COMPARISON OF DIFFERENT CONFIGURATIONS OF A COMBINED CYCLE CSP PLANT

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Abstract

A dual-pressure air receiver cycle has previously been proposed to overcome limitations of combined cycle CSP plants. This work compares different configurations of the **S**tellenbosch **Un**iversity **Di**rect **S**torage **C**harging Dual-Pressure Air Receiver (SUNDISC) cycle with each other and a single-pressure receiver reference cycle.

A steady-state model of the SUNDISC cycle has been developed and simulation runs with it were conducted with different sizes of the major components, namely, low-pressure receiver system, steam turbine, solar field and thermal storage system. The configurations were evaluated mainly through two energetic performance indicators: the annual energy yield and the annual number of hours of no power generation. The latter is a good indication of the modeled plants' ability to generate baseload electricity.

The results of the simulations indicate superior performance of the SUNDISC cycle over the reference cycle as well as favorable plant configurations in terms of annually generated energy. Proposed next steps are the inclusion of capital and operational expenditure, the expansion of the range of the varied parameters and the assessment of different operating schemes to find an economic optimum.

Keywords: SUNDISC; Dual-pressure air receiver; CSP; Combined cycle.

1. Introduction

Combined cycle concentrating solar power (CSP) plants are predicted to have higher system efficiencies than competing state-of-the-art CSP cycles [1]. However, the implementation of a thermal energy storage system (TESS) poses a challenge because of the use of a pressurized gaseous heat transfer fluid. A packed bed downstream of the gas turbine could provide a simple and potentially cost-effective storage design. This setup is also referred to as the SUNSPOT cycle [2].

The storage location in the SUNSPOT cycle limits the amount of dispatchable energy to the amount provided to the bottoming cycle. Previous annual simulations of the basic SUNSPOT cycle have shown that this is not sufficient to generate considerable baseload electricity [3]. Additionally, the amount of energy that can be absorbed by the pressurized receiver system is limited to the gas turbine's maximum heat intake, which enforces defocusing of heliostats for plants with solar multiples greater than unity.

To address these drawbacks, a dual-pressure combined cycle, in which some of the captured thermal energy can be directed directly to the storage system, has been proposed [3]. This SUNDISC cycle contains two solar receiver systems, namely a high pressure receiver system (HPRS), which is implemented into the air Brayton cycle, and a low-pressure receiver system (LPRS) that is used to directly charge the passive TESS or supply the steam generator (see Fig. 1).

In this paper, the influence of the main components' sizes on the performance of the SUNDISC cycle is investigated in order to find a sensible configuration for further research on the concept and its components.

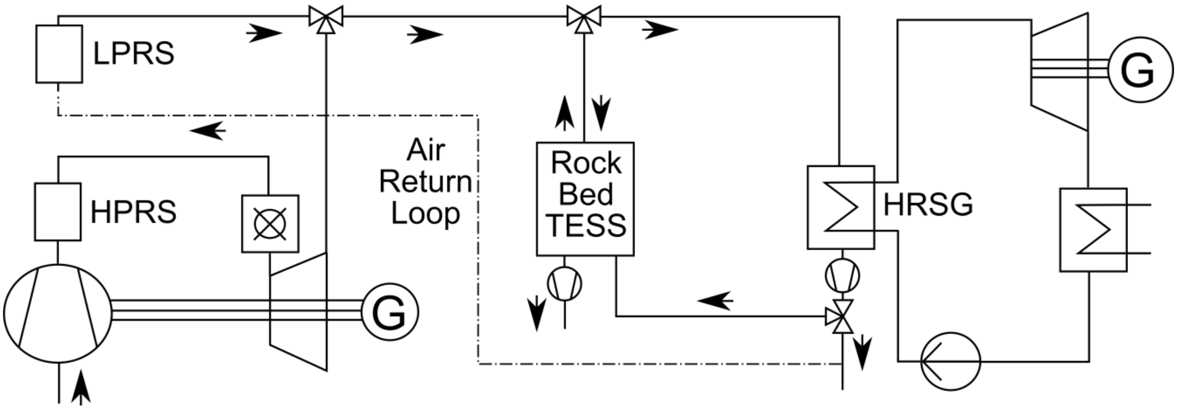

Fig. 1. Scheme of the SUNDISC cycle with optional air return loop (HRSG = heat recovery steam generator)

