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# Evaluation of annual efficiencies of high temperature central receiver concentrated solar power plants with thermal energy storage

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**Abstract**

The current study has examined four cases of a central receiver concentrated solar power plant with thermal energy storage using the DELSOL3 and SOLERGY computer codes. The current state-of-the-art base case was compared with a theoretical high temperature case, which was based on the scaling of some input parameters and the estimation of other parameters based on performance targets from the Department of Energy SunShot Initiative. This comparison was done for both current and high temperature cases in two configurations: a surround field with an external cylindrical receiver and a north field with a single cavity receiver. The optical designs for all four cases were done using the DELSOL3 computer code; the results were then passed to the SOLERGY computer code, which uses historical typical meteorological year (TMY) data to estimate the plant performance over the course of one year of operation. Each of the four cases was sized to produce 100 $MW_e$ of gross electric power, have sensible liquid thermal storage capacity to generate electric power at full rated production level for 6 hours, and have a solar multiple of 1.8.

There is a fairly dramatic difference between the design point and annual average performance. The largest differences are in the solar field and receiver subsystems, and also in energy losses due to the thermal energy storage being full to capacity. Another notable finding in the current study is the relatively small difference in annual average efficiencies between the Base and High Temperature cases. For both the Surround Field and North Field cases, the increase in annual solar to electric efficiency is <2%, despite an increase in thermal to electric conversion efficiency of over 8%. The reasons for this include the increased thermal losses due to higher temperature operation and operational losses due to start-up and shut-down of plant sub-systems. Thermal energy storage can mitigate some of these losses by utilizing larger thermal energy storage to ensure that the electric power production system does not need to stop and re-start as often, but solar energy is inherently transient. Economic and cost

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considerations were not considered here, but will have a significant impact on solar thermal electric power production strategy and sizing.

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*Keywords:* Annual Efficiency, Central Receiver, Thermal Energy Storage, DELSOL, SOLERGY, Molten Salt

## 1. Introduction

Concentrating Solar Power (CSP) focuses sunlight in order to use the heat energy of the sun. One important application of CSP is to use the heat energy of the sun to create electricity, usually at the utility scale. An advantage of CSP is the ability to store thermal energy so that the facility can match its electricity production to customer demand even when the sun is not shining. Thermal energy storage is an important technology that will enable further penetration of renewables into the electrical grid. However, the cost of CSP needs to be lower to make it fully cost-competitive with other electrical production technologies. The reduction of the cost of solar power production including CSP is the focus of the U.S. Department of Energy's SunShot Initiative.

### *1.1. Overview of concentrated solar power and central receiver systems*

In a central receiver system configuration, many mirrors (heliostats) individually track the sun and reflect the concentrated solar image onto a receiver on top of a tower. The receiver contains the working fluid, which is heated by the concentrated solar radiation. The working fluid can then be stored directly in insulated tanks and used to drive a power cycle to produce electric power on-demand (see Figure 1).

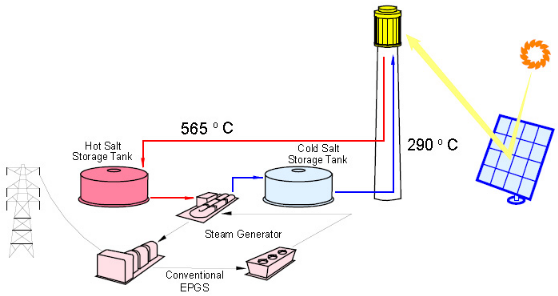


Figure 1. State-of-the-Art Molten Salt Central Receiver System (taken from Ref [1])

### *1.2. Operation at higher temperatures*

The DOE SunShot program has a great interest in improving CSP systems which use much higher temperatures [2-4] in order to realize higher power cycle efficiency and, hopefully, lower cost of electricity. It is therefore of interest to examine the effects that higher operating temperatures would have on the performance of both the thermal energy storage subsystem and on the overall system. The purpose of this analysis is to use real weather data to evaluate the annual efficiency of a high temperature, central receiver, concentrated solar power plant. This is done to evaluate potential higher operating temperatures for next generation central receiver plants.

