ELECTRICAL ENERGY STORAGE SYSTEMS FOR FUTURE POWER SYSTEMS APPLICATIONS BY MODELING

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Abstract*— *All over the world power systems are faced with great challenges because of the rapidly increasing integration of renewable energy sources. Electrical energy storage systems (ESS) can help to stabilize the output from volatile and intermittent renewable energy sources such as wind and solar energy. Basically they can be installed close to large wind farms or photovoltaic parks and provide many advantages for future integrated power systems. In this paper we study the impact of ESS on electrical power systems on a larger scale. There- fore we describe the implementation of two different charging strategies for ESS for an already developed simulation model for the German electrical power system and investigate different scenarios with respect to the installed capacities of renewable energy sources and the aggregated capacity of ESS. As a result different output parameters such as the electricity generation mix and $CO2$ emissions can be investigated. The simulation results show how ESS contribute to a) the integration of electrical power generated by renewable energy sources and b) the reduction of electricity imports and exports.

Index Terms*— *electrical energy storage systems, renewable power capacity, future power system, simulation model, energy system analysis

I. INTRODUCTION

Worldwide a massive grow of renewable power capacity is observable. According to the Renewables Global Status Report [1] the global renewable power capacity reached 1,712 GW at the end of 2014. The top countries for total installed renewable power capacity are China, the United States, Brazil, Germany, and Canada. In particular fluctuating and intermittent renew- able energy sources achieved high levels of penetration. For instance, wind power met 39.1 % of electricity demand in Denmark and 27 % in Portugal; solar PV covered 7.9 % of electricity demand in Italy and approximately 7 % in Germany, respectively.

In many countries the energy transition towards a more sustainable power system will lead to even higher renewable power capacities in the next few years. For example, the German government aims to raise the share of renewable based power generation between 40 % and 45 % in 2025 and between 55 % and 60 % in 2035 [2]. In order to reach these ambitious targets, the total renewable power capacity will be considerably higher than the annual peak load in the future because of the high variability of solar PV and wind power. According to the German Grid Development Plan [3] the total renewable power capacity will amount to 141.4 GW in2025 whereas the current annual peak load lies at 86 GW and will remain constant in the next few years. The power capacity of onshore wind power and solar PV will lie at 63.8 GW and 54.9 GW, respectively. Hence, the integration of electricity generated by renewable energy sources could lead to big challenges. The situation becomes even more complex when we take a look at the scale of a federal state. For instance, already today the total solar PV power capacity of the German federal state of Bavaria amounts to 11 GW, thus on a sunny Sunday afternoon the solar PV production is higher than the local electricity demand which lies at approximately 7 GW, leading to a theoretical surplus of approximately 4 GW. This effect is additionally enforced by the fact that combined heat and power and other conventional-fired power plants only partially reduce their output due to operating conditions. This could also be seen in negative electricity prices [4]. Hence, in the most unfavorable case some of the solar PV systems or wind power plants must be shut down in order to avoid an overload of the grid - this intermittent reduction of feed-in power is also known under the term feed-in management [5]. In order to ensure a reliable and secure grid control, ESS can help to stabilize the output of high volatile and intermittent renewable power capacities. They can be used to transfer the excess power to points in time where the power is needed, e.g., the excess power can be shifted from the off-peak load period to the peak load period. Furthermore, due to the decentralized character of ESS the excess power has not to be transferred over long distances, i.e. the excess power can be stored locally and an overload of the transmission grid can be avoided more easily and without shutting down renewable generators.

In this paper, we investigate the impact of the prioritized operation of ESS on electrical power systems on a larger scale. Therefore we assume that ESS are charged when there is a surplus of electrical power and they are discharged when the current electricity demand cannot be met by renewable power capacities, i.e. locally installed ESS enjoy priority over conventional-fired power plants. In order to study this opera- tion strategy we enhance an already developed comprehensive simulation model of the German electrical power system [6] by modifying the logic of the model and simulate different scenarios with respect to different renewable energy targets and different capacities of ESS. The simulated scenarios can be compared concerning different output parameters such as the total electricity generation mix, the CO2 emissions, the electricity imports and exports, and the utilization of power plants and ESS. The simulation results show how electrical power systems can benefit from a prioritized operation of ESS from an entire system perspective.

