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Comparison of potential sites in China for erecting a hybrid solar tower power plant with air receiver

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Abstract

In this work transient simulation results of a hybrid solar tower power plant with open volumetric receiver technology are presented for several locations in China. The open volumetric receiver uses ambient air as heat transfer fluid and the hybridization can be realized with additional firing. The solar receiver and/or the additional firing heat up the air which is then passed through a boiler of a conventional Rankine cycle. The simulated plant is based on the configuration of the solar thermal test and demonstration power plant located in Jülich (STJ). The investigated plant operates in hybrid - parallel mode which allows a constant power generation. The meteorological data for the different sites in China was taken from the software Meteonorm in a time resolution of one hour. The solar tower power simulation tool was developed in the simulation environment MATLAB/Simulink.

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Keywords: hybrid concept; solar tower power plant; transient simulation; open volumetric air receiver; China

1. Introduction

The world's first solar tower power plant based on the open volumetric receiver technology is in operation in Jülich, Germany, since December 2008. This test and demonstration plant is operated by the German Aerospace Center (DLR). At the heart of the solar tower power plant Jülich is the open volumetric receiver technology which

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consists of porous ceramic absorber modules [1]. The receiver transforms concentrated solar irradiation from the heliostat field into heat. The receiver is cooled with ambient air which blowers suck through the absorber modules. The air heats up to 680 °C as it passes through the absorber modules. The hot air is then passed through a heat recovery steam generator (HRSG) of a conventional steam Rankine cycle.

Nomenclature

DNI	direct normal irradiation
HRSG	heat recovery steam generator
LCOE	levelized cost of electricity

2. Selection of locations

Simulation results of a hybrid concept of such air receiver solar power tower were carried out and analyzed for locations in the middle of the north of China. Figure 1 shows the mean annual values of the solar irradiation calculated through Meteonorm for the year 2005 for seven potential sites.

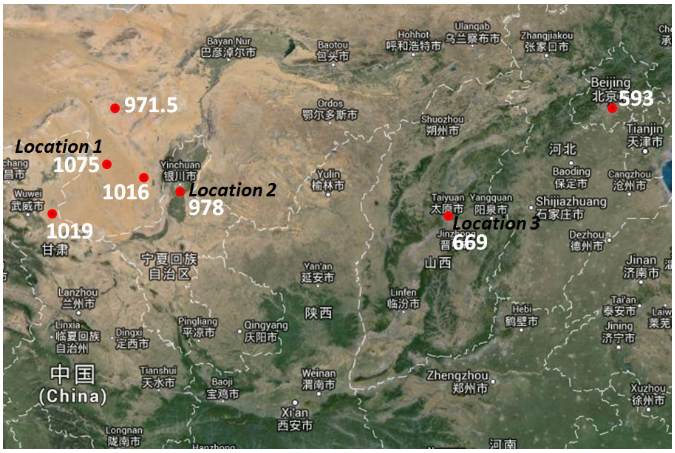

Fig. 1. Direct solar radiation (mean annual values) in China [2]

Out of the seven sites, three were selected for further analysis: 1. The desert region of Alxa Zuoqi in Inner Mongolia east of the city of Yinchuan, 2. Yinchuan-City and 3. Taiyuan-City. The selected locations satisfy the following criteria: access to natural gas supply, dissimilar values of DNI and altitude. The used geographical and solar data are shown in Table 1.

Table 1. Geographic coordinates and solar conditions of selected locations

Location	Latitude [°]	Longitude [°]	Altitude [m]	DNI [KWh/(m²a)]
Location 1: Desert	38.79 N	104.54 E	1345	1074.73
Location 2: Yinchuan –City	38.48 N	106.23 E	1111	977.97
Location 3: Taiyuan –City	37.87 N	112.54 E	788	668.73

A representation of a monthly distribution of the diffuse and global solar radiation of the three selected locations is shown in Figure 2. Additionally, the monthly ambient Temperatures for these locations are illustrated in Figure 3.

a. b. c.