2. Simulations

The simulations were conducted with an hourly steady-state model written in the MATLAB® R2011b environment. More detailed information on the model is provided in a previous paper [3]. In the following, its most important characteristics as well as the range in which the parameters were varied are described.

2.1. Model description

The modeled TESS is a rock bed tank storage as this technology is predicted to be economically attractive where suitable storage material is abundant [4]. A study has shown that this is the case for the Northern Cape Province of South Africa [5], which is assumed as the location of the plant.

The gas turbine has a nominal rating of 5.25 MW_e at a heat input of 17 MW_t, which defines the thermal rating of the HPRS. The latter is based on the REFOS pressurized volumetric receiver technology and the LPRS on the HiTRec open volumetric receiver technology, as these are the most developed, tested and published on air receiver technologies.

The plant's operating scheme is to run the gas turbine only during times of sufficient solar radiation and utilize the combustion chamber solely to overcome transients during cloudy periods, in the mornings and in the evenings. The steam turbine generates power when the gas turbine is not operating, provided the TESS is sufficiently charged. The bottoming cycle does not run in part-load.

2.2. Reference plant

Simulations with a simple model of a combined cycle plant with only a HPRS (basic SUNSPOT cycle) have given economically optimal values for the input parameters. This reference plant has a small steam turbine (1.9 MW_e), a solar multiple of 1.9 and no LPRS. The storage tank has a diameter of 13 m and a length of 10 m (see Table 1).

Parameter	Symbol	Unit	Reference	Variation range
Steam turbine nominal rating	$P_{SC,n}$	[MW_e]	1.9	1.9 – 3.0
Solar multiple (reference is only the HPRS)	-	[-]	1.9	1.9 – 3.0
Rating of LPRS	-	[MW_{opt}]	-	0 – 30
Storage tank length in flow direction	L	[m]	10	10 – 14
Storage tank diameter	D	[m]	13	13 – 15

Table 1. Varied parameter ranges

2.3. Parameter variation range

Starting from the reference values, the steam turbine nominal rating, the solar multiple, the storage length and the LRPS rating were increased. Higher mass flow rates in the storage tank when charged by an additional receiver system necessitate the storage tank diameter to be increased so that the specific mass flow per crosssectional area does not exceed a threshold of 0.4 kg/(m^2 s) [6]. The parameters' variation ranges are given in Table 1.

2.4. *Aim and key performance indicators*

The most important energetic performance indicator is the annual electricity yield. However, this figure does not provide information on the plant's capability to provide baseload capacity.

One of the aims of this study is to find a configuration of the SUNDISC cycle plant which delivers an increased amount of power generated in times of no solar irradiation. This increases the capacity factor of the steam turbine and adds dispatchability, and therefore value, to the generated electricity. As the indicator of the plant's baseload capacity, the number of hours per year in which no power is generated is calculated. In all remaining hours, the plant supplies at least the steam turbine's maximum capacity or the gas turbine's minimum capacity to the grid – depending on their ratings. This is because the steam turbine does not operate in part load, as described in Section 2.1.

Naturally, for the optimization of the components' sizes their specific costs have to be considered. However, the aim of this study is to determine trends of energetically meaningful plant and component specifications without being limited to the chosen receiver technologies. For this purpose, the energetic performance indicators provide a sufficient first assessment.

3. Results

A sensitivity analysis, in which five parameters were simultaneously varied (see Table 1), has been conducted. The results will be discussed separately for different steam turbine sizes in the following.

