for high temperature recuperator as maximum temperature is maintained well below 550°C. Even if the TIT is maintained close to 700°C, the improvements in cycle efficiency can be used to relax the stringent requirements on solar field costs and receiver costs.

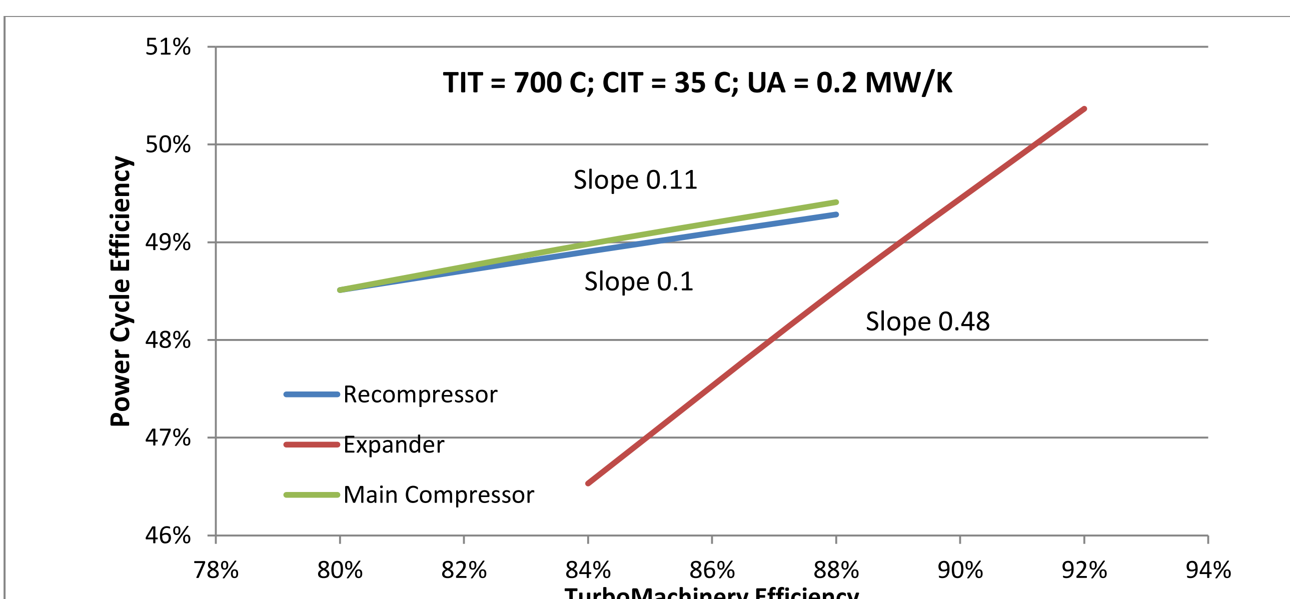

Figure 2: Dependence of Cycle Thermal Efficiency on Expander and Compressor(s) Efficiency Using Dyreby [8]

