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Transient Simulation Of A Solar-Hybrid Tower Power Plant With Open Volumetric Receiver At The Location Barstow

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Abstract

In this work the transient simulations of four hybrid solar tower power plant concepts with open-volumetric receiver technology for a location in Barstow-Daggett, USA, are presented. The open-volumetric receiver uses ambient air as heat transfer fluid and the hybridization is realized with a gas turbine. The Rankine cycle is heated by solar-heated air and/or by the gas turbine's flue gases. The plant can be operated in solar-only, hybrid parallel or combined cycle-only mode as well as in any intermediate load levels where the solar portion can vary between 0 to 100%.

The simulated plant is based on the configuration of a solar-hybrid power tower project, which is in planning for a site in Northern Algeria. The meteorological data for Barstow-Daggett was taken from the software meteonorm. The solar power tower simulation tool has been developed in the simulation environment MATLAB/Simulink and is validated.

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Keywords: solar tower; central receiver; open-volumetric air receiver; gas turbine; hybridization

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1. Introduction

The world's first solar tower power plant based on the open-volumetric-receiver technology has been built in Jülich, North-Rhine-Westphalia, Germany and is in operation as demonstration and research plant since December 2008 [1]. The plant, which has been built by Kraftanlagen München GmbH (KAM) is owned and operated by the German Aerospace Center (DLR). All partners, including the Solar-Institut Jülich (SIJ) of the Aachen University of Applied Sciences are doing research and development of this technology. Some research of the SIJ concentrates on

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the development of simulation tools to investigate new operation strategies of the plant or to hybridize the plant by a gas turbine, gas motor or additional firing (projects Hybsol, Hyperion) [2]. In this work four concepts of a hybrid solar tower power plant at a site in Barstow, USA are investigated by simulations in MATLAB/Simulink.

Nomenclature

f	electrical solar share
$LCOE_{CCPP}$	levelized costs of energy for a reference combined cycle power plant
$LCOE_{Hybrid}$	levelized costs of energy for hybrid solar tower power plant
$LCOE_{Solar}$	levelized costs of energy for the solar share of a hybrid solar tower power plant

1.1. Project Hyperion and Alsol

The research project Hyperion, short for development and economical evaluation of a heat recovery steam generator in a hybridized solar tower power plant with air receiver, concludes the investigation of the hybridization of the solar tower power plant Juelich and future hybrid solar tower power plants based on the open-volumetric-receiver technology. The main focus of the project partners, SIJ, VKK Standardkessel Köthen GmbH and IA Tech GmbH, is the design and operation of the heat recovery steam generator (HRSG). Developed transient simulation models in MATLAB/Simulink are the basis for the analysis including annual energy yield simulations.

The project Alsol's, short for solar tower power plant in Algeria, aim is to create local nuclei for solar thermal power related research, development and formation by realizing further developed and hybridized solar tower power plant on basis of the open-volumetric air receiver technology. To strengthen and to build the local capacities in this field a technology centre, a so-called Technopol, is designed and will be created additionally nearby the solar tower. The basic design of the power plant has been planned by a consortium of partners, which include the SIJ, as coordinator of the Alsol project, the Algerian partners Direction Générale de la Recherche Scientifique et du Développement Technologique (DG-RSDT), Centre de Développement des Énergies Renouvelables CDER and the German partners KAM, IA Tech GmbH and DLR [3].