The remainder of the paper is organized as fallows. In Section II we give an overview of related work in the field of modeling electrical power systems as well as ESS. Section III describes the simulation model and the modified logic of the model. In Section IV we define different scenarios based on assumptions for the development of the German electrical power system in the next years until 2023. Section V presents simulation results and the evaluation. Finally, Section VI concludes the paper with a short summary and an outlook on future work.

II. RELATED WORK

There are many publications in the field of studying the impact of ESS on electrical power systems. In general, we can distinguish between different regional scales (e.g., isolated power systems, country-scale power systems) and different types of ESS (e.g., battery energy storage systems (BESS), pumped storage units (PSU)). For instance, the impact of ESS on isolated power systems on smaller scales is investigated by Guo et al. [7], Bagen et al. [8], and Bizuayehu et al. [9]. Guo et al. [7] analyzed the impact of a battery energy storage system on the dynamic properties of an isolated power system. The isolated power system consists of two generators, different converters and a battery energy storage system. The results showed that the frequency maintenance and energy support in response to dynamic disturbances benefit from a battery energy storage system. Also Bagen et al. [8] examined how renewable energy based isolated power systems can profit from energy storage. For that reason the authors used time series models to simulate the generation and demand characteristics. Simulation results showed that energy storage can have positive impacts on the system reliability. Bizuayehu et al. [9] examined the impacts of high wind power and storage participation on a 70-bus electrical distribution system over a period of 24 hours. Therefore they used a stochastic mixed integer linear program in order to satisfy the balance between load and generation. They also took different wind scenarios, conventional generation, and ESS into account. The authors concluded that the costs of the system were reduced due to higher participation of wind power and storage. All three publications show promising opportunities in the interaction between ESS and power systems, however the applied models do not allow an investigation on a larger scale, i.e. annual CO2 emission savings and total electricity generation mixes can not be studied.

Studies on the impact of ESS on country-scaled power systems are given in Tuohy et al. [10] and Devlin et al. [11]. In Tuohy et al. [10] the authors examined the impact of large scale electricity storage at high rates of installed wind power capacity on the Irish power system from an economic perspective. Therefore they used a former model forthe unit commitment and dispatch of an power system with and without a pumped storage unit. As a result they showed that pumped storage units can reduce operating costs but the reduction would not be enough to justify the investment costs for building a pumped storage. However, uncertainties of wind power generation are not considered and no information on CO2 emissions and electricity imports and exports are given. Also Devlin et al. [11] investigated peak and of peak benefits realized by installing an ESS in the Irish power system with a high share of wind power. For modeling purposes the authors used a least-cost optimization strategy in order to ensure an economic dispatch. Similar to Tuohy et al. [10] no results on electricity generation mix and CO2 emissions are shown.Literature pertaining to ESS relevant to the subject of this paper is focused on different ESS types and their area of applications. In Yeleti et al. [12] the authors discussed many applications to the power system which are provided by ESS. For instance, ESS can quickly offer spinning reserve, they can improve the power quality and stability, and they can stabilize the output of intermittent renewable energy sources. The authors also presented a comparison of different energy storage technologies. They came to the conclusion that ESS will play a key role in future integrated power systems. A further comprehensive overview on ESS can be found in Fuchs et al. [13]. Their report offered also a good survey of storage technologies and a classification of their applications. The authors emphasize the importance of flexibility in the power system which can be provided by different storage opportunities.

The contribution of this work is to pick up the idea of applying ESS to maximize the usage of fluctuating renewable energy sources for covering the electricity demand on a larger scale. Therefore, we develop a new logic for the dispatch schedule and integrate it in our existing simulation framework. Furthermore, we study the impact of ESS on the annual electricity generation mix, the CO2 saving potential, and electricity imports and exports by the example of the German federal state Bavaria.