This high temperature operation is desired to have an upper operating temperature of 650°C and a lower operating temperature of 250°C. This operating range is not currently available in an economical and practical sensible material, but the metrics were derived from the performance goals of the DOE SunShot Multi University Research Initiative [4]. Based on the temperature ranges of interest, the system is assumed to have some kind of a chloride or carbonate salt mixture, as these salts were estimated to have the best performance in terms of volumetric energy storage density and system cost [5]. However, these salts do suffer from corrosion issues at high temperatures, especially of dissolution of chromium in containment alloys; chloride salts seem unable to form passivated oxide layers, so corrosion continues to be an issue over time [6]. Chloride salts suffer when impurities such as oxygen and water are present in tank ullage gas; this effect is less significant for carbonate salts, but the chloride content of the carbonate salts leads to high corrosion [6].

### *1.3. Overview of DELSOL3 and SOLERGY computer codes*

The DELSOL3 and SOLERGY computer codes used in this study are computer codes written in FORTRAN and developed at Sandia National Laboratories. The DELSOL3 computer code is used to calculate optimal system design and subsequent optical performance for central receiver power plants [7]. This code was used to design commercial power towers [1], and has been validated against other optical codes [7] and Solar Two data [8]. The SOLERGY computer code is used to calculate the annual performance of a central receiver power plant using conservation of energy [9]. SOLERGY has been validated with data from Solar One [10] and Solar Two [11]. The SOLERGY computer code is able to use the weather data (taken at 15 minute intervals) and tracks startup, shutdown, operational mode, and performance of plant components over the course of the year. The SOLERGY code then aggregates the performance and losses for each day and the entire year. Typical meteorological year (TMY) data used is from The Aerospace Corporation and provides meteorological data from Barstow, CA, in the year of 1977 [12].

## 2. Performance analysis

### *2.1. General system description*

This study examines four cases of a central receiver concentrated solar power plant with sensible liquid thermal storage in Barstow, CA, that will produce 100 $MW_e$ of gross electric power. The plant will provide 6 hours of thermal energy storage (for full rated turbine operation) and have a solar multiple of 1.8. The solar multiple is a ratio of the thermal energy input to the receiver to the thermal energy requirements of the power generation system at the design point [7]. A base case is first examined, which will reflect the state-of-the-art. This is taken to be a central receiver system using a binary molten nitrate salt ($NaNO_3$-$KNO_3$) heat transfer fluid which drives a conventional subcritical Rankine steam cycle with dry cooling. This base case system will be primarily modeled after the subcritical dry-cooled case in Ref [1]. The molten salt will nominally operate between 565°C and 290°C. This base case is used to validate the current model against previous work.

A High Temperature case is then compared to the base case; this high temperature case is meant to reflect a system which operates at much higher temperatures in order to drive a much more efficient power cycle. Instead of using demonstrated technologies for this case, an optimistic system will be modeled using subsystem performance goals from the DOE SunShot Initiative [2-4]. The performance goals that are included in this study are listed in Table 1 along with the associated metrics used in the base case.

Table 1. Performance Metrics for Base and High Temperature Cases.

| Subsystem | Performance Metric | Base Case [1] | SunShot Goal |
|---|---|---|---|
| Receiver | Thermal Efficiency | 89-90% | 90% [3] |
| | Heat Transfer Fluid Exit Temperature | 565°C | 650°C [3] |
| Heat Transfer Fluid | Minimum Operating Temperature | 290°C | 250°C [4] |
| Thermal Storage | Efficiency | 98.5% | 95% [2] |
| Power Block | Cycle Efficiency (with dry cooling) | 41.83% | 50% [3] |

Two different plant configurations are also examined: a surround solar field with an external cylindrical receiver, and a north solar field with a north-facing cavity receiver. The four cases to be examined in this study are then:

- Surround Field Base Case
- Surround Field High Temperature Case
- North Field Base Case
- North Field High Temperature Case

It should be noted that there is concern about the ability to operate an external solar receiver at higher temperatures and still achieve 90% thermal efficiency. While optical considerations for large scale north-fields mean that surround fields are typically more effective, it is likely that plants using a surround field at higher temperatures will take the form of something similar to a multi-cavity receiver instead of an external cylindrical receiver. The surround field with an external cylindrical receiver is used in DELSOL3 and SOLERGY for simplicity but the thermal efficiency is set at 90%.

