SIMULATION OF HYBRID SOLAR TOWER POWER PLANTS

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1. Introduction

The world's first solar tower power plant with open volumetric receiver technology has been constructed in Jülich, Germany, and is in operation since December 2008 (Koll et al., 2009). The plant was built by the general contractor Kraftanlagen München, and owned and operated by the local utility Stadtwerke Jülich GmbH. Recently the German Aerospace Centre bought the plant to intensify the R&D programs for CSP at the Jülich site with the support of the Solar-Institut Jülich (SIJ) (Hoffschmidt, 2011).

2. Solar Tower Power Plant Jülich

The solar tower power plant Jülich is built according to the PHOEBUS scheme demonstrated in Fig. 1. It includes an open volumetric receiver, which consists of porous ceramic absorber modules. Ambient air is sucked through these modules and is heated up to 680°C. In a heat recovery steam generator (HRSG), the hot air transfers its heat to a steam Rankine cycle. Cold air leaves the HRSG at about 120°C and is returned to the receiver, where it is released into the surroundings by passing it around the outer surface of each of the absorber modules. A portion of this recirculated air is sucked back into the system whereby a heat recovery is achieved. The amount sucked in again is dependent on the wind conditions, such as wind velocity as well as direction, at the receiver front.

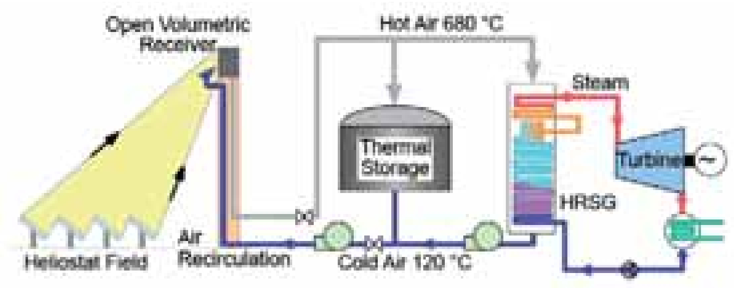

Fig. 1: Scheme of the Solar Tower Power Plant Jülich

The conventional steam cycle has an electrical output of up to 1.5 MW_e. An additional thermal energy storage system is used as a buffer for storing energy in times of high irradiance, which can be discharged after sunset or during periods of reduced solar input for enabling longer hours of steadier operation of the plant. There are different operation strategies to operate a solar tower power plant with open volumetric receiver technology in combination with the thermal energy storage. In the so-called parallel operation mode, the storage is charged while simultaneously steam generation occurs. Conversely, the storage can be discharged with or without receiver operation while simultaneously producing steam. For the case that the receiver is in operation, the hot air from the receiver is mixed with the air heated by the storage before it is used for producing steam in the Rankine cycle. For the other case when the receiver is not in operation, only the air heated by the storage is used for producing steam in the Rankine cycle. The operation control allows a direct and substantial influence on the energetic and economic efficiency of this power plant technology.

In a system layout, the integration of the storage can be customized, where the storage capacity depends on the thermal power provided by the receiver. To increase the storage capacity, the heliostat field and receiver (amongst other components) must be upscaled, while the nominal electrical output remains constant. The ratio of the thermal power provided by the receiver to the thermal power output of the HRSG is known as the solar multiple (SM). A solar multiple of 1 means that the useable solar thermal power of the receiver is sufficient for operating the steam turbine at nominal load. When increasing this ratio, the exceeding thermal energy can be stored into the thermal energy storage. Thus, a SM of 2 permits the operation of the steam Rankine cycle at full load with half of the available thermal power, while storing the same amount of thermal power into the storage.

The use of air as a heat transfer fluid (HTF) for an open volumetric solar tower system offers several benefits. Air is available for free, it is non-toxic and does not require freeze protection during times of non-operation. Operating the plant with steam parameters custom to conventional power plant engineering ensures high efficiency and an optimal use of the available solar energy. The majority of the components used in this type of solar tower power plant are standard components as used in conventional power plant construction.

3. Hybridization

As a further upgrade of the solar tower power plant with open volumetric receiver technology, a gas turbine can be used to hybridize the plant. This measure improves the availability and the capacity factor of the solar tower power plant. In regions with very high irradiation, solar thermal power plants with adequately sized thermal energy storage systems can reach a maximum of 3,000 to 4,000 nominal load hours per year. Hybridization enables the operator to produce electricity on demand for up to 8,600 hours per year. It is expected that such hybrid power plants will have a high potential for the market introduction in the next decade, especially in the target markets in North Africa.
The upgrade of a solar tower power plant with air receiver technology to a hybrid system by combining it with a gas turbine is shown in Fig. 2.