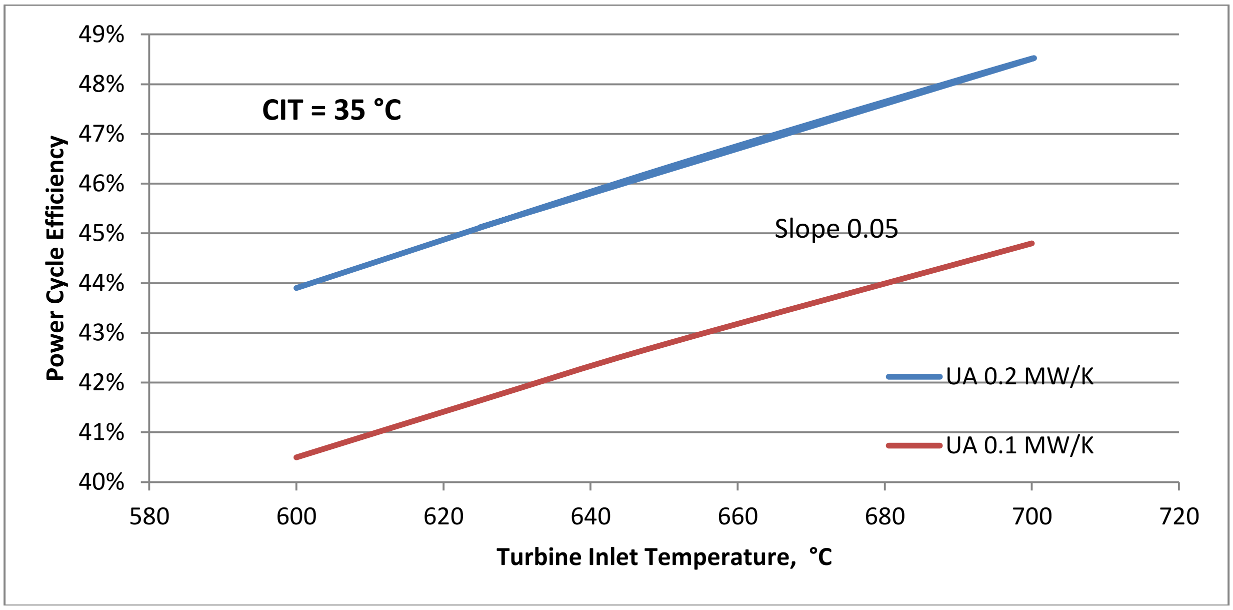

Figure 3: Dependence of Cycle Thermal Efficiency on TIT Using Dyreby [8]

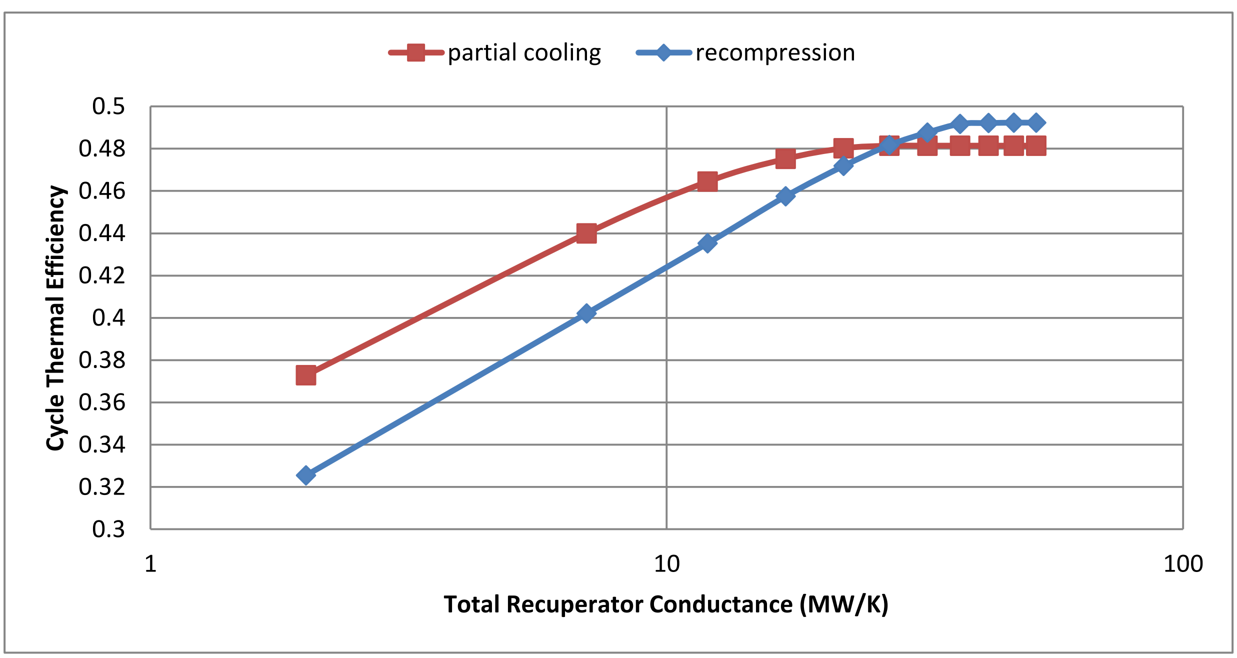

Figure 4: Dependence of Cycle Thermal Efficiency on Total Recuperator Conductance (TIT = 650°C; CIT=45°C)

3.1.3 Future Research Opportunities

Two avenues of power block efficiency improvement can be considered, namely, near term goals that involve improvements in technology readiness level (TRL) of components; and longer term goals that will need very broad improvements to TRL level.

