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A cost and performance evaluation of SUNDISC: a dual-pressure air receiver cycle

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Abstract

A dual-pressure air receiver cycle has previously been proposed to overcome limitations of combined cycle CSP plants. The economic and energetic performances of this so-called SUNDISC cycle are investigated in the present work. To do so, an annual hourly thermodynamic model is used with varying configurations of solar field size, steam turbine rating, storage capacity, low-pressure receiver system and hybridization modes.

The conducted simulations show the lowest levelized cost of electricity for small solar components and considerable fuel co-firing rates at 0.08 USD/kWh$_e$. However, solar power plants are expected to be limited to low fuel usage. When the co-firing rate is capped at 20 % and 5 %, the minimum achievable costs increase to 0.10 USD/kWh$_e$ and 0.12 USD/kWh$_e$, respectively. These latter results are generated with high steam turbine ratings as well as large low-pressure receiver systems, solar fields and thermal energy storage systems. The resulting annual time of no power generation, as a measurement of the plant's baseload capacity, was less than 800 h. If longer plant operation is aspired either cost or fuel co-firing rate increase.

The rock bed thermal energy storage system is found to add only minor costs to the plant. Large storage capacities are, therefore, viable and the technology plays a vital role in enabling baseload electricity generation from solar energy.

Refinements are recommended for the component cost model and plant operation control. The latter should be made more flexible to find optimized hybridization modes.

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Keywords: SUNDISC; combined cycle; air receiver; system analysis; CSP

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Nomenclature

HPRS	high-pressure receiver system
LCOE	levelized cost of electricity
LPRS	low-pressure receiver system
ST	steam turbine
TESS	thermal energy storage system
TNPG	time of no power generation
f_{fuel}	fuel co-firing rate [-]

1. Introduction

Combined cycle CSP plants are expected to convert solar energy more efficiently into electricity than single-cycle plants while using mostly proven power block components. It has previously been shown that a system with a passive thermal energy storage system (TESS) downstream the gas turbine outlet has inherent limitations [1]. While enabling the use of cost-effective rock bed storage systems, it limits the amount of available thermal energy at night to the exhaust heat of the gas turbine. Additionally, the pressurized receiver can only absorb as much energy as the gas turbine demands which results in high fuel co-firing rates or low solar field capacity factors.

The proposed solution to overcome these shortcomings is the Stellenbosch University Direct Storage Charging Dual-Pressure Air Receiver Cycle (SUNDISC cycle). The high-pressure receiver system (HPRS) of the cycle is used to power the gas turbine, while the low-pressure receiver system (LPRS) is used to charge the TESS and power the bottoming cycle (see Fig. 1). Some of the advantages of this cycle are: good utilization of the solar field, high solar fractions, dispatchable power generation and flexible plant layouts.

The aim of this study is to investigate the economic viability and energetic performance of different configurations of SUNDISC cycle power plants. To achieve this, annual simulations of an exemplary plant are conducted with varying ratings of the main components and different hybridization controls.

2. Modeling and simulations

The simulations are conducted with a steady-state model written in the MATLAB® R2011b environment. More detailed information on the model is provided in previous papers [1,2]. Its most important characteristics as well as settings, which were changed for the present study, are given in the following.

