Hierarchical Simulation of the German Energy System and Houses with PV and Storage Systems

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Abstract. The increase of renewable energies leads to new solutions in the field of decentralized energy storage. Houses with photovoltaic systems and battery storage systems can provide services for the power grid. But the isolated examination of only a few houses neglects the interaction of the houses with the power grid. We combine a model of the German energy system and a model of houses with photovoltaics and batteries. The two coupled hierarchical simulation models are then used to study different scenarios regarding the extension of renewable energy sources in Bavaria. Due to differences between the forecasted and real residual load and restrictions in the transmission grid, provision of control power is needed. The case studies show the amount of control power that will be provided by the houses with battery storage systems. In addition, the impacts on the electricity costs per year for a house are shown.

Keywords: Hierarchical modeling · Electrical energy system · Renewable energy · Control power · Storage system · Model aggregation · Hybrid simulation

1 Introduction

Energy system models are very important to support various stakeholders during the energy transition. These models can help to analyze and assess different configurations of the energy system in the future with respect to the share of electricity generated by renewable energy sources (RES), the extension of storage facilities or the development of thermal generation units. Hence, possible risks and miscalculations can be recognized at an early stage.

On the other hand, houses are increasingly being equipped with photovoltaic systems (PVs). Their fluctuating power generation has a great influence on the previously central power supply. To mitigate the problems, houses can be equipped with batteries which can be used to maximize the internal consumption of the generated renewable energy. But the current research also deals with how these batteries can be used to generate a benefit for the home owner and the power grid.

Here, however, the question arises if the use of these batteries is still possible if not only individual households are equipped with batteries, but a large number of

households. With a surplus of PV energy in the households and the power grid, we probably can assume that the batteries are already fully charged and can't provide the necessary control power for the grid. To analyze such problems, we present a hierarchical simulation of the German energy system coupled with a large number of houses with PV and storage systems.

The simulation model of the German energy system consists of the most relevant parts of this system on a high level. Components for the electricity demand, the electricity generated by renewable energy sources (wind, photovoltaic, hydro power, biomass), thermal generation units, and storage facilities are integrated. The electricity demand, as well as the renewable energy feed-in, is based on a stochastic model. Due to restrictions in the transmission grid and differences between the forecasted and real residual load, provision of control power is needed and provided by some of the thermal generation plants and the storage facilities.

Due to the growing number of homes with photovoltaic and battery storage systems, the batteries can also be used for the provision of control power. The simulation model of hundreds of homes with photovoltaics and batteries models the electricity demand and PV power generation of each home and the corresponding state of charge of the battery. A surplus of energy - after calculating the internal balance of electricity generation and demand - is stored at the battery if possible, a shortage of energy is compensated by discharging the battery. A remaining imbalance is compensated by the power grid. After the coupling with the German energy system model, the houses also provide control power, reducing the amount of control power generated by some of the thermal generation plants and the storage facilities. The two coupled hierarchical simulation models are then used to study different scenarios regarding the extension of renewable energy sources in Bavaria. The case studies show the amount of control power that will be provided by the houses with battery storage systems. In addition, the impacts on the electricity costs per year for a house are shown.

2 Related Work

This paper presents the coupling of a micro-scale smart grid simulation approach for homes equipped with PVs and batteries with a macro-scale electrical system simulation of the German energy system. Established model coupling approaches focus on coupling different system areas. In [1] an economic energy market model is used in combination with an electricity grid simulation. There are considered restrictions for power plants, storages and RES as well as network constraints. Another approach is presented in [2], where real-time pricing is given as an example of combining economical and technical aspects within one simulation model. A tool for controlling the data-flow between different simulators and simulations of combined models and control strategies is the mosaik platform [3] for complex simulation models of energy systems and smart grids.

Another way of doing simulations of cross-domain specific problems is to embed detailed models (e.g. of batteries like in [4]) into given simulation frameworks. Furthermore, different simulation frameworks can be used in order to solve specific problems (e.g. energy management, grid simulation). For smart energy systems, the

co-simulation of the energy system and the ICT layer can be carried out in order to improve and test control strategies, like it is done in [5]. There is presented the coupling of continuous simulation of power systems and discrete event based simulation of communication in combination with automation and control systems.

