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# The prospect of high temperature solid state energy conversion to reduce the cost of concentrated solar power

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The primary challenges in making renewable energy competitive with fossil fuels for utility scale electricity are to reduce the levelized cost and enable dispatchable power delivery. In this respect concentrated solar power (CSP) with thermal storage could play an important role, since the cost of thermal storage is lower than that of electrochemical batteries. CSP, however, is still expensive and a number of ongoing research efforts are targeted at reducing the cost *via* a number of technological development pathways. Here, we present a simplified cost model for CSP and show that increasing the temperature of the heat delivered to the power cycle is a potential pathway to reduce the cost. We also propose that solid state energy converters, possibly in combination with traditional turbines, provide additional advantages that can enable high temperature CSP systems with a lower levelized cost of electricity.

**Broader context**

As we strive to eliminate $CO_2$ emissions from our infrastructure, photovoltaics (PV) has become equal to or less expensive than fossil fuel based electricity generation in some parts of the world. However, there is a limit to the amount of PV and wind that can be utilized on the grid, before the grid becomes unstable. This brings to light the critical problem of energy storage. In this respect concentrated solar power (CSP) with thermal energy storage may become an important enabling technology, but its cost is currently still too high, even though it is less expensive than PV with batteries. Here we present a simplified cost model for evaluating CSP technologies and identify potential avenues for cost reduction. Of the different opportunities for major cost reduction, improving the power cycle efficiency by operating at higher temperatures is identified as a particularly important option to consider. Furthermore it is shown that solid state energy conversion devices, may be a new way of increasing the efficiency of converting heat to electricity, since they do not involve moving parts and may therefore be able to use brittle refractories that are unsuitable for mechanical heat engines.

## The challenges and costs associated with CSP

There are two critical challenges to making renewable energy competitive with fossil fuels at the utility scale, namely (1) reducing the levelized cost of electricity (LCOE) and (2) making the electricity dispatchable. The first requirement of lower levelized cost is intuitive, as utilities will naturally want to select the lowest cost power producer instead of more expensive alternatives. In some parts of the world, photovoltaics (PV) have reached a LCOE that is equal to or less than fossil based alternatives, a scenario known as grid parity.[1] With this great achievement, and without considering the issue of dispatchability, one might conclude that a 100% renewable based electricity infrastructure is imminent in locations with sufficient solar resource. The problem, however, is that dispatchability is critical for grid stability and to meet the temporal demand.[2–4] PV output is inherently intermittent and the cost of adding electrochemical batteries for storage would raise the cost beyond what would still be competitive with traditional use of fossil fuels.[5,6] Nonetheless, several new battery technologies are under development that could ultimately reduce this cost differential, but it is still unclear if these technologies will be able to make grid scale electricity storage cost effective.[7,8]

Renewables that are fundamentally tied to fluctuations in the environment and weather patterns are based on an unalterably intermittent energy source. As a result, the eventuality of having to incorporate some form of energy storage to enable dispatchable electricity production is unavoidable in pursuit of a 100% renewable infrastructure.[2] For example, Denholm and co-workers[9–11] have shown that with sufficiently high penetrations of intermittent renewables ($\approx$10–15%) such as wind or PV, other dispatchable power generation resources will be forced to curtail their production, which is costly and can result in an oversupply of electricity. This issue arises from a shift in the energy supply to the grid. With 10–15% of electricity supplied by PV, for example, there is an abundance of electricity available during the day, which can force other resources, such

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as fossil fuelled turbines, to turn off completely. Turning off a turbine is expensive[11] and to avoid that cost it becomes more effective to discard the electricity produced by the PV (*i.e.* negative electricity prices).[9,10,12,13]

One alternative to both PV and wind, which both have intermittent electricity production, is concentrated solar power (CSP) with thermal energy storage. The main benefits of CSP with thermal storage are the abundance of low cost thermal storage materials, high roundtrip efficiencies, high energy and power densities, as well as long cycle life. Thermal energy storage at large scale essentially solves the problem of dispatchability from a technological perspective.[9,12,13] This is exemplified by the Gemasolar molten salt power tower CSP plant in Spain, which can generate electricity 24 hours a day with variable load.[14,15] The primary issue for CSP with storage, however, is meeting the first challenge of sufficiently low LCOE. At present, CSP is also somewhat geographically limited, as its cost effectiveness depends on the location's direct normal incidence (DNI) from the sun and it is currently only approaching feasibility in dessert regions where the DNI is high.[9,12,16] Furthermore, in the forthcoming analysis it is important to acknowledge that when calculating LCOE over a significant time window, there are substantial uncertainties, which must be considered to make an informed economic decision.[17,18] Nonetheless, the purpose of the forthcoming analysis is to identify technological opportunities for significant cost reduction, which are likely to impact the economics in systematic ways.