1.2. Technology

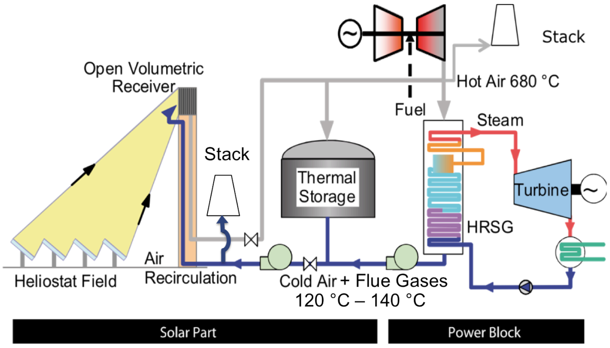

Fig. 1. Scheme of the hybrid open-volumetric solar tower power plant

The open-volumetric receiver technology, which is demonstrated in the solar tower power plant Jülich (cf. Fig. 1 without gas turbine and stack) was designed with open-volumetric receiver technology, which works on the basis of ambient air as heat transfer fluid (HTF). The receiver is made up of porous ceramic absorber modules which are heated up with concentrated solar irradiation. Ambient air is continuously sucked through the absorber modules and is heated up to 680°C. This thermal power of the hot air is transferred to a heat recovery steam generator (HRSG) which belongs to a steam Rankine cycle. An additional thermal energy storage system is used as a buffer which stores energy in times of high solar irradiance and enables operation of the plant after sunset or during periods of reduced or absent solar input. Additionally, this kind of solar thermal power plant allows the integration of a gas turbine's (GT) exhaust gases into the air piping system with ease. A stack for bypassing GT's flue gases is added to the system to increase the system's flexibility in operation.

2. Plant Configuration

The plant configuration shown in Fig. 1 is the basis for the planned power plant in Algeria within the Alsol project. The boundary conditions of the plant are listed in Table 1 [3]:

Table 1. Solar shares (absolute values) and LCOE results relative to concept 1

	Value	Unit
Operational concept	GT-hybrid parallel	-
Heliostat field	25,000	m²
Tower height	60	m
Solid bed thermal energy storage capacity	20	MWh
Hot air Temperature	680	°C
GT exhaust gas temperature	515	°C
Gas turbine design power	4.6	MW
Steam turbine power	2.5	MW
Cooling concept	Dry air cooling	-

The heliostat field is designed as North field as an advanced field design based on rows in sectors as described in [4]. This configuration has been compared to other hybrid plant layouts with nominal electric power ranging from 1.5 MW_e to around 7.1 MW_e on basis of steady-state simulations [3]. As a result of the chosen layout the plant can be operated in solar-only, parallel hybrid or combined-cycle-only (CC-only) mode as well as in many intermediate load cases providing possible solar shares from 0 to 100% that equals an electric power range of 2.5 MW_e to 7.1 MW_e. The resulting configuration showed advantages in the flexibility of following grid demand and high capacity utilization of the power block.

In this work the same plant configuration as in the Alsol project is investigated for a site in Barstow, USA and compared to the simulation results yielded before [5]. Barstow is situated nearly at the same latitude as the location in Algeria so the determined layout of the heliostat field may be quite similar to a new design at Barstow. Thus, for reasons of comparison the heliostat field is kept the same. However, the solar potential in Barstow is with 2636 kWh/m^2a about 45.6 % higher than the solar insolation of the proposed site at Bourkika (Wilaya of Tipaza), Algeria (1810 kWh/m^2a, both values are taken from meteonorm). As the plant in Algeria is already designed with a solar multiple and certain thermal energy storage (TES) capacity optimized for the available solar resource at Bourkika, it can be expected that at times of high solar insolation the capacity of the TES and the heat load of the Rankine cycle are exceeded. In the GT-hybrid parallel operation mode this means that either heliostats have to be defocused or the gas turbine has to be operated in part load and its flue gases have to be released temporarily to the ambient or the gas turbine has to be shut down completely. It might be also possible that two measures have to be applied at the same time. Because of this the investigation of the Barstow plant concludes four concepts to find an optimum of the system:

- Concept 1: gas turbine's load is reduced to 50 % part load when storage level exceeds 40 %
- Concept 2: gas turbine's load is reduced to 50 % part load when storage level exceeds 20 %
- Concept 3: reduced heliostat field size (76 % of concept 1), gas turbine operation as in concept 1
- Concept 4: reduced heliostat field size (88 % of concept 1), gas turbine operation as in concept 1