Basically, there are many publications in the field of modeling energy systems, which are relevant to the subject of this paper. In Connolly et al. [6] an overview of 37 energy system models is given. The models can be used to analyze the integration of electricity generated by renewable energy sources. The energy models can be differentiated by their applied methodology (simulation, optimization, etc.), geographical area (local, national, worldwide), scenario timeframe (one year, more years, no limit), and time-step (minutes, hourly, yearly). The authors came to the conclusion that there is no energy model available which addresses all issues related to integrating renewable energy. Generally, the applied methodology, geographical area, scenario timeframe and time-step depend on the issue which will be answered with the energy system model (see also [7]). For example, if we are interested in determining an optimal capacity expansion plan for renewable energy sources with respect to economic constraints, than we usually use an optimization framework; if we are interested in comparing different framework conditions and their impacts on the energy system, than we use a simulation-based energy model. In [8] for the strategic energy system planning a hybrid modeling concept is derived. The short-term fluctuations are analyzed in a simulation model, whereas the long-term development of the energy system is assessed in an optimization model. The developed simulation model has a high temporal resolution on shorter time scale and can be used to simulate the power plant dispatch over a maximum of one year on a national geographical area.

3 Simulation Frameworks and Coupling

In this section we describe the two used simulation frameworks and their coupling. The first simulation framework models the German energy system. The second framework is for the construction of smart energy grids.

3.1 Simulation Framework for the German Energy System

The simulation framework for the German electrical energy system is a comprehensive energy system model with a focus on the federal state Bavaria. Components for the electricity demand, the electricity generated by renewable energy sources (wind, photovoltaic, hydro power, biomass), thermal generation units, and storage facilities are integrated. The modeling of these components is described in various publications [9–11]. For instance, in [10] the modeling of the electricity demand is explained. For the demand modeling it contains a stochastic model based on the published load profiles from the ENTSO-E (European Network of Transmission System Operators for Electricity). In [11] the modeling of the feed-in of highly fluctuating photovoltaic systems and wind energy plants can be found. For the modeling of the feed-in of photovoltaic and wind energy plants a stochastic model based on official data provided

by the German transmission system operators 50Hz, Amprion, TenneT, and Trans-netBW is included.

A basic overview of the most relevant input and output parameters for the simulation framework is depicted in Fig. 1. Apart from the demand profiles and the feed-in structure of different renewable energy sources, a comprehensive set of input parameters to control the behavior of different components and the interaction between them is available.
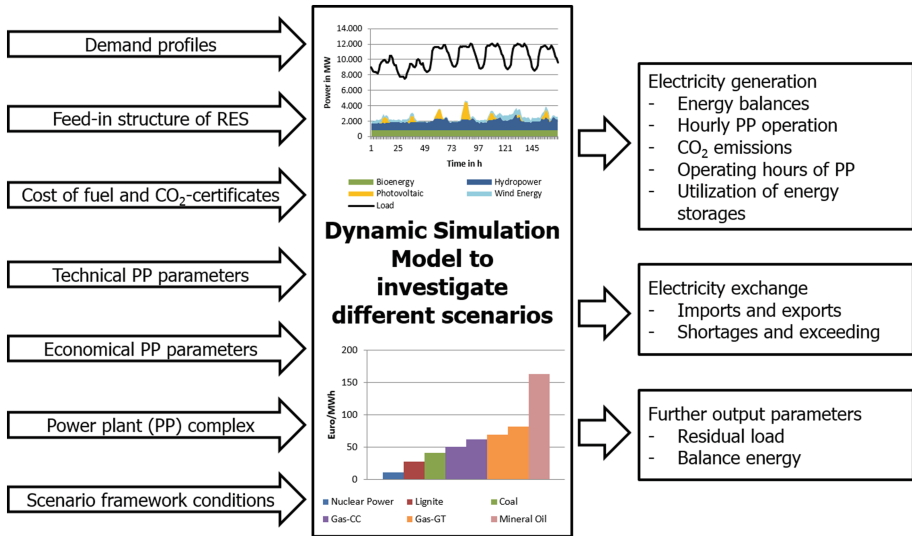
Fig. 1. Input and output parameters for the simulation framework

On the right side of Fig. 1 the output parameters are shown. In order to investigate the balance energy, forecasts for the feed-in of wind energy plants and photovoltaic systems as well as for the electricity demand are implemented. The framework is based on the commercial simulation tool AnyLogic 7 [12], which is written in JAVA. The investigated geographical area is limited to Germany and Austria.