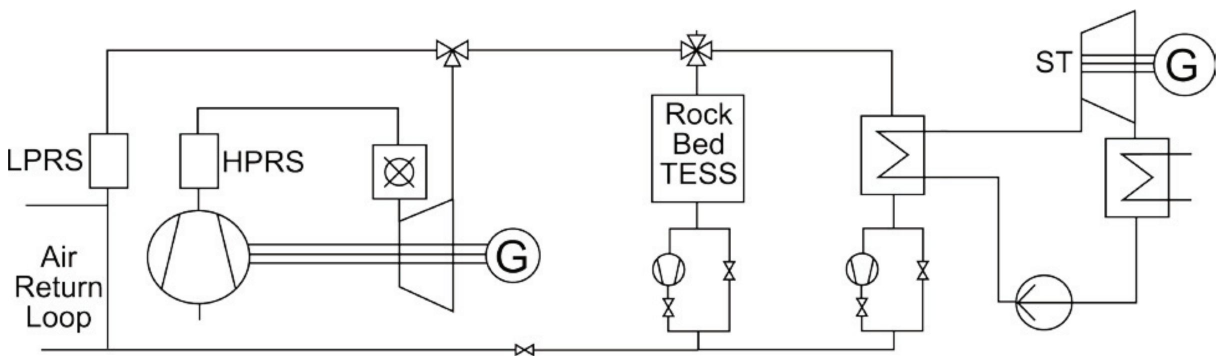

Fig. 1. Schematic of the SUNDISC cycle

2.1. Thermodynamic model

The investigated system's gas turbine has a fixed nominal rating of 5.25 MW_e at a heat input of 17 MW_t, which defines the nominal thermal rating of the HPRS. This rating implies small plant sizes and leaves room for improvement in terms of economies of scale. Larger ratings of the gas turbine system can be reached by implementing more powerful turbine models or several units in parallel (for example in multi-tower designs). This is foreseen for further stages in the developing process of a SUNDISC cycle plant.

The HPRS is based on the SOLGATE pressurized air receiver technology [3] and the LPRS on the HiTRec open volumetric receiver technology [4], as these are the most developed, tested and published on air receiver technologies.

The chosen gas turbine has a nominal turbine inlet temperature of 1102 °C. It is assumed that a receiver cluster of similar characteristics to the one of the SOLGATE project is able to supply the turbine with heat at this temperature although the demonstrated maximum outlet temperature of the cluster is only 1030 °C [5]. Fuel co-firing is therefore not required under nominal conditions.

The solar field is defined as a polar field with an 88 m high tower, similar to eSolar's Sierra SunTower design, at the geographical location of Upington, South Africa. The field's optical efficiency map, which is based on a geometrical discrete cell model [6], is then fitted with a sixth order polynomial correlation dependent on the zenith angle. This correlation is not adjusted for different solar multiples and, therefore, increased atmospheric attenuation and spillage.

The modeled TESS is a rock bed tank storage as this technology is predicted to be economically attractive where suitable storage material is abundant [1]. A study has shown that this is the case for the Northern Cape Province of South Africa [7], which is assumed as the location of the plant. The previously used model has been enhanced with a temperature-dependent correlation for the specific heat capacity of rock, which has been shown to change considerably over the temperature-range of a CSP rock bed storage [7].

2.2. Operating modes

The gas turbine is operated if the concentrated solar radiation is sufficient to run it above 60 % load. Below this threshold, thermal energy can be captured in the LPRS. If there is more solar radiation available than needed to run the gas turbine at nominal load, the surplus is directed to the LPRS as well.

The steam turbine (ST) is operated only when the gas turbine does not generate electricity. The aim of the operating logic is, therefore, near base-load electricity generation. For the purpose of this study, the ST is only operated at nominal load, which is dependent on ambient temperatures.

2.3. Cost model

Cost modeling is based on components' specific costs, whenever information was available. For the receiver systems, data could be retrieved from the ECOSTAR report [8]. Due to progress in the development of the components since publication of the report, this data has to be seen as a qualitative estimate. For example, according to the report, the specific costs of the SOLGATE and the HiTRec receivers are of similar magnitude. This seems to be a more conservative estimate for the LPRS due to the different level of complexity of both systems. Therefore, the relative cost of the LPRS is likely overestimated in this study.

The biggest merit of rock bed TESSs are the predicted low costs. However, estimates for the magnitude of these diverge considerably and are highly dependent on the containment structure [9]. One way of estimating the cost of a rock bed storage system is to calculate it as a multiple of the storage material cost. Alternatively, the TESS cost can be calculated as the sum of all its components' costs, which can – at least partially – be derived from literature [10].

Table 1. Variation ranges for parametric study

Parameter	unit	variation range
ST nominal rating	[MW_e]	2 – 10
Solar multiple (reference is HPRS)	[-]	1 – 4
Rating of LPRS	[MW_t]	0 – 40
Storage tank length in flow direction	[m]	8 – 16
Storage tank diameter	[m]	8 – 20
Number of storage tanks	[-]	1 – 2
Hybridization mode	[-]	'low'/'high'

A comparison of the calculated LCOE for different proposed material cost multipliers as well as for the component cost based calculations showed no noteworthy difference of the final LCOEs. That is, the cost for rock bed TESSs are predicted to be so low that even several-fold increases of them does not considerably influence the LCOE. Consequently, large storage system capacities are expected to be economically preferable.