What makes CSP with storage of interest for discussion here, is the fact that it already has a lower LCOE than PV with batteries, due to the high cost of batteries.[5,9,10,12,13,19–22] In this respect it is important to analyze the most significant opportunities for cost reduction within CSP, particularly with respect to power tower configurations, which can achieve higher temperatures.[23] This can be seen from the following cost model, where the net solar to electrical conversion efficiency $\eta_{S-E}$ is given by,

$$\eta_{S-E} = \eta_S \times \eta_T \times \eta_{storage} \times \eta_E \quad (1)$$

where $\eta$ is efficiency, subscripts S, T, and E denote the solar collector efficiency, the thermal receiver efficiency and the power cycle efficiency respectively. Fig. 1 shows a simple energy flow diagram for a CSP plant with thermal storage. At each stage of the energy conversion $1 - \eta$ is the fraction of the energy lost to the environment. For simplicity, in the forthcoming analysis, it is assumed that the thermal roundtrip efficiency of the thermal storage $\eta_{storage} = 1$, as thermal round trip efficiencies above 95% are common at sufficiently large scales.[9,13,14,21,23] The capital cost for all components, per unit of electrical output power, is then given by $K$ ($ per W), which depends on the specific design point,

$$K = \left(\frac{A}{S \times \eta_{S-E}}\right) \times F + \left(\frac{B}{\eta_E}\right) \times F + \left(\frac{C}{\eta_E}\right) \times t + D \quad (2)$$

In eqn (2), each term represents the capital cost for a component of the total solar-electrical conversion system per unit electrical power output. The first term represents the cost of the collector/concentrator (*e.g.* heliostat field). The second term is the cost of the solar to thermal conversion subsystem (*e.g.* tower, receiver and heat exchangers). The third term is the cost of storing the thermal energy (*e.g.* storage media and tanks). The fourth term is the cost of the thermal to electrical conversion subsystem (*e.g.* the turbine). In eqn (2), $A$ is the cost of solar energy collection *i.e.* in $ per m$^2$ of aperture area. This includes site preparation and the solar collection field (mirror, supports, drives and installation *etc.*). For parabolic trough it would also include the cost of the heat transfer fluid system. $S$ is the annual effective average solar incidence for the specific location used to set the design point (*i.e.* 200–1000 W m$^{-2}$). $F$ is the solar multiple, which is a factor representing the extent to which the collector and receiver are made larger than the power cycle. This is done so that, more energy is captured and stored during the day than will be discharged, which then allows the remaining stored energy to be used after daylight hours. $B$ is the cost of the solar receiver and heat transfer system for the case of a power tower ($ per W-th). $C$ is the cost of thermal storage ($ per Wh-th), $t$ is the number of hours of storage, and $D$ is the cost of the power cycle ($ per W-e). One must then factor in contingency ($K'$) and indirect costs ($K''$), which can be calculated from the direct equipment costs *via*,[16]

$$K' = xK \quad (3)$$

$$K'' = y(K + K') \quad (4)$$

where $x$ and $y$ are fractions of the equipment and equipment plus contingency costs used to determine the contingency and indirect costs respectively. The total overnight installed cost (in $ per W-e) is then given by,[16]

$$K_{tot} = K + K' + K'' \quad (5)$$

By making assumptions about the financing (*i.e.* interest rate and incentives), operation and maintenance costs and the lifetime of the various system components, one can use the total capital cost to estimate the LCOE. Since financial parameters are not a direct function of the technology development, our

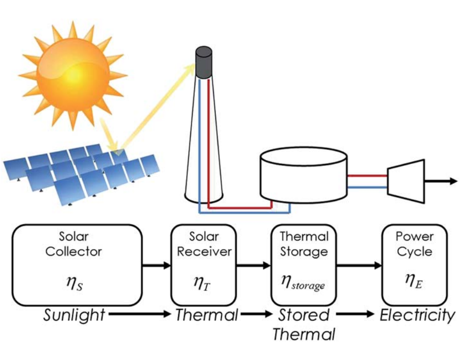


Fig. 1 Energy flow diagram for a concentrated solar power (CSP) plant.

focus here is specifically on identifying new technology development pathways that can ultimately lead to lower $K$.

The US Department of Energy's SunShot vision study[16] provides estimates and targets for $A$, $B$, $C$, $D$, $\eta_{S-E}$ and $\eta_E$. The solar to thermal energy conversion efficiency ($\eta_{S-T} = \eta_S \times \eta_T$) is typically in the range of 50–60%, for molten salt power towers due to four main sources of inefficiency, namely the loss of diffuse light (~15%), cosine losses (~20%), imperfect mirror reflection losses (~7%), spillage and heat losses in the receiver/thermal components (~10%).[16,22,23] Plugging in these numbers in eqn (2) the cost numbers match closely with the more detailed System Advisor Model (SAM)[24] used in SunShot Vision study.[16] The main advantage of our model is that it clearly shows the impact of various high level parameters on the cost and provides a framework for the wider technical community to assess the cost implications of their solar–thermal–electricity related ideas.

Our cost model is useful in identifying important areas for improvement. From the nominal values and targets used in the SunShot vision study for tower configurations (*i.e.* $A$ = \$85–185 per m$^2$, $B$ = \$110–180 per kW-th, $C$ = \$15–30 per kWh-th, $D$ = \$880–1140 per kW-e, $\eta_{S-E}$ = 20–24%, $\eta_E$ = 41.6–55%),[16] it is apparent that increasing $\eta_{S-T}$, reducing $A$, increasing $\eta_E$ and reducing $D$ are among the most significant technological improvements that can be made to reduce the LCOE of CSP. Each of these improvements could result in cost reductions as high as 15–30%. However, from a technology development perspective it is also important to identify actual technology development pathways that can allow these cost reductions to be realized.