All concepts include the parallel hybrid operation with solar follow-up mode. The gas turbine runs at full load 24 hours a day as long as solar power can be utilized completely. Solar heated air is fed to the HRSG to achieve nominal load. Excess solar power is transferred to the TES to heat it. When set point of maximum charge of TES is reached the gas turbine operation is decreased to part load with minimum of 50 % of design load in order to use all available solar power for the HRSG. If solar energy and GT's exhaust gases energy still exceed nominal HRSG load, the gas turbine has either to be shut down or flue gases have to be bypassed to a stack. Moreover it may be necessary to defocus heliostats to decrease solar power. In the simulations, operation is implemented such that solar power should be used to a maximum amount and heliostats are never defocused. The gas turbine is not shut down as it is assumed that times of unusable excess power occur very little and it would represent an additional drop in electricity generation of the whole plant. Furthermore, startup/shutdown times may take too long and would decrease the lifetime of the gas turbine. For these reasons the gas turbine's exhaust gases are bypassed to the stack for these short time periods. Although this means that stack losses will occur the flexibility of operation can be maintained.

In concepts 1 and 2 the plant layout is not modified but the plant operation is changed. The set point of maximum charge of TES is varied from 40 % for concept 1 to 20 % for concept 2. Concepts 3 and 4 keep the set point at 20 % of maximum charge of TES. These two concepts distinguish themselves in terms of the heliostat field size according to minimize the time periods when gas turbine's flue gases are bypassed to the stack, although more solar heated air is generated at lower DNI with larger field sizes. The amount of heliostats was decreased in concept 3 to about 76 % and in concept 4 to 88 % of the amount of heliostats in concept 1. Another advantage of using less heliostats is that the investment is decreased significantly compared to the first two concepts.

Other optimization parameters are the TES capacity or the usage of another gas turbine model with different exhaust gas parameters. Due to reasons of comparison with the designed plant in Alsol these two components are kept equal.

3. Simulation Tool

3.1. Modeling

The simulation model has been programmed in MATLAB/Simulink [6]. In the model library (cf. Fig. 2) of SIJ most of the components of the power plant have been modeled as steady-state, either with underlying physical models or user-defined performance maps for a single component. Furthermore, for some of the components transient models have been developed to take the inertia into account. To maintain a fast computation speed, only the components with high thermal inertia were considered transient such as the receiver, the thermal energy storage system, the HRSG and the feedwater storage.

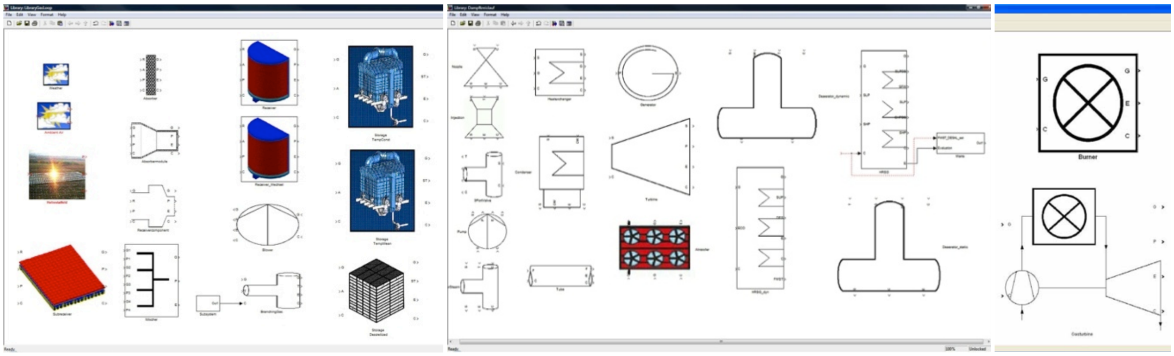

Fig. 2. Model libraries for solar cycle (left), Rankine (middle) and hybrid (right) components

These models were developed because investigations showed that up to 30% less annual electricity generation is calculated compared to a steady-state model [7]. These results were achieved already with a transient model of the feed water tank and a simplified HRSG model, which describes the thermal inertia of the water content only in the evaporator. Due to that a more detailed transient HRSG model has been developed to include all effects that describe the transient behavior caused by the fluctuating solar power.

