Evaluating the value of concentrated solar power in electricity systems with fluctuating energy sources

Benedikt Lunz[1,2,3,a], Philipp Stöcker[1,2,3], Robert Pitz-Paal[4] and Dirk Uwe Sauer[1,2,3]

[1] *Electrochemical Energy Conversion and Storage Systems Group, Institute for Power Electronics and Electrical Drives (ISEA), RWTH Aachen University, Germany*
[2] *Jülich Aachen Research Alliance, JARA-Energy, Germany*
[3] *Institute for Power Generation and Storage Systems (PGS), E.ON ERC, RWTH Aachen University, Germany*
[4] *German Aerospace Center (DLR), Institute of Solar Research, Köln, Germany*

[a)] Corresponding author: batteries@isea.rwth-aachen.de

Abstract. The paper presents a method for evaluating the value of CSP in electricity systems in comparison to other technologies. The low parametrization effort of the model allows for conducting studies for different electricity systems and scenarios within a manageable time frame. CSP systems in possible German electricity systems 2050 can be used at its best, when the share of fluctuating renewables (FRES) is low. Under these conditions CSP is a cost-effective solution to meet CO_2-reduction goals of 90 % in comparison to 1990. With FRES shares above 70 % the utilization of CSP systems would be too low to be competitive.

INTRODUCTION

In traditional electricity systems the supply of energy follows the fluctuating demand. Power systems with high shares of fluctuating energy sources like wind and solar power face new challenges: in addition to fluctuating loads, fluctuating generation has to be balanced [1]. This is achieved by the use of flexible generation, storage and power-to-X-technologies. The developed tool uses a simplified method to identify a cost-minimal mix of technologies which are able to supply this flexibility to the electricity system. For a given load demand and a predefined capacity of fluctuating renewable energy systems like wind or PV it calculates the technology mix with the lowest generation cost, that is able to cover this residual load. Concentrated solar power (CSP) is a valuable source of flexibility as it can be easily combined with thermal storage and a co-firing unit guaranteeing electricity production independent of solar irradiation [2]. With the developed method a first estimate on the value of CSP electricity generation in a system context in comparison to alternative technologies can be given.

CSP systems can be designed to meet specific load requirements by adjusting the size of the solar field and the storage capacity and eventually fossil fuel co-firing requirements to the size of the turbine nominal output. Increasing the size of the solar field lead to a higher nominal solar thermal output than the turbine can accept so that the surplus energy can be used to charge the storage that can be used to cover the load in times of no or low insolation. Optimizing the plant for a specific load curve requires a detailed plant performance and cost model that simulate the operation over one or more years under the meteorological boundary conditions of a given site. Such tool needs to be repeatedly applied for different design configuration to calculate the annual performance, investment and O&M cost to find the most suitable design. Public domain software tools like Greenius [6] or SAM [7] are available to perform such calculations, but detailed performance and cost data of all subsystems need to be specified by the user. In addition, optimization of a plant design is not performed automatically by these tools. In the context of this study, the optimization procedure of the design and the performance calculation have been simplified in order to be implemented them in the overall concept that seeks for the cost optimal technology mix to cover the residual load curve.

The advantage of our proposed method is the relatively small amount of necessary input data and the high computational speed. By that the value of CSP for different national power systems and different scenarios can be identified in a very efficient way. The needed input data for our model is summarized in TABLE 1.

TABLE 1. Summary of needed input data

Data	**description**
Residual load curve of future power systems	Generation from fluctuating renewable energy sources (FRES) minus load demand for one year (preferably hourly resolution)
Interest rate	Needed for investment and costing
Fuel costs	Coal, oil, gas, biomass
Costs for CO_2 emissions	To price CO_2-emissions
Technical parameters for used technologies	Efficiency, specific CO_2-emissions, etc.
Economical parameters for used technologies	Investment, depreciation period, O&M costs, etc.
Potential limits	Limit for installed capacity or used primary energy

In the following the proposed method is described for the example of Germany's power system in 2050.

Method

The method is basically divided into three steps: Firstly, the residual load which has to be covered is determined on hourly basis for a full year. Secondly, all available technologies are technically as well as economically characterized in a unified manner for the specific requirements of the residual load. Thirdly, technologies are ranked to fulfill the load curve based on full costs and under the constraint, that the residual load can be covered all the time.