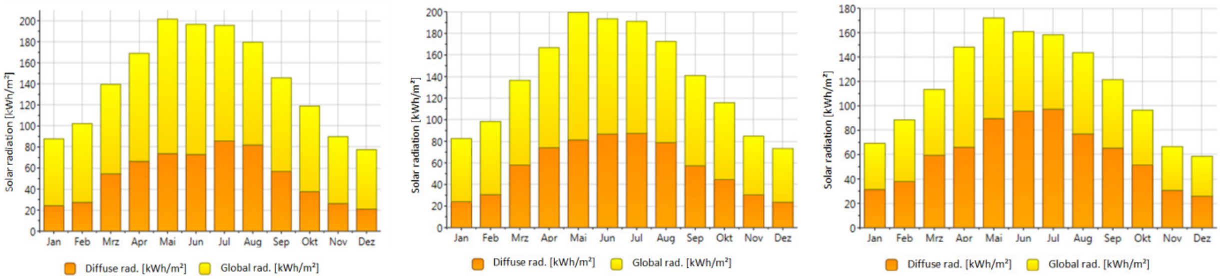

Fig. 2. Monthly solar radiance (a) Location 1, (b) Location 2, (c) Location 3 [3]

a. b. c.

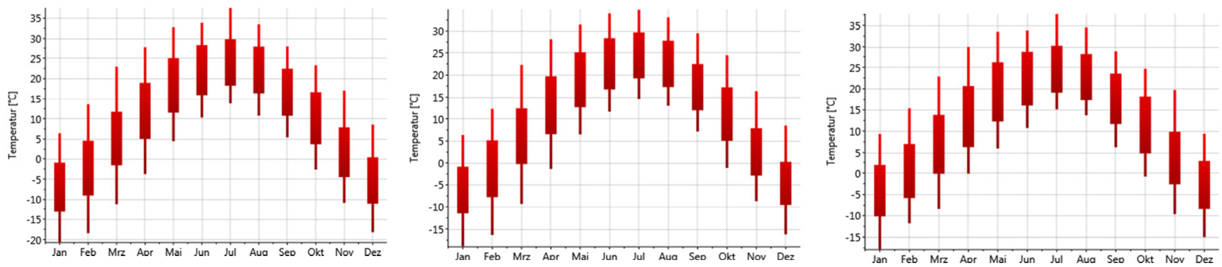

Fig. 3. Monthly ambient Temperature (a) Location 1, (b) Location 2, (c) Location 3 [3]

Location 2 and 3 show a higher diffuse radiation in comparison to location 1. These higher diffuse irradiation values possibly arise due to influencing air pollution caused by the nearby densely populated regions as well as higher humidity levels in the air especially during summer time. Location 1 and location 2 have very similar global irradiation values. The direct irradiation levels from location 1 are slightly higher than at the other locations due to the effect of clear sky and lack of vegetation which is typical of desert regions. All three locations have a similar ambient Temperature distribution throughout the year.

3. Plant configuration of the hybrid solar tower concept

This kind of solar thermal power plant allows the uncomplicated integration of a natural gas burner into the air piping system (Figure 4). In the presented concept, a thermal energy storage system is not considered as the supplementary firing will provide the thermal power difference required for the steam cycle to operate at nominal conditions at times when solar radiation is insufficiently high or (temporarily) unavailable.

