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Diffusion and system impact of residential battery storage under different regulatory settings

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ABSTRACT

Cost reductions of rooftop photovoltaics and battery storage, increasing retail electricity prices as well as falling feed-in remuneration provide strong incentives for many German households to engage in self-consumption. These developments may also affect the electricity system as a whole. Against this background, we jointly apply a prosumer simulation and an agent-based electricity market simulation in order to investigate the long-term impacts of a residential battery storage diffusion on the electricity market. We analyze different regulatory frameworks and find significant effects on the household level, yet only moderate system impacts. In the long run, the diffusion of residential battery storage seems difficult to govern, even under a restrictive regulation. In contrast, the way the batteries are operated may be easier to regulate. Policymakers and regulators should focus on this aspect, since a system-friendly battery operation supports the system integration of residential photovoltaics while having little impact on the households' self-sufficiency.

1. Introduction

Since the introduction of the Renewable Energies Act in 2000, more than 1.8 million photovoltaic (PV) systems with a nominal capacity of 49 GW_p have been installed in Germany (Bundesverband Solarwirtschaft, 2020c), including more than 1 million small-scale rooftop systems with 6.4 GW_p (50Hertz et al., 2019a). These high installation rates have led to drastic cost decreases for electricity generated by rooftop PV systems (Kost et al., 2018). At the same time, the retail electricity prices faced by German households have followed an upward trend in the past years (Bundesverband der Energie- und Wasserwirtschaft, 2020). As a consequence, *grid parity* has been reached in Germany around 2012, meaning that the cost of self-produced electricity from PV systems has fallen below the retail electricity prices. The politically driven reduction of PV feed-in remuneration – as a reaction to the falling generation cost – further increases the attractiveness of self-consumption (Wirth, 2020).

Moreover, prices for lithium-ion batteries have decreased by more than 50% since 2013 and continue to decline. Consequently, in the past years, about every second new small-scale PV system in Germany has been equipped with a battery storage in order to increase self-consumption. As of today, more than 180000 battery systems have already been installed (Bundesverband Solarwirtschaft, 2020b). In contrast, most PV systems installed before 2012 feed large shares of their electricity into the grid. However, feed-in tariffs under the Renewable Energies Act are only granted for 20 years after installation. Thus, starting from 2020, the first of these systems will not receive such remuneration anymore. Since retrofitting the existing PV systems with battery storage is often profitable, this will most likely lead to additional battery installations (Fett et al., 2018). However, despite the potentially significant impacts on the electricity market, literature investigating the long-term impacts of residential battery storage diffusion is still scarce.

Against this background, we propose a novel modeling framework consisting of a prosumer simulation and an agent-based electricity market simulation, which is applied to Germany and its neighboring countries. In contrast to most of the existing literature, the prosumer simulation includes a calibrated diffusion model in order to account for certain non-financial drivers of households' investment decisions. The developed methodology allows us to analyze transformation pathways in great detail while accounting for the respective actors' (households and utilities) perspectives and their mutual influence. A particular emphasis is put on the regulatory framework. We simulate the status quo of the German regulation for self-consumption, a more system-friendly operational strategy, and a restrictive regulation comprising fixed grid

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charges as well as a self-consumption charge. Following this procedure, we are able to quantify long-term impacts of residential battery storage in a realistic and complex real-world setting. This enables us to provide policy advice regarding an adequate regulatory framework for self-consumption.

The remainder of this paper is structured as follows. In Section 2, we briefly review the relevant literature on residential battery storage and derive the research gap our paper aims to fill. Section 3 introduces the proposed simulation framework including the required input data. In Section 4, we provide an overview of the investigated scenarios and discuss the results of our simulations. Section 5 discusses limitations of the study. Finally, we summarize our findings, draw conclusions and derive policy implications in Section 6.

2. Literature review and research gap

Given the scope of our work, the following literature review explicitly focuses on quantitative studies that investigate the system impact of residential battery storage. In contrast, we do not delve into the large body of literature taking a pure household perspective (e.g., Bertsch et al., 2017; Fluri, 2019; Kaschub et al., 2016; Klingler, 2017; Schopfer et al., 2018). Although the research interest in system impacts of residential battery storage has grown over the past years, literature that simultaneously considers the household and the utility perspective is still scarce and neglects certain important aspects.

Jägemann et al. (2013) analyze the impact of the current regulatory framework in Germany on investments in residential battery storage and ultimately, the system impact of these storage units. The authors use two different optimization models, which are iteratively applied until convergence has been reached. In the first model, several sample households minimize their electricity cost by carrying out investments in optimally sized photovoltaic and battery storage systems. The second model takes the households' decisions into account and minimizes the cost of the electricity system by deciding on investments in large-scale generation technologies and optimally operating these units. The resulting electricity prices are in turn an input to the household optimization model. Despite the proximity to our concept, two important aspects are not considered by Jägemann et al. (2013). Firstly, all households are assumed to invest as soon as a battery storage system becomes profitable. However, a lack of information and uncertainty about PV battery storage and its costs – as well as other non-financial drivers – have an essential impact on households' investment decisions. This needs to be considered, e.g., by applying a diffusion model. Secondly, different operational strategies of the battery storage systems are not taken into account, but a maximization of self-consumption is assumed as the sole goal of each household. These two aspects are likely to lead to a substantial overestimation of the amount of battery storage being installed and are therefore crucial.

Say et al. (2019) apply a bottom-up simulation model to estimate investments in residential battery storage and analyze their impact on the electricity system. Their case study relies on demand and photovoltaic electricity generation time series of 261 real households in Australia. Using different feed-in tariff schemes, Say et al. first determine optimally sized photovoltaic and battery storage system investments for the different households. The resulting changes in the residual demand of all households are then aggregated to estimate impacts on the network and the retailer revenues. In a subsequent study, the methodological approach is extended by coupling the household simulation model with an optimization model of the Western Australian electricity system (Say et al., 2020). Like this, the authors are able to analyze the system impacts of large amounts of residential battery storage. However, the system optimization model is only applied for a single future year (2030). Consequently, the transformation pathway of the system cannot be investigated and the residential electricity prices need to be defined exogenously rather than being derived from simulated wholesale prices. Moreover, also the work by Say et al. (2019, 2020) neither applies a diffusion model nor considers different operational strategies.

Klingler et al. (2019) investigate the diffusion of residential battery storage in the EU countries, Norway and Switzerland. For this purpose, they apply the electricity system optimization model ELTRAMOD to derive wholesale electricity prices and then determine optimally sized battery storages for an average household per country. Finally, the authors use a diffusion model to estimate the total installed battery capacities for all countries. Also in this study, the impact of different operational strategies for the batteries is not analyzed. Moreover, ELTRAMOD is only used to provide wholesale electricity prices, rather than to evaluate system effects of residential battery storages.

Schwarz et al. (2019) use an agent-based model to analyze the diffusion and system impacts of residential battery storages in California under different policy scenarios. Their approach consists of three modules. Firstly, future wholesale electricity prices are forecasted based on a simple linear regression model. Secondly, these prices are converted to retail electricity prices. Thirdly, several sample households decide on a potential adoption of a photovoltaic and battery storage system. Much like in the studies mentioned above, the authors do not account for non-financial drivers of the households' investment decisions. Moreover, the module depicting the Californian wholesale market is strongly simplified and is therefore not able to properly account for long-term market dynamics.

Yu (2018) investigates systemic effects of residential battery storages in France. For this purpose, levelized costs of electricity generation for a photovoltaic and battery storage system are estimated. Subsequently, changes in the French residual load duration curve are calculated if all detached houses in France were to use such a system. The study by Yu makes some strong simplifications. Firstly, only one generic household is considered, although the diversity of household load profiles and solar profiles plays a crucial role. Secondly, no diffusion model is used, but all households are assumed to invest directly. Thirdly, the impact of different operational strategies and changes in the regulatory framework are neglected. Fourthly, France is considered as an isolated system without electricity exchange and pumped storage units. This is a particularly critical assumption given the strongly interconnected European electricity system. In consequence, the system impacts of residential battery storages in France are likely to be heavily overestimated.

In summary, our article complements the existing literature in a number of important aspects. We propose a novel modeling framework consisting of a prosumer simulation and an agent-based electricity market simulation. As previously described, most of the related literature only includes rudimental (if any) representations of the wholesale electricity market. In contrast, our agent-based approach allows to investigate transformation pathways in great detail while accounting for the respective actors' (households and utilities) perspectives and their mutual influence. Apart from the work of Jägemann et al. (2013), the proposed approach is the only in the literature to consider bidirectional dependencies between the different decision parties involved. Moreover, existing studies typically neither apply diffusion models nor consider alternative operational strategies for the batteries. In consequence, the system impacts of residential battery storage are likely to be substantially overestimated. This is sometimes further intensified by the use of standard load profiles which neglects the crucial role of diversity in terms of household load profiles and solar profiles. Our paper addresses the risk of overestimation by using a diffusion model, considering different operational strategies, and relying on empirically measured household load profiles. For the described reasons, the novel approach presented in the following is very well suited to capture dynamic long-term impacts of residential battery storage diffusion in Germany under different regulatory settings.

3. Methodology and data

3.1. Overview of the simulation framework

In order to capture both, the household and the utility perspective, we apply a novel modeling framework comprising a prosumer simulation and an agent-based electricity market simulation (Fig. 1). In both models, an individual actor's perspective is taken. The decisions of the household agents affect those of the utility agents (via changes in the residual load curves) and vice versa (via changes in the wholesale electricity prices). Thus, household agents and utility agents iteratively adjust their decisions until convergence has been reached[1]. In Section 3.2, we present more details on the prosumer simulation, while Section 3.3 introduces the agent-based electricity market model PowerACE.