Calculation of possible residual loads for 2050

As future power systems are analyzed, we use a simulation model for calculating the residual load. The residual load $P_{res}(t)$ is defined as difference from fluctuating infeed $P_{FRES}(t)$ and the load demand $P_{load}(t)$:

$$P_{res}(t) = P_{FRES}(t) - P_{load}(t) \tag{1}$$

In Germany's power system the fluctuating infeed mainly consists of PV and wind:

$$P_{FRES}(t) = P_{PV}(t) + P_{wind}(t) \tag{2}$$

The PV infeed is calculated by using a physical-technical model which translates direct and diffuse irradiation data into PV infeed. The same is true for the wind infeed, which is calculated based on measured wind speed data. The weather year 2008 was used for the calculation. The load curve is from the year 2010[1] and scaled linearly by the demand. All calculations are made under the assumption that no grid constraints exist. The installed capacities of PV and wind as well as the electricity demand are defined by a scenario corridor, which was developed in [3]. The scenario corridor describes possible power systems for Germany in 2050, see FIGURE 1.

[1] The load curve from 2008 was not used due to the effects of the economic crisis on the characteristic.

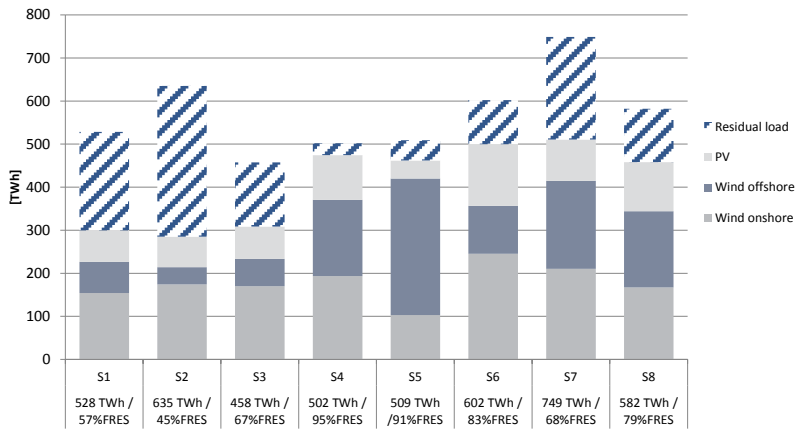


FIGURE 1. Scenario corridor for Germany's power system 2050

Technology mapping

To assure a stable operation of the power system, the residual load has to be zero for all times. To guarantee that, the positive residual load $P_{res,\ pos}$ is divided into "slices" of 1 GW:

$$P_{res,pos}(t) = \sum_{n=1}^{\frac{\max(P_{res}(t))}{1GW}} P_{res,pos,n}(t) \tag{3}$$

Beginning with $P_{res,\ pos,1}$, technologies which are able to cover the load curve with minimal costs are assigned. When the last positive slice is covered, a negative residual load is remaining. For that, the same procedure is executed, but with a different technology portfolio which is able to operate with negative loads (i.e. power-to-X technologies).

Modelling of technologies

To determine the full costs of a technology to operate on a slice of the residual load, a simulation run for each possible technology (e.g. flexible electricity producers, storage devices) is conducted. Investment costs as well as variable costs like maintenance and fuel costs are considered. Due to different technical characteristics, four technology groups are used to model the technology portfolio.

Flexible generation with unlimited storage

The unlimited storage in this technology group is represented by fossil or biogenic fuels. The full costs of a technology of the type 1 $C_{1,n}$ consist of investment cost C_{invest}, the fuel costs C_{fuel}, the costs for CO_2-emissions C_{CO2}, operation and maintenance costs $C_{O\&M}$ and start costs C_{start}:

$$C_{1,n} = C_{invest} + C_{fuel} + C_{CO_2} + C_{O\&M} + C_{start} \tag{4}$$

The annuity method is used to calculate a yearly value of C_{invest}:

$$C_{invest} = C_0 \cdot \frac{(1+i)^u \cdot i}{(1+i)^u - 1} \tag{5}$$

In (5), C_0 is the overall investment, i is the interest rate and u is the usage period. The fuel costs are calculated with the delivered electrical energy E_{el}, the conversion efficiency η and the specific fuel costs for the primary energy carrier $c_{fuel,th}$ related to thermal energy:

$$C_{fuel} = \frac{E_{el}}{\eta} \cdot c_{fuel,th} \tag{6}$$

The costs of CO_2-emissions are calculated by the primary energy input, the specific CO_2-emissions of the energy carrier in t/MWh$_{th}$ and the costs per ton of CO_2 c_{CO2}:

$$C_{CO_2} = \frac{E_{el}}{\eta} \cdot e_{CO_2} \cdot c_{CO_2} \tag{7}$$

Yearly operation and maintenance costs are calculated as a percentage $c_{O\&M}$ of the overall investment:

$$C_{O\&M} = C_0 \cdot c_{O\&M} \tag{8}$$

The start costs account for all costs in relation to a starting process. These are for example higher deterioration, extra fuel feed and extra personnel costs. Starting process from a cold and warm state are distinguished. The specific costs for a starting process c_{start} are multiplied by the number of starts n_{start}:

$$C_{start} = c_{start,cold} \cdot n_{start,cold} + c_{start,warm} \cdot n_{start,warm} \tag{9}$$