Similarly, it is noted that the SunShot performance goal for the receiver thermal efficiency of ≥90% is not much different than the current state-of-the-art value of ~89%. This is due to the fact that when operating a receiver at higher temperatures, it is much more difficult to obtain a thermal efficiency of 90% for two main reasons: higher thermal losses and changing emissivity wavelengths. The receiver will lose more heat to the ambient surroundings at higher temperature through convection and conduction, but especially through radiative losses, which are proportional to $T^4$. Additionally, the radiative emissions from the receiver at the higher temperature will more closely match the wavelengths of the incoming solar radiation. Ideally, a solar receiver would have high absorptivity in the solar radiation wavelengths and low emissivity in the wavelengths at which the receiver radiates heat at its operational temperatures. However, it is very difficult to engineer materials or coatings to have high absorptivity and low emissivity in the same wavelengths. As such, the High Temperature case in this study will reflect a receiver which can operate at higher temperatures while achieving the same or slightly better relative thermal performance.

### *2.2. Overview of performance analysis methodology*

For each case, DELSOL3 is used to design the solar field, receiver dimensions, and tower height. This is done by finding the optimum design for a 100 $MW_e$ plant based on minimization of capital cost within DELSOL3. The cost parameters are based on those found in Ref [1] and are held constant for all cases. While many of the important SunShot targets involve cost [2-4], the current study holds cost parameters constant in DELSOL3 and leaves the evaluation of the effect of changing cost parameters for future work. Once an optimum design is obtained, a performance calculation is done in DELSOL3 to calculate the optical efficiency of the solar field. The resulting optical efficiency matrix is then passed to SOLERGY along with the total heliostat mirror area of the plant design. The optical efficiency matrix from DELSOL3 is corrected for receiver absorptivity because this is handled separately in SOLERGY. SOLERGY then runs using these inputs, along with its own input parameters and the TMY weather file, to evaluate plant performance over the year.

### *2.3. Development of DELSOL3 and SOLERGY input parameters*

Many of the input parameters for both DELSOL3 and SOLERGY are very similar to Ref [1], including heliostat parameters and flux limitations on the receiver. Many other parameters are the same as well, and notable differences will be described here.

For this study, an overall receiver thermal efficiency is assumed and the appropriate DELSOL3 and SOLERGY parameters are adjusted to approximate this level of performance. For all cases, a receiver efficiency of 90% is assumed; this is based both upon current state-of-the-art receiver thermal performance [1, 3] and the SunShot receiver thermal efficiency target [3].

$$\eta_{\rm th} = \frac{\alpha Q_{in} - Q_{loss}}{Q_{in}} = \alpha - \frac{Q_{loss}}{Q_{in}} \quad (1)$$

The overall receiver efficiency is shown in ( 1, where $\eta_{th}$ is the thermal efficiency of the receiver, equal to 0.9; $\alpha$ is the solar absorptance of 0.94 (this value is based on Pyromark paint [1] which is assumed to have high temperature capability for simplicity in this study, though an alternative material is likely needed at the high temperatures); $Q_{in}$ is the incident power on receiver, and $Q_{loss}$ is the power loss due to radiation and convection. The power absorbed to the working fluid of the receiver (the thermal rating of the receiver in SOLERGY) is found by determining the thermal power requirements of the electric power generation system turbine and scaling this value by the solar multiple. The absorbed power can then be used with the receiver thermal efficiency to find the incident power on the receiver, as the absorbed power is simply the incident receiver power scaled by the receiver efficiency. Once the incident and absorbed power levels have been calculated, they are used with the receiver absorptivity to calculate the thermal loss of the receiver for the specified efficiency. These loss values are then normalized per unit receiver area for comparison. The thermal loss per unit area will be for the area of external receiver surface for the surround field cases. The thermal loss per unit area will be for the rectangular aperture area for the north field cases. These calculations are summarized in Table 2.