South Africa does not have a secured long-term supply of conventional natural gas in large quantities [11]. Additionally, the infrastructure towards the solar-rich regions in the Northern Cape Province is limited. Liquefied natural gas (LNG), however, can be assumed to be available uncapped at a constant price of 10.6 USD/GJ in real terms according to the IRP 2010 [11]. The cost of fuel supply is modeled with this specific cost estimate.

Specific costs for the remaining major plant components, namely gas turbine system, heliostat field and Rankine cycle, are derived from the SOLGATE report [3].

As the plant is not modeled in a great level of detail and some components' specific costs are rough estimates, the resulting LCOE data has significant uncertainty and should be considered for qualitative comparisons between configurations only.

2.4. Parameter variation ranges

Simulations are conducted with the above described model in hourly time-steps. Storage size, solar multiple, ST ranking, LPRS rating and hybridization mode are varied in the ranges given in Table 1. In the 'low' hybridization mode, the combustion chamber is only used to reach minimum load of the gas turbine in times of low irradiation and, thus, utilize more solar energy in the mornings, afternoons or during cloudy periods. In the 'high' mode, the combustion chamber is used to run the gas turbine whenever the TESS has been entirely depleted. This automatically results in almost 8760 hours of power generation per year.

The solar multiple is referenced to the HPRS only and defined as the maximum radiation available to the receivers at any hour of the year divided by the nominal rating of the HPRS. A solar multiple of unity corresponds to a mirror aperture area of approximately 27 000 m^2.

2.5. Key performance indicators

The most widely-used economic performance indicator for CSP plants is the LCOE. However, it does not value dispatchability, base-load capability and CO_2-emissions. Therefore, additional figures of merit are taken into account, namely the annual time of no power generation (TNPG) and the fuel co-firing rate. As for this study, the ST is only run at full load and the gas turbine at least at 60 % load, whenever electricity is generated, it is of considerable magnitude. Therefore, the TNPG is a valid indicator of baseload power generation.

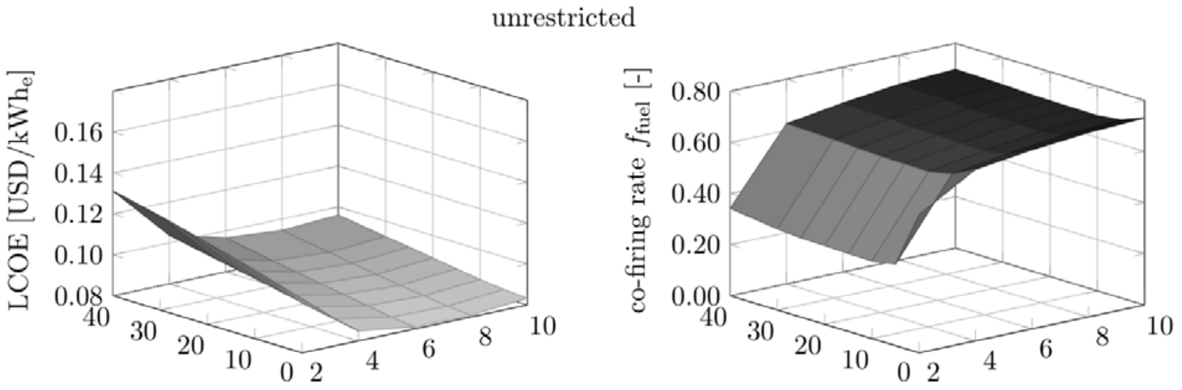

Fig. 2. (left) LCOE and (right) fuel co-firing rate over LPRS and steam turbine rating without restrictions of co-firing rates

3. Results

In the following, the results of the parametric study, in which seven parameters were simultaneously varied, are shown. The data is presented in three-dimensional plots with the LPRS rating on the x-axis and the steam turbine rating on the y-axis. For the remaining parameters, the values that produce the lowest LCOE are chosen. These local minimum LCOE values then define the z-value of the data points. As this economic evaluation does not consider dispatchability and fuel co-firing of the plant configurations, these indicators are shown in terms of the before mentioned TNPG and co-firing rate. The most desirable set-up has to be identified depending on individual project's requirements.

3.1. Minimum LCOE (unrestricted co-firing)

At first, all simulation results are compared solely on the basis of LCOE minimization. No restrictions in terms of maximum hybridization rate or TNPG are implemented. The results for various ST and LPRS ratings are shown in Fig. 2. Each point in the plot represents the lowest LCOE found for any combination of the remaining parameters storage volume, solar multiple and hybridization mode.