In the analysis for Germany, we use the following technologies in this group: Hard coal and lignite fired steam power plants, lignite steam power plant with carbon capture and storage (CCS), gas turbines and gas-steam power plants fired with natural gas and biogas, motor power plants, industrial combined heat and power (CHP) and wood power plants. The detailed technology parameters can be found in [3].

Flexible generation with thermal storage

CSP-systems are categorized as flexible generation as their power output can be decoupled from the fluctuating solar irradiation by using a thermal storage and/or a co-firing unit. By that they are able to complement the fluctuating technologies PV and wind.

CSP systems are modelled according to Fig. 2. For each “slice” of the residual load an optimization of the size of the collector field, the share of co-firing and the size of the thermal storage are made with the goal to minimize the full cost to deliver the electricity needed.

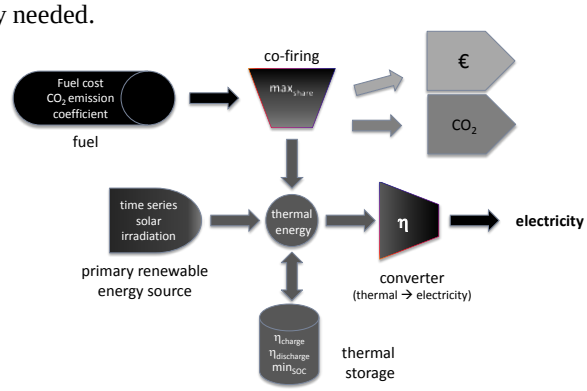


FIGURE 2. Schematic representation of the CSP systems modelled.

The logic design of this optimization process is shown in Figure 3. First, the residual load is evaluated for its peak power demand $P_{el,nom}$ under consideration of the HVDC transmission losses from a site e.g. in North Africa or Southern Europe to Germany. Then, the outer loop is entered, where the collector field output power $P_{th,solar}$ is optimized via sequentially decreasing its yearly mean thermal power output from an upper estimate ($2*P_{el,nom}/\eta_{th\rightarrow el}$) until no further cost reduction is observed. For each step inside this loop, the co-firing (COF) share is optimized together with the size of the thermal storage. For all loop iterations, the necessary net storage capacity $E_{storage,th}$ is calculated (as explained in chapter Storage technologies) and full costs of the current setting are computed. Placing a limit on the share of electric energy provided by co-firing is implemented, but not shown here for clarity.

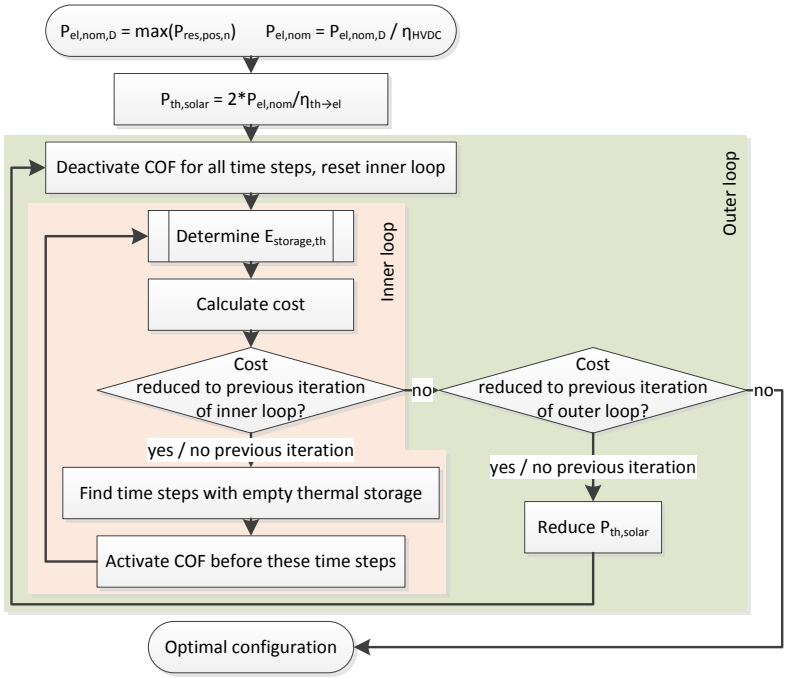


Figure 3: Logic design of optimization for flexible generation with thermal storage