Near term technology improvement for SCO2 cycle components

The first generation cycle component development at SETO focused on separate compressor and turbine design, except for the integral geared compressor-expander design. However, laying out a separate compressor and turbine within the power block leads to efficiency losses and leakage; an innovative approach will require inline layout of compressor and expander in a single pressure housing, with a corresponding reduction in the number of bearings and seals. Another area of research is the use of process gas for bearings that will enable a more compact and efficient turbo-compressor train and within a single pressure housing. Also gas bearings may reduce or eliminate lube oil. Even with oil-lubricated systems, increases in efficiency may result from reduced expander leakage and by less round trip losses due to common mounting of expander and compressor. A similar path to further efficiency improvement for geared expander-compressor is not readily apparent, except by reducing the number of stages.

Power cycle efficiency is strongly impacted by recuperator effectiveness, but the efficiency plateaus as conductance increases (Figure 4). For printed circuit heat exchangers, increases in recuperator effectiveness beyond 92% come with substantial cost. Realizing this, and considering thermal transient impacts on the header junctions, SETO has funded a switched regenerator made of packed beds as replacement for PCHE recuperators [12]. Several variants involving multiple bed systems have been analyzed. The regenerator bed system fits in exceptionally well with lower turbine inlet temperature cycles, since the turbine outlet temperatures will be reasonably low, permitting the use of low cost carbon steel vessels, with or without insulation between the particles and the solid walls. For certain ranges of operating parameters (matrix capacity ratio or switching time, and net transfer units), effectiveness greater than 0.98 can be obtained in the laboratory. The cost of the system is relatively low owing to the composition made of vessels, particle beds and switching valves and may attain costs as low as 100 $/kW_e$. However, the system inherently operates in a perpetually transient mode. While analysis indicate the thermal transients do not impact the regenerator, turbomachinery performance is bound to be affected.

Long term technology improvement for SCO2 cycle components

The design of sCO_2 compressors has focused on efficient operation across a range of inlet conditions due to inlet temperature variation caused by air cooling. While this is of importance to the CSP industry which focuses on dry cooling in the desert environments, modifying the compressor inlet temperature or the compression process is a low technology readiness level (TRL), high impact strategy. Compressor power input exceeds 30% of the expander output power. It should be noted that even in the dry conditions of desert Southwest USA the average temperature drops well below the critical point for much of the year, suggesting the possibility of liquid inlet conditions.

Poerner *et al*. [15] analyzed wet gas compression from sCO_2 framework. A wet gas compressor is capable of handling 40-60% liquid mass fraction in its flow; while wet gas compressors have been operated in oil and gas industry, no experience exists in sCO_2. Extension of operating and design experience in industry to sCO_2 leads to the conclusion that two phase operation reduces efficiency and increases compressor power. Applying the analyses over a full calendar year to desert southwest operation at or near the critical point results in 5-6% improvement in power cycle efficiency. However, significant advancements in aerodynamic, mechanical design and shaft sealing must be achieved, and consideration of liquid volume fraction and liquid mass fraction for sCO_2 *vis-à-vis* subsea wet gas in practical design, makes this a very low TRL level technology worthy of consideration.

Isothermal compression is a process during which the working fluid is compressed at constant temperature and requires the least compression work in comparison to other compression. The idea behind implementing isothermal compression is to remove the heat of compression created during the process, as well as the increased enthalpy due to the changing specific heat. Southwest Research Institute has conducted research with regards to designing an internally-cooled compressor concept for CO_2 (not supercritical) and other compression technologies that significantly reduce required power [16]. The concept removes the heat of compression that uses a coolant through the diaphragm. Heo *et al.* [17] analyzed the recompression Brayton cycle with (as yet undesigned) isothermal compression and noted significant power cycle efficiencies with simplified cycle layout, reduced CO_2 flow rates, and reduced precooler volume. Cycle efficiency improvements of the order of 6% was noted, together with a simplified cycle layout, and presumably, lower costs.