3.2. Prosumer simulation

3.2.1. Investment decisions

Similarly as Say et al. (2020), we use empirically measured household load profiles and consider them as representative for the total household electricity consumption. This approach allows to account for the diversity of households' load curves and avoid biases that result from aggregated or synthesized data (Quoilin et al., 2016; Schopfer et al., 2018; Fett et al., 2019).

The prosumer investment module assumes economically rational behavior of the households and a fixed investment horizon of 20 years (the period of the guaranteed feed-in tariff for PV installations in Germany). Net present values (NPVs) are determined for every combination of PV system size[2] (0–10 kW_p with step size 0.5 kW_p) and battery size (0–10 kWh with step size 0.5 kWh) as well as for each sample household. For this purpose, the total costs including investment, expenditures for electricity, and income from PV feed-in remuneration are calculated and compared to the costs under the benchmark *no investment* case. These calculations require to simulate the battery operation for each system configuration and sample household (see Section 3.2.2).[3] Additional model inputs are wholesale electricity prices from the electricity market simulation (Section 3.3), projections of the different components of the retail electricity price, and forecasts for PV and battery installation costs.[4] Households assume a constant PV feed-in remuneration and an electricity price that increases by 2% per year, both based on their installation year. These model inputs are summarized in Table 1. Finally, for each sample household, if profitable investments exist, the system configuration with the highest NPV is chosen. The described process is also performed for existing PV systems to consider the retrofit of battery storage systems after the expiry of the guaranteed 20-year feed-in tariffs. It is assumed that the PV system has a remaining lifetime of 15 years if the inverter is replaced.

Since we are interested in the transformation pathway, the investment module is run for each simulation year. In contrast to most of the related literature (see Section 2), we also consider certain non-financial drivers of households' investment decisions by combining the results of the investment module with a diffusion model (Section 3.2.3). Following this procedure, we finally obtain the additional PV feed-in and self-consumption, which are used to compute the self-reinforcing effect on the different charges and levies. This effect occurs because the increased feed-in has to be remunerated through the renewable energy levy, while at the same time, the grid consumption – to which the charges and levies are allocated – is reduced by the self-consumed electricity volume (for more details, see Fett et al., 2019).

3.2.2. Operational strategies

Under the current regulatory framework and retail electricity tariffs, German households are neither exposed to dynamic prices nor to dynamic remuneration for excess electricity fed into the grid. Consequently, as of today, residential battery storage systems are most commonly operated with the sole objective of maximizing self-consumption (Klingler, 2017). This is reflected in our reference operational strategy (later referred to as *default*) that works as follows. The PV generation is first used to cover the household's electricity demand. Excess PV generation charges the battery or – if the battery is already fully charged – is fed into the grid. Contrary, if the household's electricity demand exceeds the current PV generation, the battery supplies electricity to the household until it is fully discharged. Demand not covered by PV generation and battery discharging is supplied by the electricity grid. No exchange between battery and the grid is allowed.

Alternatively, households could also use a forecast-based operational strategy and thereby potentially relieve the grid (Dehler et al., 2017; Deutsch and Graichen, 2015). We therefore additionally implement the so-called *dynamic feed-in limitation* (later referred to as *dynamic*) as proposed by Bergner et al. (2014). The aim of this operational strategy is to lower the peak PV feed-in as far as possible while keeping the impact on self-sufficiency at a minimum. This is achieved by shifting the battery charging to the hours with the highest PV generation around noon, rather than charging the battery directly as soon as a PV surplus occurs. Thus, in the dynamic strategy, the behavior for supplying the household's electricity demand stays the same, only the charging behavior of the battery is controlled differently. The battery is only charged if the excess PV generation is above a virtual feed-in limit. In contrast, PV generation below the virtual feed-in limit is self-consumed or – if the household load is not high enough – fed into the grid. The virtual limit is determined such that considering the current state of charge, the expected PV generation and household demand, the battery would be fully charged by the end of the day. For a formal description of the algorithm, please refer to the original article by Bergner et al. (2014). Since we assume perfect foresight for the PV and load forecast, households can maintain the same self-sufficiency rates under the *dynamic* strategy as compared to the *default* strategy. Thus, households can be considered indifferent with respect to the operational strategy. For this reason, the investment decisions (Section 3.2.1) are always based on the *default* strategy.

3.2.3. Diffusion model

Due to non-financial aspects, e.g., a lack of information and uncertainty about PV battery storage and its costs, only a small portion of the economic potential of residential battery storage is realized (Steinbach, 2015). This is often neglected in the literature, leading to an overestimation of the diffusion numbers and the impact of residential battery storage (see Section 2). To address this shortcoming, we use a Bass diffusion model (Bass, 1969) to estimate the number of potential adopters for PV battery storage systems. The model formulation is shown in Eq. (1), where $N(t)$ denotes the cumulative number of (potential) adopters for PV battery storage systems up to time t. In a Bass model, the process of technology adaption is explained by innovation effects (represented by the coefficient of innovators p) and imitation

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[1] In a similar fashion as Jägemann et al. (2013), we use the deviation of the cumulative yearly residential PV and battery storage capacities between two iterations as the criterion for convergence. For our simulations, we define convergence as a deviation below 2%. In all scenarios under investigation, one iteration is sufficient to fulfill this criterion.

[2] The size limit is chosen because prosumers with PV systems above 10 kW_p receive a lower feed-in remuneration (Bundesverband Solarwirtschaft, 2020a) and have to pay the self-consumption charge of 40% of the renewable energy levy (§ 61a EEG 2017).

[3] Please note that since the household load profiles and the insolation profiles are assumed to remain unchanged throughout the simulation period, the battery operation only needs to be calculated once for each system configuration and sample household. Two matrices containing self-consumption and self-sufficiency rates can then be determined and re-used in each simulation year.

[4] Specific investments in PV and storage systems are assumed to be size-independent, which leads to a slight underestimation of system sizes (Dietrich and Weber, 2018).

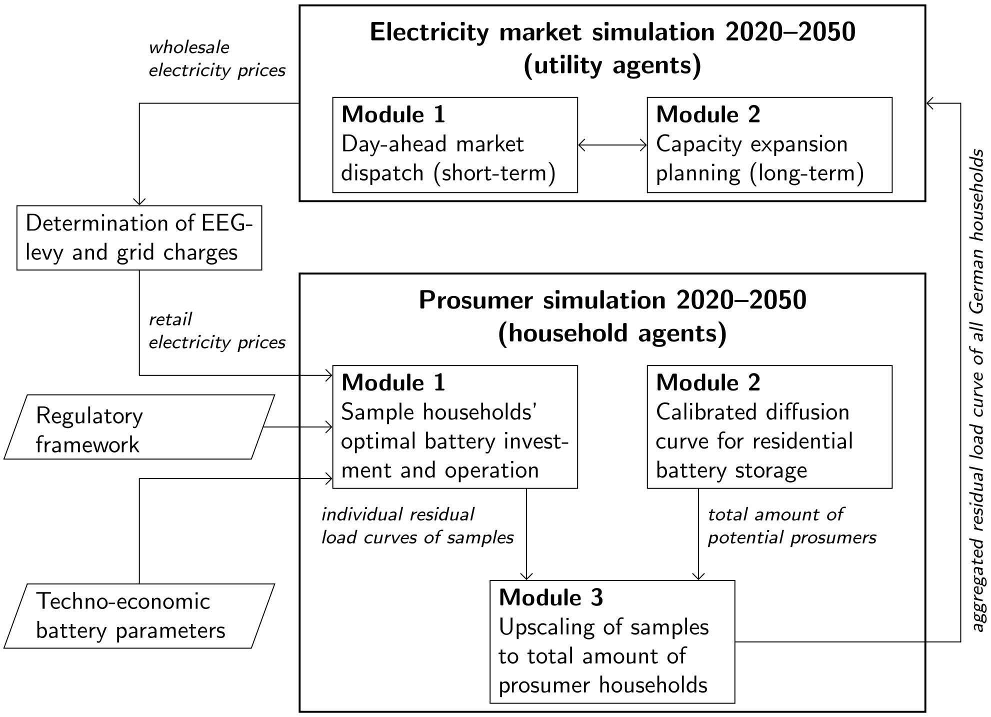

Fig. 1. Overview of the applied simulation framework. In the prosumer simulation, several agents representing sample households decide on optimal battery sizes and their operation. Using a calibrated diffusion model, the residual load curves of the individual households after battery operation are then scaled up to obtain an aggregated residual load curve of all German households. In the electricity market simulation, the utility agents react on the changes of the residential load curves and adjust their capacity expansion planning and day-ahead market dispatch accordingly. The resulting wholesale electricity prices serve as an input for the households' decisions to invest in battery storages. If required, the prosumer simulation and the electricity market simulation are run in multiple iterations until convergence has been reached.

effects (represented by the coefficient of imitators q). The total market size M is set to 11.15 million, which is the number of (semi-)detached houses that are inhabited by the owner[5] and have suitable roofs for PV systems (Prognos, 2016). In order to determine the parameters p and q, a nonlinear regression using the historical installations of small-scale PV systems (<10 kW$_\mathrm{p}$) in Germany is carried out.

$$N(t) = M\frac{1 - e^{-(p+q)(t-t_0)}}{1 + \frac{q}{p}e^{-(p+q)(t-t_0)}} \tag{1}$$

The Bass model provides projections for the number of potential adopters of PV battery storage in each simulation year. Since we approximate the real household load by the load profiles of 162 measured households (see above), the results for these sample households are then scaled up to the numbers of potential adopters. Whether the sample households invest in PV battery storage systems is determined in the investment module described in Section 3.2.1. In case that none of the investment options is profitable for a given load profile, the respective households are considered as potential adopters again in the subsequent simulation year.