The full costs of CSP-systems (type 2) $C_{2,n}$ are calculated similar to technologies of type 1. The overall investment C_0 is split up into the independently sized parts collector field C_{coll}, power block C_{PB} (including co-firing unit), thermal storage $C_{storage,th}$ and HVDC (high-voltage direct-current) electricity transmission to Germany C_{HVDC}. In addition to O&M costs a factor for contingencies is considered for the CSP system.

The costs of the collector field are calculated as follows:

$$C_{coll} = A_{coll} \cdot c_{coll} = \frac{P_{th,solar}}{\eta_{sol\rightarrow th} \cdot e_{solar}} \cdot c_{coll} \tag{10}$$

A_{coll} is the size of the collector field and c_{coll} the area-related costs of the field. The size of the collector field is calculated using thermal power $P_{th,solar}$, mean solar radiation e_{solar} and the collector efficiency $\eta_{sol\rightarrow th}$.

The costs of the thermal storage are determined with storage net capacity $E_{storage,th}$, the specific thermal storage costs $c_{storage,th}$, the storage efficiency (roundtrip, mean value including self-discharge) $\eta_{storage}$ and the minimum state-of-charge SOC_{min} of the thermal storage:

$$C_{storage,th} = \frac{E_{storage,th}}{\eta_{storage} \cdot (1 - SOC_{min})} \cdot c_{storage} \tag{11}$$

The fuel costs and costs for CO_2-emissions are calculated analogous to technology type 1.

For this paper we exemplarily investigate the value of CSP for the German power system. Due to the low direct irradiation level in Germany only CSP locations in southern Europe or North Africa with a long-distance electricity transmission are considered. For estimating the transmission costs, the costs for a direct HVDC-transmission C_{HVDC} are regarded:

$$C_{HVDC} = \frac{P_{el,nom,D}}{\eta_{HVDC}} \cdot c_{HVDC} \cdot l_{HVDC} \tag{12}$$

$P_{el,nom,D}$ is the power which has to be delivered to the German power system, η_{HVDC} is the transmission efficiency, c_{HVDC} are the power related specific costs including converter stations and transmission lines/cables and l_{HVDC} is the length of the transmission system. The transmission efficiency has also to be considered for the dimensioning of the CSP system, as the losses has to be supplied by that.

The parameters for CSP systems in a reference and progress case are summarized in TABLE 2.

TABLE 2. Parameters for CSP systems

Parameter	**variables**	**reference**	**progress**
Overall efficiency HVDC	η_{HVDC}	87 %	87 %
Depreciation time HVDC in years	u_{HVDC}	40	40
Length of transmission system in km (location Marocco)	l_{HVDC}	2600	2600
Investment HVDC per GW and km	c_{HVDC}	325.000 €	250.000 €
Efficiency turbine (steam->electricity)	$\eta_{th \rightarrow el}$	45 %	45 %
Efficiency co-firing (gas->electricity)	$\eta_{gas \rightarrow el}$	48 %	50 %
Overall efficiency (solar->electricity)	$\eta_{sol \rightarrow el}$	20,5 %	22,0 %
Efficiency collector (solar->steam)	$\eta_{sol \rightarrow th}$	46 %	49 %
Auxiliary power usage		10 %	10 %
Efficiency thermal storage	$\eta_{storage}$	98 %	98 %
Investment power block per GW_{el}	c_{PB}	670.000.000 €	590.000.000 €
Investment storage per GWh_{th}	$c_{storage}$	13.500.000,0 €	11.000.000,0 €
Investment collector field per m^2	c_{coll}	68 €	55 €
Depreciation time CSP system in years	u_{CSP}	30	30
Mean solar irradiation in W/m^2 (Marocco)	e_{solar}	335	335
Contingencies		27 %	25 %
O&M costs per investment	$c_{O\&M}$	2 %	2 %
Fuel costs co-firing per GWh_{th} (calorific value)		33.100 €	33.100 €
specific CO_2-emissions co-firing in t/ GWh_{th}		201,6	201,6

Storage technologies

The technology class “storage technologies” (type 3) summarizes pumped-hydro storage, adiabatic compressed air storage (A-CAES), hydrogen and methane storage, battery storage and demand side management.