III. METHODOLOGY

In this section we describe the applied simulation framework for the German electrical power system. Secondly, we explain two different logic of the model for the dispatch schedule.

A. Simulation Framework

The before mentioned special situation of Germany motivated us to develop a comprehensive simulation model in order to study the future development of electrical power systems with all of their major components and stochastic influences. As components for electricity generation we implement object classes for different renewable energy sources (solar PV systems, wind onshore, wind offshore, hydro power, biomass, geothermal energy), conventional power plants by using different types of fossil fuels (lignite, hard coal, gas, oil) and combined heat and power plants. Further components describe the electricity demand and ESS (battery energy storage systems, pumped storage units).

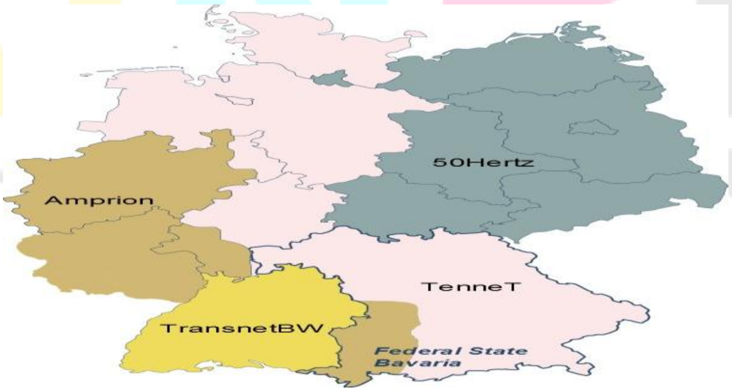


Fig. 1. Transmission grid areas of Germany.

For the modeling of these components a hybrid simulation approach is used, i.e. we combine Discrete-Event Simulation and System Dynamics in one framework. For implementation purposes we use the commercial multi-method simulation software Anylogic [14]. More detailed information about the modeling and implementation can be found in several of our applications[6], [15], [16].The developed model can be characterized by simultaneous a high time resolution and a long planning horizon with manageable computation times.

In contrast to many other power system models [10] we do not implement the German electrical power system as a single node. In order to consider the electrical power exchange of different regions, we use a multiple node approach based on the transmission grid areas of 50Hertz, Amprion, TenneT, and TransnetBW which are also depicted in Figure 1. Due to the great north-south sweep of the area of TenneT and the north- south divide [17] with regard to wind speeds we decided to split the area of TenneT in TenneT North and TenneT South (mainly the Federal State Bavaria, see also Figure 1). TenneT South covers more than 85 % of the geographical area of Bavaria and along with the small area of Amprion in Bavaria we define a further node – the Federal State Bavaria. Hence, the German electrical power system is currently modeled by five nodes. Every single node is composed by entities of different components described above. Each entity can be instantiated by a huge number of input parameters considering different structural properties of each region. For instance, in north of Germany the wind is more blowing and therefore the feed-in behavior of wind power plants is totally different to wind power plants in the south of Germany. Moreover, lignite- fired and hard coal-fired power plants can mainly be found in the transmission grid areas of 50Hertz and Amprion whereas gas-fired plants are also located in the areas of TenneT South and Transnet BW.

The model simulates the German electrical power system by using the hourly economical dispatch of power plants based on the residual load which describes the difference between the electricity demand and the electricity generated by must run capacities such as renewable energy sources and combined heat and power, i.e. the entire electrical power system is based on power balances of each simulation step.