Ma *et al.* [18] proposed to use the residual heat of sCO_2 in the cold end of the supercritical CO_2 cycle to drive an absorption chiller, which chills the CO_2 exiting the precooler further before it enters the main compressor. Economic evaluations of a CSP plant integrated with a recompression sCO_2 cycle integrated with an absorption chiller were performed to investigate its feasibility as an alternative to the stand-alone supercritical CO_2 cycle. Results show that the optimized thermal efficiency of the cycle is 5.19% higher than the stand-alone sCO_2 cycle. The levelized cost of electricity and payback period for the plant integrated with the chiller are reduced by 0.46–0.77 ¢/kWh, respectively, with an annual full-load hour ranging from 5000 to 8500 hours. To be noted is that such large LiBr heat pumps (10 MWth capacity for a 10 MWe plant) have not been built at inlet temperatures of ~ 100 °C.

Further improvements in efficiency of the compressor and turbine can be sought; for the compressor, replacement of radial by axial compressor design may be valid beyond the 100 MWe net power scale, with attendant increases in efficiency from the low 80s to 90%. The expander efficiency can be optimized further by increasing the number of stages for a larger size machine. A synchronous expander will eliminate the cost and efficiency penalty of the generator gearbox. While these are traditionally evolutionary improvements, for sCO_2, such improvements are made harder by the compactness of equipment and high density.

3.2 Power Block Cost

3.2.1 Current Research

As mentioned in Section 3.1.1, cost has been a prime consideration for expanders [9, 11], compressors [10], recuperators [9, 12], and primary heat exchangers [21, 22]. Whereas SETO has not set individual cost targets and instead focused on the overall power block costs, researchers and analysts have subdivided the overall system cost and proposed sub-component level targets. Further cost savings are demanded to attain the 5 ¢/kW goal, and they are the topic for future research.

3.2.2 Value to CSP

The value to the LCOE of CSP plants in reducing power block cost and increasing power block cycle efficiency can be seen in Figure 5, which shows that the targeted power block cost and cycle efficiency improvements each contribute approximately a 10% reduction from the current LCOE. In addition, Figure 1 shows that decreasing the power block cost to 700 $\$/kW_e$ allows for further relaxation on thermal efficiency and solar field cost, indicating that power cycle cost reduction is an attractive target for improving overall CSP system costs.

3.2.3 Future Research Opportunities

While the previous section focused on efficiency improvements, it was noted in Section 2 that power cycle cost reduction to 700 $\$/kW_e$ will lessen the required reduction on solar field costs. Research conducted under SETO funding has shown significant reductions of turbomachinery cost, both for compressors and expanders, and integral geared designs. Such cost information is vendor-proprietary but compressor-expander costs may be reduced below the 200 $\$/kW_e$ threshold. Inline single pressure housing of compressor and expander with a reduced number of dry gas seals and improved bearings are attractive possible paths to such cost reductions.