The calculation for storage technologies also involves optimization to determine the cost optimal size of capacity and charging unit for any slice of the residual load. Storages serve the current positive slice with energy that was stored previously from negative residual load or from flexible generation with unlimited storage operating in positive slices below the current slice when those would idle otherwise. The optimization follows the logic design shown in Figure 4, first setting the discharge power $P_{el,discharge}$, that is fixed by the needs of the current slice and then setting the charge power $P_{el,charge}$ to the largest meaningful value. The two nested loops optimize the recharge from flexible generation in slices below the current slice by activating it for critical time steps, while optimizing the charge power by decreasing it until no further cost reduction is observed. For all loop iterations, the necessary storage size $E_{storage}$ is determined and the full costs are calculated. The implementation covers additional options not shown here like constraints for the power to capacity ratio, power and/or capacity limits and bidirectional charge/discharge units.

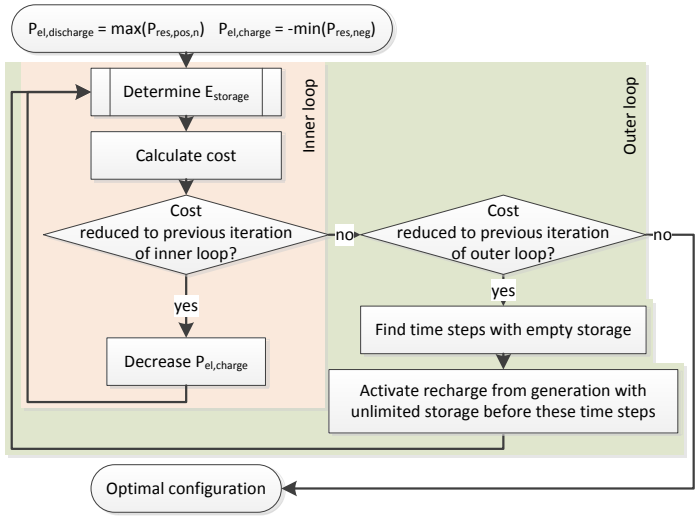


Figure 4: Logic design of optimization for storage technologies

Determining the necessary storage capacity from any given storage power time series is pretty straightforward. Given such a storage power time series, the total amount of energy going into the storage must be greater than the total amount of energy drained from the storage plus any losses. We integrate the power time series to get the corresponding energy time series E(t) for the case of no upper or lower capacity limits (see Figure 5). From this energy time series, the capacity is mostly determined by the largest relative discharge difference, i.e. the largest positive difference $E(t_1) - E(t_2)$ between the values of the curve at any two points t_1 and t_2 with $t_1 < t_2$. The initial SOC is set accordingly, so that the energy time series bottoms at 0 SOC. In case we want to ensure $E(t_{end}) \geq E(t_0)$, we have to increase the capacity by $E(t_0) - E(t_{end})$, if this difference is positive, and the initial SOC also needs to be adjusted.

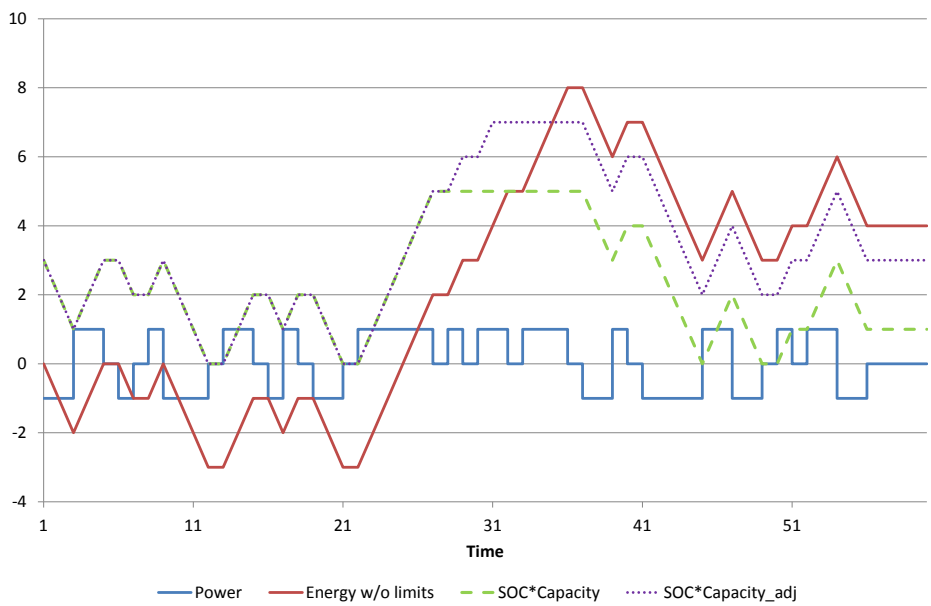


Figure 5: Exemplary power and energy time series for storage capacity determination