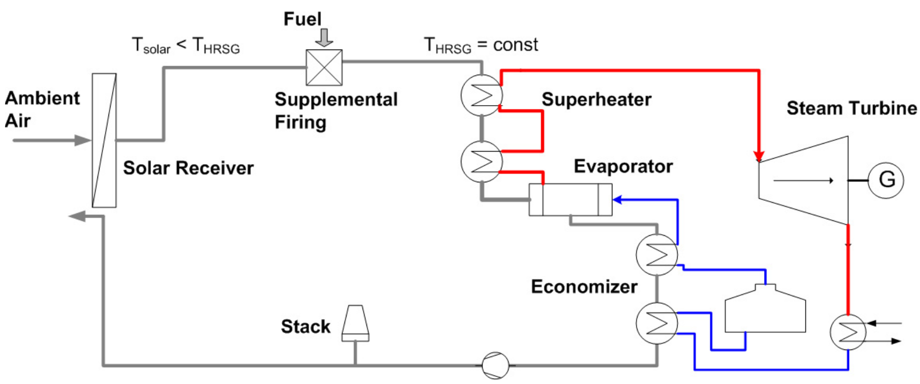

Fig. 4. Schematic of the hybrid open volumetric solar tower power plant

The objective of the hybrid operation strategy is to keep the mass flow and temperature of the hot air entering the HRSG constant and close to the design condition in order to reach a high thermal efficiency. During night time the Rankine cycle will be operated by the gas burner only allowing 24 hour operation of the plant.

The access to natural gas supply piping plays an important role for the location of the plant. The gas price considered for the evaluation of the hybrid concept is 0.45 €/m³. The electricity price for the heavy industrial sector is assumed to be 0.06 €/kWh [4][5]. The presented plant configuration (cf. Fig. 4) is taken for the simulation of all three simulated power tower sites. The boundary conditions of the plant are listed in Table 2. A constant and identical air mass flow rate was considered for all three locations.

Table 2. Technical data of the hybrid concept

	Value	Unit
Operational concept	Parallel solar-hybrid (burner)	-
Heliostat field area	25,000	m²
Tower height	60	m
Hot air Temperature	680	°C
Steam turbine power	1.8	MW_e
Cooling concept	Dry air cooling	-

4. Simulation tool

4.1. Description of used simulation model and abilities

For being able to compute the annual electricity production of a solar thermal power plant with air receiver, a complex software tool was developed at the Solar-Institut Jülich (SIJ) [6] over the past few years. The simulation model was programmed in MATLAB/Simulink [7] and is based on a model library (cf. Fig. 2) which includes most of the components of the power plant. A plant is built up by interconnecting individual components. Most components are represented as steady-state models and are programmed either with underlying physical models or user-defined performance maps. For some of the components with high thermal inertia such as the receiver, the thermal energy storage system, the HRSG and the deaerator, transient models were developed. The combination of steady-state and transient models allows maintaining a fast computation speed [8][9].

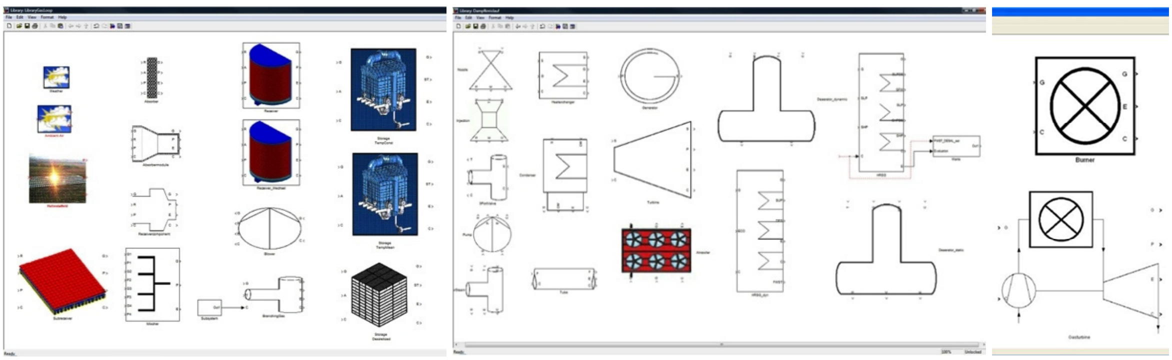

Fig. 5. Model libraries for solar cycle (left), Rankine (middle) and hybrid (right) components

To increase the HSRG model accuracy, a more detailed transient HRSG model was developed to include all effects that describe the transient behavior caused by the fluctuating solar power. These transient models also consider variations of the gas mixture entering the HRSG and fluctuations of the water steam cycle conditions caused by the change of the ambient temperature. This detailed transient HRSG model was used for the simulations of the presented work.