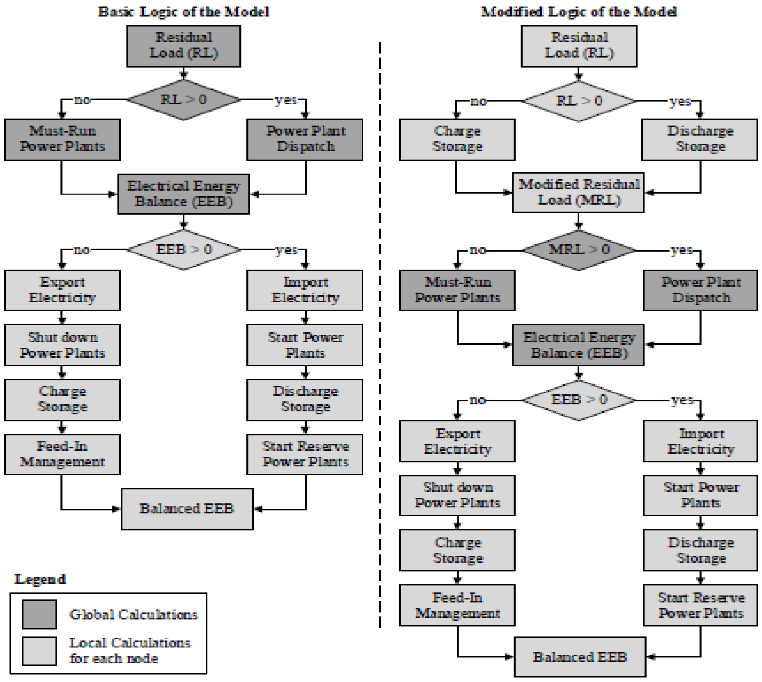


Fig. 2. Illustration of the basic and modified logic of the model.

Due to the multiple node approach the electricity exchange between nodes under consideration of net transmission capacities is also calculated. With our model it is possible to evaluate a large range of output parameters, e.g., electricity generation balances, CO2 emission balances, electricity imports/exports of a single node, hours of operation of power plants, utilization of ESS, residual load values, and fuel consumption. Every output parameter can be assessed on different time scales (hourly, weekly, monthly, annually) for the German electrical power system and each node, respectively. Currently, we use this model to analyze different scenarios for the development of the German electrical power system until 2025, but due to its component- based and lightweight design, the model can be applied to any other region worldwide as long as appropriate input parameters are available.

B. Logic of the Model

As above mentioned this work aims to study how electrical power systems can benefit from the prioritized operation of ESS on a larger scale. Therefore we implement a modified logic of the model. In the following we shortly describe the current basic logic of the model and the modified ones which are shown in Figure 2.

Basic Logic of the Model: In order to explain the basic logic of the model which represents the logic of the real systemin an abstract way we start with the calculation of the global residual load. The global residual load RLglobal is given by

$$RL_{\text{global}} = \sum_{i \in \text{TSO}} RL_i,$$

where RLi describes the local residual load for node i ∈ {50Hertz, Amprion, Bavaria, TenneT North, TransnetBW}

and can be calculated by subtracting the electricity gener- ated by different renewable energy sources and combined heat and power plants from the local electricity demand at node i. Based on the sign of the global residual load we schedule the economical dispatch of power plants. If RLglobal is already negative we have to consider feed-in power of power plants which cannot be switched off due to technical or economical restrictions, e.g., minimum operation times. If the sign of RLglobal is positive, electricity generated by conventional power plants is needed to cover the demand and the economical dispatch is scheduled.

After that we calculate a global power balance and derive local power balances for each node. In general, the electricity demand of each node cannot be covered by the feeding power plants in the respective area and the local power balance of each node is different to zero. Based on the sign of the local power balance of each node we implement several mecha- nisms. Firstly, we calculate electricity imports and exports to adjacent nodes. If the local power balance is still different to zero, the model allows to change power plant schedules (so- called redispatch [18]) by shutting down or starting power plants in the affected node. If there is not enough power plant capacity available, we provide also the possibility to charge or discharge ESS in the affected node. In the case that the ESS are already fully charged and there is still a surplus of electricity, we have to reduce the feed-in power from renewable-based plants (feed-in management, see also [5]). In the other case we can identify potential capacity gaps and if necessary mechanisms for starting reserve power plants are implemented.