3.2. Validation

For the validation of the developed software tool and especially of the transient models, comparisons against measured data of the STJ have been conducted. Single model validations such as the validation of the HRSG [8] as well as complete power plant system tests have been conducted. First validations of the electrical output of simulation and real plant data show good agreement (Fig. 3).

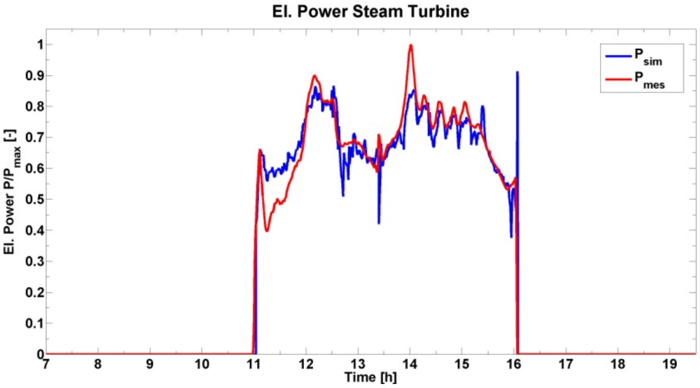

Fig. 3. Validation of the electrical output of simulation tool with measured data of the STJ

Although this day in autumn shows larger differences in the amplitudes (due to larger thermal inertia than considered in the models) the absolute values agree well which is important for annual yield calculation. The computed energy generation of this day differs on average only about 5 % compared to real plant data whereby some single time points of the electrical output deviate between -28 % to +8 %. The larger deviations occur only due to model specific assumptions but as can be seen do not distort the overall energy yield dramatically.

3.3. Simulation

The different concepts have been implemented in MATLAB/Simulink by connecting the single component models according to the above described plant layout (cf. Fig. 1). For each simulation a parameter set has been specified and fed to the model. In addition, the operation strategy and the underlying control mechanisms had to be implemented for each concept. The GT-hybrid parallel operation strategy aims at generating maximum electricity output with maximum solar share. Therefore the gas turbine is run at full load as long as possible and provides waste heat to the HRSG. The steam turbine is run at part load while no solar heat input is available. When solar power rises it is provided additionally to the HRSG to achieve nominal live steam conditions. As the maximum heat input of the HRSG is exceeded the surplus solar heat is fed to the TES to still operate the gas turbine at nominal load. The maximum heat input depends on the mass flow and temperature of the entering gas flow into the HRSG. The mixed gas flow consists of the receiver and exhaust gas mass flow at different temperature levels. The temperature of the receiver mass flow is normally higher than the exhaust gas temperature during operation. Thus, the temperature of the mixed gas flow varies between different temperature levels depending on the share of both single flows. If the solar generated heat increases while gas turbine is at full load the absolute value of the maximum mixed gas mass flow decreases due to its increasing temperature. Thus, is equivalent for maintaining a constant volume flow so that the air mass flow has to be adjusted to keep the maximum mass flow limit that changes consistently with the mixed gas temperature. This characteristic dependency was determined in several simulations and used as basis for the control of the maximum heat input.