For validating the software tool and especially of the transient models, the simulated values were compared to measured data of the STJ. Validations of individual components such as the HRSG [9] as well as of the complete power plant system were carried out. First validations of the electrical output of simulation and real plant data show good agreement.

4.2. Simulation of hybrid concept for locations in China

The hybrid concept presented in this work was implemented in MATLAB/Simulink by interconnecting the individual plant component models according to the described plant layout (cf. Fig. 4). Using Meteonorm weather data for the period of January to December 2005, the hybrid concept was simulated for the three locations in China (cf. Table 1). For each simulation a set of parameters was specified and used as input for the simulation. The implemented operation strategy defined for the hybrid plant facility for the annual simulation is based on constant nominal electrical power generation. When the DNI profile decreases, the thermal power output of the receiver drops down as a result. In solar only mode there are two possible applicable operation strategies: *i)* maintaining a constant air temperature level by continuously adapting the mass flow to the solar radiation input or *ii)* maintaining a constant air mass flow which results in the air temperature to fluctuate according to the level of solar radiation input. For the investigated hybrid concept the air mass flow was kept constant at nominal level during night time and periods of the day with low solar radiation. A fuel mass flow rate control was implemented for the burner to maintain the set point air temperature at the boiler inlet. The temperature of the condenser was simulated by taking into account ambient temperature variation and a constant cooling system power.

4.3. Results

The operation strategy implemented for the simulation fulfills a parallel hybrid operation with a gas burner as described in 4.2. Figure 6 shows the DNI, fuel mass flow rate and the generated electrical power of the steam turbine's generator from 26th to 27th May 2005. The day 26 May 2005 was an operation day with fluctuating solar irradiation whereas the 27 May 2005 showed a solar irradiation profile with little fluctuations. Figure 7 shows the simulated temperature profiles of the air at the receiver outlet and burner outlet, the steam temperature at the steam turbine inlet as well as the air mass flow rate.

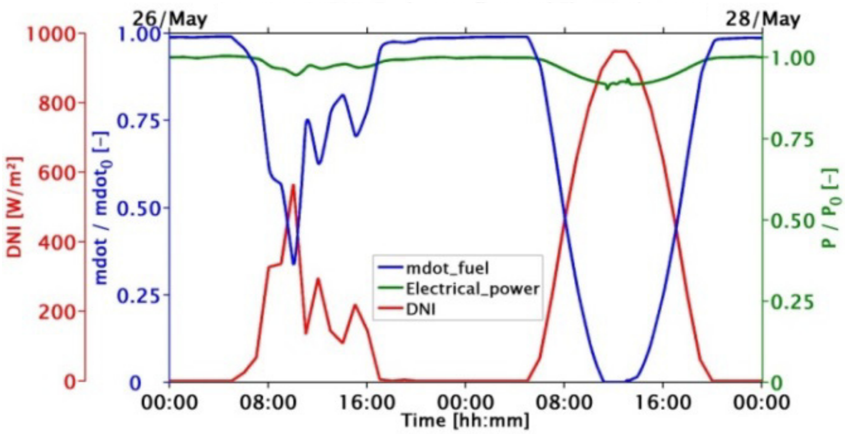

Fig. 6. Fuel mass flow rate and electrical power generation for days with different DNI profile.