3.1. *Small steam turbine* (1.9 MW$_e$)

The reference plant's configuration with a small steam turbine of only 35 % of the gas turbine's capacity results in an annual energy yield of 22 GWh$_e$ and a time of no power generation (TNPG) of 1700 h (see Fig. 2 and Fig. 3).

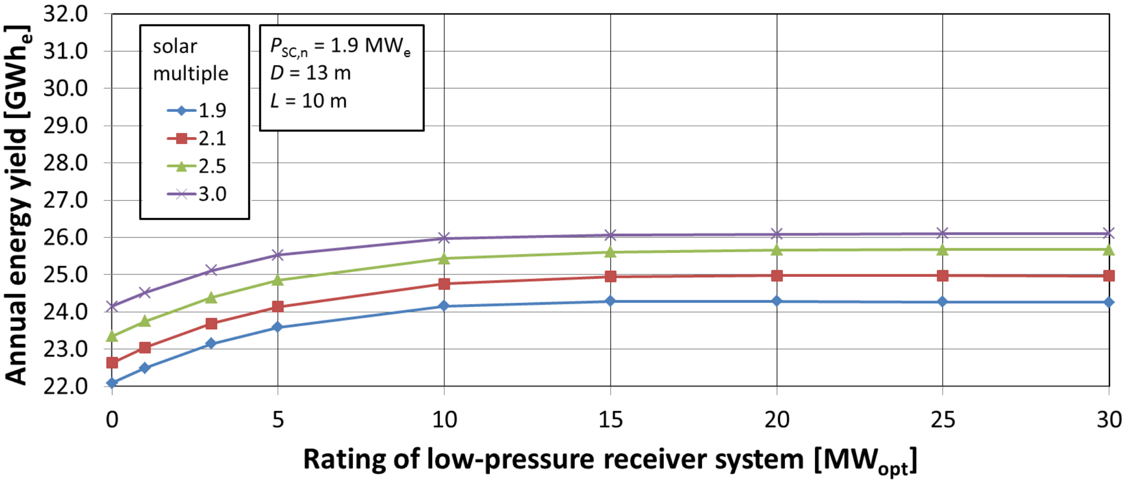

Fig. 2. Annual energy yield of configurations with a small steam turbine

Variations of the solar multiple and the rating of the LPRS result in annual yields of up to 26 GWh$_e$ (+18 %) and a TNPG of only 200 h (-88 %). Almost the complete gain is already achieved with a LPRS capacity of 10 MW$_{opt}$ and the influence of higher solar multiples decreases. From the present results it can also be deduced that the addition of 10 MW$_{opt}$ of LPRS lead to approximately the same annual energy yield as a single-pressure cycle with a solar multiple of 3.0. However, the TNPG is much lower if the LPRS is included and the cost of it is likely to be lower than that of increasing the solar field size by 50 % [1].