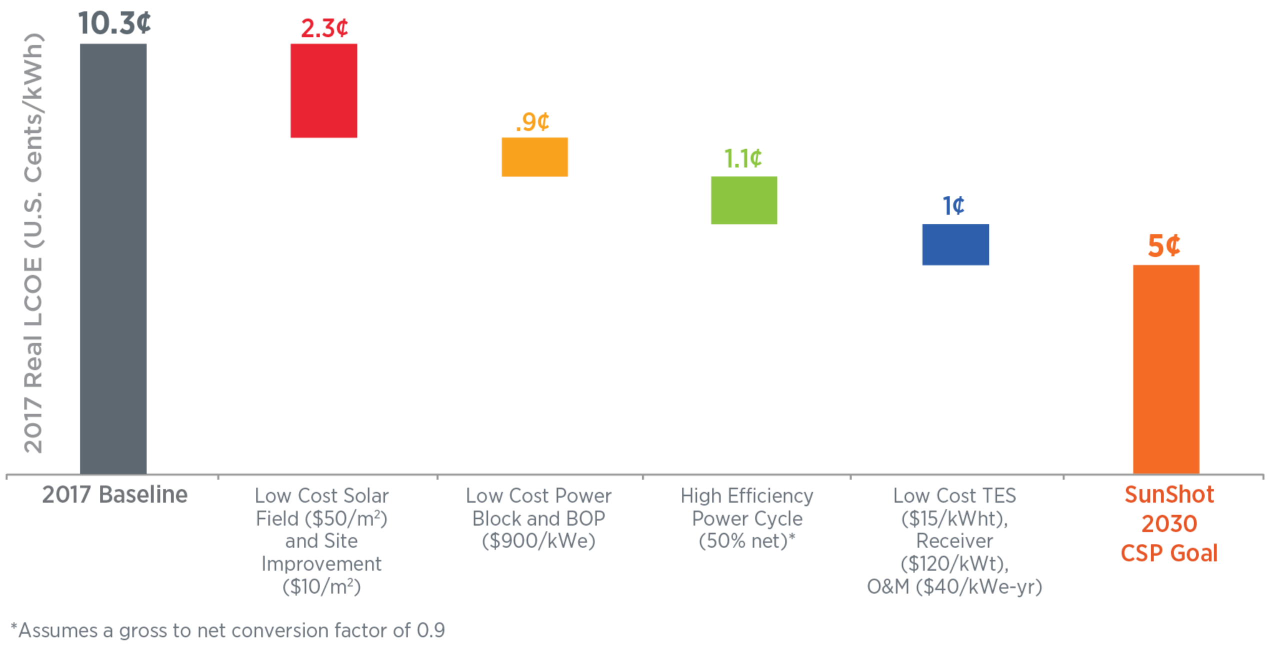

Figure 5: A cost reduction pathway to move from present day CSP LCOE to the 5¢/kW_e target. Reducing power cycle cost accounts for about 20% of the total cost reduction. Increasing power cycle efficiency (allowing a size reduction in other subsystems) accounts for an additional 20% of the cost reduction.

Recuperator costs have been proposed to target 250 $/$kW_e$ of the total 900 $/$kW_e$ budget. SETO has funded research in regenerators that may reduce cost. Hinze at al. [25] suggested that a regenerator made of stainless steel, together with valves will cost around 189 $/$kW_e$. Further cost reductions have been proposed by using carbon steel vessel and cheaper valves for a potential path to 150 $/$kW_e$. In addition, rapid reductions in PCHE cost have also been attained, and can be continued to be attained if high nickel alloys are not required as materials of construction. In parallel, a plate fin compact heat exchanger project has been funded by SETO, for, at least, low temperature recuperators [26]. A novel cermet material for recuperators has also been developed [21] with a cost target under 150 $/kWe, where the ability to machine channels (instead of etching), low cost material manufacturing, and the high thermal conductivity of the developed material, greatly reduce the potential cost of the finished recuperator.

Primary HTM-sCO_2 heat exchangers and air pre-coolers are discussed in Sections 3.4 and 3.5.

3.3 Primary Heater Temperature Change

3.3.1 Current Research

Current research in molten salt-sCO_2 heat exchangers and particle to sCO_2 heat exchangers has been focused on optimizing the recompression Brayton cycle (RCBC) and limited to a ΔT between 180-200 °C. The primary heat exchanger in the sCO_2 power cycle is driven by the temperature drop in sensible heat thermal energy storage systems (isothermal TES is not discussed here). State of the art molten nitrate salt power towers operate at a cold tank outlet temperature of 270 °C and a hot tank inlet temperature of 565 °C. For the RCBC, the optimum ΔT across the heat exchanger is ~150-180 °C. Novel salts under consideration for a Gen3 CSP high temperature molten salt power tower are binary KCl-$MgCl_2$ or ternary NaCl-KCl-$MgCl_2$. While these salts are lower cost and more thermally stable than nitrate solar salt, the thermal conductivity, density, and specific heat capacity of the molten chlorides at high temperatures are considerably lower than the nitrates.

A compounding disadvantage is the smaller ΔT between the hot and cold salt tank causing the salt storage tank volume to double and the diameter increases by 40% for an equivalent quantity of energy to be stored.