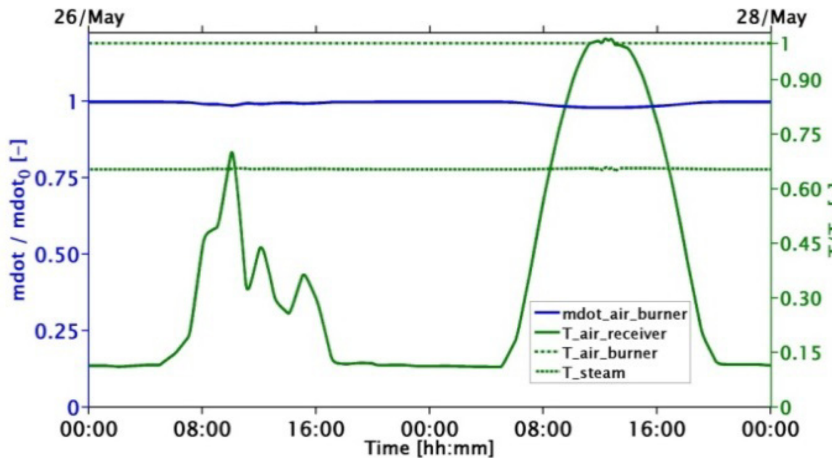

Fig. 7. Simulated temperatures levels at receiver, burner and steam turbine, and mass flow at the burner output.

The air mass flow in the boiler remains almost constant at the normalized nominal mass flow value. The normalized air mass flow slightly increases during night operation due to the increased fuel mass flow which is mixed into the air mass flow when the solar irradiation decreases. This increase in air mass flow as well as a decreased condenser temperature at night time led to a low increase of the electrical power generation. Due to the decrease of the ambient Temperature during the night, the Temperature of the cooling fluid in the condenser also drops down. Figure 8 shows the air ambient Temperature profile during the 26th and 27th May. The temperature in the supplementary firing system is automatically switched on when the available solar irradiation cannot provide the thermal power required to maintain the set point gas temperature.

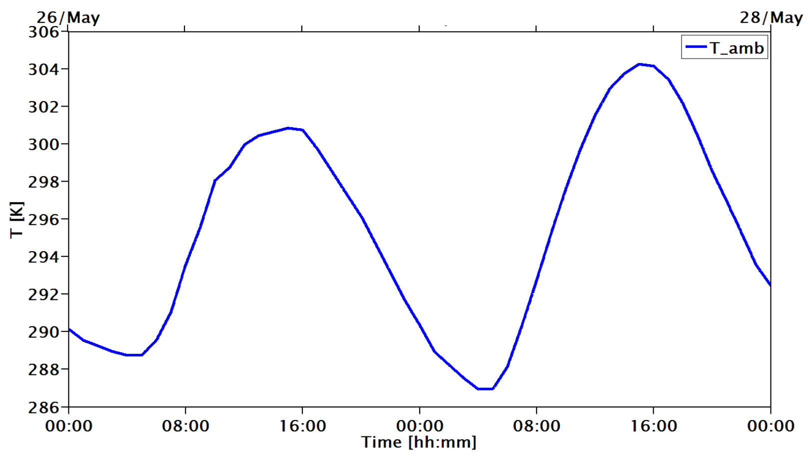

Fig. 8. Ambient temperature level

In Figure 6 and 7 it is shown that at low solar irradiation the maximum air temperature reaches only 75 % of the nominal temperature. In this period the burner operates in parallel with the solar receiver to increase the nominal temperature to 100 %. In this period of parallel operation the burner's fuel mass flow is above 25 %. On the second day of operation (cf. Fig. 6-7) the receiver temperature reaches nominal level between 11:40 a.m. and 1:20 p.m. and consequently the burner is switched off during that period; instead, the electrical power decreases slightly due to the missing fuel mass flow rate from the burner side. Significant reduction of the fuel consumption is noticed on days with clear sky and steady solar irradiation. During the night hours the burner operates at nominal power and the fuel mass flow is accordingly high. The calculated annual operation costs of the hybrid solar tower power plant concept for the three investigated locations are illustrated in Figure 9 below.