In addition to potential adopters calculated using the Bass diffusion model, owners of existing PV systems (taken from 50Hertz et al., 2019a) whose feed-in tariffs ran out after 20 years are considered as potential adopters for battery storage systems. Moreover, households whose retrofitted systems reach the end of their lifetime, are also taken into account as additional potential adopters again.

3.3. *Electricity market simulation*

In order to investigate the system impacts of a large-scale diffusion of residential battery storage systems in Germany, we apply PowerACE, an established agent-based simulation model. Originally developed for long-term scenario analyses of the German electricity market, PowerACE has been substantially extended in the past years and now includes a representation of multiple interconnected market areas in Europe. The model has a long-term character with typical time horizons ranging from 2015 up to 2050. At the same time, the short-term perspective is modeled at a high temporal resolution of 8760 h/a.

In PowerACE, several agents represent the major market participants such as utility companies, consumers or regulators. As is typical for agent-based approaches, the different agents follow their own goals and the system behavior ultimately emerges from the individual actors' decisions. For example, the utility companies can decide on the daily operation of their conventional power plants and utility-scale storage units on the day-ahead market (short-term perspective) as well as on investments in new generation and utility-scale storage capacities (long-term perspective).

For the simulation of the day-ahead market, the utility companies in all market areas first create price forecasts in order to estimate the running hours of their generation fleet on the subsequent day (Fraunholz et al., 2021b). The respective agents then prepare hourly bids including both variable and start-up costs for each of their power plants. Moreover, price-inelastic bids for renewable feed-in, electricity demand and utility-scale storage units are created by a single trading agent per market area. Please note that the bids for both the electricity demand and the renewable feed-in include the impact of the residential battery storage systems. A central market operator collects the supply and demand bids from all market areas and matches them with the objective of maximizing social welfare subject to the limited interconnector capacities (Ringler et al., 2017). This step is a simplified representation of EUPHEMIA (NEMO Committee, 2019), the algorithm used for the real-world day-ahead market clearing process across multiple interconnected market areas. Finally, all utility companies determine their individual power plant dispatch based on the outcome of the market clearing. Please note that the model-endogenous representation of utility-scale storage operation and electricity exchange across market areas allows to account for potential balancing effects of these flexibility options, which are likely to reduce the system impact of residential battery storages.

Additionally to the day-ahead market simulation, the utility companies have the opportunity to invest in new generation and utility-scale storage capacity once per simulation year. For this purpose, the

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[5] Under German legislation, self-consumption is only possible if the consumer and the owner of the PV system are the same person.

Table 1
Overview of the input data used for the prosumer simulation.

Model parameter	Unit	Value	Sources
Model characteristics			
Empirical household profiles	#	162	Tjaden et al. (2015); Kaschub (2017)
Simulation time step	h	0.25	Kaschub et al. (2016)
Investment horizon	a	20 (new) 15 (retrofit)	Fett et al. (2018)
Yearly discount rate	%	4	Fett et al. (2019)
Photovoltaics			
Evaluation range	kW$_p$	0–10	Own assumption
Specific investment[a]	EUR/kW$_p$	1169–537	Ram et al. (2019)
Lifetime	a	20 (new) 15 (retrofit)	Fett et al. (2018)
Operation & maintenance cost	EUR/(kW$_p$ a)	24.26	Kaschub et al. (2016)
Specific annual yield	kWh/kW$_p$	1087	Kaschub (2017)
Battery storage			
Evaluation range	kWh	0–10	Own assumption
Energy-to-power ratio	kWh/kW	1	Kaschub et al. (2016)
Specific investment[a]	EUR/kWh	794–193	Ram et al. (2019)
Lifetime	a	20	Kaschub et al. (2016)
Round-trip efficiency	%	88	Fett et al. (2019)
Cost and remuneration of electricity			
Yearly increase of retail prices[b]	%	2	Fett et al. (2019)
Yearly decrease of feed-in tariff	%	1	Bundesverband Solarwirtschaft (2020a)
Renewable energy levy	EUR/kWh	time series	Öko-Institut and Agora Energiewende (2019)
Yearly increase of surcharges[c]	%	1	50Hertz et al. (2019b,c,d); Bundesverband der Energie- und Wasserwirtschaft (2020); Fluri (2019)

[a] Due to technological learning, the specific investments are assumed to decrease from 2020 to 2050.

[b] Expected by the household agents for the investment decision. The realized retail prices may differ.

[c] Only applicable for grid charges, CHP surcharge, §19 surcharge, and offshore wind surcharge. Other surcharges are assumed to remain constant.

Table 2
Overview of the input data used for the electricity market simulation with PowerACE. The table is based on a previous study (Fraunholz et al., 2021a) since we mostly make use of the same data sets.

Input data type	Resolution	Sources and comments
Conventional power plants	unit level	Bundesnetzagentur (2017) for Germany, S&P Global Platts (2015) for all other countries, and own assumptions
Fuel prices	yearly	EU Reference Scenario (de Vita et al., 2016)
Carbon prices	yearly	EU Reference Scenario (de Vita et al., 2016), scaled to reach 150 EUR/t (CO$_2$) in 2050
Investment options	yearly	Louwen et al. (2018); Schröder et al. (2013); Siemens Gamesa (2019), and own assumptions (cf. Tables 6 and 7)
Interconnector capacities	yearly	Ten-Year Network Development Plan (ENTSO-E, 2016)
Electricity demand	hourly, market area	historical time series of 2015 (ENTSO-E, 2017), scaled to the yearly demand given in the EU Reference Scenario (de Vita et al., 2016)
Renewable feed-in	hourly, market area	historical time series of 2015 (ENTSO-E, 2017), scaled to reach an overall renewable share in relation to electricity demand of 80% in 2050

respective agents estimate the profitability of different investment candidates based on long-term price forecasts. In an iterative procedure, a stable investment plan (more precisely, a Nash-equilibrium) across all considered market areas is then determined (Fraunholz et al., 2019).

As a detailed bottom-up simulation model, PowerACE relies on substantial amounts of input data. Table 2 provides an overview of the data used in this study and the respective sources. In order to adequately account for cross-border effects, the applied version of PowerACE covers Germany as well as the surrounding countries.[6] Please note that the developments of electricity generation from renewables as well as electricity demand are exogenous inputs to PowerACE and remain unchanged for all scenarios to be investigated (Section 4.1). Additional model-endogenous investments in renewable technologies are therefore not considered. Fig. 2 shows the assumed composition of the renewable electricity generation as well as the total yearly electricity demand. The output data most relevant for this article comprises wholesale electricity prices up to 2050, the dispatch of conventional power plants and utility-scale storages, as well as electricity exchange flows between the different market areas. All these result data sets are determined at an hourly resolution over the time period from 2020 to 2050.

4. Results and discussion

In the following, we present the results of our simulation study. To start with, Section 4.1 introduces the investigated scenarios. Subsequently, we gradually move from a lower level (individual households) to an intermediate level (aggregated households) and finally a higher level perspective (European electricity system). To that end, Section 4.2 focuses on the prosumer households' investment decisions, while Section 4.3 describes the resulting impact of the installed residential batteries on the aggregated load patterns of all prosumer households. Then again, Section 4.4 describes how the changes in the load patterns affect the capacity expansion planning of the utility companies. Finally, Section 4.5 shows how all aforementioned developments influence the ability of the electricity system to integrate the increasing amounts of residential PV capacity.

4.1. Overview of the investigated scenarios

In order to analyze the effects of possible policy changes on the diffusion of battery storage systems and the resulting system impacts, we define four scenarios which are summarized in Table 3 and briefly described in the following.

- The scenario *No Storage* is a reference electricity market simulation without any residential battery storage. This scenario serves as a benchmark to which the remaining scenarios are compared.
- In the *Status Quo* scenario, the grid charges are based on the households' power consumption. Surplus solar energy fed into the grid is remunerated with a guaranteed feed-in tariff for 20 years. The battery storage systems are operated using the *default* self-consumption maximizing operational strategy (cf. Section 3.2.2). This scenario aims to represent the current German regulation for prosumers.

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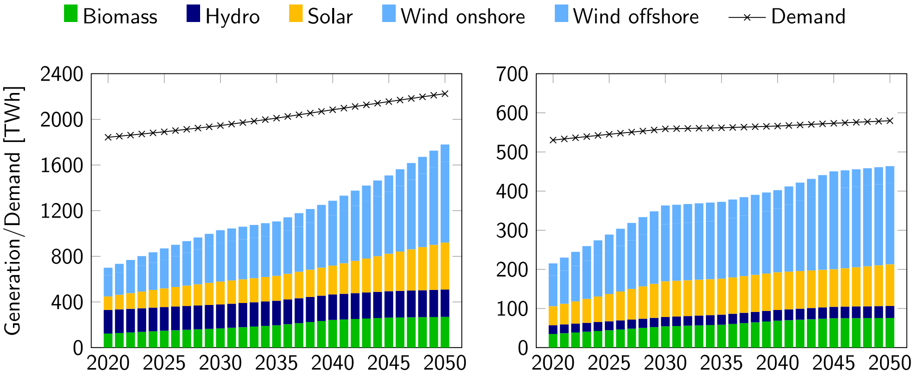
[6] The following countries are considered in the electricity market simulation: Austria, Belgium, Czech, Denmark, France, Germany, Italy, Netherlands, Poland, Switzerland. Please note that the diffusion of residential battery storage is only considered in Germany. For a graphical illustration, see Fig. 5 in the Appendix.