The lowest calculated LCOE in the simulation range is approximately 0.08 USD/kWh$_e$, found for steam turbines of larger ratings than the gas turbine (6 MW$_e$ to 8 MW$_e$) and no LPRS. The solar multiple and storage volume are also at – or close to – their lowest values (see Table 2). The TNPG is negligible for all shown set-ups at less than 150 h per year, which is achieved by high co-firing rates. In fact, all shown local minima (in the investigated range) are found for the 'high' hybridization rate, in which the gas turbine is run on fuel whenever the TESS is depleted.

Table 2. Parameters and performance indicators of configuration with lowest LCOE for different restrictions

Parameter	unit	unrestricted	co-firing ≤ 20 %	co-firing ≤ 5 %
ST nominal rating	[MW$_e$]	8	10	8
Solar multiple (reference is HPRS)	[-]	1.0	3.4	3.8
Rating of LPRS	[MW$_t$]	0	40	40
Storage tank length in flow direction	[m]	16	14	16
Storage tank diameter	[m]	8	14	16
Number of storage tanks	[-]	1	2	2
Hybridization mode	[-]	'high'	'high'	'low'
Fuel co-firing	[%]	72	20	0.9
TNPG	[h]	83	61	789
LCOE	[USD/kWh$_e$]	0.08	0.10	0.12

This leads to the high fuel co-firing rates seen in Fig. 2 (right). The few remaining hours of no power generation are caused by a control logic that is meant to avoid turbine start-ups for single hours.

Co-firing rates in the order of 60 % to 70 % indicate that the solely economic optimization of the cycle favors configurations in which most of the thermal energy is supplied through fuel combustion rather than concentrated solar radiation. Therefore, a small solar field, a small storage and no LPRS are found most viable in the given range. Although this is a valid configuration for certain projects, configurations with higher solar shares are investigated in the following.

3.2. Restricted co-firing rate

In this section, the validity of results is determined by maximum co-firing rates. That is, the operating strategy is not changed but results that produce co-firing rates larger than the given thresholds are not used in the local optimization.

At first, the allowable co-firing rate is limited to 20 %, which is assumed to be an exemplary value for regions with unproblematic fuel supply and tariffs that allow for this extend of fuel usage. The dependency of the LCOE on LPRS and ST rating shown in Fig. 3 (top) is significantly different from the one of the unrestricted study in Fig. 2 (left), as solutions with larger ratings appear most favorable in the former. The most viable solution with a maximum of 20 % co-firing can be found for the largest receiver and steam turbine as well as a large solar multiple of approximately 3.4. Additional parameters and performance indicators of the configuration can be found in Table 2.

The resulting fuel co-firing rates of the data points can be seen in Fig. 3 (middle). The minimum LCOE values for configurations with a large LPRS rating or a small ST rating require fuel co-firing between 15 % and 20 %. For large ST and small LPRS ratings, however, co-firing rates are almost constant at approximately 2 %, which is caused by the 'low' hybridization mode. These latter solutions are generated with large storage volumes and medium to large solar multiples. Economically and to achieve baseload electricity generation, the solutions with 'high' hybridization rates are significantly more advantageous than the ones with lower co-firing rates (see also Fig. 3 (bottom)).

CSP plants are often located in isolated regions without viable access to large quantities of fuel for hybridization. In other cases, legislation limits the allowable percentage of energy derived from fuel combustion. Therefore, an additional analysis was performed in which the co-firing rate was limited to a maximum of 5 %.

As expected, decreasing the allowable co-firing rate to 5 % increases the minimum achievable LCOE (see Fig. 4 (top)). The configuration of the plant with the lowest LCOE is similar to the one found for a maximum co-firing rate of 20 %, however, with the important difference that the 'low' hybridization rate generates the lowest cost (see Table 2). The range of LPRS and ST ratings that produce similar LCOE values to the lowest one is extended, as can be seen in Fig. 4 (top).Within these ranges in which the LCOE is almost constant, the other two performance indicators should be closely looked at to find an overall preferable configuration.

Fig. 4 (middle) shows that only configurations with low ST ratings and high LPRS ratings economically favor the 'high' hybridization mode. The reason being that 'high' hybridization leads to co-firing rates higher than 5 % except for ranges in which the thermal energy demand on the TESS is low and the supply is high through large receiver ratings.