A second aspect of the implemented operation strategy is to minimize the need of dumping exhaust gases to ambient, which may occur when the maximum capacity of TES is reached. At this point the gas turbine's load is reduced to 50 % that represents the minimum load. The solar share of the HRSG's heat supply can be increased and balances out the reduction of the exhaust gas heat. When the solar power is increasing even more the surplus heat cannot be processed in the plant. In simulation the exhaust gas flow is bypassed partly to ambient as the solar heated air mass flow is rising. For minimizing the need and the times of bypassing the flue gases a counter measure can be introduced. When the capacity of the storage reaches a certain set point the gas turbine's load is decreased to 50 % part load. As a result the solar heat supply into the HRSG increases and the heat supply to the TES is decreased. This is intended to prevent a rapid charging of the storage and to postpone the time point when the maximum capacity of the TES is reached. At this time the exhaust gases are still released into the ambient via a stack. The implementation of this control measure is conducted for all concepts.

3.4. Results

The implemented operation strategy could be modeled as described before for the parallel hybrid operation. Fig. 4 shows the simulated gas mass flows (left) of the hybrid solar tower power plant and the simulated electrical power and stored energy (right) at an operation day with high solar radiation. The illustrated mass flows include the air mass flow coming from the receiver, gas turbine's exhaust gases, charging/discharging air mass flow to/from the TES and the mixed mass flow entering the HRSG.

At the beginning of the day the entire solar heat air mass flow is led into the HRSG. This mass flow increases until noon due higher solar radiation. When the maximum heat supply of the HRSG is reached the excess is used to heat the TES, which starts at 6:30 h. The set point of 40 % capacity of the TES is met at 8:30 h, so that the gas turbine's load is 50 %. Due to that the storage's charge increases at a lower rate because of a reduced air mass flow entering the TES.

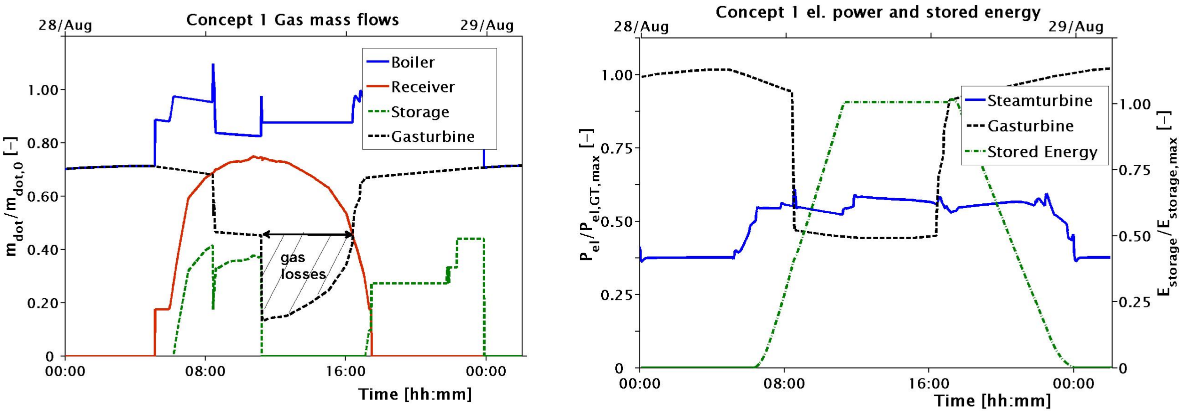

Fig. 4. Concept 1: simulated gas mass flows (left), generated electrical power and charge of the TES (right) for an operation day with high solar radiation

Although, the GT is operated at 50 % part load, the storage's maximum capacity is reached and the entire solar heat generated by the receiver is sent to the HRSG. As the gas turbine's exhaust gas mass flow cannot be further reduced the surplus is released to ambient (hatched area gas losses). In the afternoon the solar heated air mass flow decreases and the gas turbine can operate at nominal load again.

When the available solar mass flow cannot provide the maximum solar mass flow the storage can be discharged (17:00 h) and the stored thermal energy decreases. By using the TES the electrical power of the steam turbine can be maintained at nominal load till almost 0:00 h.