Table 2. Power Level Calculations.

| | Base Case | | High Temperature Case | |
|---|---|---|---|---|
| | Surround Field | North Field | Surround Field | North Field |
| Gross Electric Rating | 100 $MW_e$ | 100 $MW_e$ | 100 $MW_e$ | 100 $MW_e$ |
| Turbine Efficiecy | 41.83% | 41.83% | 50% | 50% |
| Turbine Thermal Rating | 239.06 $MW_{th}$ | 239.06 $MW_{th}$ | 200 $MW_{th}$ | 200 $MW_{th}$ |
| Solar Multiple | 1.8 | 1.8 | 1.8 | 1.8 |
| Absorbed Power ($Q_{abs}$) | 430.31 $MW_{th}$ | 430.31 $MW_{th}$ | 360 $MW_{th}$ | 360 $MW_{th}$ |
| Incident Power ($Q_{in}$) | 478.2 $MW_{th}$ | 478.2 $MW_{th}$ | 400 $MW_{th}$ | 400 $MW_{th}$ |
| Thermal Loss ($Q_{loss}$) | 19.128 $MW_{th}$ | 19.128 $MW_{th}$ | 16 $MW_{th}$ | 16 $MW_{th}$ |
| Receiver Area | 829.38 $m^2$ | 563.55 $m^2$ | 678.58 $m^2$ | 422.71 $m^2$ |
| Loss/Area | 23.1 $kW_{th}/m^2$ | 33.9 $kW_{th}/m^2$ | 23.6 $kW_{th}/m^2$ | 37.9 $kW_{th}/m^2$ |

The loss per unit area values increase for the high temperature cases over the respective base cases. The values for the surround field cases especially do not seem to be a very large increase, which is counter-intuitive for a higher temperature scenario. However, the way in which these loss values were calculated does not explicitly take the higher temperature into account for the thermal losses. This was done in order to compare different receiver configurations using an optimistic technical target (90% thermal receiver efficiency at high temperature), instead of using disparate methods and assumptions to calculate thermal losses for the different cases. A possible explanation for the lower than expected increase in the loss per unit area value for the surround field cases is to assume the multi-cavity, high absorptivity, and low emissivity conditions discussed previously.

The DELSOL3 computer code uses a round-trip efficiency for the thermal storage subsystem when calculating the necessary thermal input required for the plant [7]. Therefore, the values for thermal storage efficiency identified in the base case from Ref [1] and the SunShot performance goals can be used directly. The SOLERGY code uses a constant value of heat loss for the thermal energy storage subsystem rather than an efficiency value. This value was obtained by scaling values from Ref [1] linearly with temperature and system size.

The DOE SunShot goal for high temperature, dry-cooled power cycle efficiency is ≥50%, this value is used for the high temperature case turbine efficiency [3]. The DELSOL3 and SOLERGY default values of turbine efficiency (41.83%) were used for the base case [7, 9], which is the value for a Rankine cycle with a dry-cooled condenser [1].

In DELSOL3, the turbine efficiency is a single value for the design point power level [7]. In SOLERGY, the design point turbine efficiency was de-rated to account for somewhat lower efficiencies during sub-rated operation of the turbine (e.g., during turbine startup) [9]. The default de-rating in SOLERGY was scaled to the higher design point efficiency.