(a) All countries **(b) Germany**

Fig. 2. Assumed annual renewable electricity generation and gross electricity demand (a) aggregated across all countries and (b) in Germany. In 2050, an overall renewable share of 80% is reached. *Source:* de Vita et al. (2016), and own assumptions.

Table 3

Overview of the investigated scenarios. Three settings with different regulatory frameworks are compared to a reference case without residential battery storage.

Scenario	Battery operation	Feed-in limit	Grid charges	Feed-in remuneration	Self-consumption charge
No Storage	–	–	–	–	–
Status Quo	default	70%	volumetric	feed-in tariffs	none
Dynamic	dynamic	70%	volumetric	feed-in tariffs	none
Restrictive	dynamic	50%	fixed	market prices	40% of renewable energy levy

- In the scenario *Dynamic*, the cost structure for prosumers is identical to the Status Quo scenario. However, the operational strategy is changed to the forecast-based *dynamic* strategy (cf. Section 3.2.2). This scenario is designed to analyze the impact of a more system-friendly operational strategy.
- The scenario *Restrictive* also relies on the dynamic operational strategy, but the maximum PV feed-in capacity is reduced to 50% of the installed capacity. This was, e.g., a requirement in the recently expired subsidy scheme of the German *Kreditanstalt für Wiederaufbau* (Figgener et al., 2018). Additionally, the grid charges are included in the basic charge of the electricity tariff.[7] Being independent from the actual consumption, the grid charges can then be considered as pure costs of grid access. In contrast to the two previous scenarios, the fed-in electricity is remunerated with the PV-weighted mean of the wholesale prices determined in the electricity market simulation (cf. Section 3.3). Furthermore, it is assumed that the *de minimis* threshold is removed, meaning that also prosumer households have to pay the self-consumption charge of 40% of the current renewable energy levy. The objective of this scenario is to analyze the impacts of a more restrictive regulation for self-consumption as compared to the rather favorable regulatory framework currently in place.

4.2. Investments decisions of the prosumer households

Our simulations confirm that the regulatory framework has a substantial impact on the PV and battery investment decisions of the modeled sample households as well as the corresponding amounts of self-consumption (see Table 4).

Due to the high levels of feed-in remuneration and retail electricity prices,[8] only new residential PV systems with the maximum capacity of 10 kW_p are being built in the scenarios Status Quo and Dynamic in 2020. This does not change throughout the simulation period, since increasing cost of electricity as well as declining installation cost overcompensate the gradual decrease of the feed-in remuneration. Given the less favorable regulation for self-consumption in scenario Restrictive (cf. Section 4.1), substantially smaller new systems are initially installed. However, from 2040 on, much like in the other scenarios, households only invest in new PV systems with the maximum size.

The situation is somewhat different for the retrofit of existing PV systems, i. e, the installation of a new inverter which comes along with a lifetime extension of 15 years. Until 2030, the results for retrofit systems are identical in all scenarios since only systems already existing today are retrofit and this is always profitable for the respective households. In 2040, 2050, the retrofit systems corresponds to those model-endogenously built 20 years earlier. Consequently, the PV systems under the scenario Restrictive are once again much smaller than those in the other scenarios.

As regards residential battery storage, the more liberal regulation in the scenarios Status Quo and Dynamic leads to substantially larger storage volumes being installed than in scenario Restrictive. This holds for both, new systems and retrofit systems. The total storage capacities and volumes of all households are depicted in Fig. 4. In scenario Restrictive, around one quarter less storage is installed in 2050.

The investment decisions of the households are a direct outcome of their profitability analyses. Consequently, alongside the larger systems also the realized NPVs of the systems being built increase substantially. This finding clearly shows how using batteries to increase self-consumption is becoming a more and more profitable business case for the majority of households over time.

The generally smaller PV and storage systems in scenario Restrictive also lead to smaller amounts of self-consumption by the households. However, this is particularly true up to 2030, whereas later on, the self-consumption levels become more similar in all scenarios for the newly

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[7] For this purpose, the total electricity consumption of the household sector (128.6 TWh) is allocated to all 40.96 million households in Germany (Fett et al., 2019). Thus, the fixed grid charges are based on an average electricity consumption of 3140 kWh per household.

[8] For details, please refer to Table 8 in the Appendix.

Table 4

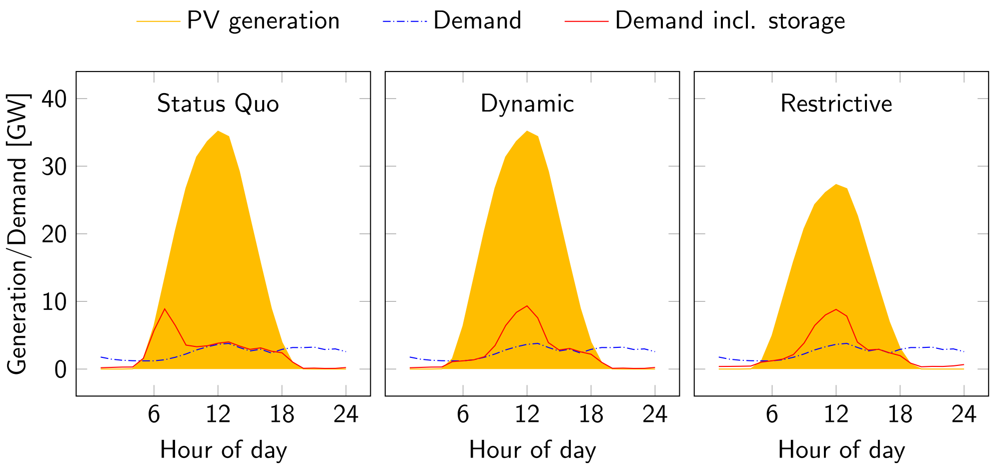
Aggregated results from household perspective for selected simulation years. The less favorable regulatory framework for self-consumption leads to substantially smaller installation sizes in scenario Restrictive. Due to decreasing investment costs and increasing retail electricity prices, the differences between the scenarios become smaller over time. For the sake of conciseness, the tabulated values only show the arithmetic mean across all considered households. Table 8 in the Appendix additionally provides the respective standard deviations.

Model result	Unit	Status Quo/Dynamic[a]				Restrictive			
		2020	2030	2040	2050	2020	2030	2040	2050
New systems									
PV capacity	kW_p	10.0	10.0	10.0	10.0	1.3	5.9	10.0	10.0
Storage volume	kWh	2.6	6.5	7.5	8.1	0.0	4.6	6.1	6.9
Self-consumption	MWh	2.5	3.2	3.3	3.3	0.8	2.7	3.2	3.2
NPV of installation[b]	kEUR	5.2	10.7	14.3	17.4	0.7	3.1	7.0	10.1
Retrofit systems									
PV capacity	kW_p	2.8	6.4	10.0	10.0	2.8	6.4	1.3	5.9
Storage volume	kWh	1.3	6.0	7.5	8.1	0.1	4.3	1.6	6.4
Self-consumption	MWh	1.4	2.8	3.3	3.3	1.1	2.6	1.1	2.9
NPV of installation[b]	kEUR	0.1	2.2	4.0	5.2	0.0	0.5	0.2	2.2

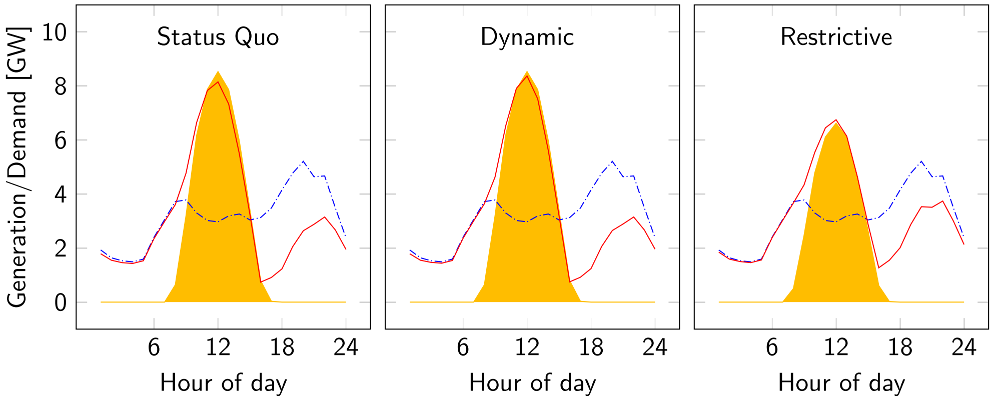
Abbreviations: NPV—net present value, PV—photovoltaics.

[a] Under perfect foresight, the operational strategy of the battery does not affect the profitability of an investment, but the resulting household load profiles and indirectly the wholesale electricity prices. However, since the results of the two scenarios Status Quo and Dynamic are almost identical, only the values for Status Quo are presented.

[b] The values show the realized NPVs of the investments. Given the agent-based approach with only limited foresight about future electricity prices, some household agents may overestimate the profitability of an investment, leading to slightly lower realized NPVs.