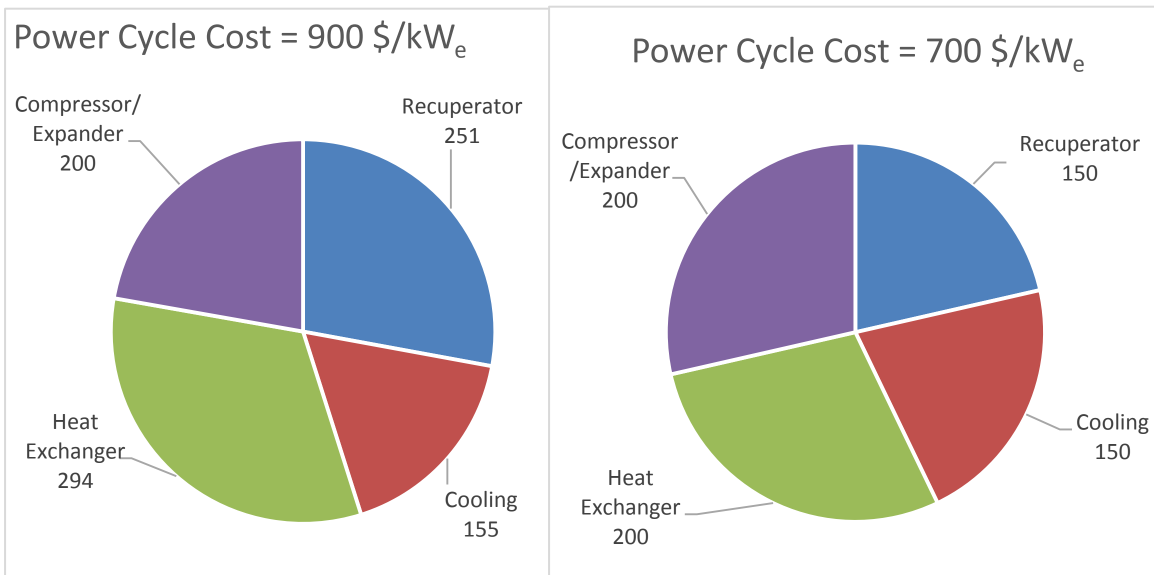

Figure 6: Proposed Cost Breakdown of Power Cycle for two Cases; 900 $/kW$_e$ from [24], and 700 $/kW$_e$

Table 1 Comparison of Thermal Energy Storage Tank Design Parameters between molten nitrate (Gen2) and molten chloride (Gen3)

Salt	Average Density	Average specific Heat	Thermal Energy Storage	ΔT	Volume of TES	Volume of Tank	Height of Salt Tank	Diameter of Salt Tank
	kg/m^3	kJ/kg.K	MWh	°C	m^3	m^3	m	m
Nitrate	1750	1.53	3,000	270	14,341	15,000	20	31
Ternary Chloride	1653	1.14	3,000	180	27,583	29,000	20	43

3.3.2 Value to CSP

As shown in Table 1, even though the TES capacity is unchanged (3,000 MWh) between the Gen-2 molten nitrate system and Gen-3 chloride system, the volume has doubled, increasing the cost of the tank. Furthermore, if the tank has to be made of high nickel alloy materials, one can note that the cost of the thermal energy storage system can easily increase by a factor of ten, as nickel alloys cost more than 4 times the stainless steel. This adds motivation to switch from RCBC to a cycle with a slightly broader ΔT across the primary heat exchanger. For example, the partial cooling cycle makes use of an added cooling step of the main compressor flow after a flow split beyond partial compression. Kuhalnek and Dostal [19] claim an increase of 75°C (from 200°C to 275°C) for a TIT of 700°C; later work by Neises and Turchi [7] suggest a smaller effect of 54°C. In either case, a saving of 20-27% is indicated in tank volume. A lower recuperator conductance requirement and lower maximum temperature for recuperator design is indicated.

3.3.3 Future Research Opportunities

Partial cooling does offer some improvement and cost reduction opportunities; in addition, the present research development in compressors can be applied to partial cooling compressors without significant modification. The research in regenerators can also be applied to partial cooling without modifications.

However, the increase in ΔT afforded by partial cooling cycles is still not sufficient to achieve the 15 $/MWth goal set by SETO with a conventional 2-tank system design. Further cycle improvements are warranted with power cycle research closely coupled with thermal energy storage research to reduce TES costs further.

3.4 HTF-sCO_2 Heat Exchanger

3.4.1 Current Research

Further research in the design of primary (HTM-to-sCO_2) heat exchangers is critical. The primary heat exchanger design for CSP is challenging owing to the need to accommodate high temperature and potentially corrosive fluids in the primary and secondary channels. This creates the need for new materials, coatings, manufacturing processes, and innovative designs to attain a goal of 200 $/kW$_e$ (100 $/kWth).