In order to consider transmission grid restrictions between the different regions of Germany, a multipoint modelling approach is used. The geographical area and the division in different points are depicted in Fig. 2. Due to differences between the forecasted and real residual load, the provision of control power is also taken into account. Currently, control power can be provided by electricity storage facilities and thermal generation units. If the model is coupled with the simulation framework for houses, the control power is at first provided by the houses' batteries. If more electricity is generated than needed, the surplus is stored in the houses' batteries, the electricity storage facilities, or the generation of thermal generation is down-regulated. Conversely, if the real residual load is higher than the forecasted one, positive control power is needed. In this case first the houses' batteries are discharged, then the electricity storage facilities are discharged, or the thermal generation units can be started to
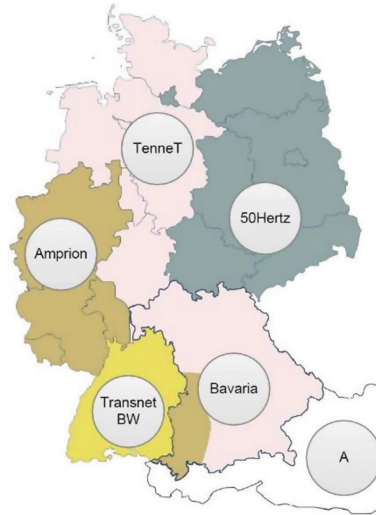
Fig. 2. Considered geographical area and division in different points

provide positive control power. Finally, the electricity demand and electricity generation should be in balance.

3.2   Simulation Framework for Houses with PV and Storage Systems

The simulation framework i7-AnyEnergy [13] is designed for the fast construction of smart grid energy system models with renewable energy sources and storage systems [14]. It is based upon the hybrid simulation tool AnyLogic 7 [12] and utilizes its state chart paradigm for control decisions and its system dynamics paradigm for energy and cost flows. From its build in components for energy demand, PV, battery, controller, and costs a house can be constructed (Fig. 3, left) using the interface/filter concept described in [13] for the coupling of components.

The strategy for the internal house controller without a control power request from the German energy system simulation is to first use the energy from the PV for the internal demand. A remaining surplus charges the battery; a remaining demand discharges the internal battery. If the battery can't be charged or discharged because of its state of charge or restrictions in the charging/discharging power, the remaining electricity is bought from or sold to the power grid. This strategy maximizes the internal consumption of the energy from the PV.

On the other hand, with a request of control power from the German energy system simulation at first the internal balance of the energy from the PV, the internal demand, and the requested control power is computed. Again a remaining surplus charges the battery; a remaining demand discharges the internal battery. If the remaining charging/discharging power of the battery is less than required, it is at first used for the residual power of the internal demand and PV balance. Only from this balance
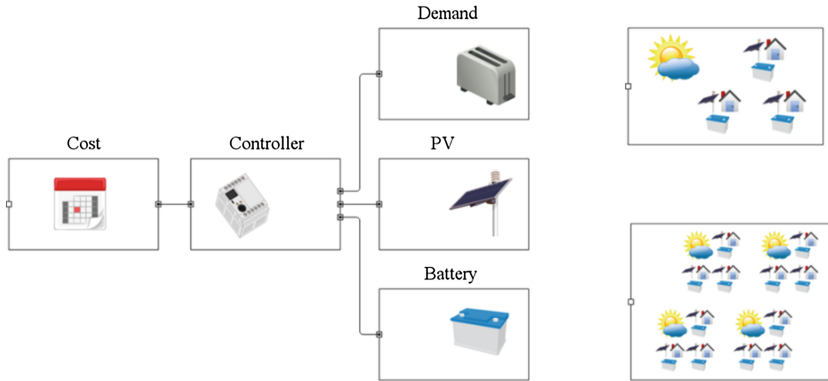
Fig. 3. Components of the simulation framework i7-AnyEnergy: a house with PV and battery (left), local region with one hundred houses with one weather model for the solar irradiation (right top), four local regions (right bottom)

remaining electricity is bought from or sold to the power grid. The control power that can't be used or charged/discharged internally can't be bought or sold, of course.

A group of one hundred houses is connected to a weather model for the solar irradiation (Fig. 3, right top). For the simulation of four different solar irradiations for houses in four different regions, the four groups of houses are equipped with different weather models (Fig. 3, right bottom).