Judging from Fig. 4 (top) and (middle), configurations with ST ratings of 8 MW_e to 10 MW_e and LPRS ratings of 30 MW_t to 40 MW_t appear almost equally favorable. However, Fig. 4 (bottom) shows considerable differences in the annual number of hours, in which no power is generated within these ranges. An additional restriction in terms of maximum allowable TNPG is, therefore, introduced in the following.

3.3. Restricted co-firing rate and TNPG

In addition to the maximum co-firing rate of 5 %, an exemplary threshold value of 1000 h has been chosen as the minimum annual TNPG. This value is low and, therefore, challenging which reflects in the limited number of valid results in Fig. 5 (top). Due to the incomplete set of results, these are shown as scattered data instead of a surface as done in the previous figures. No configuration with an ST rating of more than 8 MW_e satisfies the restriction as their thermal energy demand is too high to 95 % from solar radiation. In general, the triangular shaped space with no valid results in Fig. 5 (top) to (bottom) represents configurations in which the LPRS does not provide enough energy for the respective ST rating, regardless of the other components' ratings.

The preferred configuration of a plant with these restrictions has to be identified depending on individual projects' specifications and priorities. The lowest LCOE was achieved with the identical setup as without the TNPG limitation (see Table 2).

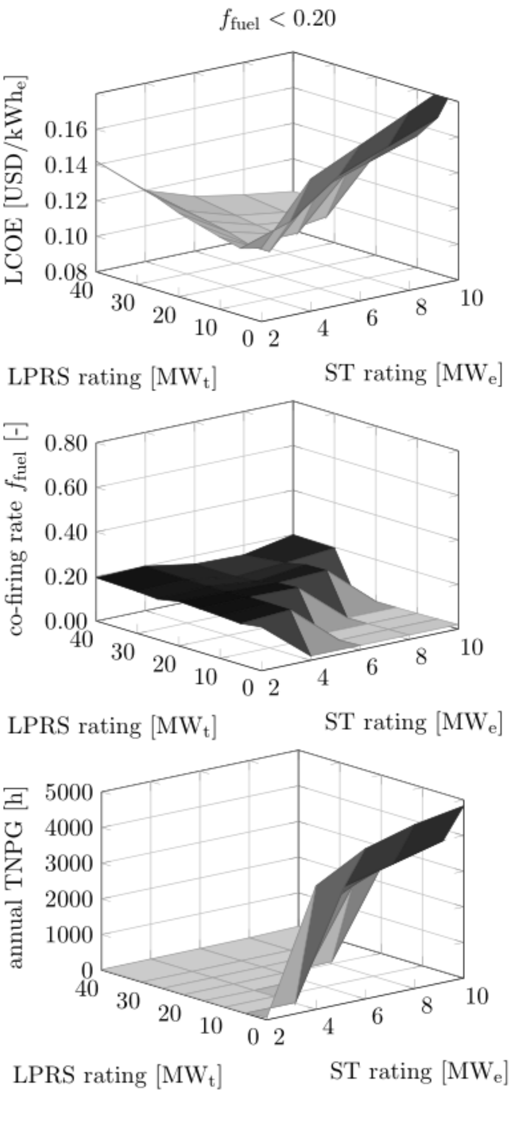

Fig. 3. (top) LCOE, (middle) co-firing rate and (bottom) annual TNPG for a maximum co-firing rate of 20 %