There are parameters in SOLERGY that calculate and account for the various electrical parasitic loads in the CSP plant. This section of the SOLERGY code was not included in the original version, and thus is not listed or described in [9], but is described in a later report [13]. These electrical parasitics are taken out after the gross power (100 $MW_e$ in this study) has been produced by the electric power generation system. Many of the input parameter values were taken directly from Ref [1], including the power to run the heliostat field per unit mirror area, the number of time steps in receiver hold mode, and baseline parasitics for forced and scheduled outages [1]. These parameters were held constant for all four cases considered here. Other parameters (such as pump parasitics) were scaled with system size from Ref [13].

## 3. Results

A summary of results from DELSOL3 are given in Table 3. These DELSOL3 results show one of the chief values of achieving the higher efficiency goals of the SunShot program. The solar field, which often accounts for 50% of the capital cost of a CSP plant [14], is significantly reduced in size. The above values reflect a 13.9% and a 10.9% decrease in the number of heliostats required for going from the Base to the High Temperature case for the surround field and north field, respectively. It should be noted that the plant design was done in DELSOL3 individually for each case based on a gross power output of 100 $MW_e$ and 6 hours of thermal storage. This method results in four distinct plant designs that incorporate the operational conditions noted above, instead of scaling a single plant design to each of the four cases.

Table 3. Summary of DELSOL3 Optimized System Design Results.

| | Surround Field – Base Case | Surround Field – High Temperature Case | North Field – Base Case | North Field – High Temperature Case |
|---|---|---|---|---|
| Tower Height | 177.63 m | 160.53 m | 263.16 m | 228.95 m |
| Receiver Dimensions | 12.0 m (D) x 22.0 m (H) | 12.0 m (D) x 18.0 m (H) | Aperture: 20.56 m (W) x 27.41 m (H) | Aperture: 20.56 m (W) x 20.56 m (H) |
| | | | Cavity: 12.22 m (D) x 30.15 m (H) | Cavity: 12.22 m (D) x 22.61 m (H) |
| Number of Heliostats | 9618 | 8282 | 9093 | 8099 |
| Land Use | 5.956 $km^2$ | 5.347 $km^2$ | 5.544 $km^2$ | 5.215 $km^2$ |

### *3.1. SOLERGY plant performance results*

A summary of results from SOLERGY for all four cases is shown in Table 4. The values in Table 4 indicate the fractional efficiency of each subsystem for the design point and the annual efficiency. The “Storage Full” Subsystem is representative of the loss that occurs when the Thermal Energy Storage subsystem is full to capacity; at this point in operation, heliostats must be defocused and energy discarded since there is nowhere to store the additional energy. The capacity factor is a useful metric for comparing the availability of a power source, so this will be calculated from the SOLERGY output. The capacity factor is a ratio of the total electric power produced to the amount of electric power produced if the generator was running at full capacity all the time. It is noted that the capacity factors for each case are very close to the same value; this is because each case was scaled to have 6 hours of thermal energy storage for the turbine efficiency of that particular case. Since the relative amounts of thermal storage do not change between the cases, the capacity factor does not change very much either.

Table 4. Summary of Subsystem and Overall Efficiencies from SOLERGY Results and Calculated Capacity Factors.

| | Surround Field – Base Case | | Surround Field – High Temperature Case | | North Field - Base Case | | North Field - High Temperature Case | |
|---|---|---|---|---|---|---|---|---|
| Subsystem | Design Point | Annual | Design Point | Annual | Design Point | Annual | Design Point | Annual |
| Field | 0.63689 | 0.56151 | 0.63955 | 0.56398 | 0.66959 | 0.56548 | 0.64281 | 0.54452 |
| Storage Full | N/A | 0.949 | N/A | 0.944 | N/A | 0.964 | N/A | 0.960 |
| Receiver | 0.89998 | 0.78560 | 0.90000 | 0.77256 | 0.89998 | 0.79691 | 0.90000 | 0.78945 |
| Piping | 0.99970 | 0.99961 | 0.99943 | 0.99927 | 0.99970 | 0.99961 | 0.99943 | 0.99926 |
| Thermal Storage | N/A | 0.99575 | N/A | 0.99012 | N/A | 0.99570 | N/A | 0.98998 |
| Power Block | 0.41830 | 0.40982 | 0.50000 | 0.49015 | 0.41830 | 0.40961 | 0.50000 | 0.48983 |
| Parasitics | N/A | 0.828 | N/A | 0.792 | N/A | 0.828 | N/A | 0.792 |
| Overall | N/A | 0.14131 | N/A | 0.15795 | N/A | 0.14667 | N/A | 0.15833 |
| Capacity Factor | | 48.5% | | 48.8% | | 47.5% | | 47.8% |