All in all we aim to have a balanced power balance in each node and finally for the global German electrical power system in every simulation step, i.e. in each node the differ- ence between the electricity demand and feeding of power plants/operation of ESS equals to zero.

1) Modified Logic of the Model:

In contrast to the basic logic the modified logic of the model starts directly with the residual load of each node and is depicted at the right side of Figure 2. As already mentioned it is a more local- based approach, where discharging of ESS enjoys priority over conventional power plants. Based on the sign of the residual load of each node, ESS can be charged or discharged primarily. When the sign of the local residual load is negative, we have already a surplus of electricity generated by renewable energy sources and we try to charge ESS with the excess power. If the sign of the local residual load is positive, we try to cover the electricity demand by discharging the ESS. Subsequently, we calculate a so-called modified residual load for each node. Based on the modified residual load of each node we calculate the global residual load by adding up all local modified residual loads. After that we perform the exact same procedure as already explained for the basic logic of the model.

IV. SCENARIOS

After we explained the applied simulation framework and the basic and modified logic of the model we introduce briefly basic assumptions of the development of the German electrical power system in this section. Secondly, we define scenarios which can be differentiated by renewable power capacity, different ESS capacities, and their operation mode.

A. Assumptions

In order to study the impact of ESS on future electrical power systems we have to make assumptions on the an- nual electricity demand, the development of the conventional power plant fleet, and the aggregated capacity of ESS. Our assumptions are based on the scenario framework conditions of the German Grid Development Plan 2030 [3], the German Renewable Energy Law (EEG) [19], the Bavarian Energy Concept [20], and a study on the potential to build pumped- hydro storage units in Bavaria [20]. A summary of the installed capacities regarding conventional power plants for the German electrical power system is given in Table I. We see a tremen- dous decline of total conventional power plant capacities until 2030.

Installed capacity in GW of different conventional energy sources based on scenario B 2030 [3].

	Ref 2014	**Germany 2030**
Nuclear	**12.1**	**0.0**
Lignite	**21.0**	**9.4**
Hard coal	**26.1**	**14.7**
Gas	**29.1**	**29.3**
Oil	**3.8**	**1.2**
Others	**4.3**	**2.7**
In total	**105.7**	**69.0**

The given installed capacities are distributed on over 300 modeled power plants. Each power plant can be specified by its capacity, specific CO2 emissions, efficiency, type, final phase- out year, and allocation to one of the five nodes. The annual gross electricity demand and annual peak load amounts to600 TWh (Bavaria: 90 TWh) and 86 GW (Bavaria: 12.5 GW), respectively.In Section V we will present simulation results on the impact of ESS on electrical power systems using the example of the German federal state Bavaria. In order to define various scenarios, we introduce two different extension targets for renewable power capacity (see also Table II) and two different options on building new ESS differentiated by the type as well as the aggregated capacity (see also Table III).

TABLE II

Installed capacity in GW of different renewable energy sources based on the Bavarian Energy Concept [20] and own assumptions.

	Ref 2013	Low	High
Solar PV	10.6	15.5	21.9
Wind Power	1.1	5.0	6.5
Hydro Power	2.8	3.0	3.0
Bio Energy	1.2	1.4	1.8
Others	< 0.1	0.3	0.3
In total	15.8	25.2	33.5

TABLE III

Different assumptions for the extension of pumped-hydro storage units (PSU) and battery electrical storage systems (BESS) based on [21] and [12]

	Ref 2013	PUC Extension	BESS Extension
Total capacity in (Gwh)	3.35	38.6	38.6
Charging Power (in GW)	0.553	5.8	17.31
Discharging Power (in GW)	0.553	5.8	17.31
Efficiency	0.8	0.8	0.7

Table III shows different assumptions for the aggregated capacity as well as charging and discharging power for two different ESS options. The first one is based on the building of new PSUs in Bavaria according to a study on potential pumped-hydro storage units in Bavaria [20]. We assume the building of new PSUs with a total capacity of 38.6 GWh corresponding to approximately 50 % of the entire potential in Bavaria. A second options describes the building of local BESSs with the same capacity but another ratio between total capacity and charging/discharging power as well as worse efficiency [12].