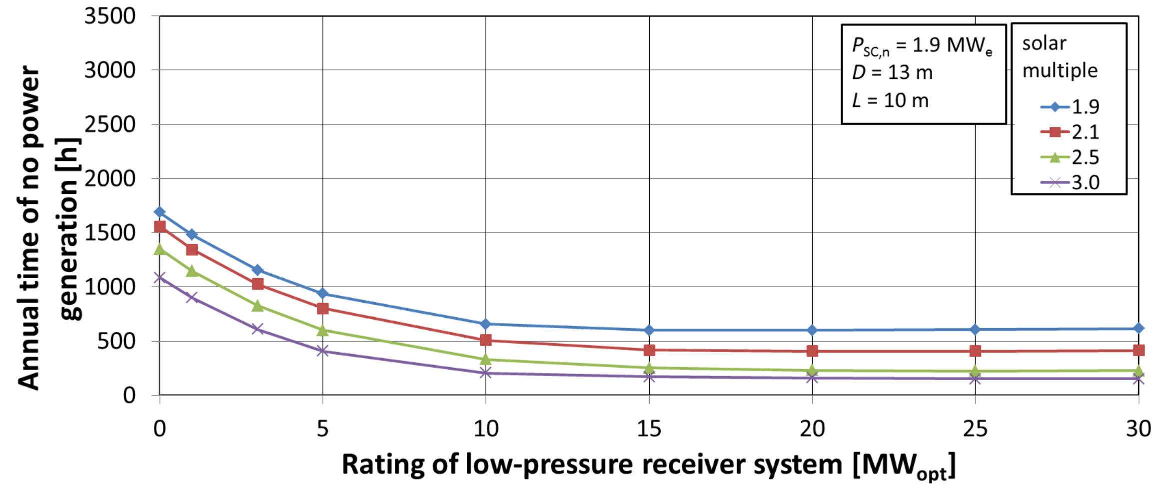

Fig. 3. Annual time of no power generation of configurations with a small steam turbine

Simulations of plants with larger storage tanks (in terms of length and diameter) do not show significant improvements for this small power block.

3.2. Medium-size steam turbine (2.5 MW_e)

When a bigger steam turbine of approximately half the capacity of the gas turbine is employed, higher annual energy yields can be achieved. The influence of high solar multiples and high LPRS ratings on this performance indicator is more pronounced (see Fig. 4).

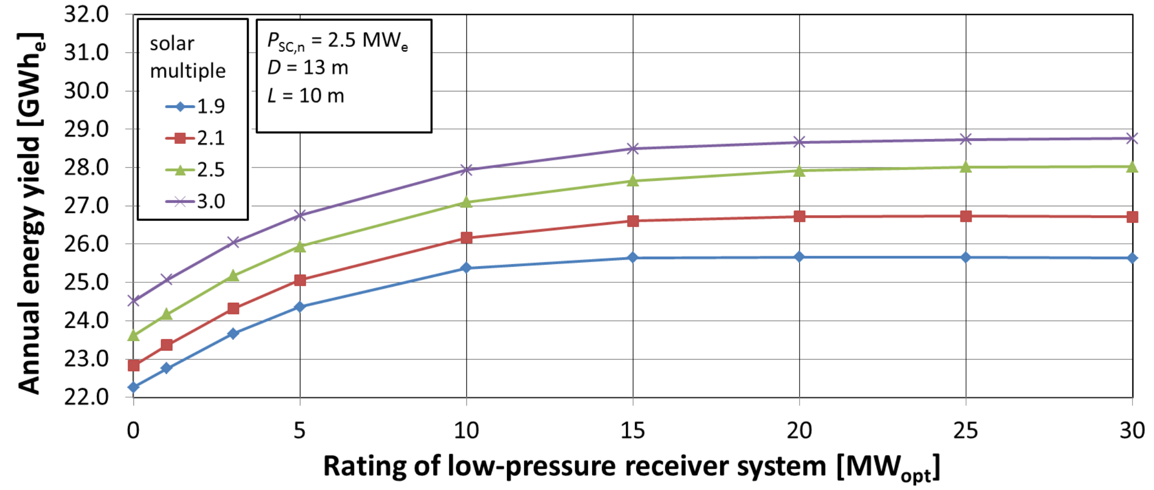

Fig. 4. Annual energy yield of configurations with a medium-size steam turbine

The annual TNPG is much higher for systems employing a medium-size steam turbine (see Fig. 5), which indicates that not enough energy can be stored to overcome longer times of low insolation and still supply the larger steam turbine. Larger storage systems mostly benefit plants with high solar multiples while smaller heliostat fields do not harness enough energy to fill the TESS sufficiently (see Fig. 6).