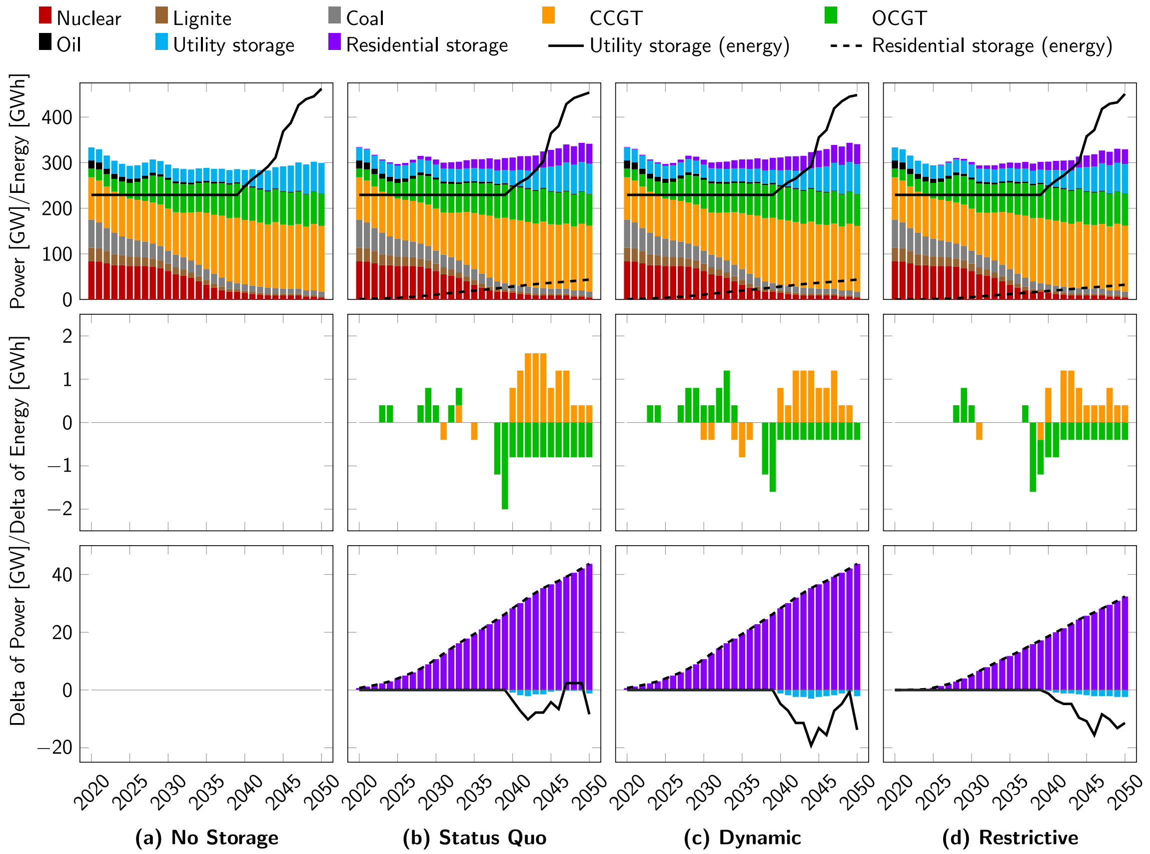


(a) Exemplary summer day (August 1, 2050)



(b) Exemplary winter day (February 1, 2050)

Fig. 3. Demand patterns of prosumer households under the different scenarios. The regulatory framework strongly affects the alignment of PV generation and electricity demand. While a high PV overproduction occurs in summer, substantial self-consumption rates can be achieved in winter.



(a) No Storage **(b) Status Quo** **(c) Dynamic** **(d) Restrictive**

Fig. 4. Installed capacities of conventional power plants as well as utility and residential storage. The figure shows the absolute values (top) and the deltas with respect to the case without residential battery storage diffusion (middle/bottom). Across all scenarios, the residential battery storages replace rather small amounts of peak load and utility storage capacity. *Abbreviations:* CCGT—combined cycle gas turbine, OCGT—open cycle gas turbine.

installed systems.

Overall, we can conclude that the ongoing cost reductions for PV and storage systems render investments in these technologies profitable for many households even under a far more restrictive regulation (comprising a lower PV feed-in limit, fixed grid charges, a feed-in remuneration via market prices, and a self-consumption charge) than in place today. Thus, while the impact of the regulatory framework may be significant in the medium term up to 2030, it gradually diminishes in the longer term.

4.3. *Load shifting of the prosumer households*

Let us now move on to the impact of the regulatory framework and the prosumer households' investment decisions on their demand patterns. In Fig. 3, the aggregated PV generation as well as the electricity demand of all prosumer households is shown for an exemplary summer and winter day in 2050.

In summer, a substantial PV overproduction can be observed across all scenarios. This is because investments in large PV systems are profitable for two reasons (cf. Section 4.2). Firstly, prices for PV installation are assumed to decline further until 2050. Secondly, the feed-in remuneration remains relatively high – even in scenario Restrictive, where the remuneration is determined as the PV-weighted mean of the simulated wholesale electricity prices.

In scenario Status Quo, the residential batteries are directly charged as soon as a PV surplus exists. Consequently, by the time of peak PV production (around 12pm), the batteries are already fully charged and the high surplus PV generation is fed into the grid. Contrary, in scenario Dynamic, the battery charging is shifted by a few hours and therefore much better aligned with the PV production pattern. The discharging of the batteries is however not affected by the operational strategy and similar to the scenario Status Quo. In scenario Restrictive, an overall smaller amount of PV generation[9] can be observed due to the smaller system sizes. The general patterns of battery charging and discharging are however similar to scenario Dynamic.

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[9] As previously indicated, the total renewable electricity generation is an exogenous input to the electricity market simulation and remains unchanged for all scenarios. Thus, if households invest in smaller PV systems, we assume this to be compensated by more utility-scale PV systems. This is because the expansion of renewables is typically driven by technology-specific political targets.

The picture is completely different in winter. Due to the much lower PV generation, the prosumer households are able to self-consume almost their entire produced electricity either directly or by charging their batteries[10] This finding holds for all scenarios. Interestingly, since very little PV generation is fed into the grid, the battery charging and discharging patterns between the default operational strategy in scenario Status Quo and the dynamic strategy in scenarios Dynamic and Restrictive differ much less than in summer. Due to the smaller system sizes, we can again see a lower residential PV generation in scenario Restrictive.

In summary, we find strong impacts of the regulatory framework on the load shifting carried out by the prosumer households. Moreover, significant seasonal differences between summer and winter exist in terms of PV production and consequently self-consumption as well as grid feed-in.

4.4. *Utility-scale generation and storage capacities*

As already described in Section 4.2, substantially less residential storage is built in scenario Restrictive as compared to the scenarios Status Quo and Dynamic. We now change perspective and focus on the impact of the residential storage diffusion on the expansion planning of the utilities. For this purpose, Fig. 4 shows the capacities of conventional power plants as well as utility and residential storage. Since the effects are rather small in magnitude, the middle and bottom part of the figure additionally shows the deltas with respect to the scenario No Storage.

Interestingly, despite more than 40 GW of residential battery storage capacity in the scenarios Status Quo and Dynamic – and still more than 30 GW in scenario Restrictive – these units only replace small amounts of conventional power plants and utility storage capacity. This is closely related to the residential storages' relatively small energy-to-power ratio[11] of 1 (cf. Table 1). Consequently, while the households' batteries replace little utility storage *capacity* (in GW), they do indeed replace substantial amounts of utility storage *volume* (in GWh). This effect occurs because the profitability of utility storage investments is largely affected by the availability of cheap charging electricity due to a surplus of renewable generation. Residential storage, however, is a competing flexibility option in this regard, since it also relies on surplus PV generation for charging. Due to the more system-friendly storage operation, the described effect is more pronounced in scenario Dynamic. In terms of conventional power plants, we can observe a small shift from open cycle gas turbines (OCGT, typically used as peak load units) to combined cycle gas turbines (CCGT, medium load units). This is likely because the residential storages slightly increase the expected operating hours of conventional power plants, which renders CCGTs more profitable than OCGTs.

Table 5

Market-related curtailment of renewable electricity generation. The values show the arithmetic mean over the simulation years 2020–2050. Clearly, a dynamic feed-in limit incentivizes a more system-friendly operation of the residential battery storages. This leads to lower curtailment volumes, i.e., a better system integration of residential photovoltaics in the scenarios Dynamic and Restrictive.

Scenario	All countries [TWh/a]	thereof Germany [TWh/a]
No Storage	15.00	5.33
Status Quo	14.82 (−1.2%)	5.13 (−3.6%)
Dynamic	14.38 (−4.1%)	4.76 (−10.7%)
Restrictive	14.43 (−3.8%)	4.77 (−10.5%)

Overall, the impact of the residential battery diffusion on the utilities' expansion planning is rather small. This finding is largely attributable to balancing effects arising from utility storage dispatch and electricity exchange with the German neighboring countries.

4.5. *System integration of residential photovoltaics*

Another relevant effect on system level is that by creating additional electricity demand at times of high PV generation, residential battery storage could support the system integration of renewables, or more specifically residential photovoltaics. Given our ambitious assumptions on the share of renewable electricity generation with respect to total electricity demand (80% in 2050, cf. Table 2), situations with surplus renewable generation would occur much more frequently in the future than today. Thus, an important indicator for the ability of a system to accommodate renewables is the amount of market-related curtailment.[12] Against this background, Table 5 shows the mean yearly curtailment volumes for the different scenarios.

On the German level, the residential battery storages indeed contribute to a reduction of the renewable curtailment. Interestingly, the way the storages are operated seems more important than the installed storage volumes. While the curtailment is only reduced by less than 4% under the default operational strategy (scenario Status Quo), the dynamic operational strategy (scenarios Dynamic and Restrictive) leads to more than 10% decrease in curtailment. This is remarkable, since substantially less residential storage is installed in scenario Restrictive (cf. Fig. 4).

Moving on to the overall system perspective comprising all modeled countries, the percentage decrease of curtailment is obviously lower since the total curtailment volumes are roughly three times as high as in Germany alone. The reductions of curtailment are again much higher in the scenarios Dynamic and Restrictive than in scenario Status Quo. Please recall that the diffusion of residential storage also affects the expansion of utility-scale storage. In this regard, it is interesting to see that the impact of the dynamic operational strategy even overcompensates the higher utility storage volumes of scenario Status Quo (cf. Section 4.4).