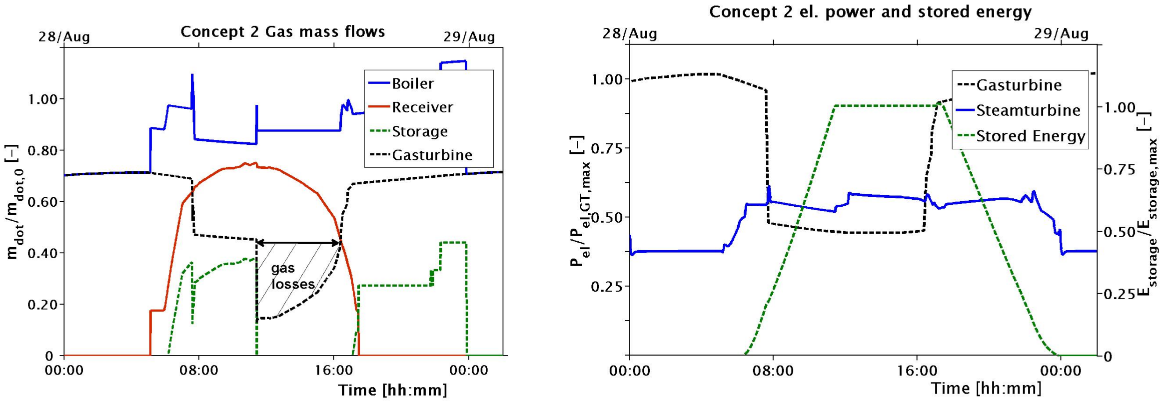

Fig. 5. Concept 2: simulated gas mass flows (left), generated electrical power and charge of the TES (right) for an operation day with high solar radiation

In concept 2 the gas turbine starts operating earlier at part load than in concept 1 due to the given set point for the TES charge of 20 % when the gas turbine is supposed to decrease the load (cf. Fig. 5). As a result the maximum charge of the storage is reached at a later time and the gas losses can be reduced slightly.

In Fig. 6 it is shown that there are no exhaust gas losses in concept 3. The solar power of the reduced heliostat field and generated in the receiver is just sufficient to charge the TES to maximum during the day. The gas turbine has still to be operated at part load to prevent the bypassing of exhaust gases. Nevertheless, the gas turbine's part load period can be strongly shortened compared to concepts 1 and 2. Concept 4 shows a similar behavior as the first two concepts (Fig. 7). Because of a reduced amount of heliostats the available solar heat is lowered and thus leads to reduced exhaust gas losses.

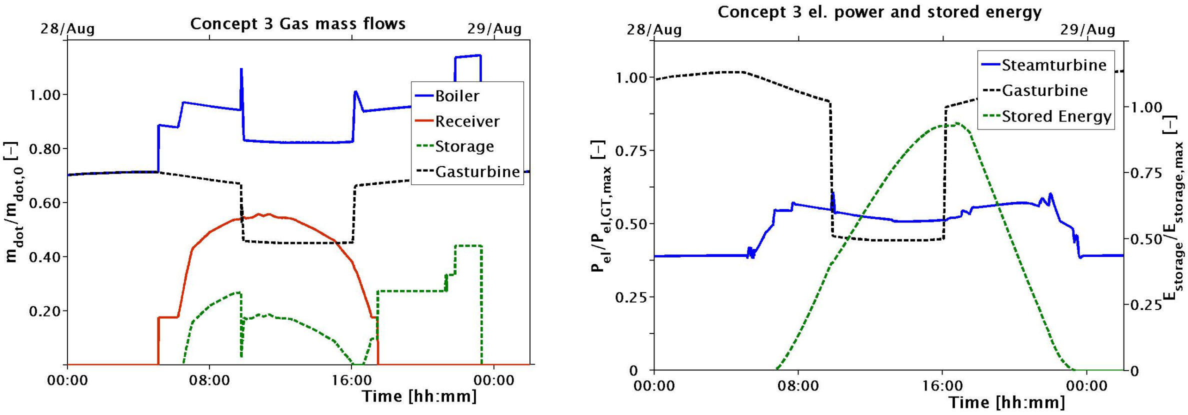

Fig. 6. Concept 3: simulated gas mass flows (left), generated electrical power and charge of the TES (right) for an operation day with high solar radiation