3.3. Large steam turbine (3.0 MW_e)

The largest investigated steam turbine has a rating of almost 60 % of the gas turbine, which enables annual energy yields of more than 31 GWh_e (see Fig. 7). The maximum yield with the reference solar multiple of 1.9 is 27 GWh_e, which is equal to an increase of 20 %. However, the TNPG for the latter configuration cannot be lowered below 1500 h (see Fig. 8). These findings indicate that at least in a system with a bigger steam turbine, larger solar multiples (with reference to the HPRS) appear favorable from a dispatchability point of view.

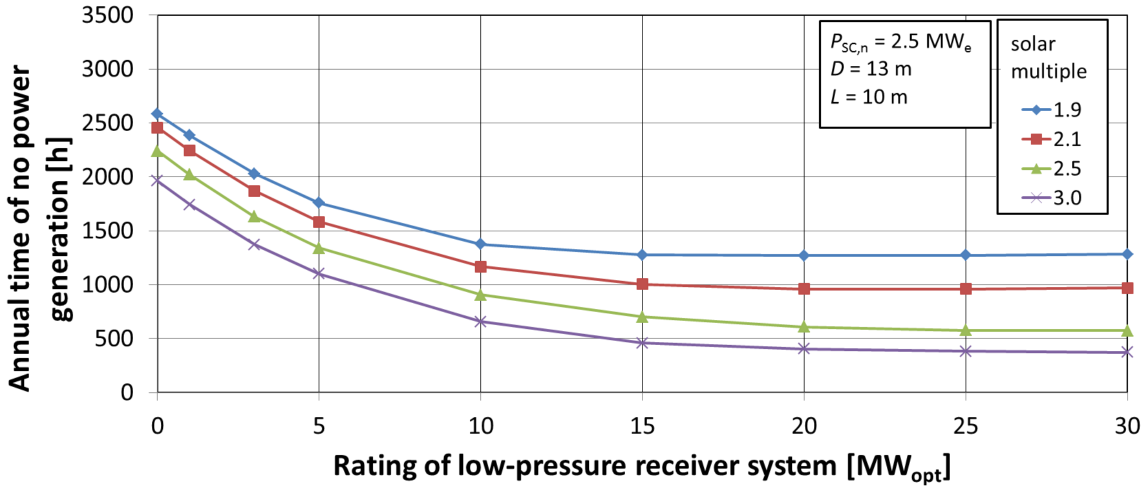

Fig. 5. Annual time of no power generation of configurations with a medium-size steam turbine

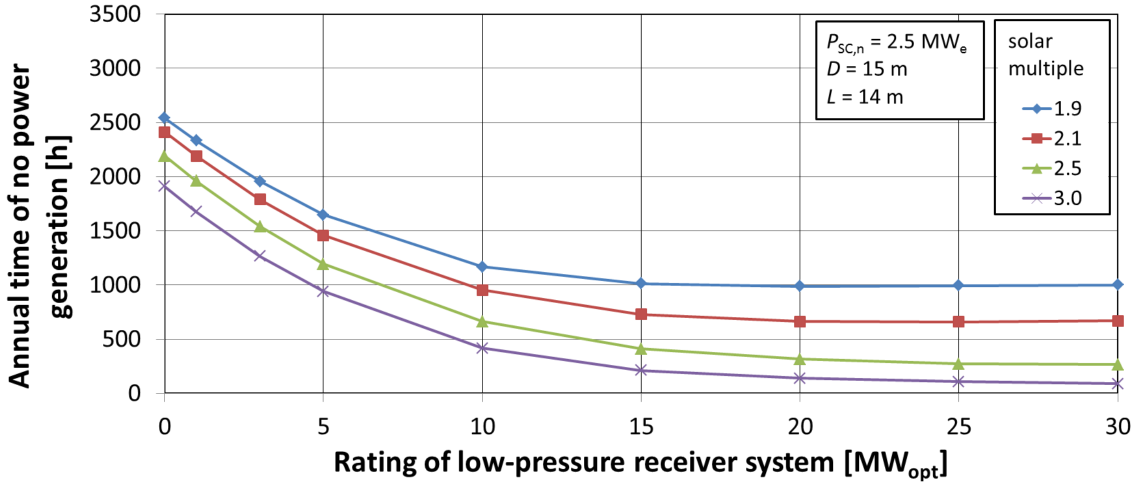

Fig. 6. Annual time of no power generation of configurations with a medium-size steam turbine and a large storage tank