For example, innovative approaches to increasing the optical efficiencies embedded in $\eta_{S-T}$ might involve the usage of small modular and easily installed parabolic dishes with efficient transport of the concentrated light from the non-stationary focal point of each dish to a central stationary receiver on the ground *via* fibre optic cables.[25–27] The biggest benefits of such an approach are the elimination of cosine losses and the tower structure altogether. The optical efficiencies of this approach, however, would require significant improvements to become commercially viable.[26] Nonetheless, the ability to transmit highly concentrated sunlight through fibre optic cables efficiently and new ways of efficiently coupling light into fibres from a parabolic reflector would be breakthroughs for CSP. Direct reduction of the material and installation costs associated with the solar collector ($A$ in eqn (1)) is another major opportunity for LCOE reduction. Specifically, innovative heliostat designs that are more easily installed, use less material, and/or utilize smaller reflectors that can reach higher concentrations is a particularly promising direction.[28,29] Each of these potential pathways to the improvement of subsystems and components of a CSP system are the subject of ongoing research efforts. Improving the cost/performance ratio of the power cycle, however, warrants deeper discussion.

## Power cycle analysis

If we restrict ourselves to only using turbomachinery for the power cycle, then the technological pathways for either decreasing the turbine cost or increasing its efficiency are limited. Turbomachinery is a well-established industry with well-established costs and therefore the most likely decrease in the cost/power ratio, $D$, would be due to an increase in efficiency. Increasing the power cycle efficiency directly decreases the first three terms of eqn (2). It also decreases the amount of waste heat, which ultimately reduces geographic restrictions associated with cooling water requirements. Improving the efficiency of power generation turbines, however, has limited prospects other than increasing the temperature, because the turbomachinery itself is already extremely efficient. Brayton or Rankine cycle turbines generally operate by heating a compressible fluid from ambient temperature ($T_{amb}$) to a higher temperature ($T_H$) and then letting the hot fluid expand through an expansion turbine, returning to $T_{amb}$. The theoretical maximum work output ($W_{max}$) of such a device is thermodynamically limited by the entropy flows in and out of the system, which are carried by the heat input and waste heat respectively. The maximum work can be evaluated from the change in exergy for the working fluid,

$$dW_{max} = dH - T_{amb}dS \qquad (6)$$

where d$H$ is the change in the enthalpy and d$S$ is the change in the entropy. For a gas, the heat input can be expressed as $dQ = dH = C_P dT$ and the change in the entropy is given as $dS = \frac{dQ}{T} = \frac{C_P dT}{T}$, where $C_P$ is the heat capacity. Assuming the heat capacity can be treated as constant, the ratio of the maximum work to the heat input then gives the limiting efficiency as,

$$\eta = \frac{W_{max}}{Q} = \frac{\int_{T_{amb}}^{T_H} dW_{max}}{\int_{T_{amb}}^{T_H} dQ} = 1 - \frac{T_{amb}}{T_H - T_{amb}} \ln\left(\frac{T_H}{T_{amb}}\right) \qquad (7)$$

It is important to note that the efficiency in eqn (7) is lower than Carnot efficiency evaluated between $T_H$ and $T_{amb}$, because Carnot efficiency assumes all the heat and entropy is delivered to the system at the peak temperature $T_H$. In a turbine, however, the working fluid is heated from $T_{amb}$ to $T_H$ and therefore the heat and entropy is delivered over a range of temperatures $T_{amb} \le T \le T_H$. Thus eqn (7) can also be derived by simply assuming that each unit of heat input to the fluid $dQ = C_P dT$ can be converted in a hypothetical Carnot cycle between $T$ and $T_{amb}$, where $dW_{max} = dQ\left(1 - \frac{T_{amb}}{T}\right)$.

Fig. 2 shows a comparison of eqn (7) along with the efficiencies of typical Rankine and combined cycle turbines, both of which are very close to this limit. Fig. 2 therefore shows that the remaining room for efficiency improvement in power generation turbines is only a few percent in most cases. This also means that today's turbines already operate near their thermodynamic limits and the main avenue for significant efficiency improvements beyond a few percent is to simply increase $T_H$.

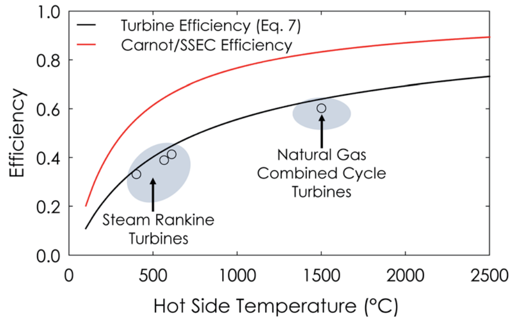


Fig. 2 Comparison of estimated maximum efficiency for a turbine and a Solid State Energy Conversion (SSEC) device. The upper limiting efficiency for turbomachinery is lower than Carnot efficiency because it is based on a sensible heat input, while Carnot efficiency, which applies to SSEC devices, utilizes a constant temperature heat input.

For turbomachinery, the technological barrier to increasing $T_H$ arises from materials limitations and not the highest temperature that can be achieved in the fuel combustion. It is an ongoing technical challenge to engineer refractory materials with long cycle life, that are strong, ductile and oxidation/corrosion resistant under such extreme conditions.[30–32] However, over the last few decades great progress toward combating this issue has been made through blade cooling, thermal barrier coatings, super alloys and single crystalline materials.[30,33] The issue of cycle life is critical, as existing materials could be used at much higher temperatures, but would experience shorter lifetimes. The choice of operating point is therefore based on economic considerations, as component lifetimes do not directly change the cost/power ratio but can strongly impact the LCOE. The effect on LCOE includes not only component replacement cost, but for short lifetimes could also substantially increase the total time the device is out of service for maintenance. The details of these ramifications are not the central focus here, but we do acknowledge their importance.