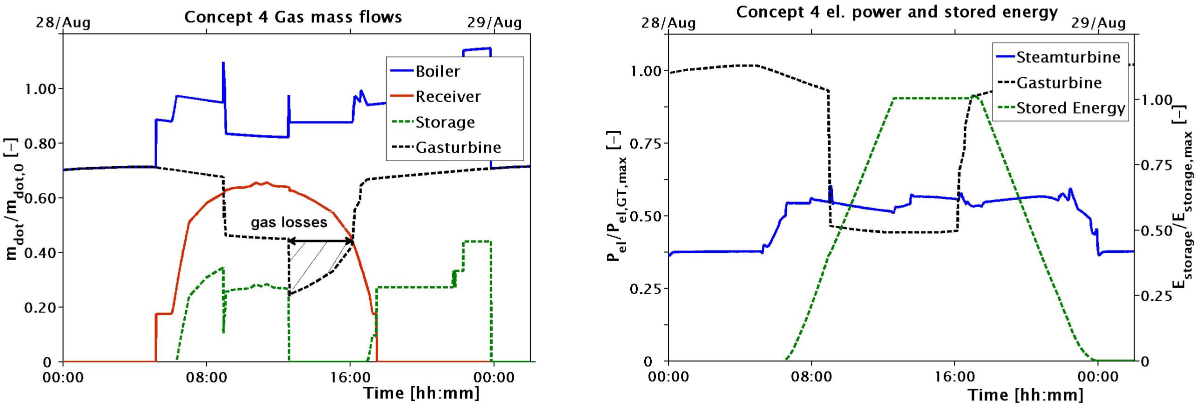

Fig. 7. Concept 4: simulated gas mass flows (left), generated electrical power and charge of the TES (right) for an operation day with high solar radiation

In general, the simulations showed also the reduction of the gas turbine's electricity generation with increasing ambient temperatures as can be seen at around 8:00 h. Furthermore, it can be noticed that there is a significant drop in the electrical power when the gas turbine operates at part load, which is valid for all concepts. The steam turbine can be operated at its nominal load for a long period due to the high solar radiation. However, because of the part load of the gas turbine the electrical power of the complete power plant decreases. This discontinuity in electricity generation has to be optimized in further studies.

3.5. Annual Performance Simulation

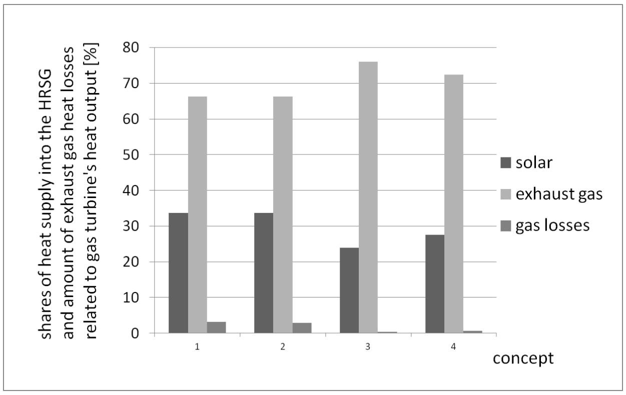

Fig. 8. Comparison of different heat supplies and exhaust gas losses for the investigated concepts

The annual performance simulations were conducted within MATLAB/Simulink for a time period of one year with the meteorological data taken from meteonorm. The maximum simulation time step was chosen to 60 s with a variable-step-type solver so that dependent on the model and the relative tolerance of 0.1 smaller time steps are chosen by the solver automatically.

The solar shares of the heat supply to the HRSG varied significantly within the different concepts (cf. Fig. 8). In concept 3 and 4 the solar share is less than in the first two concepts that exceed a share of 30 %. The obtained solar share of concept 3 is even below 25 %. On the other hand the largest gas losses occur in concepts 1 and 2.