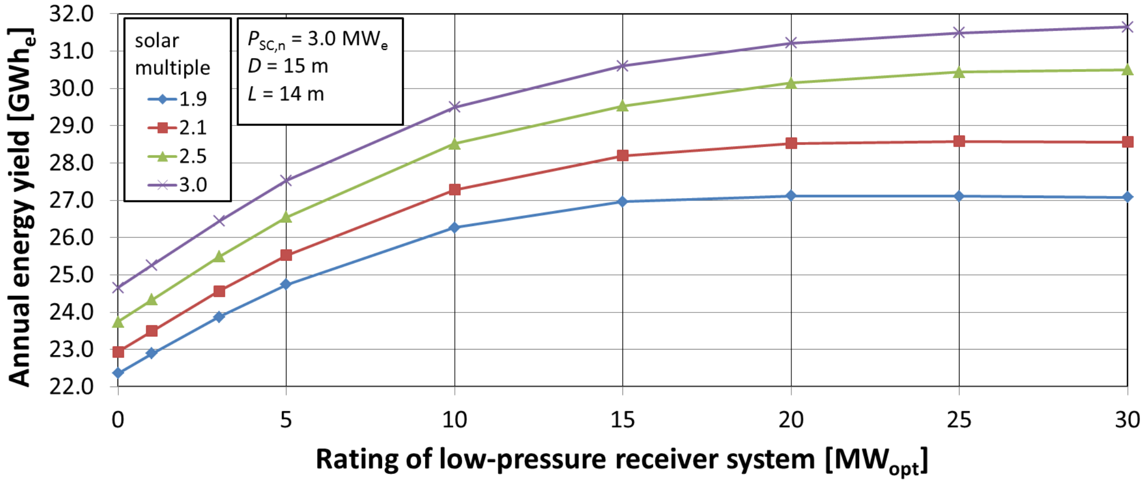

Fig. 7. Annual energy yield of configurations with a large steam turbine and a large storage tank

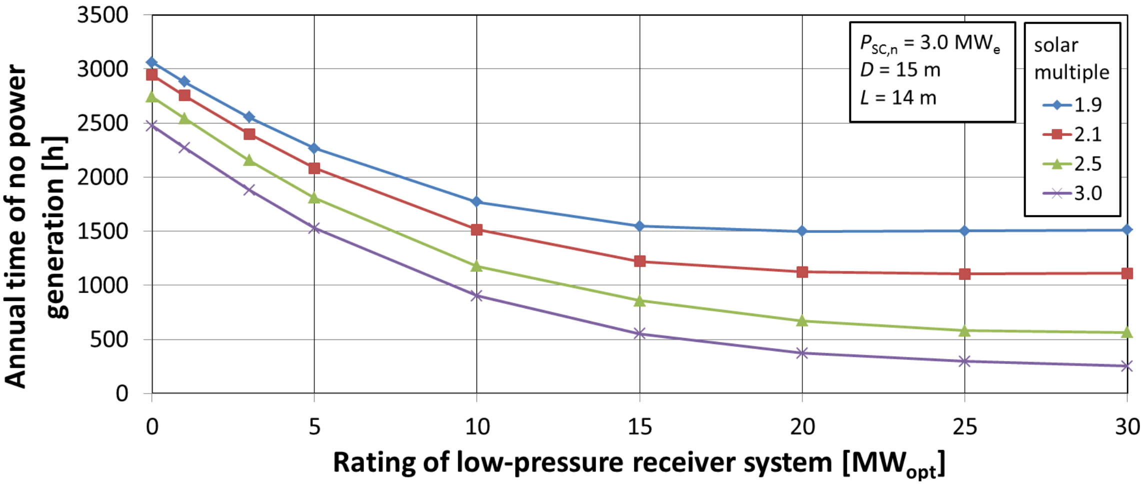

Fig. 8. Annual time of no power generation of configurations with a large steam turbine and a large storage tank