In summary, we find the operational strategy of the residential battery storages to be an important driver for their ability to support the system integration of renewables. However, at the same time, it is crucial to consider interdependencies between different flexibility options, in this particular case, residential storage and utility storage.

4.6. *Sensitivity analyses*

In order to investigate a higher diffusion rate as well as the impact of

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[10] The initial household demand is sometimes higher than the PV generation in the morning hours, but nevertheless battery charging is carried out. This effect is caused by the diversity of households' demand patterns. A simple numerical example with two prosumer households is useful to illustrate this. Let us assume that household 1 has a demand of 1.0 units and a PV generation of 0.5 units, while household 2 has no demand at all and generates 0.4 units of electricity. Since batteries are typically discharged in the morning hours, household 1 then directly self-consumes all produced electricity and covers the rest of its demand from the grid. Contrary, household 2 has a surplus generation of 0.4 units and uses this to charge its battery. Consequently, although the aggregated initial demand of both households (1.0 units) already exceeds the aggregated available PV generation (0.9 units), the aggregated demand is further increased by storage charging of household 2, leading to an overall aggregated demand of 1.4 units. Fig. 6 in the Appendix shows the same setting for a sensitivity with a single standard load profile. Here, the described effect does not occur.

[11] While the energy-to-power ratio relates the storage volume (e.g., in GWh) to the storage capacity (e.g., in GW), the reciprocal of this is referred to as the *C-rate* of a battery.

[12] Apart from market-based curtailment of renewables, insufficient grid capacities can lead to additional grid-related curtailment. Although this is currently an issue in Germany and intensively discussed (e.g., Hladik et al., 2020), our paper focuses on the market side while grid aspects are out of the scope.

using a single household load profile rather than several empirically measures ones, we carry out two additional sensitivity runs.

In scenario *High Diffusion*, the number of potential prosumers in each year is increased by 50%. Nevertheless, the overall system impacts remain small. Interestingly, the positive impact of the residential storages on the curtailment volumes is less pronounced in scenario High Diffusion than in the scenarios with the dynamic operational strategy (Dynamic, Restrictive). This confirms our previous finding that the operational strategy may be more crucial in this regard than the installed residential storage volumes.

In scenario *Standard Load Profile*, we find the prosumer households to invest in smaller battery storage systems than in scenario Status Quo, because the standard load profile is smoother than the empirical ones. Consequently, smaller batteries are sufficient to reach similar levels of self-consumption as in scenario Status Quo.

For more details on the results of the sensitivity runs, please see Appendix C.

5. Limitations

Despite substantial modeling effort, our work has certain important limitations, which we briefly address and qualitatively discuss in the following.

Firstly, while we consider the German neighboring countries in the electricity market simulation, we only model residential battery storage diffusion in Germany. This assumption is based on Germany's clear leadership regarding residential PV and battery storage systems. Currently, Germany is accountable for two of three battery units installed in Europe and this trend is expected to continue in the years to come (SolarPower Europe, 2020). At the same time, Germany has a high level of retail electricity prices. Consequently, residential storage is profitable for many German households already today, which is not the case in most other European countries. Unfortunately, since the regulatory framework for self-consumption differs substantially across Europe, the developed prosumer simulation model is currently only applicable for Germany. Nevertheless, in order to get a more complete picture, our approach should be extended to countries like Italy and Austria in future work.

Secondly, we assume the empirically measured household demand profiles to remain constant throughout the simulation period from 2020 to 2050. However, the shape of the electricity demand is likely to change in the future, e.g., driven by efficiency improvements as well as the electrification of heat and transport (Boβmann and Staffell, 2015). Depending on the flexibility of the new electric household applications, this could have different effects on investments in residential battery storages and their operation, which we are unable to quantify with our approach. Under the reasonable assumption that technologies like heat pumps and e-mobility offer additional demand flexibility for households, the installed battery storage systems would become smaller (Kaschub, 2017). Therefore our work is likely to provide an upper bound on the impact of residential battery storage.

Thirdly, the dynamic operational strategy for batteries is implemented with perfect foresight regarding PV generation and electricity demand. In reality, forecasting errors need to be considered, which slightly reduce the households' self-sufficiency (Bergner et al., 2014). However, additional adjustments to the regulatory framework, e.g., a reduction of the feed-in limit, could account for this aspect and create an incentive for households to apply a dynamic operational strategy nevertheless.

Finally, we have exogenously set technology-specific policy targets for renewable expansion. Consequently, even if households invest in less PV capacity due to the regulatory framework conditions, this is compensated by additional utility-scale PV generation. Thus, with our current modeling framework, we do not analyze the impact of prosumer households in general, but rather the impact of residential battery storage diffusion and operation. The assumption of a politically driven renewable expansion is reasonable for the current German setting. Nevertheless, dynamic model-endogenous investments in utility-scale renewable technologies could be considered in future work.

6. Conclusion and policy implications

In this article, we developed and applied a novel modeling framework to investigate the long-term impacts of residential battery storage diffusion in Germany. The proposed approach is the first in the literature to consider bidirectional dependencies between the decisions of households and utilities, the technology diffusion process, and alternative operational strategies for the residential batteries. In a simulation study, different regulatory settings for self-consumption were analyzed, leading to a number of relevant results which can be summarized as follows.

On the household level, a more restrictive regulation – comprising a lower PV feed-in limit, fixed grid charges, a feed-in remuneration via market prices, and a self-consumption charge – leads to investments in substantially smaller photovoltaic and storage systems in the medium term. As compared to the relatively liberal regulation currently in place, storage installations in 2020 are negligible and installation sizes are still roughly one third smaller in 2030. However, in the longer run, this effect gradually diminishes and by 2040, self-consumption becomes profitable for most households despite the unfavorable regulation. This effect is, amongst others, driven by a cost decrease of photovoltaics and battery storage as well as an increase in retail electricity prices from 0.30 to 0.39 EUR/kWh (current regulation) and from 0.21 to 0.26 EUR/kWh (restrictive regulation). In terms of battery operation, we find a forecast-based dynamic strategy to align photovoltaic generation and battery charging significantly better than a default strategy following the sole objective of maximizing self-consumption. Importantly, if reasonably accurate forecasts on photovoltaic generation and electricity demand are available, the self-sufficiency of households would only marginally suffer from this dynamic strategy. However, driven by relatively high feed-in remuneration (0.07 EUR/kWh in 2050), households are likely to invest in large photovoltaic systems up to 10 kW_p, such that over 70% of photovoltaic generation are fed into the grid in summer regardless of the operational strategy of the battery.

Despite the strong impacts of residential battery storage on an individual household level, we find moderate impacts on the utilities' capacity expansion planning. There are three major reasons for this result, all of which are related to our innovative modeling approach. Firstly, we apply a diffusion model leading to a gradual battery expansion over time, such that even by 2050, only a fraction of the households invests in photovoltaic and storage systems. Secondly, the diffusion process of the residential batteries also affects the electricity market simulation. Since the utilities plan their investments in multiple decision periods, lock-in effects may occur: if a certain amount of power plants is built at a time with little residential storage, it will remain in the system even if the residential storage capacity increases later on. Thirdly, other flexibility options like utility-scale storage and electricity exchange with the German neighboring countries have a tremendous balancing effect.

Nevertheless, the positive impact of a dynamic operational strategy for the residential battery storages is also visible on the system level. The more system-friendly operation reduces the curtailment of renewables in Germany by some 10% and therefore contributes to a better system integration of residential photovoltaics than under the default operational strategy, where curtailment is reduced by less than 4%.

Our findings have important policy implications. Even if restrictive regulatory frameworks for self-consumption are set up, the diffusion of residential battery storage seems difficult to steer in the long term. However, on a system level, we find the way the residential batteries are operated to be more crucial than the amount of storage installed. Fortunately, relatively simple regulatory adjustments, such as a reduction of the maximum feed-in limit for residential photovoltaics, are suitable to incentivize a more system-friendly operation of the residential storages. Apart from the electricity market impact, the operational strategy of the residential batteries is also likely to have a substantial impact on the distribution grid level. This aspect should therefore be investigated in future research. Additionally, dynamic time-of-use tariffs could further incentivize a system-friendly operation of residential storage. However, in the German context, this would probably require substantial changes to the current tariff design. This is because a large portion of the residential electricity prices does not origin from the wholesale cost of generation, but rather from a number of taxes and levies. Since these are currently static, there is only a small margin between high-price periods and low-price periods. Consequently, taxes and levies might need to be designed dynamically in order to increase the lever.

CRediT authorship contribution statement

Daniel Fett: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Writing – original draft, Visualization. **Christoph Fraunholz:** Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Writing – original draft, Visualization. **Dogan Keles:** Conceptualization, Validation, Writing – review & editing, Supervision, Project administration, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix. A Input Data

Fig. 5 illustrates the regional scope of the applied simulation framework. An overview of the techno-economic characteristics of the different investment options modeled in PowerACE is provided in Tables 6 and 7

Fig. 5. Overview of the market areas covered by PowerACE. While the diffusion of residential battery storage is only considered in Germany (dark gray), the electricity market is also simulated for all neighboring countries (light gray) to account for cross-border effects.

Table 6

Conventional power plant investment options modeled in PowerACE with their respective techno-economic characteristics. *Source:* Schröder et al. (2013); Louwen et al. (2018), own assumptions.