3.3   Model Coupling

The simulator i7-AnyEnergy and the simulation framework for the German electrical energy system are coupled in order to investigate the provision control power by charging or discharging the houses' batteries. The two simulation models are implemented with AnyLogic and can therefore be combined as two components of a superordinate simulation model (Fig. 4) using the interface/filter concept described in [13].

The component *Write* is responsible for writing the results to disk and the component *Graph* for displaying intermediate results during the runtime. The component *Experiment* contains the parameters for different simulation runs, e.g., different battery capacities or PV peak powers. The System Dynamics component *Controller* interconnects and synchronizes the two models *Germany energy system* and *Houses with PV and battery*. The *Controller* scales the simulation values of the 400 houses up to 200,000 houses and connects them to the model of the federal state of Bavaria. The 200,000 houses correspond to 25 % of about 800,000 households with four or more persons in Bavaria.

The details of the component *Controller* are shown in Fig. 5. The control power surplus of 20,982 kW in the Bavarian part of the German energy system (*e_net_balance*, calculated by *Germany energy system*) is scaled down to the 400 houses (*e_net_houses_bal*) of the house simulation model. The *Controller* askes the houses to
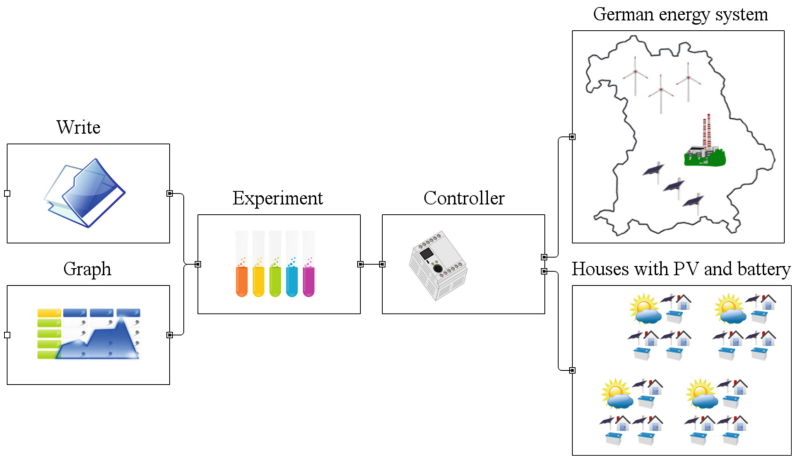
Fig. 4. Components of the hierarchical simulation model of renewable energy systems with storage

charge their combined batteries with 41.964 kW (*e_net_houses_r*) – the maximal combined charging power at the moment is 1600 kW – and the function *calc_e_net_houses_r* distributes the power among the houses according to their reported individual remaining charging/discharging power. The houses agree to charge their batteries with the requested power of 41.964 kW (*e_net_houses_a*, calculated by
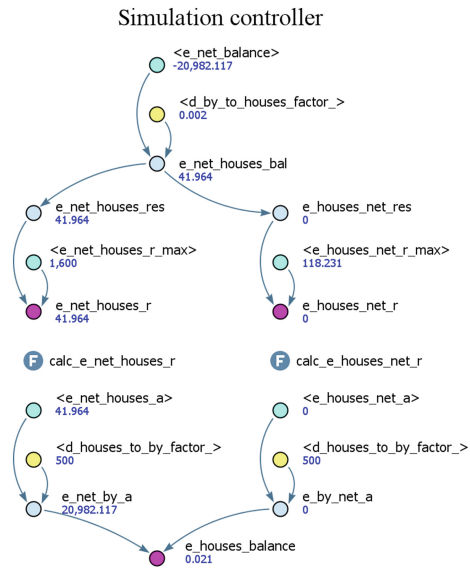
Fig. 5. The System Dynamics model of the component *Controller* coupling the German energy system simulation and the simulation of the houses with PVs and batteries

Houses with PV and battery). This value is scaled up to 200,000 houses (20,982 kW for *e_net_by_a*) and converted to GW (*e_houses_balance*) for the *Germany energy system* component.

For this snapshot the whole control power surplus of the energy system can be compensated by the houses; no control power has to be provided by electricity storage facilities or thermal generation units of the component *Germany energy system*.

4   Hierarchical Simulation of the Coupled Models

The described hierarchical simulation model is used for the analyses of different scenarios. After the definition of the parameters, simulation results for the energy costs for a house and the fractions of delivered control power with respect to the German energy model's requests of control power are given.