B. Scenarios

Based on the described assumptions we define different scenarios which are shown in Table IV. In the interests of comparability we also introduce a reference scenario assuming a low extension of renewable power capacity and no extension of the current storage capacity. Further scenarios can be differentiated by the renewable power capacity, ESS and the used logic of the model.

TABLE IV
Overview of the investigated scenarios

Scenario	Renewables	ESS	Logic
Reference	low	ref.	basic
Rlow-PSU-NoPrio	low	PSU	basic
Rlow-PSU-Prio	low	PSU	modified
Rlow-BESS-Prio	low	BESS	modified
Rhigh-PSU-NoPrio	high	PSU	basic
Rhigh-PSU-Prio	high	PSU	modified
Rhigh-BESS-Prio	high	BESS	modified

V. SIMULATION RESULTS

In this section we show simulation results on the electricity generation mix, electricity imports and exports as well as CO2 emissions on an annual basis. Moreover, we show the operation of ESS in the scenario Rhigh-PSU-Prio for one week in an hourly resolution. Therefore, we implemented all scenarios in our simulation framework and simulated each scenario ten times.

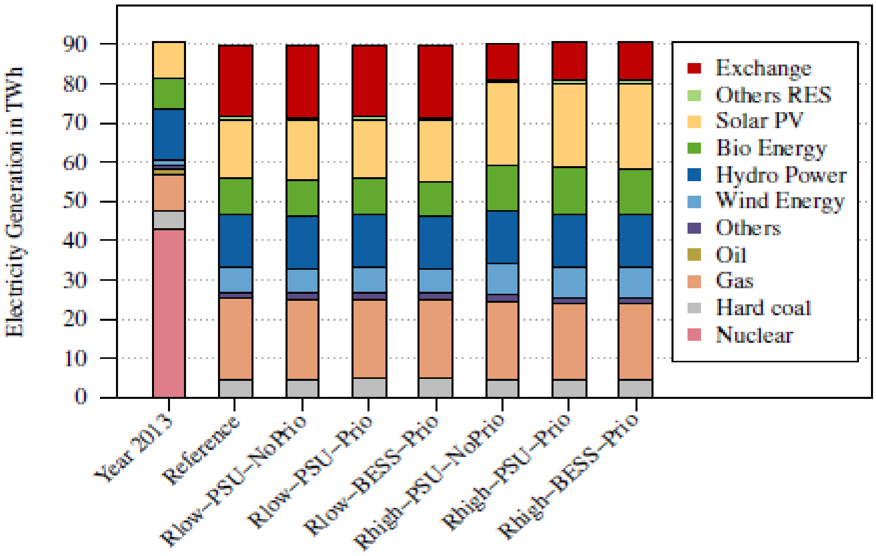


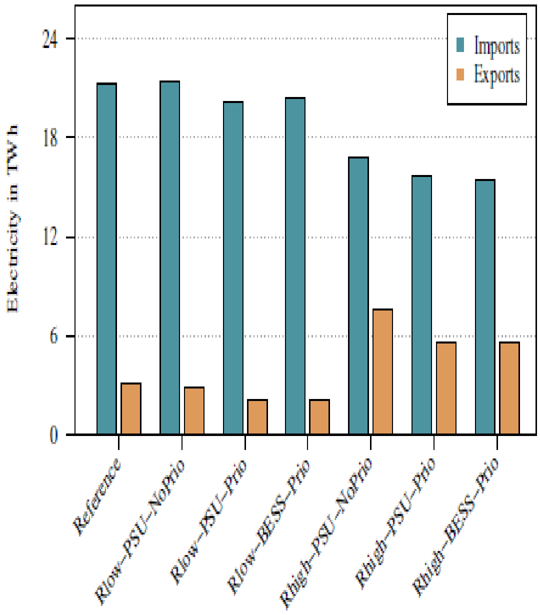
Fig. 3. Electricity generation mix for the simulated scenarios.