Technology	Block size [MW_{el}]	CCS	Net efficiency[a] [%]	Lifetime [a]	Building time [a]	Specific investment (2015–2050)[a] [$\frac{EUR}{kW_{el}}$]	O&M costs fixed [$\frac{EUR}{kW_{el}}a$]	O&M costs var.[b] [$\frac{EUR}{MWh_{el}}$]
Coal	600	no	45–48	40	4	1800	60	6
		yes	36–41			3143–2677		30
Lignite	800	no	43–47	40	4	1500	30	7
		yes	30–33			3840–3324		34
CCGT	400	no	60–62	30	4	800	20	5
		yes	49–52			1216–1078		18
OCGT	400	no	40–42	30	2	400	15	3

Abbreviations: CCGT—combined cycle gas turbine, CCS—carbon capture and storage, OCGT—open cycle gas turbine, O&M—operation and maintenance.

[a] Resulting from technological learning, the net efficiency is assumed to increase over time. Since conventional power plants can generally be regarded as mature technologies, it is further assumed that only the specific investments of the CCS-technologies are declining.

[b] Including variable costs for carbon capture, transport and storage, where applicable.

Table 7

Electricity storage investment options modeled in PowerACE with their respective techno-economic characteristics. *Source:* Louwen et al. (2018); Siemens Gamesa (2019), own assumptions.

Technology	Block size [MW_{el}]	Storage capacity[a] [MWh_{el}]	Round-trip efficiency[b] [%]	Lifetime[b] [a]	Building time [a]	Specific investment (2015–2050)[b] [$\frac{EUR}{kW_{el}}$]	O&M costs fixed[b] [$\frac{EUR}{kW_{el}}a$]
Li-ion battery	300	1200	85–95	20–30	2	3149–572	63–11
		3000				7643–1388	153–28
RF battery	300	3000	75–85	20–30	2	4206–892	84–18
A-CAES	300	3000	60–75	30	2	1095	22
ETES	300	1200	50–60	40	2	600	12
		3000				672	13

Abbreviations: A-CAES—adiabatic compressed air energy storage, ETES—electric thermal energy storage, O&M—operation and maintenance, RF battery—redox-flow battery.

[a] For RF batteries and A-CAES, a substantial share of the investment expenses is related to the converter units. Consequently, for economic reasons, only higher storage capacities of 3000 MWh^{el} are eligible as investment options for these technologies.

[b] Resulting from technological learning, round-trip efficiency and lifetime are assumed to increase over time for the emerging storage technologies. Analogously, specific investments and fixed costs for O&M are assumed to decline.

B Detailed Results from Household Perspective

Table 8 is an extended version of Table 4, which additionally includes a summary of the (partly model-endogenous) cost and remuneration of electricity under the different scenarios, as well as standard deviations for the results on system installations.

Table 8

Aggregated results from household perspective for selected simulation years (extended version of Table 4). The less favorable regulatory framework for self-consumption leads to substantially smaller installation sizes in scenario Restrictive. Due to decreasing investment costs and increasing retail electricity prices, the differences between the scenarios become smaller over time.

Model parameter/result	Unit	Status Quo/Dynamic[a]				Restrictive			
		2020	2030	2040	2050	2020	2030	2040	2050
Cost and remuneration of electricity[b]									
Retail electricity price[c]	EUR/kWh	0.30	0.32	0.34	0.39	0.21	0.22	0.23	0.26
Fixed grid charge	EUR/a	–	–	–	–	278.90	308.10	340.30	375.90
Self-consumption charge	EUR/kWh	–	–	–	–	0.03	0.02	0.01	0.01
Feed-in remuneration[d]	EUR/kWh	0.10	0.09	0.08	0.07	0.03	0.06	0.07	0.07
New systems (mean ± SD)									
PV capacity	kW_p	10.0 ± 0.0	10.0 ± 0.0	10.0 ± 0.0	10.0 ± 0.0	1.3 ± 0.7	5.9 ± 2.2	10.0 ± 0.0	10.0 ± 0.0
Storage volume	kWh	2.6 ± 1.2	6.5 ± 2.2	7.5 ± 2.3	8.1 ± 2.2	0.0 ± 0.1	4.6 ± 1.9	6.1 ± 2.1	6.9 ± 2.2
Self-consumption	MWh	2.5 ± 0.9	3.2 ± 1.1	3.3 ± 1.1	3.3 ± 1.1	0.8 ± 0.5	2.7 ± 1.1	3.2 ± 1.1	3.2 ± 1.1
NPV of installation[e]	kEUR	5.2 ± 1.9	10.7 ± 3.1	14.3 ± 4.1	17.4 ± 5.1	0.7 ± 0.5	3.1 ± 1.4	7.0 ± 2.2	10.1 ± 2.9
Retrofit systems (mean ± SD)									
PV capacity	kW_p	2.8 ± 1.6	6.4 ± 2.0	10.0 ± 0.0	10.0 ± 0.0	2.8 ± 1.6	6.4 ± 2.0	1.3 ± 0.7	5.9 ± 2.2
Storage volume	kWh	1.3 ± 0.9	6.0 ± 2.0	7.5 ± 2.3	8.1 ± 2.2	0.1 ± 0.2	4.3 ± 1.6	1.6 ± 0.9	6.4 ± 2.3
Self-consumption	MWh	1.4 ± 0.6	2.8 ± 1.0	3.3 ± 1.1	3.3 ± 1.1	1.1 ± 0.4	2.6 ± 0.9	1.1 ± 0.6	2.9 ± 1.2
NPV of installation[e]	kEUR	0.1 ± 0.2	2.2 ± 0.9	4.0 ± 1.4	5.2 ± 1.8	0.0 ± 0.0	0.5 ± 0.3	0.2 ± 0.2	2.2 ± 0.9

Abbreviations: NPV—net present value, PV—photovoltaics, SD−standard deviation.

[a] Under perfect foresight, the operational strategy of the battery does not affect the profitability of an investment, but the resulting household load profiles and indirectly the wholesale electricity prices. However, since the results of the two scenarios Status Quo and Dynamic are almost identical, only the values for Status Quo are presented.

[b] If not stated otherwise, see Fett et al. (2019) for the calculation procedure of the different elements.

[c] Including model-endogenous wholesale electricity prices from PowerACE.

[d] Current yearly feed-in tariff (Status Quo/Dynamic) or PV-weighted mean of the wholesale electricity prices in the respective year (Restrictive).

[e] The values show the realized NPVs of the investments. Given the agent-based approach with only limited foresight about future electricity prices, some household agents may overestimate the profitability of an investment, leading to slightly lower realized NPVs.

C Results of the Sensitivity Analyses

In the following, we present and briefly describe the results of the two additional sensitivity runs, which focus on the impact of a 50% higher diffusion rate (scenario *High Diffusion*) and the role of using a single household load profile rather than several empirically measured ones (scenario *Standard Load Profile*). In order to put the results of the sensitivities into perspective, we mostly compare them to scenario Status Quo, sometimes also to the scenarios Dynamic and Restrictive, all of which are described in detail in Section 4.

In terms of the prosumer households' PV and battery investment decisions (summarized in Table 9), scenario High Diffusion is identical to scenario Status Quo for both, new and retrofit systems. This is because the same sample households are considered and only the diffusion rate is increased by scaling the yearly investments to 150% of Status Quo. In scenario Standard Load Profile, the diversity of investments in new PV and storage systems is lost, since only a single load profile is considered for all prosumer households. As in scenario Status Quo, already in 2020, only PV systems with the maximum size are built. From 2030 onward, battery system sizes in scenario Standard Load Profile are somewhat smaller as compared to scenario Status Quo. Since the standard load profile is smoother than the empirical ones, smaller batteries are sufficient to reach an even slightly higher self-consumption than in scenario Status Quo. In terms of retrofit PV systems, the sizes are identical to scenario Status Quo in 2020 and 2030, since the same systems already existing today are considered. However, storage sizes are smaller, since no diversity in household load profiles is considered. In 2040, 2050, the new systems built model-endogenously in 2020 and 2030, respectively, are retrofit.

Table 9

Aggregated results from household perspective for selected simulation years (sensitivity analyses). In scenario High Diffusion, the outcomes are identical to scenario Status Quo, yet a faster diffusion process takes place. Since the diversity of households' load profiles is not considered in scenario Standard Load Profile, all newly built systems have an identical PV and storage size.

Model parameter/result	Unit	High Diffusion				Standard Load Profile			
		2020	2030	2040	2050	2020	2030	2040	2050
Cost and remuneration of electricity[a]									
Retail electricity price[b]	EUR/kWh	0.30	0.32	0.34	0.39	0.30	0.32	0.34	0.39
Fixed grid charge	EUR/a	–	–	–	–	–	–	–	–
Self-consumption charge	EUR/kWh	–	–	–	–	–	–	–	–
Feed-in remuneration[c]	EUR/kWh	0.10	0.09	0.08	0.07	0.10	0.09	0.08	0.07
New systems (mean ± SD)									
PV capacity	kW$_p$	10.0 ± 0.0	10.0 ± 0.0	10.0 ± 0.0	10.0 ± 0.0	10.0 ± 0.0	10.0 ± 0.0	10.0 ± 0.0	10.0 ± 0.0
Storage volume	kWh	2.6 ± 1.2	6.5 ± 2.2	7.5 ± 2.3	8.1 ± 2.2	3.5 ± 0.0	5.5 ± 0.0	6.5 ± 0.0	7.0 ± 0.0
Self-consumption	MWh	2.5 ± 0.9	3.2 ± 1.1	3.3 ± 1.1	3.3 ± 1.1	3.2 ± 0.0	3.5 ± 0.0	3.6 ± 0.0	3.7 ± 0.0
NPV of installation[d]	kEUR	5.2 ± 1.9	10.7 ± 3.1	14.3 ± 4.1	17.4 ± 5.1	5.6 ± 0.0	11.5 ± 0.0	15.1 ± 0.0	18.4 ± 0.0
Retrofit systems (mean ± SD)									
PV capacity	kW$_p$	2.8 ± 1.6	6.4 ± 2.0	10.0 ± 0.0	10.0 ± 0.0	2.8 ± 1.6	6.4 ± 2.0	10.0 ± 0.0	10.0 ± 0.0
Storage volume	kWh	1.3 ± 0.9	6.0 ± 2.0	7.5 ± 2.3	8.1 ± 2.2	0.8 ± 1.5	5.1 ± 0.3	6.5 ± 0.0	7.0 ± 0.0
Self-consumption	MWh	1.4 ± 0.6	2.8 ± 1.0	3.3 ± 1.1	3.3 ± 1.1	1.7 ± 0.6	3.1 ± 0.3	3.6 ± 0.0	3.7 ± 0.0
NPV of installation[d]	kEUR	0.1 ± 0.2	2.2 ± 0.9	4.0 ± 1.4	5.2 ± 1.8	0.0 ± 0.1	2.1 ± 0.4	3.8 ± 0.0	4.9 ± 0.0

Abbreviations: NPV—net present value, PV—photovoltaics, SD−standard deviation.