4.1   Basic Assumptions

In order to investigate the impact of many battery storages in households on a larger scale, we have to define some basic assumptions for the year 2023. The year 2023 is the first year in Germany without nuclear energy. The framework conditions for Germany without Bavaria can be found in [15]. The scenario framework of the German Netzentwicklungsplan [15] also provides a list of thermal generation units which are in service in 2023. For Bavaria itself we define three different configurations of the installed power for wind energy plants, photovoltaic systems, biomass-fired plants, hydro power plants and geothermal power plants which are shown in Table 1.

Table 1. Different configurations for the extension of renewable energy sources in Bavaria

	Total installed power in the year 2023 (in MW)				
	Hydro power	Photovoltaic systems	Wind power plants	Biomass-fired plants	Geothermal power plants
2013 (ref.)	2,900	10,562	1,125	1,171	22
Pessimistic	2,900	13,444	2,521	1,245	300
Realistic	2,900	15,489	5,029	1,456	300
Optimistic	2,900	22,105	6,559	1,838	300

The pessimistic and the optimistic scenarios are used for the simulation runs and each scenario is combined with different scenarios for the households (Table 2). The row *Reserved* gives the state of charge of the battery in percent that is reserved for the power grid. A house can't use the energy stored in the battery for its own demand if the state of charge is lower than the reserved state of charge. The costs of energy from the power grid is 0.29 €/kWh. The PV feed in tariff for PV energy exported to the grid is 0.125 €/kWh. The costs regarding to energy charged or discharged because of balancing power are set to 0 €/kWh. Therefore the energy costs of a house after one

Table 2. Configurations for the maximal charging and discharging power, the capacity of the battery, the reserved capacity for the purpose of power compensation, and the peak power of the PV of a house

| Battery	Dis-/Charge [kW]	8				12			
	Capacity [kWh]	10				20			
	Reserved [%]	0	25	50	75	0	25	50	75
PV	Peak power [kW]	3				6			

year with respect to the costs of a house that doesn't provide control power reflect the costs of providing control power.

4.2   Simulation Results

The hierarchical model was simulated with the previous described 24 different parameter sets over a period of one year. The electricity energy costs for one house are given in Fig. 6. If the house is equipped with a 10 kWh battery, a 3 kW PV, and no
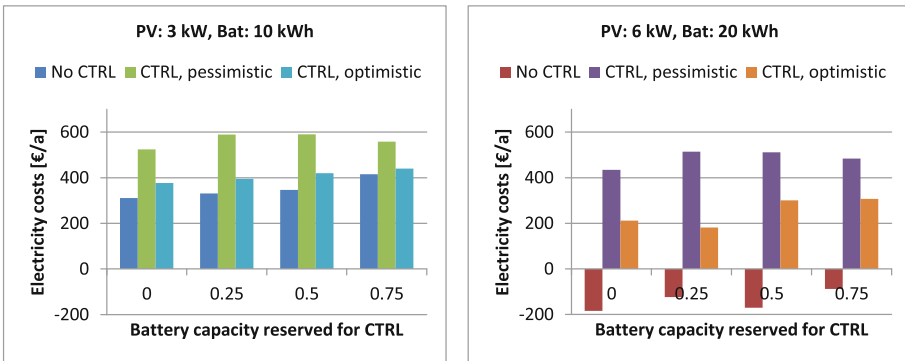

**Fig. 6.** Mean electricity costs per year for a house with respect to different scenarios
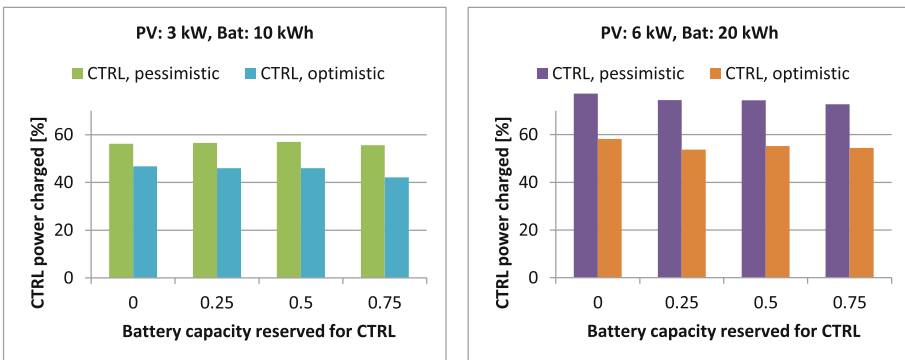
Fig. 7. Fraction of the requested negative control power charged into the batteries