In light of these considerations, the materials problem remains difficult, particularly because of the required mechanical properties and corrosion resistance to exhaust gasses. Many brittle materials (*i.e.* oxides), have high melting points, inherent stability in oxidizing environments and corrosion resistance, but the requirement of strength and ductility is difficult to meet. It is important to recognize, however, that to some extent, the need for mechanical ductility and durability is fundamentally tied to the use of mechanical motion to drive a generator. Converting heat to mechanical work/motion is the principle function of a turbine and it implicitly suggests the presence of dynamic thermal stresses in the construction materials. It is important to acknowledge, however, that the conversion of heat to mechanical work is not strictly required, as solid state energy conversion (SSEC) technologies can convert heat directly to electricity without moving parts.

SSEC devices such as thermoelectrics (TE),[34–37] thermionics (TI),[38–40] thermally regenerative electrochemical systems (TRES)[41] and photovoltaics (PV) or thermophotovoltaics (TPV)[42–44] have all been demonstrated as standalone devices and may have the potential to overcome the temperature limitations of turbomachinery, because they do not involve high temperature moving parts. The second important advantage of SSEC devices is that they can utilize constant temperature heat inputs, similar to the way an idealized Carnot cycle would operate. As a result, the limiting thermodynamic efficiency for SSEC devices is Carnot efficiency and not eqn (7), which suggests that there is much greater room available for improving their efficiencies.

Currently, none of the aforementioned SSEC devices are as efficient or cost effective as turbomachinery at large scale, but design and testing of these devices has been largely targeted at the same temperature range where turbomachinery is applicable (*i.e.* ≈100–1500 °C). Outside this temperature range (*i.e.* above ≈1500 °C for Brayton cycles or above ≈750 °C for steam based Rankine cycles) it might prove advantageous to use a SSEC technology that rejects its waste heat to a standard turbine based mechanical cycle, as illustrated in Fig. 3. Other configurations are also possible, but would depend on the specific SSEC technology being employed, its efficiency, power density and various other integration considerations. For example, specifically in the case of solar energy conversion, configurations involving spectral splitting could also be particularly attractive if used with PV. Nonetheless, in the configuration shown in Fig. 3, the SSEC device could effectively serve as a topping cycle, where its waste heat is discharged at sufficiently high temperature that a large fraction can still be converted to electricity *via* a turbine (Fig. 3). From this perspective, the topping cycle only improves the overall power cycle efficiency, provided that the waste heat can be efficiently transferred to the bottoming cycle and that the heat losses directly to the environment are negligible, which is often the case. In this case the overall efficiency of tandem heat engines is given by $\eta_2 = \eta_{top} + (1 - \eta_{top})\eta_1$, where $\eta_1$ is the efficiency of the original bottoming cycle (*i.e.* the turbine) and $\eta_{top}$ is the efficiency of the topping cycle (*i.e.* the SSEC device).

This same strategy is used today in natural gas combined cycles (NGCCs), where the high temperature waste heat of a Brayton cycle gas turbine is used to provide heat to a steam based Rankine cycle, which then produces additional power and increases the overall efficiency. Employing a SSEC technology to reach higher temperatures and higher overall system efficiencies would be challenging both from a cost and performance/reliability standpoint, but it is not unfeasible. Operating technologies at extreme temperatures is in general full of a

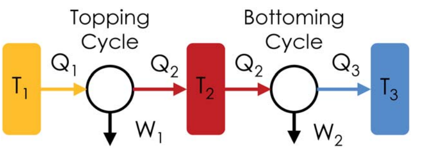


Fig. 3 Illustration of tandem heat engine configuration. The topping cycle is a high temperature heat engine, which rejects its waste heat to a bottoming cycle. The waste heat of the topping cycle is rejected at a sufficiently high temperature that the bottoming cycle can then convert a significant fraction to work.

myriad of technical challenges that must be overcome. However, the principle difference between SSEC and turbomachinery is the lack of the requirement of moving parts, which is in part related to the need for mechanical strength and ductility at high temperature. By focusing on SSEC technologies, many refractory materials such as oxides, carbides, nitrides, borides *etc.*, which tend to be brittle and are difficult to engineer for turbomachinery, might become viable options for SSEC technologies. By opening up the classes of materials that can be used for a given application, SSEC technologies could potentially take advantage of the scientific/technological advances in ceramics processing, reaction bonding and brazing that have occurred over the last few decades.[45–52]

The second key benefit of SSEC devices is that they can utilize constant temperature heat inputs, which have the potential for higher overall efficiencies and higher exergetic efficiencies in the context of solar energy than fossil fuels. For example, one could transfer all of the absorbed thermal energy from the sun directly to a SSEC device at $T_H$. In this case, all of the heat from the sun would be transferred into the power cycle at the peak hot side temperature $T_H$, the same way it is modelled in the idealized Carnot cycle. On the other hand, if one were to burn fuel to heat a SSEC device, one would have to stage a series of SSEC devices that operate at progressively lower and lower temperatures to gradually extract the heat, which is less exergetically efficient.

To further illustrate the significance of this fundamental difference in maximum efficiency, in Fig. 2 for comparison, we also show Carnot efficiency, which is the appropriate limit for SSEC devices. Correspondingly, Fig. 4 shows one example of how the capital cost of a CSP plant would decrease as $T_H$ is increased, assuming all costs remain fixed and the only impact higher temperature has is to raise the efficiency. Fig. 4 shows that SSEC devices offer a new paradigm to potentially lower the capital cost and ultimately LCOE of CSP by enabling higher efficiency. Fig. 4 also shows that for the nominal values in the SunShot vision study,[16] reducing the power cycle cost/power ratio far below $0.1 per W has diminishing returns. Here we emphasize that the results in Fig. 4 merely represent several example cases, and that the framework described herein is more important for new insights.