Two types of primary heat exchangers, namely, a molten salt-to-sCO_2 heat exchanger [21], and a solid particle-to-sCO_2 heat exchanger [22], are currently being developed under SETO funding. Both heat exchangers make use of diffusion bonded microchannels; the molten salt heat exchanger makes use of a proprietary, advanced cermet developed for this purpose. The particle heat exchanger uses a plate with transverse microchannels, and with a moving bed of solid particles flowing down between the plates. However, a completed molten salt-to-sCO_2 heat exchanger made from high nickel alloys to withstand entrance and exit temperatures in excess of 700 °C has not been built. The ability to etch and bond high Ni alloys such as 740H and Haynes 282, and the ability to attain 200-300 $/kW$_e$ is still to be proven.

3.4.2 Value of Heat Exchanger Research to CSP

Thermal energy storage is an essential feature of CSP plants. The stored energy from the HTM is transferred to sCO_2 through the primary heat exchanger. With the turbine inlet temperature at 715°C, the HTM inlet temperature may be as high as 750-800 °C. Material selection and cost-compliant (200 $/kW$_e$) design of such heat exchangers in 40-400 MWth scale is still a crucial research goal for the DOE. Development of this heat exchanger is a gating challenge for Gen3 CSP.

3.4.3 Future Research Opportunities

Development of a molten salt-sCO_2 heat exchanger inherently involves many of the material selection, degradation, and reliability challenges in both the molten salt thermal transport and the sCO_2 systems. Silicon carbide and advanced cermets have been considered as potential solutions. If a more traditional material is chosen, it has to be proven that this alloy is capable of withstanding corrosion due to molten salt and sCO_2, considering the dissimilar performance requirements on alloy components (e.g., chromium) in the two fluids. All heat exchangers must be validated in a loop with primary and secondary flow of vastly different fluids, but at > 700 °C temperatures.

The particle-sCO_2 heat exchanger is currently being tested in a 100 kWe scale at Sandia [112]. Future research may include a focus on abrasion and erosion of stainless steel and high nickel alloys by moving particles. For commercial scale applications (> 100 MWe), it may be determined that a fluidized bed heat exchanger is more appropriate; in that case, research into the development of such an exchanger must be pursued. Simultaneous optimization of particle properties (thermophysical, optical, size) and heat exchanger features (influencing cost) can create a complex optimization problem for a particle system’s receiver, thermal storage, and heat exchange.

3.5 Dry Cooling

3.5.1 Current Research

The air cooled heat exchanger design for precoolers has not received the same level of attention as other components, considering the cost and the need to maintain as low a compressor inlet temperature as possible above the critical point. Sienecki , Moissetysev, and Lv [20] explored air cooled heat exchanger design using vendor (Harsco) data and published correlations. They settled on a design of a finned tube crossflow heat exchanger with a total cooling power of 145 MWth and a minimum cost of $20 million, suggesting a 150 $/kWe, assuming a 50% efficiency for the 700 °C CSP case. Their parallel design using printed circuit heat exchanger was found to be several times more costly. An alternate air cooled, parallel plate printed circuit heat exchanger design was developed by Vacuum Process Engineering (VPE) for small scale application and is being considered for use in the particle-sCO_2 heat exchanger project. In parallel, microtube heat exchangers are also being considered. Research areas should focus on improving beyond the well-known finned tube technology with a goal of at least reducing the cost by a third using compact heat exchanger technology.

3.5.2 Value of Heat Exchanger Research to CSP

Dry cooling is a critical research topic for CSP cycles. Development of a heat exchanger that will be both low cost and high performance, is a significant value to CSP. In addition, the cost budget for dry cooling is no more than 150 $/kWe (of total power cycle cost of 900 $/kWe); if the total cost is to be reduced to 700 $/kWe, no more than 100-125 $/kWe is likely to be available for dry cooling. Further research in dry cooling to reduce cost and improve compressor inlet cooling temperature could provide for an overall reduction in power cycle cost or enable headroom within the budget for other power block component costs.