battery capacity is reserved, the costs increase by approximately 200 €/a in the case of the pessimistic scenario and by approximately 70 €/a in the case of the optimistic scenario with respect to the case where no control power is provided. If the house is
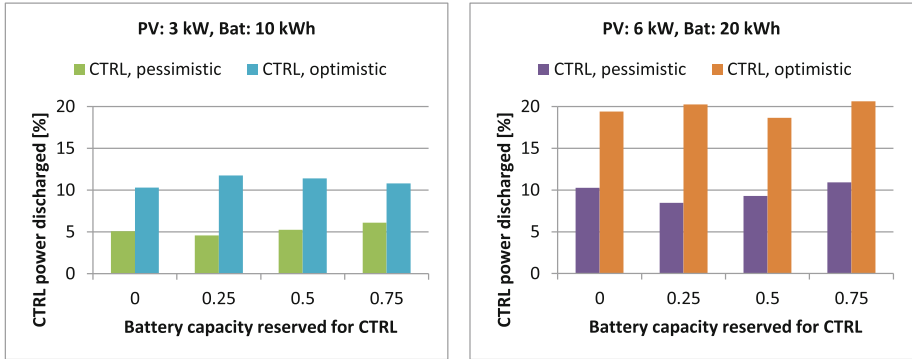
Fig. 8. Fraction of the requested positive control power discharged from the batteries
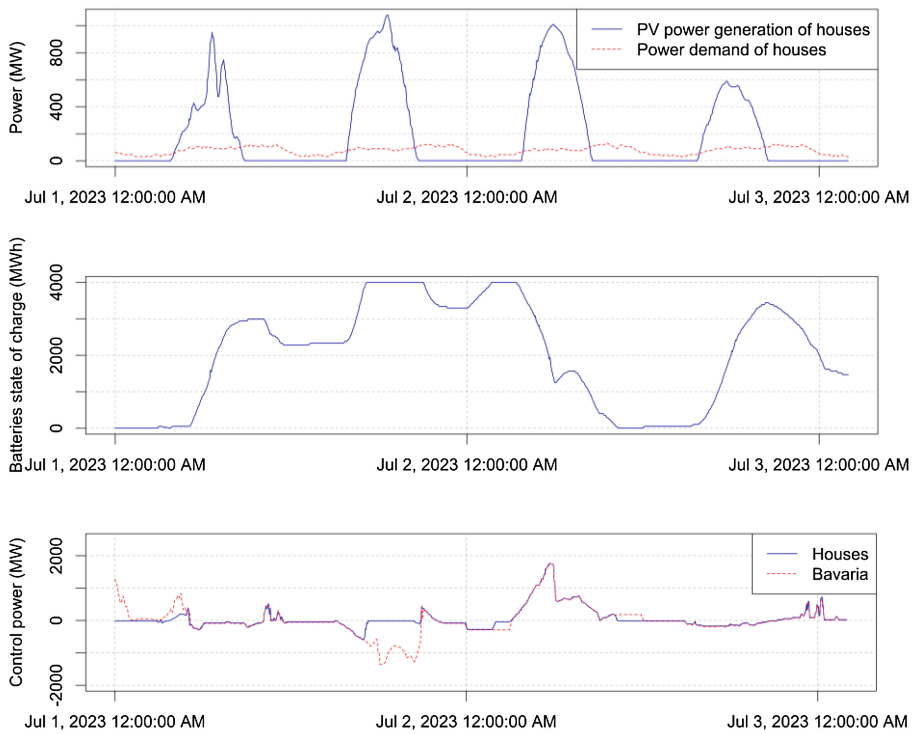
Fig. 9. The Graph component containing plots of the power demand and PV power generation of 200,000 houses, their combined state of charge of the batteries, and the needed control power of Bavaria and provided control power of the houses

equipped with a 20 kWh battery, a 6 kW PV, and no battery capacity is reserved, the costs increase by approximately 620 €/a in the case of the pessimistic scenario and by approximately 400 €/a in the case of the optimistic scenario with respect to the case where no control power is provided.

The fraction of control power charged/discharged with respect to the requested control power increases with a larger battery and PV (Figs. 7, 8). In general a higher fraction of the requested negative control power can be charged into the batteries than positive control power can be discharged. The reserved battery capacity has only a minor influence on these values but increases the costs.