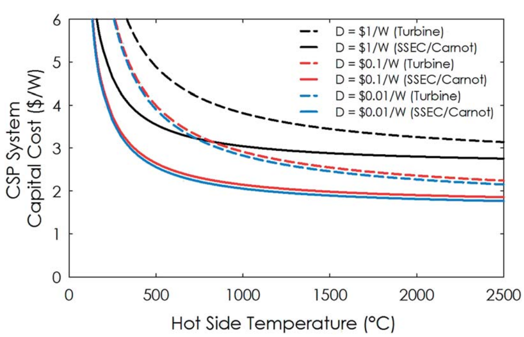


Fig. 4 CSP capital cost *vs.* temperature. The capital cost is calculated using the following nominal values obtained from the SunShot vision study:[16] $A$ = $85 per m$^2$, $S = 400$ W m$^{-2}$, $\eta_S\eta_T\eta_{storage} = 0.55$, $F = 2.7$, $B$ = $0.11 per Wh-th, $C$ = $0.015 per Wh-th, and $t = 15$ h. Three values for the power cycle cost/power ratio are also shown for each type of heat engine $D$ = $1 per W, $0.1 per W and $0.01 per W. The power cycle efficiency is calculated using eqn (7) for a turbine and using $1 - \frac{T_{amb}}{T_H}$ for Carnot efficiency, where $T_{amb} = 25$ °C.

Adding a component to the system, such as a SSEC device, adds to the total power output, but also adds capital cost. Consequently, an important question to consider is whether or not the cost/performance ratio needed for a SSEC device to lower the overall system LCOE is so low that it is unreasonable to expect that any device could ever be efficient and inexpensive enough to meet such a target (*i.e.* $\ll$ $0.10 per W). Here we assume that the lifetime of the SSEC device is the same as that of a turbine, so that the way $D$ for a SSEC device affects the LCOE is the same as that of a turbine. To estimate the cost/performance ratio required, we can further simplify eqn (2), by grouping the first three terms as a single cost that is inversely proportional to the power cycle efficiency $\eta_E$. The sum of these terms amounts to the cost of the solar to thermal conversion system (*i.e.* in $ per W-th), and allows us to rewrite eqn (2) as,

$$K = \frac{C_T}{\eta_E} + D,\ C_T = \frac{A}{S\eta_{S-T}} \times F + B \times F + C \times t \tag{8}$$

here $C_T$ essentially represents the capital cost of all the components needed to supply dispatchable thermal energy to the power cycle. If we take the case where the SSEC device is added to the system as a topping cycle that rejects its waste heat to a turbine, we can determine how high the cost/power ratio (in $ per W-e) can be for the SSEC device, such that it would still lower the total system cost/power ratio $K$. This maximum cost/power ratio can therefore be determined by requiring that the addition of the SSEC device still lowers the total capital cost $K$, which would in turn lower the LCOE. This condition is only met when the capital cost ($K_1$) for the system with only the turbine is higher than the system with the turbine and the SSEC device ($K_2$). For the most direct comparison we assess the two cases where the cost of the rest of the system $C_T$ is unchanged. In case 1 the power cycle consists of only a turbine with efficiency $\eta_1$ and cost $D_1$. In case 2 the power cycle consists of the same turbine with a SSEC topping cycle. Here, we reiterate an important assumption, which is that all of the heat $Q_1$ is transferred to the SSEC cycle first, at the peak temperature in the system, then a certain fraction of that heat is then converted to work $W_{SSEC} = \eta_{SSEC}Q_1$. Once the heat input has passed through the SSEC device all remaining unconverted waste heat is transferred to the turbine bottoming cycle at its lower hot side temperature. In this staging of the heat engines, we implicitly assume all of the waste heat from the SSEC is transferred to the turbine and that heat loss to the environment during this transition is effectively zero, which is generally the case for today's combined cycles at sufficiently large scales. Under these assumptions, the SSEC device increases the overall power cycle efficiency to $\eta_2 = \eta_{SSEC} + (1 - \eta_{SSEC})\eta_1$, but also increases the total power cycle cost to,

$$D_2 = D_{SSEC}\left(\frac{\eta_{SSEC}}{\eta_2}\right) + D_1\left(\frac{\eta_1(1-\eta_{SSEC})}{\eta_2}\right) \tag{9}$$

here, the combined power cycle cost/power ratio is $D_2$ a properly weighted sum of the two component power cycle costs, where the cost per unit electrical power output of each cycle is scaled by its respective fraction of the total electrical power output. Requiring that $K_2 < K_1$ (lower LCOE), then results in the following inequality,