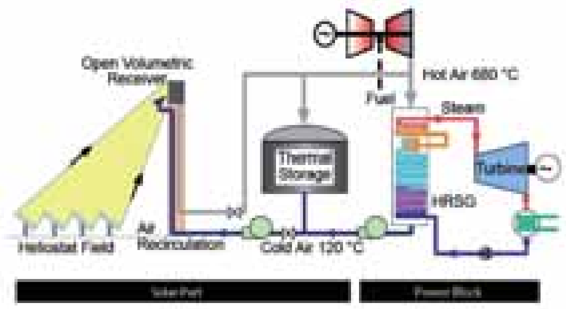

Fig. 2: Hybrid solar tower power plant with open volumetric receiver

During hours of lower and intermediate solar irradiation, the flue gases of the gas turbine provide the heat energy to the HRSG together with the available solar heat input from the receiver. In this so-called parallel operating mode the gas turbine's exhaust gases are mixed with the hot air from the receiver before entering the HRSG. A suitable gas turbine, the Solar Turbine Saturn 20, has been chosen (cf. Tab. 1) (Saturn 20 Generator Set, 2011). The heat input provided by the flue gases does not provide sufficient energy to operate the HRSG at full load, which means that during the night the plant is operated at about 40% part load. In the daytime this is advantageous because a solar energy input can be added to the energy of the flue gases, thus full load operation becomes possible without the operator being forced to shut down the gas turbine. Any solar heat input exceeding the 40% threshold is stored into the thermal energy storage. When the solar heat input is still above the 40% and the thermal energy storage's capacity is fully charged the gas turbine's heat input has to be throttled.

Tab. 1: Solar Turbines Saturn 20 Main Data

Property	Value	Unit
Output power	1,210	kW
Heat rate	14,795	kJ/(kW_e h)
Exhaust flow	23,540	kg/h
Exhaust temp.	505	°C

For simulating the annual electricity production of solar thermal power plants several software tools have been developed. In the SIJ a software tool for the simulation of open volumetric solar tower power plants as well as of hybridized plants has been created. It is important to investigate the profitability of a selection of plant configurations at different sites by determining the annual electricity production, which has a main effect on the profitability. Therefore a comparison between three simulation models for the site Algiers in Algeria, North Africa, has been made to show differences in the annual electricity yield dependent on the plant configuration. These configurations differ from each other in the SM and thermal energy storage capacity. The system layout for each plant configuration, especially the design of heliostat field and thermal energy storage, has to be created. The heliostat field layouts were computed with the program WinDelsol 1.0, which is based on DELSOL 3 (Kistler, 1986), for the plant configurations with the solar multiple 1, 2 and 3. Fig. 3 shows the heliostat field layout for the configuration with solar multiple 2.

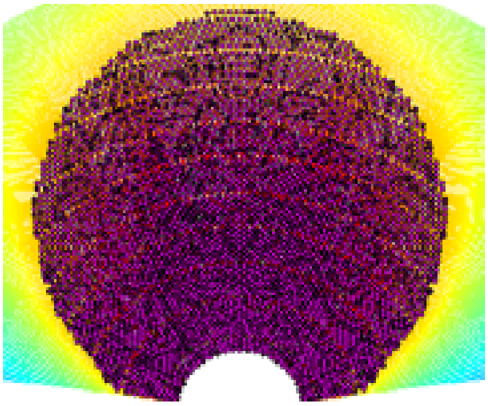

Fig. 3 Heliostat field layout for solar multiple 2

2079 heliostats with 8 m^2 mirror surface are yielded for solar multiple 1. Similar receiver design and dimension of the Jülich plant has been used for this configuration. The storage dimension and capacity was doubled compared to the thermal energy storage in Jülich. This was possible because solar insolation is significantly higher than in Jülich, allowing the storage to supply heat to the HRSG for about 3 hours at nominal load.

The design parameters determined for each configuration are inputs for the simulation models. Furthermore, WinDelsol computes a performance matrix of the heliostat field dependent on the solar position over the year so that the heliostat field's optical losses can be considered.

4. Simulation

3.1. Modelling

The investigation of the different hybrid solar tower power plant configurations is conducted with developed simulation models that have been developed and implemented in MATLAB/Simulink. A model library which includes the major components of the solar tower power plant has been developed in MATLAB/Simulink from which the required components can be chosen for the simulation. Fig. 4 shows the model libraries for the solar cycle (left side), the Rankine components (middle) and the components for hybridization (right). The solar cycle library for instance contains models of the heliostat field, receiver, blowers and the thermal energy storage.