Some intermediate results during the runtime like the power demand of the 200,000 houses, the PV power generation, and the state of charge of the batteries are shown in Fig. 9. The graph *Bavaria* shows the control power needed in Bavaria and the graph *Houses* the control power provided by the houses.

5   Conclusion

The described simulation model of the German energy system and the simulation model of 400 houses with PV and batteries scaled up to 200,000 houses have been coupled forming a hierarchical simulation model. The German energy system model calculates the control power needed in the federal state of Bavaria due to differences between the forecasted and real residual load and restrictions in the transmission grid. The batteries of the houses are used to fulfill the demand of positive or negative control power. With such a coupled hierarchical model, the mutual interference of the two models and their strategies can be simulated. The combined simulation model was used for different experiments, which should answer the question of whether control power can be provided and at what cost. It was shown that the costs depend on the size of the battery and PV, and that more negative than positive control power can be provided.

References

1. Raths, S.: Multi level european electricity market simulation using network flow algorithm and lagrangian relaxation. In: OR2013 Conference: International Conference on Operations Research, Rotterdam (2013)
2. Fuller, J.: Transactive modeling and simulation capabilities. In: NIST Transactive Energy Challenge Preparatory Workshop, Gaithersburg, MD (2015)
3. Rohjans, S., Lehnhoff, S., Schütte, S., Scherfke, S., Hussain, S.: mosaik - a modular platform for the evaluation of agent-based smart grid control. In: 4th IEEE PES Innovative Smart Grid Technologies Europe (ISGT Europe), Copenhagen (2013)

4. Palensky, P., Widl, E., Stifter, M., Elsheikh, A.: Modeling intelligent energy systems: co-simulation platform for validating flexible-demand EV charging management. IEEE Trans. Smart Grid **4**(4), 1939–1947 (2013)
5. Stifter, M., Kazmi, J.H., Andrén, F., Strasser, T.: Co-simulation of power systems, communication and controls. In: 2014 Workshop on Modeling and Simulation of Cyber-Physical Energy Systems (MSCPES), pp. 1–6, Berlin (2014)
6. Connolly, D., Lund, H., Mathiesen, B.V., Leahy, M.: A review of computer tools for analyzing the integration of renewable energy into various energy systems. Appl. Energy **87**(4), 1059–1082 (2010)
7. Möst, D., Fichtner, W.: Einführung zur Energiesystemanalyse. In: Möst, D., Fichtner, W., Grundwald, A.: Energiesystemanalyse, pp. 11–31. Universitäts-Verlag Karlsruhe (2009)
8. Rosen, J.: The future role of renewable energy sources in European electricity supply: A model-based analysis for the EU-15, Universitäts-Verlag Karlsruhe (2008)
9. Pruckner, M., German, R.: A hybrid simulation model for large-scaled electricity generation systems. In: Pasupathy, R., Kim, S.H., Tolk, A., Hill, R., Kuhl, M.E.: Proceedings of the 2013 Winter Simulation Conference, pp. 1881–1892. Washington, D.C. (2013)
10. Pruckner, M., Eckhoff, D., German, R.: Modeling country-scale electricity demand profiles. In: Tolk, A., Diallo, S.Y., Ryzhov, I.O., Yilmaz, L., Buckley, S., Miller, J.A.: Proceedings of the 2014 Winter Simulation Conference, pp. 1084–1095. Savannah, GA (2014)
11. Pruckner, M., German, R.: Modeling and simulation of electricity by renewable energy sources for complex energy systems. In: Proceedings of the 47th Annual Simulation Symposium (ANSS 2014), pp. 1–9, Tampa, FL (2014)
12. AnyLogic 7. http://www.anylogic.com
13. Bazan, P., German, R.: Hybrid simulation framework for renewable energy generation and storage grids. In: Proceedings of the International Workshop on Demand Modeling and Quantitative Analysis of Future Generation Energy Networks and Energy Efficient Systems, Bamberg (2014)
14. Bazan, P, Luchscheider, P., German, R.: Rapid modeling and simulation of hybrid energy networks. In: Proceedings of the 2015 SmartER Europe Conference, Essen (2015)
15. 50Hertz Transmission GmbH, Amprion GmbH, TenneT TSO GmbH, TransnetBW GmbH: Szenariorahmen für die Netzentwicklungspläne 2015 – Entwurf der Übertragungsnetz betreiber (2014)