$$D_2 - D_1 \leq C_T\left(\frac{1}{\eta_1} - \frac{1}{\eta_2}\right) \tag{10}$$

The inequality in eqn (10) represents the allowable increase in the total power cycle cost, which is afforded by the decrease in the first term of eqn (8), $C_T/\eta$. The increased efficiency, leads to increased power output and thus the total capital cost can remain the same with a higher power cycle cost $D_2$. Fig. 5 shows estimates for the increase in power cycle capital cost $D_2 - D_1$, which is inherently a function of $\eta_{SSEC}$. As the thermal system cost ($C_T$) increases, the value of the heat input is higher and consequently a higher price can be paid for a device that can convert a greater fraction of the high valued heat to electricity. On the other hand, as the turbine/bottoming cycle efficiency increases, the value added by the topping cycle is lessened, thereby lowering the allowable increase in power cycle cost (Fig. 5b). In Fig. 5 $D_2 - D_1$ is shown for two values of the turbine's efficiency $\eta_1$, 40%,[16] which roughly corresponds to state of the art Rankine cycles ($T_H \sim 550$–700 °C, Fig. 5a) and 60%, which corresponds to state of the art combined cycles ($T_H \sim 1400$–1500 °C, Fig. 5b). For each turbine efficiency, several curves are shown for different thermal system costs $C_T$, which range from $1–6 per W-th based on the range of system costs outlined in the SunShot vision study.[16] With these assumptions, the allowable increase in total power cycle cost for a topping cycle in tandem with a Rankine cycle is ≥$0.5 per W for SSEC efficiencies in the range of 5–20%, depending upon $C_T$. This allowable increase, however, corresponds to the total combined power cycle's cost/power ratio, which is a combination of the topping cycle cost/power ratio $D_{SSEC}$ and the bottoming cycle's cost/power ratio $D_1$. What is of primary interest here is the maximum $D_{SSEC}$ that would still lower the total capital cost $K$. It is important to note here that $D_{SSEC}$ represents not only the cost of the SSEC device, but also includes the cost of all additional equipment (*i.e.* heat exchangers) needed for interfacing with the higher temperature heat input as well as the turbine bottoming cycle. Substituting eqn (9) into eqn (10) and solving for $D_{SSEC}$ then results in the following simplified inequality,

$$D_{SSEC} \leq K_1 - C_T \tag{11}$$

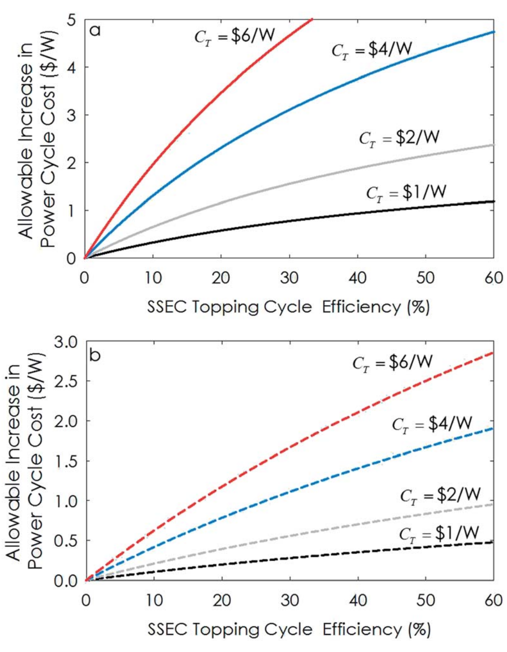


Fig. 5 Maximum allowable increase in cost of a power cycle *vs.* efficiency. (a) shows the maximum allowable increase in the cost/power ratio for a system where the SSEC rejects heat to a 40% efficient (*i.e.* steam Rankine) bottoming cycle. Each curve corresponds to a different CSP thermal system cost ranging from $1–6 per W-th. A combined SSEC/turbine power cycle with the corresponding SSEC efficiency shown on the horizontal axis can have a total cost/power ratio $D_2$ greater than the turbine itself $D_1$ by any amount below the curve and will still reduce the overall system cost and LCOE. (b) shows the maximum allowable increase in combined power cycle cost, where the bottoming cycle is 60% efficient (*i.e.* a combined cycle Brayton and Rankine cycle in tandem).

An interesting result is that eqn (11) is independent of the SSEC efficiency $\eta_{SSEC}$. This is because $\eta_{SSEC}$ affects the left and right hand sides of eqn (10) in the same way. For a fixed $\eta_1$, increasing $\eta_{SSEC}$ increases $\eta_2$, which increases the right hand side of eqn (10). Increasing $\eta_{SSEC}$, however, also increases $D_2$ by the same amount, because as more power is produced by the SSEC device, $D_{SSEC}$ comprises a larger fraction of $D_2$ (see eqn (9)) and the left hand side of eqn (10) consequently increases. The inequality states that if the cost of the SSEC device is less than $K_1 - C_T$, then the total system cost will be lower than the case without the SSEC device. Thus the maximum allowable cost for the SSEC device is when $D_{SSEC} = K_1 - C_T$. By substituting eqn (8) and examining the maximum allowable cost, eqn (11) can be rewritten as $D_{SSEC\_MAX} = D_1 + C_T\left(1 - \frac{1}{\eta_1}\right)$. This is an important result, because it shows that the maximum allowable cost/power ratio for the SSEC device is always greater than the cost of the turbine ($D_{SSEC\_MAX} \geq D_1$), since $C_T \geq 0$ and $\eta_1 \leq 1$. This suggests that the long term economic feasibility of using a SSEC device as a topping cycle is not unrealistic. If, for example, our analysis showed that $D_{SSEC\_MAX}$ is small (*i.e.* $D_{SSEC\_MAX} \ll$ $0.10 per W-e), one could conclude that using SSEC devices to lower the cost of CSP would be unfeasible. Since turbine cost/power ratios are typically on the order of $0.5–2 per W,[16] it is conceivable that SSEC technologies could reach the same range of cost, with sufficient research and development.