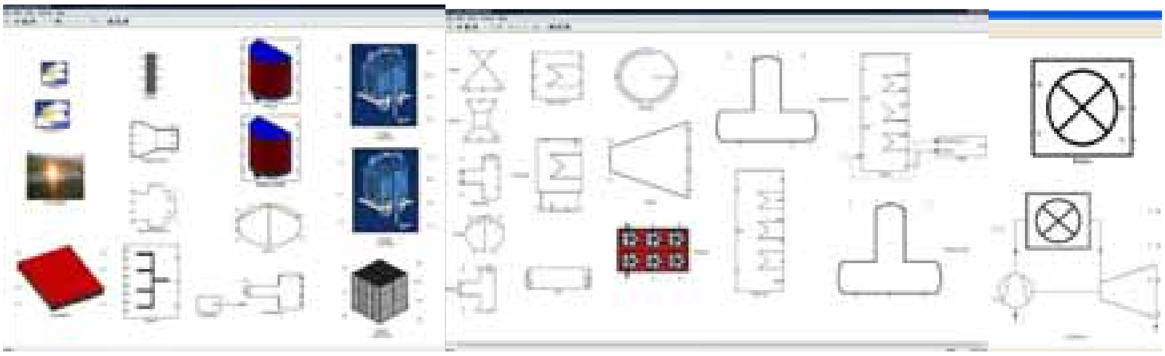

Fig. 4: Model libraries for solar cycle (left), Rankine (middle) and hybrid (right) components

The models were developed for steady-state simulation. Hence, a direct time dependency is not included. In addition, three models were created that model transient behavior. The thermal energy storage, the evaporator part of the HRSG, based on Karstensen and Sørensen (2004), and the feed water storage tank (FWST), taken from Ordys (1994), were developed to model the thermal inertias of the storage material and the water masses.

The different models have been validated with other simulation software and showed good agreement (Alexopoulos et al., 2008, 2009). Each model component was validated with other simulation tools and layout designs.

3.2. Simulation

Simulations for three different hybrid plant configurations have been conducted for the site Algiers. The individual components of the power plant are connected to model the system as a whole. The electrical generation capability of the Rankine cycle is 1.5 MW_e, identical to the Jülich plant, but additional electricity is produced by the Solar Saturn 20 gas turbine, which is operated in parallel mode. The configurations differ in size of the heliostat field, receiver and the capacity of the thermal energy storage. Weather data for Algiers from the year 1987 in hourly resolution has been used in the simulation. The quasi-steady-state simulations are computed in time steps of 60 seconds.

Fig. 5 shows the power plant performance on 6th November 1987 for the plant design with a SM of 2. The graphs are shown in a normalized way, which means that the electrical power output is given with respect to the steam turbine’s nominal electrical capacity. The thermal storage’s energy content is shown with respect to its nominal thermal energy capacity. The electrical power output of the gas turbine and the steam turbine is constant during the night and the morning. With the insolation (DNI) rising after about 10 a.m., the steam turbine’s electricity generation increases to about 90% of the steam turbine’s nominal capacity. From 11 a.m. onwards the storage is charged. The charging continues until about 2:30 p.m. because until this time the combined energy input from the receiver and the gas turbine exceeds the energy requirement of the HRSG. Hence, the excess energy can be stored. At about 3:30 p.m. the receiver is shut down because the insolation is insufficient for achieving adequately high air temperatures. As a consequence the storage is discharged from about 6 p.m. until midnight, while the gas turbine is operating. In these hours, the steam turbine generates about 63% of the nominal steam turbine load.