Further results of the different concepts normalized to concept 1 are summarized in Table 2. The lowest produced solar thermal powers are yielded in concepts 3 and 4. In contrast the use of thermal power of the exhaust gas can be enhanced in these concepts as the gas turbine operates at part load for shorter periods and the exhaust gas losses are lowered. The electricity yield of the steam turbine is 4.2 % less at concept 3 than concept 1. On the other hand the electricity production of the gas turbine is 5.6 % higher than in concept 1. This means that the absolute electrical energy yield is highest in concept 3. Moreover this concept obtains a very low auxiliary consumption. That is why the net production is almost 3.3 % higher than in concept 1. The gas losses can be reduced by nearly 90 % for concept 3.

Table 2. Simulation results relative to concept 1

	Concept 1 (%)	Concept 2 (%)	Concept 3 (%)	Concept 4 (%)
Thermal power receiver	100.0	100.0	72.5	83.3
Thermal power exhaust gas (boiler)	100.0	99.3	111.0	106.7
Gross electricity production steam turbine	100.0	99.7	95.8	97.6
Gross electricity production gas turbine	100.0	98.2	105.6	102.9
Auxiliary consumption	100.0	98.6	94.2	98.4
Net electricity production	100.0	98.8	103.3	101.4
Exhaust gas losses	100.0	89.4	10.8	23.1

With these simulation results and assumed investment costs the levelized cost of energy (LCOE) can be calculated. As the solar share is different the LCOE of the complete hybrid power plant is not sufficient to compare the concepts. In dependence of the obtained electrical solar share the separate LCOE of the solar generated electrical energy can be determined according to equation 1. In this equation it is assumed that the share of fossil generated energy is comparable to electricity generated in a combined cycle power plant (CCPP). Because of that the fossil LCOE is assumed to be equal with the LCOE of a reference CCPP.

$$LCOE_{Solar} = \frac{LCOE_{Hybrid} - (1-f)\cdot LCOE_{CCPP}}{f} \tag{1}$$

The computed solar shares of the heat supplied to the HRSG and the electricity production including gas turbine's and steam turbine's produced electricity as well as the LCOEs in relation to concept 1 are listed in Table 3. The results show that the highest solar share is yielded for concept 2. In comparison to concept 1 it can be seen that decreasing the GT's load already at a set point of 20 % of the maximum TES charge results in better usage of the solar generated heat although the increase is not remarkable. Reducing the heliostat field size decreases the solar share as can be seen for concepts 3 and 4. In turn, the LCOE of these concepts can be reduced. For concept 3 the lowest hybrid LCOE is obtained due to the lowest investment for the heliostat. In addition, for concept 3 the highest net electricity generation could be achieved because of the high availability of the GT. However, the solar share is the lowest and thus the solar LCOE are higher than obtained for the other concepts. The lowest solar LCOE could be determined for concept 1.

Table 3. Solar shares (absolute values) and LCOE results relative to concept 1

	Concept 1 (%)	Concept 2 (%)	Concept 3 (%)	Concept 4 (%)
Thermal solar share	32.6	32.8	23.8	27.3
Electrical solar share	11.2	11.4	7.7	9.1
LCOE	100.0	101.3	93.3	97.8
LCOE solar	100.0	101.6	115.0	112.8

4. Conclusion

The simulation tool for open-volumetric solar tower power plants developed at the SIJ is applicable for detailed and transient simulations of different plant configurations including hybridized concepts. A validation of the tool against real plant data has been presented shortly.

The annual energy yield study of different concepts of a hybrid solar tower power plant at Barstow showed that concept 3 had the lowest LCOE. The operation strategy implemented was aiming at maximum electricity generation with highest solar share.

Next investigations have the objective to analyze a demand-orientated electricity supply with a hybrid solar tower power plant.

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