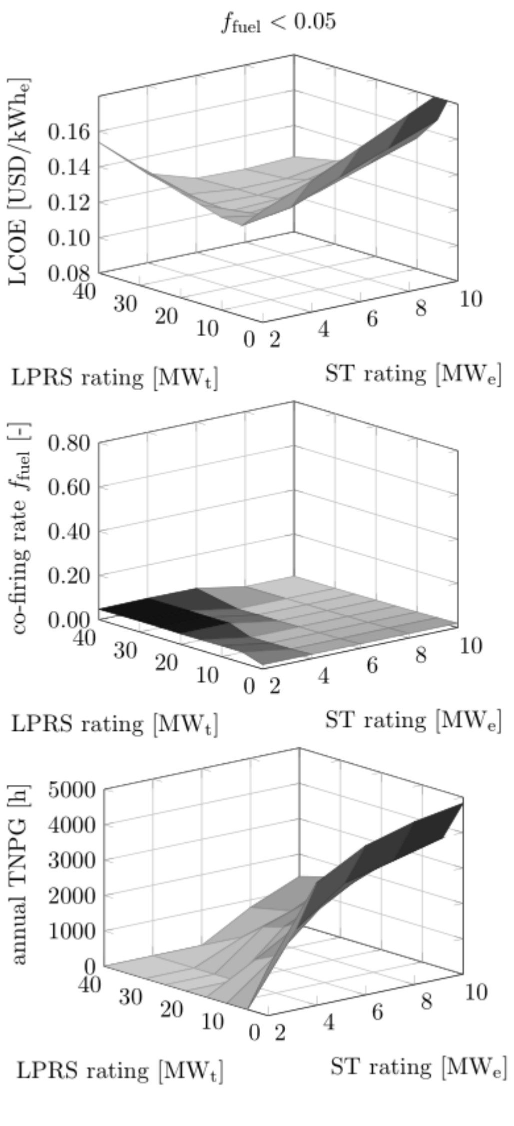

Fig. 4. (top) LCOE, (middle) co-firing rate and (bottom) annual TNPG for a maximum co-firing rate of 5 %

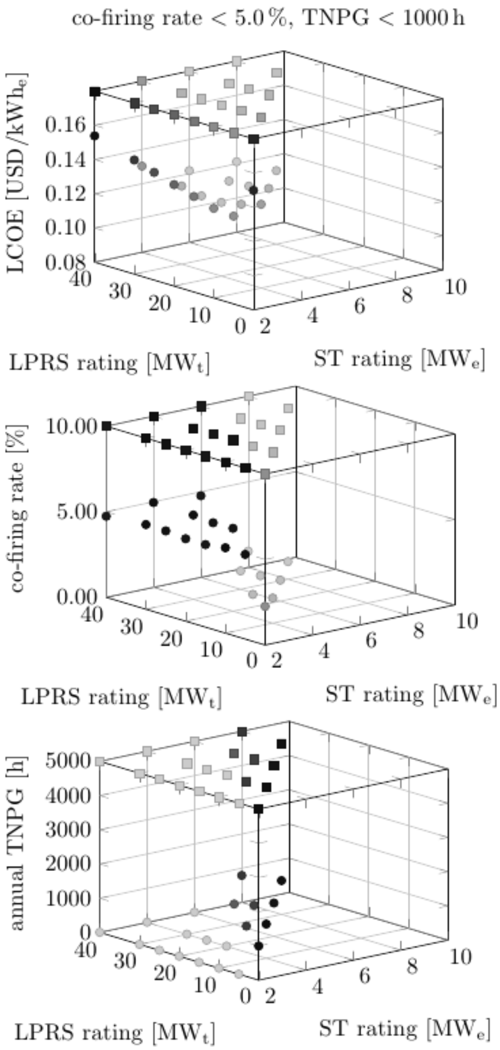

Fig. 5. (top) LCOE, (middle) co-firing rate and (bottom) annual TNPG for a maximum co-firing rate of 5 % and a maximum TNPG of 1000 h. The square markers illustrate the position of the x- and y-position of the data points.

4. Conclusion and outlook

A parametric study has been conducted, in which TESS capacity, steam turbine rating, LPRS rating, solar multiple and hybridization control of a SUNDISC cycle plant were varied. The lowest LCOE for the given location, cost model, parameter range and operating control were found at 0.08 USD/kWh$_e$ with fuel co-firing rates of more than 60 %. If such high co-firing rates are permitted, configurations without the LPRS and small solar components (field, receiver and TESS) are most viable.

Subsequent investigations with maximum co-firing rates of 20 % and 5 % produced minimum LCOE values of 0.10 USD/kWh$_e$ and 0.12 USD/kWh$_e$, respectively. These were generated for large solar components and ST rankings of 6 MW$_e$ to 10 MW$_e$. While these ST ratings enable close to constant electricity generation throughout the day and night, their thermal energy demand cannot be supplied by solar components of ratings within the pre-defined ranges. An increasing steam turbine size, therefore, increases the time of no power generation per year.

Further limitation of allowable TNPG values further narrows the variety of viable configurations.

A noteworthy finding is that the predicted low costs of rock bed thermal energy storage systems make sizeable storage capacities viable. The discharge capacity of most systems that were found to be most viable exceeds 24 h of full turbine load.

Future work is recommended in refining the plant control and, specifically, allow for more flexibility in the hybridization modes. The limitation to a 'high' and a 'low' mode suppresses potentially more viable solutions. Additionally, the cost modeling of the components, fuel and generated electricity should be made more accurate once more detailed information is available.

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