## 4. Discussion

The differences between the Base cases and the High Temperatures cases in the current study were examined. The solar field contributes a large loss to system efficiency; most every case loses approximately 43.6% of the available energy in the solar field. The North Field cases lost slightly more, which stems from the fact that a cavity receiver will have higher spillage losses. The losses from heliostat defocusing due to the thermal storage being full is very similar for all four cases, since they all have 6 hours of thermal storage, around 4 or 5% loss. This loss would be mitigated by additional thermal energy storage capacity. Receiver losses are fairly similar for all four cases due to the fact that thermal losses were calculated such that the receiver thermal efficiency would be 90% for each case. Heat losses from piping and thermal storage are slightly larger for the High Temperature cases, as they were scaled with temperature, but are a small effect in all cases. There is an obvious effect on turbine efficiency when comparing the Base Case to the High Temperature Case for both the Surround and North Field cases; the higher turbine efficiency used for the High Temperature case leads to much smaller loss for electricity production. There is a moderate increase in the electrical parasitic loss between the Base and High Temperature cases for both the Surround and North Field cases. The parasitics include baseline parasitics, electrical energy to power and stow the field, the hot and cold salt pumps, as well as electrical parasitics for the turbine and cooler. Many of the individual sources of parasitic load are relatively the same, but the parasitic load of the turbine plant relative to the gross electric power produced is 6.83% for the High Temperature Cases while only 3.17% for the Base Cases. This is due to the higher turbine plant parasitics assumed for the higher temperature and higher thermal-to-electric efficiency turbine. However, this ~3% difference is somewhat less than other losses, as it is relative to the gross electric power produced, and not the input thermal energy in the plant.

As can be seen from the overall efficiencies, the increase in annual efficiency is fairly small between the Base and High Temperature cases. The annual solar-to-electric efficiency was calculated with and without the electric parasitics, and is shown in Table 5. Even without the increase in electrical parasitic load between the Base and High Temperature cases discussed previously, the increase on an annual basis is ~2%. This is not to say that the increase is negligible; a ~2% efficiency increase overall is a ~12% increase relative to the energy produced for the Base case. However, the difference between a nominal 8% increase in thermal to electric conversion efficiency (~20% relative to the Base case) and the resulting overall increase in efficiency of ~2% (~12% relative) is quite large. Considering the efficiency increases on both an absolute and relative basis are important to get a better understanding of the effects of future operating conditions and for comparison to other technologies. Economics were not considered in this study, but an increase in operating temperature of 100 K or more will require new materials throughout the plant, including heat transfer and storage media as well as containment materials.

Development and use of these new materials will likely come at significant cost, and so a better understanding of the trade-offs between cost and increased efficiency is important.

Table 5. Solar to Electric Annual Efficiencies with and without Parasitic Electrical Loads.

| Case | Solar to Electric Annual Efficiency, Gross | Solar to Electric Annual Efficiency, Net |
|---|---|---|
| Surround Field Base Case | 17.07% | 14.13% |
| Surround Field High Temperature Case | 19.95% | 15.79% |
| North Field Base Case | 17.71% | 14.67% |
| North Field High Temperature Case | 20.00% | 15.83% |