The costs of a storage system comprise investment costs C_{invest}, costs for fuel $C_{fuel,recharge}$ and CO_2-emissions $C_{CO2,recharge}$ from recharging from power plants and O&M costs $C_{O\&M}$:

$$C_{3,n} = C_{invest} + C_{fuel,recharge} + C_{CO_2,recharge} + C_{O\&M} \tag{13}$$

The investment can be divided into the storage unit (calculated analogue to thermal storage) and the charging and discharging systems. For each of these components an individual depreciation time is used [5]. The depreciation time of the storage unit $u_{storage}$ is calculated by the minimum of cyclic and calendric lifetime (l_{cyclic}, $l_{calendric}$):

$$u_{storage} = \min(l_{cyclic}, l_{calendric}) \tag{14}$$

The cyclic lifetime is calculated using maximum numbers of cycles n_{cyclic}, the storage gross capacity $E_{storage,gross}$ and the energy throughput $E_{throughput}$ per year:

$$l_{cyclic} = \frac{n_{cyclic} \cdot E_{storage,gross}}{E_{throughput} / \text{year}} \tag{15}$$

Power-to-X-technologies

The remaining negative residual load is assigned to power-to-X-technologies in a similar manner as the positive residual load to technology class 1. The regarded technologies are power-to-hydrogen and power-to-heat. As they generate a value by producing hydrogen or heat, the respective fuel and CO_2-emission costs are counted negative under the assumption, that natural gas would be used for hydrogen and heat production instead. The technologies are only assigned if they can generate a positive value by considering the investment and O&M costs on the one hand and the credits by saved gas and CO_2 on the other hand. If the costs are higher than the credits, fluctuating renewable generation is curtailed.

Restrictions and assumptions

To keep the necessary model input parameters in a manageable amount, some restrictions apply:

- The calculations are limited to one nation's electricity system (in the case of this paper Germany), import of electricity is only modelled for CSP systems.
- The model is limited to the electricity sector. The heat and traffic sector is only regarded with respect to flexibility for the electricity sector (power-to-heat, flexibility by demand-side-management)
- The selection of technologies is based on a macroeconomical basis. The levelized cost of electricity (LCOE) is minimized based on investment and O&M costs of the electricity system. Microeconomical aspects or market regulations are not regarded.
- All calculations are made for the year 2050 with a greenfield strategy. The transformation from now until 2050 is not modelled.
- No grid restrictions apply (copper plate approach).
- For the calculation of fluctuating renewables the weather year 2008 is used, which comprises some challenges with respect to energy supply by renewables (longer dark calm periods).
- The share of wind and photovoltaic is set by a scenario corridor and not a optimization parameter itself.
- Fuel costs and CO_2-costs for 2050 are taken from [4]. Price for natural gas: 33,10 EUR/MWh_{th}, CO_2-costs: 76 EUR/t.
- All cost calculations are based on prices from 2014 without consideration of inflation. An interest rate of 8 % is used.

RESULTS

In the following a validation of the CSP implementation as well as results with respect to the potential role of CSP in the German power system 2050 is given. Furthermore, details about the cost break down of the modelled CSP systems are shown.

Validation of CSP implementation

The results from the simulation model were compared to results from the CSP modelling software Greenius [6] for validation purposes using detailed performance, site and cost data that are in agreement with the assumptions in

table 2. For these calculations the progress parameter set was used and the LCOE of CSP systems was calculated for all 8 scenarios and all slices of the residual load. Furthermore, the full load hours were calculated for the slices of the residual load and used as the horizontal axis in Fig. 6.

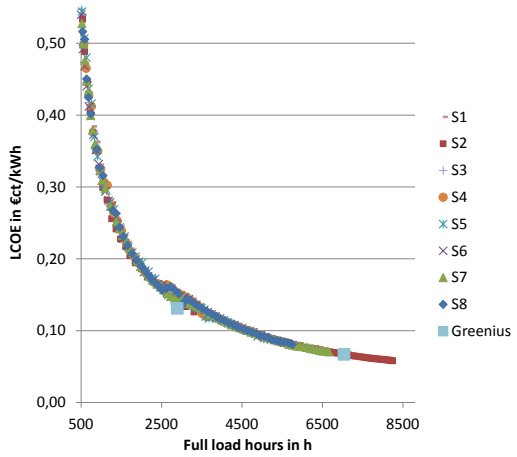


FIGURE 6. LCOE of CSP systems depending on full load hours for the 8 scenarios with technological progress parameter assumptions. As a comparison two points calculated with the CSP-modelling tool Greenius are shown.