Fig. 6 shows the maximum allowable cost/power ratio for the SSEC device $D_{SSEC\_MAX}$ as a function of the thermal system cost $C_T$, for both $\eta_1 = 40\%$ and 60%. Here, the maximum $D_{SSEC}$ that would lower the total capital cost is shown for $D_1 =$ $0.5 per W-e, $1 per W-e and $2 per W-e, which is the range of commercial turbomachinery.[16] In Fig. 6 it is again apparent that as the

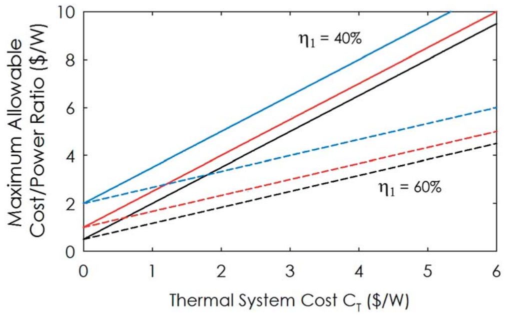


Fig. 6 Maximum allowable cost/power ratio $D_{SSEC}$ for a SSEC topping cycle *vs.* thermal system cost. The maximum allowable cost/power ratio for the SSEC device is given in eqn (11) and is shown here for values of $D_1$ = \$0.5 per W-e, \$1 per W-e and \$2 per W-e and turbine efficiencies of 40% (solid lines) and 60% (dashed lines). The corresponding value of $D_1$ for each line is given by the vertical axis intercept (\$0.5 per W-e, \$1 per W-e, \$2 per W-e).

thermal energy input $C_T$ increases in value, the cost that can be incurred for a topping cycle increases. Here it is important to note that the additional cost that can be incurred for a device that improves the overall system efficiency by any amount is substantial, as Fig. 6 shows $D_{SSEC\_MAX} \geq 2D_1$ for $C_T$ > \$3 per W-th in both cases and is independent of $\eta_{SSEC}$. Fig. 6 shows that in general, when $C_T$ > \$2 per W, $D_{SSEC\_MAX}$ is >\$1 per W and even in the limit of zero cost for the thermal energy input ($C_T$ = 0), $D_{SSEC\_MAX} = D_1$.

The order of magnitude estimates shown in Fig. 5 and 6 and discussed herein suggest that using a SSEC device as a topping cycle does not require economically unfeasible cost/performance targets, such as $D_{SSEC\_MAX} \ll$ \$0.10 per W-e. However, although there are potential advantages to using SSEC devices, SSEC devices will require extensive research and development to reach these goals. In addition to the technology development challenges associated with improving the cost/power ratio, reliability and lifetime of SSEC devices, there are a number of other system level integration issues that have to be overcome. For example, capturing solar energy at much higher temperatures could require a significantly more expensive, optical concentration system and/or thermal system infrastructure. Another issue is minimizing heat losses to the environment. These losses generally scale with the surface area exposed to the environment and thus it is important to optimize the SSEC device geometry for maximum volumetric power density. In the case of the topping cycle configuration, the heat exchange between the SSEC and turbine is another aspect that would require a system level redesign and optimization. Depending upon the SSEC technology employed, along with its power density, operating temperatures and the heat transfer media employed, additional heat exchangers may be required, which add to the cost. These issues will depend strongly on the SSEC technology being employed and the specific details and constraints of the application. However, such issues do not appear insurmountable from a technical perspective. Nonetheless, it is important to consider this approach because other options for increasing the power cycle efficiency are very limited. Thus, the use of SSEC devices to reach higher efficiencies and lower costs *via* higher temperatures is an important pathway to consider in the pursuit of a renewable option that can enable high penetration at a cost competitive with fossil fuels.

## SSEC feasibility

In addition to cost, it is also important to consider whether or not there are other technological or manufacturing barriers that could render a specific SSEC technology infeasible. Issues such as the device lifetime, the cost and abundance of the most expensive and rare materials/components, scalability, efficiency and power density differ for each of the aforementioned SSEC technologies. Here we provide, to the best of our knowledge, a brief evaluation of these issues for each SSEC technology mentioned. Varying amounts of literature are available for each technology, and the reader is strongly encouraged to consult other works for more detailed assessments of each technology. Nonetheless a concise evaluation of the aforementioned issues is still warranted herein.

### Thermoelectrics (TE)

TE devices have been used by NASA because of their high reliability and long lifetime without maintenance. Lifetimes have exceeded 30 years[53,54] and they can be made from common and somewhat abundant semiconductors, such as SiGe. TE devices can exhibit power densities ranging from 0.1–10 kW $m^{-2}$ and there do not appear to be any insurmountable issues associated with their manufacturing or scalability,[53,55] as they are currently deployed commercially in high end vehicles for individual seat temperature control. To date, the efficiency of TE devices ranges from ~1–15% depending upon the temperature range,[53,55–57] but research has been primarily focused on lower temperatures than would be required for a CSP topping cycle configuration. High temperature TE devices could potentially take advantage of new classes of materials, such as oxides,[58,59] but would likely require significant advances in the development of high temperature electrical contacts as well as materials and methods of stabilizing dopants.