A. Electricity Generation Mix

Figure 3 shows the electricity generation mix for each scenario. In comparison to the year 2013 in each scenario a positive exchange balance is identifiable, i.e. electricity imports are higher than electricity exports. The phase-out of nuclear energy is compensated by a higher electricity generation from gas-fired plants, renewable energy sources, and electricity imports. The electricity generation mix in scenarios with low renewable power capacity extension (Rlow- PSU-NoPrio, Rlow-PSU-Prio, Rlow-BESS-Prio) equals to the reference scenario. Hence, the extension of ESS and their operation mode has only little effects in this case. The situation is different when we take a look at scenarios with a high extension of renewable power capacity (Rhigh-PSU-NoPrio, Rhigh-PSU-Prio, Rhigh-BESS-Prio). The exchange balance is lower than in the reference scenario, and a slightly difference between the operation strategies of ESS is also observable. In order to study the operation strategies of ESS in detail, we take a look at the electricity imports and electricity exports in detail.

B. Electricity imports and exports

Figure 4 depicts the electricity imports and exports for the simulated scenarios. We find significant influences in the scenarios where the charging and discharging of ESS enjoy priority. Both the electricity imports and electricity exports are lower in these scenarios (Rlow-PSU-Prio, Rlow-BESS-Prio, Rhigh-PSU-Prio, Rhigh-BESS-Prio) compared with scenarios without prioritized charging and discharging of ESS (Rlow- PSU-NoPrio, Rhigh-PSU-NoPrio). For instance, in the scenario Rhigh-PSU-Prio the electricity imports are 27 % lower than in the scenario Rhigh-PSU-NoPrio. This electricity can



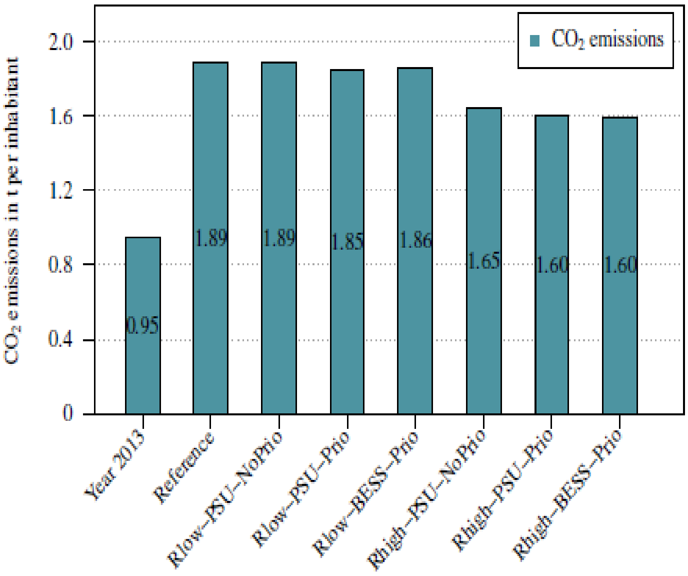


Fig. 4. Electricity imports and exports for the simulated scenarios. Fig. 5. Annual CO2 emissions in tons per inhabitant

be consumed locally because of the prioritized ESS operation A difference between the used storage technology is not observable.

CO2 emissions

Figure 5 shows the annual CO2 emissions in tons per inhabitant. It can firstly be noted that in all scenarios the CO2 emissions are higher than in the year 2013. One of the reasons is the phase-out of nuclear energy in Germany until the end of 2022. Secondly, we can see that a higher extension of renewable power capacity has a positive effect on the CO2 emission balance. In the scenarios with a higher share of renewable power capacity the CO2 are 13 % lower than in the scenarios with lower extension targets. A comparison between the scenario Rhigh-PSU-NoPrio on the on side and the scenarios Rhigh-PSU-Prio and Rhigh-BESS-Prio on the other side shows that prioritized charging and discharging of storage can contribute to CO2 savings.