It could be shown that the implementation of the CSP technology in our simulation model yields very similar results compared to the reference values of the Greenius software.

Results for the German electricity system 2050

In the following results for the German electricity system 2050 with a CO_2 reduction of 90 % compared to 1990 with respect to the usage of CSP are shown. The first research question is how the usage of CSP affects the electricity system and what influence the parameter assumptions for CSP have. Figure 7 shows the share of installed power in the electricity system without considering PV and wind. In the case “without CSP” CSP was not in the technology portfolio and therefore could not be selected during the technology mapping procedure. In the two other cases CSP was permitted with different parameter assumptions (reference and progress parameter set). The following can be concluded:

CSP is only used in systems with a share of fluctuating renewables below 70 %, i.e. scenarios S1-3 and S7. This is due to the fact, that in scenarios with higher FRES-share the utilization of CSP-systems is too low and therefore not competitive in comparison to alternatives like gas turbines and gas-steam power stations.

If CSP is used, it replaces primarily generation from geothermal energy and gas-steam biomass power plants. These are CO_2-free generation technologies which are normally used with high utilization due to the relatively high investment. In the case of scenario S1, CSP replaces also hydrogen storage.

When assuming the progress parameter set 5-10 % more CSP power is used. Then also generation from gas-steam plants with natural gas is replaced to a larger extent.

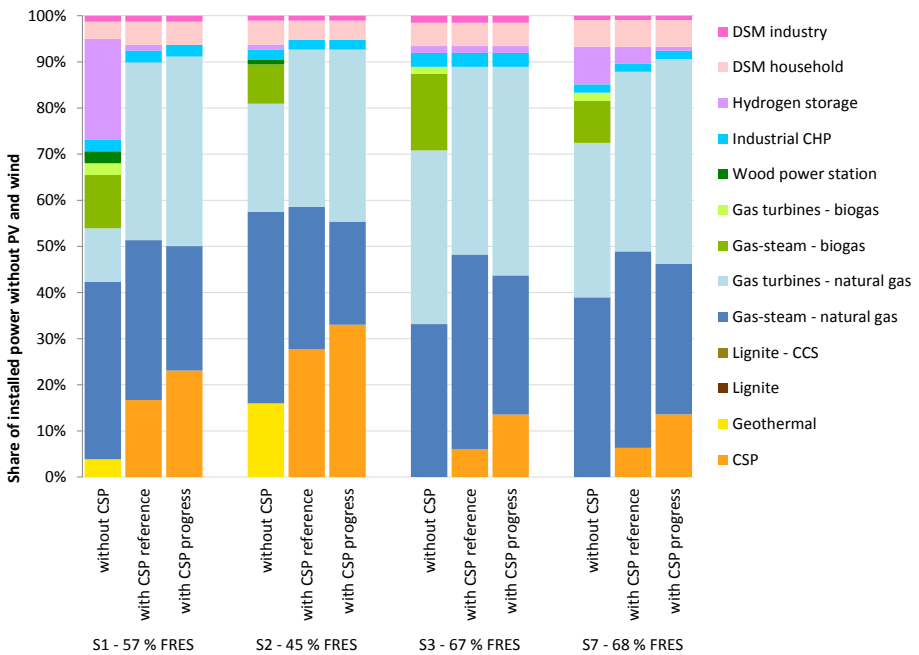


FIGURE 7. Share of installed power (without PV and wind) for scenarios S1-S3 and S7. Without CSP, with CSP reference data set and with CSP progress dataset respectively. The CO_2-emissions are 90 % lower than in the year 1990 in all cases.

The cost effects of CSP usage are shown in FIGURE 7. In systems above 70 % FRES-share, the possibility of CSP usage has no effect on the electricity costs. As explained above, CSP systems are not competitive in these cases and are therefore not used, independently from the parameter assumptions. However, it needs to mentioned that scenarios with this high FRES-share lead to higher overall electricity cost. The biggest cost decrease from CSP usage can be seen in scenario S2 with a FRES-share of 45 %. To hold the CO_2 goal of 90 % reduction, relatively expensive generation from geothermal energy is used in the case without CSP. This can be replaced by cheaper CSP production and therefore a cost decrease up to 25 % with the progress dataset is possible. The higher the FRES-share is the smaller is the effect of CSP usage on overall electricity costs.