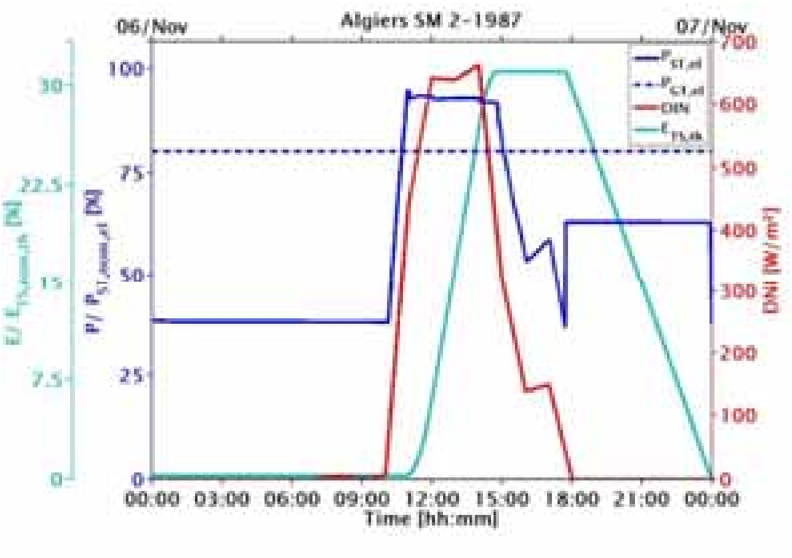

Fig. 5: Power plant performance of the variant with a SM 2 on 6th November

This example demonstrates that with a configuration with a SM of 2 or 3 and the appropriate thermal energy storage capacity, a continuous plant operation can be realized even on days with low insolation.

Tab. 2 shows an overview of the three simulation results. With the exception of the results for the insolation power dump from the heliostat field and the gas turbine's flue gas heat loss, the configuration with a SM of 1 is taken as the reference case. The results for the configurations with a SM of 2 and 3 are given as a percentage with regard to the results of SM of 1. The mentioned defocusing of heliostats is regarded in the simulation in such a way that the concentrated power that is discarded is computed.

Tab. 2: Simulation results for the three different configurations

Value	SM1	SM2	SM3	
Insolation power onto the heliostat field	100	224	311	%
Receiver power	100	234	291	%
Fed-in fossil heat input	100	82	76	%
Gross el. generation steam turbine	100	122	130	%
Total gross el. generation	100	108	111	%
Total net el. generation	100	107	109	%
Fuel share on generated el. energy by steam turbine	74	50	43	%
Solar share on generated el. energy by steam turbine	26	50	57	%
Fuel share on fed-in energy rel. to total el. generation	91	82	78	%
Solar share on fed-in energy rel. to total el. generation	9	18	22	%

As expected the results show that the heliostat field computed by WinDelsol for the configurations with a SM of 2 and SM of 3 concentrate twice and three times the thermal power, respectively, compared to the field with SM of 1. Nevertheless, the steam turbine's electricity generation capacity has only increased to 122 % for a SM of 2 and 130 % for a SM of 3, compared to the configuration with a SM of 1.

Insolation has to be dumped, which means that heliostats have to be driven out of focus. Furthermore, exhaust gas losses occur because the gas turbine operates in nominal load and is not shut down when the storage's capacity is reached. For this reason the flue gases and the contained exergy are released to the surroundings unused. With higher solar multiples, continuous steam turbine operation can be achieved at a limited increase of the overall annual electricity generation. In addition, the solar share on the annual electricity generation can be increased. The solar share can be computed with respect to the steam turbine's electricity generation or to the total electricity generation, which includes the gas turbine's electricity generation as well. The definitions of both solar shares are given by the following equations:

$$a_{solar} = \frac{E_{Rec}}{E_{Rec} + E_{Fossil}} \quad \text{(eq. 1)}$$

$$a_{tot,solar} = \frac{E_{ST,e,solar}}{E_{ST,e} + E_{GT,e}} \quad \text{(eq. 2)}$$

Eq. 1 gives the solar share based on the energy delivered by the receiver and the exhaust gas heat which are passed through the HRSG. The second definition includes the solar produced electricity relative to the total electricity generation. The simulation results show that for a SM of 2 the solar share can be increased by a factor of 2. The further upgrade to the configuration with a SM of 3 increased the solar share only slightly because the thermal energy storage's capacity is limited.

5. Discussion and Conclusion

The development of the different model libraries in Matlab/Simulink allows the simulation of various hybrid solar tower power plant configurations at different scales and for different locations. The design computations with the aid of WinDelsol and the use of the computed parameters show good agreement, which could be demonstrated for different solar multiples.

According to the results of the simulations it could be shown that when solar tower power plants are designed with solar multiples greater than 1 also the optimum thermal energy storage capacity must be considered. From a purely technical point of view the storage capacity has to be chosen such as no solar energy nor thermal energy of the exhaust gas is dissipated. The optimum storage capacity as well as the best solar multiple configuration is eventually chosen dependent on the economical boundary conditions and not only on thermodynamics.

In future calculations, the economical evaluation will be included for the layout of the storage capacity and the SM. The simulation models will then have reached a more advanced level regarding their transient behavior so that even more accurate simulations can be performed.

6. Acknowledgements

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