Lastly, it must be noted that the current study assumed that the high temperature case would utilize a sensible liquid similar to a molten salt system. While research is ongoing to develop molten salt formulations that can reach high enough temperatures to match the SunShot performance targets, there are many other research projects that are examining latent, thermochemical, and solid sensible heat storage. This means that some of the implicit or explicit assumptions made here would not necessarily hold. Mostly this will affect the DELSOL3 optical designing of the receiver, in which the molten salt assumption comes to bear on many design decisions within the code. However, aside from the north and surround field differences described above, there are many other design considerations that still hold true in the DELSOL3 code. For example, the design and spacing of the solar field is likely to continue to follow similar principles, though the design and cost of heliostats may change. The SOLERGY code uses energy flows within the plant, and so does not explicitly assume a particular kind of heat transfer fluid or mechanism. That said, many of the input parameters in the current study assumed a molten salt-type system, such as the electric parasitics from the hot and cold salt pumps. However, this is held as an acceptable assumption, due to the fact that some sort of parasitic will be required to move mass or energy within the system. Additionally, the current study uses a direct storage system, whereby the heat transfer fluid is directly stored in the thermal energy storage subsystem. Depending on future developments in receiver and thermal storage technology, additional heat exchangers may be needed here or elsewhere in the system; these heat exchangers will necessarily impose an efficiency loss on the thermal energy transferred, lowering the overall system efficiency further. Furthermore, the startup times for the receiver and steam generator imposed additional energy penalties which lead to discarded heat; additional heat exchangers will increase this effect. These transient effects are a major source of loss in the current study, and will continue to be a major concern for transient renewable energy.

## 5. Conclusion

The current study has examined four cases of a central receiver concentrated solar power plant with thermal energy storage using the DELSOL3 and SOLERGY computer codes. The differences between a current state-of-the-art base case was compared with a theoretical high temperature case, which was based on the scaling of some input parameters and the estimation of other parameters based on performance targets from the Department of Energy SunShot Initiative. This comparison was done for both a surround field with an external cylindrical receiver and a north field with a single cavity receiver. Each of the four cases was sized to produce 100 $MW_e$ of gross electric power, have thermal storage capacity to generate electric power at full rated production level for 6 hours, and have a solar multiple of 1.8.

One notable conclusion is the fairly dramatic difference between the design point and annual average performance. Differences between design point and annual average performance for individual cases are outlined in Table 4. The largest differences are in the solar field and receiver subsystems and also in energy losses from the thermal energy storage being full to capacity. These differences between the design point and annual average efficiency values are typically due to losses incurred while system components are starting up and shutting down, especially in the receiver subsystem. Additional losses in the receiver subsystem are from more power being sent to the receiver than its input rating, necessitating heliostats to defocus and discard their energy in order to not damage system components. Lastly, energy is discarded when excess energy is input to the receiver while the thermal energy subsystem is full due to defocusing heliostats. Some of these losses can be mitigated by increased system size, but transient effects are inherent to solar energy.

Another notable finding in the current study is the relatively small difference in annual average efficiencies between the Base and High Temperature cases. For both the Surround Field and North Field cases, the absolute increase in annual solar to electric efficiency is <2% (~12% relative increase). This is despite an absolute increase in thermal to electric conversion efficiency of over 8% (20% relative). The reasons for this include the increased thermal losses due to higher temperature operation and operational losses due to start-up and shut-down of plant sub-systems. The thermal losses were estimated using optimistic (not currently achievable) technical performance targets, and so the current study could even over-predict the performance of high temperature operation in a real system. The operational losses are a major source of loss for the system as a whole, and are due to the transient nature of solar power and are therefore difficult to overcome. Thermal energy storage can mitigate some of these losses by ensuring that the electric power production system does not need to stop and re-start as often, but additional storage brings additional capital costs and must be justified through techno-economic analyses and favorable power purchase agreements. However, the losses from these transient conditions emphasize why a plant might be constructed with significant thermal storage even if the power purchase agreement did not incentivize use of storage.

Lastly, it is notable that the current study only considers thermal and electric system performance, while many of the SunShot Initiative targets include goals for system and component cost. Cost is not considered in the current study, but will have a major effect on the cost of solar energy since capital cost of the plant is obviously a major consideration for solar thermal power plants.

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