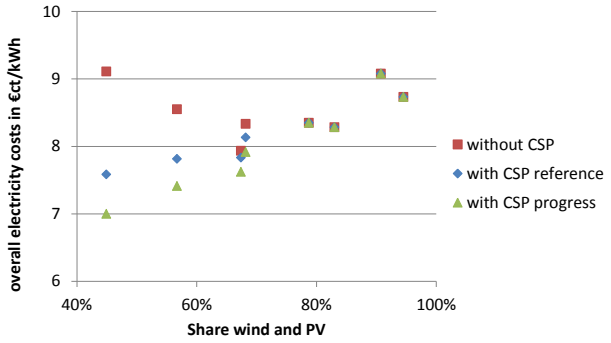


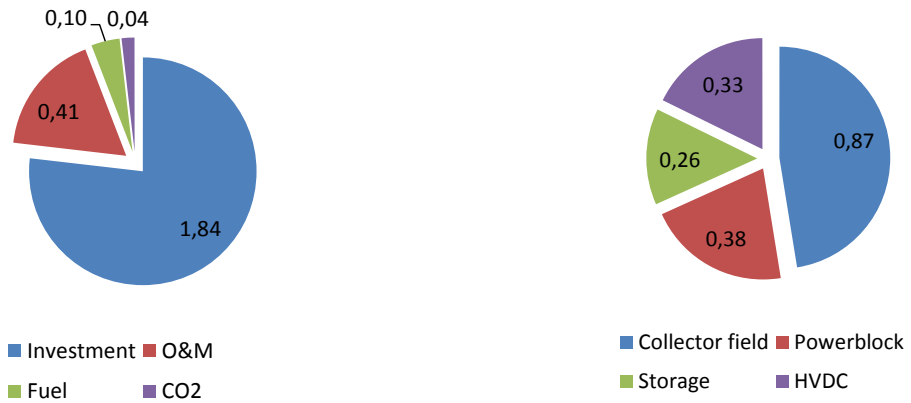
FIGURE 8. Overall electricity costs for different shares of wind and PV. Without CSP, with CSP reference data set and with CSP progress dataset respectively.

As an example the dimensioning of the used CSP system in scenario S3 with the reference parameter set is summarized in Table 3. In this case, 4 GW of CSP is used with a utilization of more than 6000 hours. To meet the demand of the residual load during the whole year a thermal storage which can guarantee production even without solar irradiation for around one day is used. To bridge even longer periods without sun, a co-firing unit is used which delivers around 6 % of the electrical energy. The LCOE of the system is around 10 €ct/kWh.

TABLE 3. Dimensioning parameters for CSP system in scenario S3, reference parameter set

Electrical power output power block in GW	4
Electricity output in TWh	24,8
Full load hours	6210
Power output collector field in GW_th	17,5
Size collector field in km^2	140
Capacity thermal storage in GWh_th	169
Share electricity production by co-firing	6%
LCOE in EUR/kWh	0,096

Figure 9 shows the cost breakdown for the overall CSP system costs and for the investment in detail. More than 75 % of the yearly costs are the depreciation of the investment and around 20 % O&M costs. Fuel and CO_2-costs only play a minor role. The biggest part of the investment is the collector field with around 50 %, powerblock and the HVDC connection have relatively similar shares and a smaller part are the costs for the thermal storage. From that the costs for the HVDC transmission can be calculated to be around 1.3 €ct/kWh.



(a) (b)

FIGURE 9. Cost breakdown for overall costs (a) and investment (b), Scenario S3-with CSP reference. Values in billion EUR (annuity)

CONCLUSION

The presented method allows for evaluating the value of CSP in electricity systems in comparison to other technologies. For parametrization of the model only a manageable amount of input parameters is necessary. By that, studies can be conducted with relatively low effort for different electricity markets and scenarios. Results for possible German electricity systems in 2050 show, that the strengths of CSP systems can be used at its best, when the share of fluctuating renewables (FRES) is low. In this case, CSP is a cost-effective solution to meet CO_2-reduction goals of 90 % in comparison to 1990. With FRES shares above 70 % the utilization of CSP systems would be too low to be competitive.

In future studies the proposed method shall be applied to other nation's electricity systems to identify their specifics with regard to the system role of CSP.

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