4. Conclusion

Annual hourly simulations have been conducted with a model of the SUNDISC cycle. The sizes of the steam turbine, the solar field, the low-pressure receiver system and the storage tank (diameter and length) were varied simultaneously to find sensible configurations in terms of annual energy yield and electricity dispatchability. The results of some exemplary configurations are given in Table 2.

For the smallest investigated solar multiple (1.9 with reference to the HPRS only), the LPRS should have a lower rating than the HPRS, independent of storage size. Increases in rating above 10 MW$_{opt}$ (for a small steam turbine) or 15 MW$_{opt}$ (for a medium-size steam turbine), show only negligible improvements.

Larger solar multiples than the one of the reference plant lead to higher energy yields and less time of no power generation in all configurations. However, the improvements in systems with small steam turbines are small.

Increasing the volume of the storage tank had only a small effect on the two key performance indicators. This indicates that the chosen reference configuration already has a sufficiently big storage. Due to the expected low price of the rock bed TESS, high storage capacities could nevertheless prove economically favorable.

Parameter	Unit	Reference	Variations						
Solar multiple	[-]	1.9	**3.0**	1.9	1.9	1.9	1.9	**2.5**	**2.5**
$P_{SC,n}$	[MW$_e$]	1.9	1.9	1.9	**2.5**	**2.5**	**3.0**	**3.0**	**3.0**
D	[m]	13	13	13	15	15	15	15	15
L	[m]	10	10	10	12	12	14	14	14
LPRS rating	[MW$_{opt}$]	0	**10**	**10**	0	**15**	**15**	0	**15**
E_a	[GWh$_e$]	22.1	26.0	24.2	22.3	26.1	27.6	23.7	29.5
TNPG	[h]	1688	206	558	2545	1058	1547	2741	859

Table 2. Input parameters and performance indicators of exemplary configurations

When comparing the influence of higher solar multiples to adding a LPRS, it is remarkable that the cycle with a LPRS rating of 15 MW$_{opt}$ and a solar multiple of 1.9 achieves similar energy yields to a cycle without a HPRS but a much larger solar multiple of 3.0. The TNPG is considerably lower for the SUNDISC cycle plants in any of the tested configurations. Due to the high specific cost of a solar field, economic benefits are also expected.

5. Future work

In order to take the capital cost of the components into account, detailed cost modeling is preferable. This could allow for optimization for the levelized cost of electricity (LCOE) or, if variable pool prices are considered, for the internal return rate.

Furthermore, simulations should be extended to larger steam turbines, smaller storage systems and smaller solar multiples. The economically best option of these can, as mentioned above, only be found if capital costs for all components are included. If variable pool prices are taken into account, simultaneous power generation from both cycles could be favorable in times of peak-demand.

Utilizing a different hybridization control with higher co-firing rates could also be considered. However, availability of the supplementary fuel can be a limiting factor for locations in the Northern Cape Province and the environmental benefit of the plant would be lowered.

Additional cost savings and/or efficiency improvements could be achieved by increasing the LPRS outlet temperature to a higher value than the gas turbine exhaust temperature. The latest HiTRec manifestations can reach outlet temperatures of more than 700 °C, compared to assumed gas turbine outlet temperatures of 530 °C. In one conceivable layout of the SUNDISC cycle, the TESS would be charged with air of different temperatures from the respective different receiver systems. For this setup, limitations of the heat recovery steam generator, the storage medium, the storage tank and of thermocline destratification have to be investigated.

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