### Thermionics (TI)

For TI devices, lifetime is a critical challenge.[60] Cesium vapour based converters have exhibited the highest efficiencies (>10%) and power densities,[38,61,62] but cesium is consumed, as it can corrode the emitter/collector surfaces.[61] Previous designs have been largely focused on metal electrodes, however, carbide, nitride, boride and oxide ceramics have been largely unexplored and could exhibit much greater corrosion resistance. To our knowledge a lifetime of one year was achieved in Russian Topaz space program, but this was primarily limited by cesium consumption.[60,61] This issue, however, may be surmountable with corrosion resistant ceramics. Nonetheless, the lifetime would need to be greatly increased for TI to become feasible for terrestrial power applications if cesium is used. Other TI based approaches have also been developed that can work at lower temperatures[63–65] and can utilize semiconductor electrodes.[39,66,67] With small amounts of cesium, high power densities can be achieved and there do not appear to be any insurmountable scalability issues associated with manufacturing conventional TI devices. If small devices with microscale dimensions are used, however, scalability of the manufacturing could become a limiting issue, depending upon the specific fabrication processes involved.[67] If applied in the context of CSP, TI devices may also become limited by the maximum optical concentration that can be achieved, as high temperatures >1500 °C are most desirable and can theoretically lead to efficiencies above 10%. One major advantage of TI is it potential for extremely high power densities 10–1000 kW $m^{-2}$.[40,68] A second major advantage is the weak dependence of the efficiency on the cold side (collector) temperature, which naturally lends itself to the topping cycle configuration.[40,68]

### Thermophotovoltaics (TPV)

TPV devices are essentially the same as PV devices and should exhibit similar lifetimes (>20 years).[69,70] TPV devices also rely on common semiconductors, which are abundant, although some of the best performing devices have used expensive single crystal substrates.[71–73] Nonetheless, reusable substrate procedures have been demonstrated for some systems, which could dramatically lower the cost, and such procedures are potentially scalable to achieve large system sizes.[74,75] When considering the power density of TPV (1–100 kW $m^{-2}$), the capital cost of cells fabricated from reusable substrates has the potential to be significantly less expensive than turbomachinery.[75] TPV efficiencies are often reported in the range of 10–20%,[42,71–73] but this is usually based only on the cell characteristics. Systems level innovation, modelling and optimization is lacking and how the system level efficiency will differ from that of the cell is of critical importance. If highly efficient spectral control strategies are developed, a solar TPV system could likely exhibit much higher efficiency than the values reported for individual cells, because below band gap energy can be recycled.[42,72]

### Thermally regenerative electrochemical systems (TRES)

A number of different types of TRES have been investigated,[76] but sodium based alkali metal thermo electric converters (AMTEC) have received the most attention.[77] The lifetime limiting component of AMTEC devices are the electrodes, which have been predicted to last from 5–20 years depending on the rate of grain growth, which varies with different materials and hot side temperatures.[76–78] The major advantage of TRES is that it can achieve 10–15% efficiency with power densities in the range of 0.01–10 kW $m^{-2}$ and rejects heat at sufficiently high temperature that it can be used in bottoming cycle.[76,77] In this respect a TRES is a natural topping cycle. The cost of TRES is unclear, but could be driven by the cost of the electrodes. To date more expensive Rh and Pt based electrodes exhibit longer lifetimes at higher temperatures,[78] but Mo based electrodes may be more cost effective and further research and development is needed to demonstrate integrated systems that can utilize solar energy. Nonetheless, one of the key advantages of a TRES is that it can simultaneously store heat and electricity. In this respect, such a device would able to store heat from the sun, but could also supply the utilities with added services by offering to store excess electricity in the same device.

Each SSEC device discussed herein, has its own set of advantages and technical challenges that remain. However, by comparison to turbomachinery which has received consistent research and development support, SSEC devices have received much less sustained attention. Given the materials challenges associated with further increasing the temperature/efficiency of turbines, one should consider if alternative cycles that can provide supplemental enhancements in performance are a worthwhile research investment, particularly since the cost requirements in the context of CSP are not unreasonable.

## Conclusions

We have presented a simplified cost model for CSP systems that enables identification of the dominant costs. Our analysis suggests that among the major opportunities for cost reduction, reducing the power cycle cost/power ratio is one of the most difficult. Further analysis indicated that the room for improving the efficiency of turbomachinery is primarily limited to operating at higher temperatures. Materials limitations, however, prevent access to higher temperatures with sufficient lifetime and the need for mechanical strength and ductility is a particularly daunting challenge, because it generally renders many ceramics unfeasible. The requirement of mechanical strength, nonetheless can be partially alleviated by using alternative heat engine technologies such as SSEC devices, which do not have moving parts and therefore can potentially be made from brittle materials. Subsequent analysis showed that SSEC technologies also offer potential advantages thermodynamically, since they can be used with a constant temperature heat input, which has added benefits in the context of solar energy conversion. As a result, operating a SSEC device in tandem with turbomachinery as a topping cycle is one particularly attractive configuration. A straightforward estimation of the capital costs of systems with and without the SSEC device as a topping cycle showed that the cost target for a SSEC is not unreasonably low. Our analysis shows that the cost targets for SSEC devices are always higher than the bottoming cycle cost/power ratio, and depends on the value of the thermal energy input and the bottoming cycle efficiency. The analysis also showed that at reasonable efficiencies (*i.e.* on the order of 10%) an increase in the power cycle cost/power ratio is also tolerable and can exceed $0.5 per W-e. These results suggest that SSEC devices could offer significant value towards reducing the cost of CSP and could be feasible with further research and development. Other challenges associated with system integration, however, are also critical, but given the limited alternative prospects for raising the power cycle efficiency, the use of SSEC is a particularly interesting approach for long term development.

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