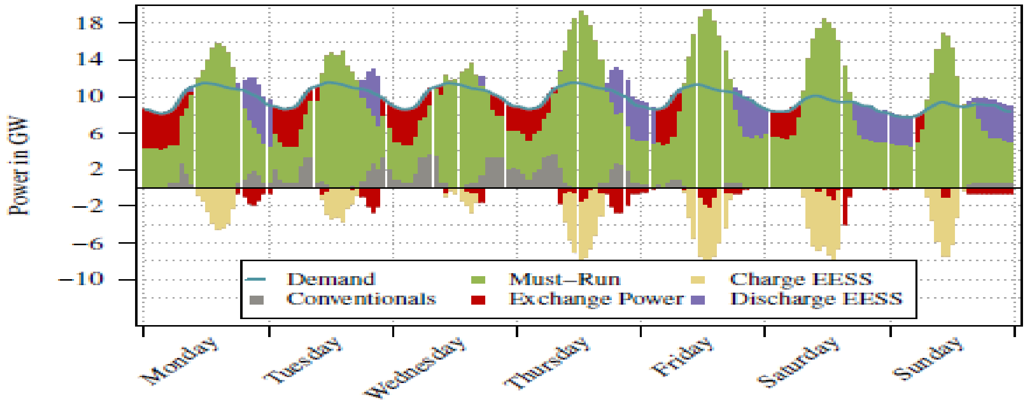


Fig. 6. Operation of ESS for one summer week in an hourly resolution in the scenario Rhigh-PSU-Prio.

D. Operation of ESS in an hourly resolution

Figure 6 describes the operation of ESS for one summer week in an hourly resolution in the scenario Rhigh-PSU-Prio. Due to the high extension of renewable power capacity and further must-run power plants (e.g., waste-to-energy plants) we assess a surplus of electrical power during the day. Around noon the feed-in power of renewable energy plants and further must-run power plants is almost twice as high as the electricity demand. Without the prioritized operation of ESS we would have to export the excess power during the day and import electricity in the evening hours to cover the demand. Figure6 shows the operation of ESS. Depend on the feed-in of renewable power capacity the ESS charges between 11 a.m. and 5 p.m. under consideration of the current state of charge and maximum charging power. Subsequently, from 6 p.m. until midnight the ESS discharges in order to cover the demand Hence, the electricity demand during the evening hours could be covered by electricity which is generated during the day. When the ESS are empty electricity imports are needed to cover the demand, e.g., Tuesday morning, Wednesday morn- ing, and Friday morning. All in all electricity imports and exports can be reduced with the implemented charging strategy of ESS.

VI. CONCLUSION

This paper examined the impact of ESS on electrical power systems on a larger scale. Therefore we further developed an already existing simulation framework for the German electrical power system. We implemented a different logic of the model in order to study the prioritized charging and discharging of ESS. Subsequently, we investigated various scenarios which can be differentiated by their extension targets of renewable power capacity, ESS capacities, and the operation mode of ESS. Our simulation results showed that electrical power systems can profit on the prioritized operation of ESS. It was shown that ESS displace electricity exports when the feed-in of renewable power capacity is high. Moreover, the CO2 emissions can slightly be reduced especially when the extension of renewable power capacity is high. The charging and discharging of ESS was also demonstrated for one week in the summer in a hourly resolution in order to understand the prioritized operation of ESS in detail.Future work includes the further development of the logic of the model. In future electrical power systems the integration of electric vehicles will become more and more important. The batteries of electric vehicles can be used as temporary ESS. We aim to integrate these kind of storage in order to investigate the impact on large scaled power systems and to develop intelligent charging and discharging strategies for batteries of electric vehicles.

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