3.5.3 Future Research Opportunities

Topics of research interest may include:

1. Reducing the footprint and cost of traditional air cooled finned tube heat exchangers
2. Development of microchannel and microtube heat exchangers with desired costs
3. Integration of heat rejection with cooling via sorption and other heat pumps; with desalination efforts; and with hot/cold water storage with heat rejection to night sky in the desert.

3.6 O&M of sCO_2 cycles within CSP applications

3.6.1 Current Research

O&M costs are a significant contributor to the LCOE of CSP plants, owing to the complexity of operation of the steam power block together with the solar field, and compounded by the relatively small size of CSP compared to other thermal power plants. The primary public reference for CSP O&M costs is NREL/TP-550-47605 [23], the data from which are incorporated into NREL's System Advisor Model (SAM). In contrast, O&M costs of combustion turbine and combined cycle plants are well known, including the Electric Power Research Institute (EPRI) State-of-the-Art Power Plant Combustion Turbine Workstation v 9.0 data for existing plants reported on FERC Form 1, confidential data from other operating plants, and vendor publications.

The power block O&M cost(s) for the molten-salt power tower in the current release of SAM (based on updates to NREL/TP-550-47605) are: Fixed O&M cost by capacity =25 $/kW-year; variable O&M cost by generation = 2.3 $/MWh. In comparison, Combustion Turbine (CT) plant maintenance cost (excluding fuel) can be obtained from Newel et al [24] as: Fixed O&M cost = 5 $/kW-year, variable O&M cost = 4.3 $/MWh. The goal for the sCO_2 cycle O&M within the CSP framework can be set to attain middling values of fixed O&M costs of 10 $/kW-year and variable O&M cost of 2 $/MWhr. Note this target does not include O&M costs for the thermal transport or collector subsystems.

3.6.2 Research Opportunities for O&M Improvement

Two avenues for O&M improvement can be considered. First, the use of more compact components and use of lower impeller temperature (to remove the need for active cooling), elimination or reduction of lube oil cooling in the power block and using process gas as coolant, can all help reduce cost. The use of air cooled heat exchangers, recuperators and heat exchangers as the only components other than generators suggest significant avenues for O&M cost reduction.

The second avenue for research pertains to autonomous control. CSP plants are typically located in remote areas with large plant sizes of several square miles. Operator rooms may be common to multiple solar fields, and the ability of operators to react to plant upsets outside of the control room will be time-constrained. Nor will it be expected that the in-control room operator will be able to anticipate and cover all contingencies with a new power cycle. This is an excellent opportunity for development of autonomous power cycle operation (since the power cycle is somewhat disconnected from the field operations by thermal energy storage).

Autonomous control involves independent decision making capability such that diagnostics, adaptability to evolving conditions and even self-maintenance is included within the control system. Automated control, which is common in most plants today, consists of rigidly defined control loops responding to a defined set of input conditions. It requires operator action, except for normal operation events; decision-making is left to the human. Being compact, with a limited set of instrumentation, the sCO2 power cycle is well amenable as a test bed for autonomous control.

4 Conclusions

DOE has helped to promote CSP technology to its current status through a variety of past and current demonstration and research and development initiatives. An important contributor to the success of SETO's 2030 goals is expected to be the incorporation of the sCO_2 cycle into CSP systems.

This work presented the current stage of development in the power cycle from the perspective of the DOE's CSP research program. Considerable improvements pertaining to the CSP "boundary conditions" have to be incorporated into CSP research. Several research pathways related to turbomachinery component development, power cycle efficiency improvement and cost control, heat exchanger research, dry cooling component research, and power cycle O&M research, have all been identified. DOE has helped to promote CSP technology to its current status through a variety of past and current demonstration and research and development initiatives. An important contributor to the success of SETO's 2030 goals is expected to be the incorporation of the sCO_2 cycle into CSP systems.

This work presented the current stage of development in the power cycle from the perspective of the DOE's CSP research program. Considerable improvements pertaining to the CSP "boundary conditions" have to be incorporated into CSP research. Several research pathways related to turbomachinery component development, power cycle efficiency improvement and cost control, heat exchanger research, dry cooling component research, and power cycle O&M research, have all been identified. As R&D continues to advance high temperature sCO_2 cycles towards commercialization, developing such cycles within the critical parameters described would enable the cycle's integration with a concentrated solar-thermal heat at a cost compatible with significant US deployment

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