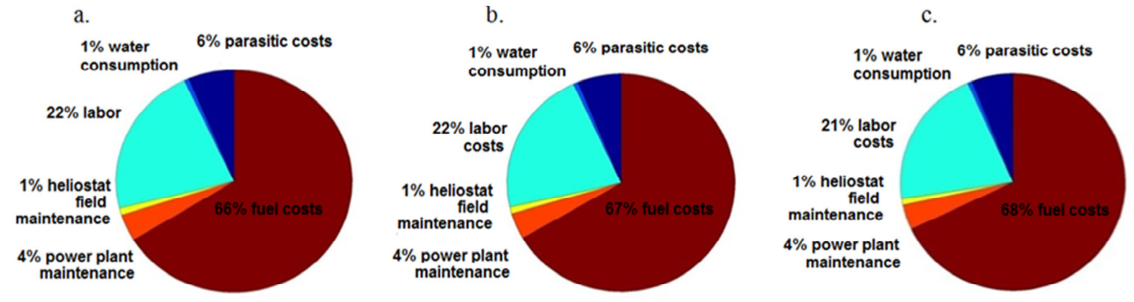

Fig. 9. Operation cost for (a) Location 1, (b) Location 2, (c) Location 3

The cost of the consumed fuel represents a share of 66 % of the total operation costs at Location 1. This is followed by labor costs with 22 % of the total operation costs. The main electrical power consumer with respect to parasitic costs due to own consumption are the air blowers. Maintaining a constant air flow rate throughout the plant's operation, the air blowers contribute 6 % of the total cost. In comparison to the other two locations, Location 1 has the lowest fuel consumption because it has slightly higher monthly direct solar radiation values. With 1 % and 2 % respectively, the difference in fuel consumption of Location 2 and 3 compared Location 1 is very small. Further calculated results of fuel consumption, solar share and LCOE for the different locations are summarized in Table 3.

Table 3. Normalized fuel consumption and LCOE

	Unit	Location 1	Location 2	Location 3
Fuel consumption	-	1.000	1.017	1.080
Solar share	%	16	14	10
LCOE	-	1.000	1.008	1.037

The fuel consumption at Location 2 and Location 3 is 1.7 % and 8 % higher than at Location 1. As a consequence of the high fuel consumption, the LCOE at Location 3 is 3.7 % higher than at Location 1. With a difference of 0.8 % in LCOE and 1.26 % in solar share between Locations 1 and 2 are fairly similar. The lowest solar share was calculated for Location 3; only about 9.67 % of the thermal energy required for nominal operation is provided by the solar side.

5. Conclusion

The simulation tool developed at the SIJ can be used for carrying out detailed and transient simulations of hybrid plant concepts for any defined site. The investigated sites with high annual solar irradiation energy resource have lower gas consumption costs due to the higher solar share. This leads to an increase in the solar tower power plant's investment costs for installing the necessary infrastructure. Further investigation regarding the selection of an ideal location should be carried out for large hybrid solar tower power plants and should include costs for installing necessary piping infrastructure.

Despite of the large differences in the DNI profile between the three investigated locations, small variation in fuel consumption, solar share und LCOE were predicted. Even for Location 1, which has the best solar conditions throughout the year among the investigated sites, the consumption of natural gas for the operation of the burner during night operation is foreseen to be high. Based on the solar and weather conditions of the two simulated days, a hybrid plant of small capacity as presented here therefore has a fossil fuel dependency of about 85 % when operated round-the-clock.

The highest solar share of about 15 % is achieved for Location 1 while the solar share for Location 3 is 6 % lower. This difference in solar share leads to an additional annual fuel consumption of 8 % compared to Location 1. The fuel consumption to solar share ratio is approximately 1.33.

The potential sites in China to erect a hybrid solar tower power plant are locations with annual solar radiation resources above 950 kWh/(m²a). Significant differences between Location 1 and 2 are hardly seen.

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