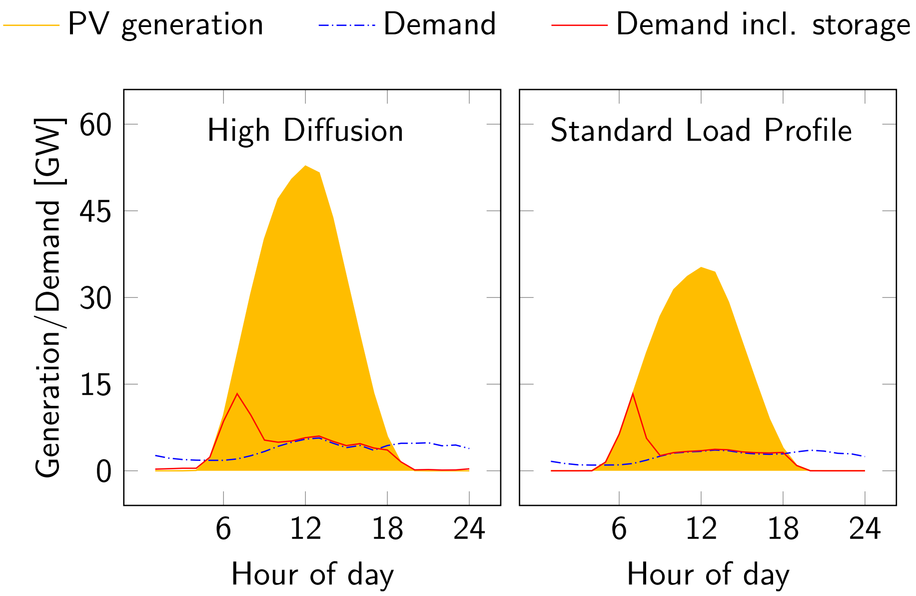
[a] If not stated otherwise, see Fett et al. (2019) for the calculation procedure of the different elements.

[b] Including model-endogenous wholesale electricity prices from PowerACE.

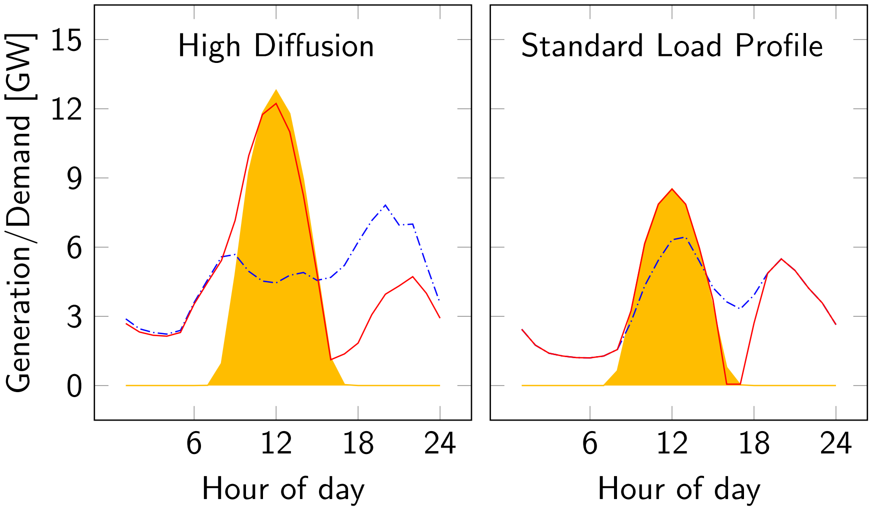
[c] Current yearly feed-in tariff (exogenous assumption).

[d] The values show the realized NPVs of the investments. Given the agent-based approach with only limited foresight about future electricity prices, some household agents may overestimate the profitability of an investment, leading to slightly lower realized NPVs.

Fig. 6 illustrates the load shifting of prosumer households by using their residential batteries. Again, the results of scenario High Diffusion are identical in shape to those of scenario Status Quo. However, due to the scaling, the values of generation and demand are 50% higher. In scenario Standard Load Profile, steeper load gradients occur as compared to scenario Status Quo. This is because the lacking diversity in household load profiles does not allow for balancing effects, but all households operate their storages in the exact same way.



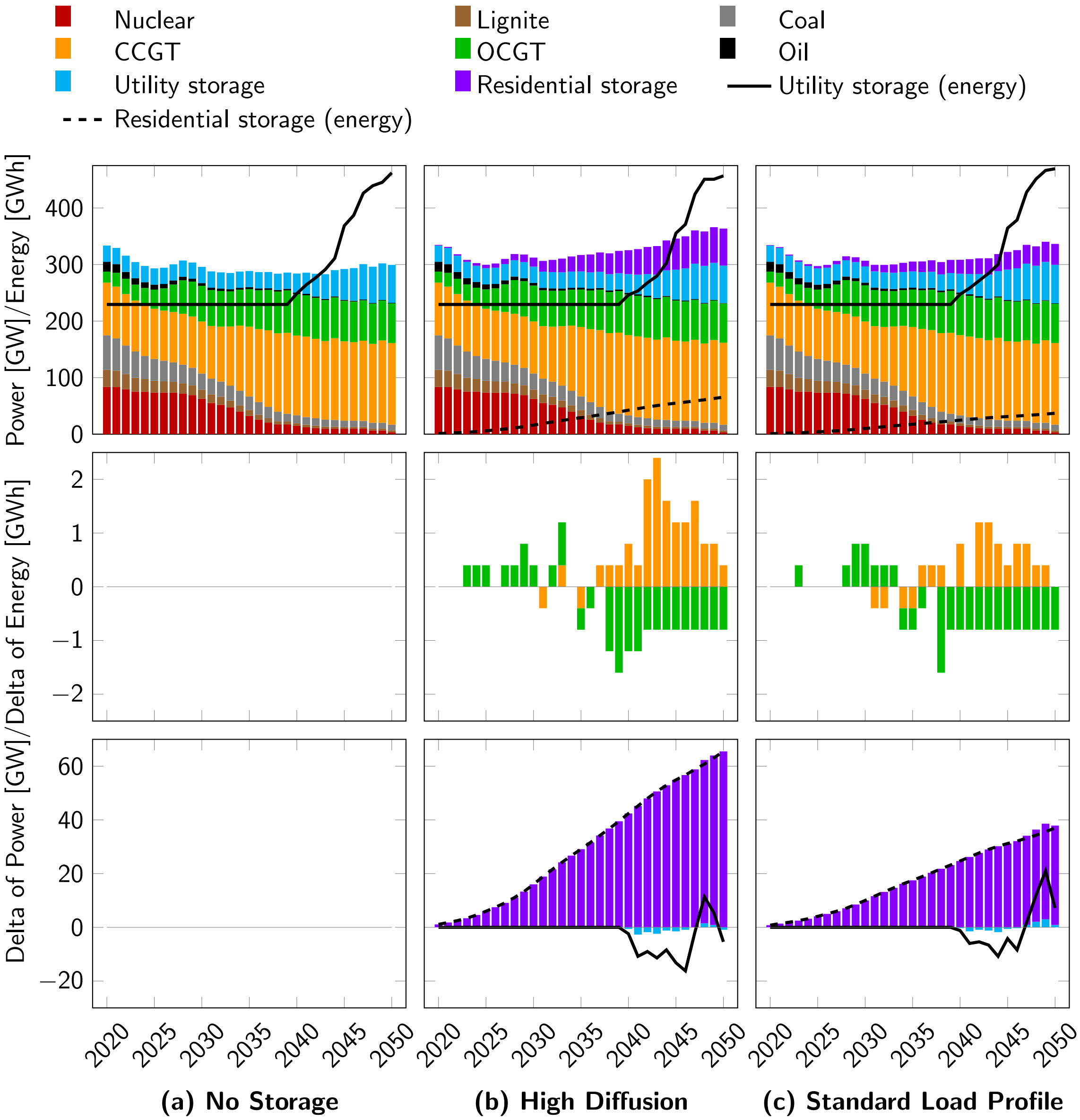
(a) Exemplary summer day (August 1, 2050)



(b) Exemplary winter day (February 1, 2050)

Fig. 6. Demand patterns of prosumer households under the different scenarios (sensitivity analyses). The curves of scenario High Diffusion have the same shape as those of scenario Status Quo, yet the absolute levels of generation and demand are 50% higher. In scenario Standard Load Profile, steeper load gradients can be observed as compared to Status Quo.

As regards the impact of the residential battery storages on utilities' expansion planning, the effects of the sensitivity scenarios High Diffusion and Standard Load Profile are qualitatively similar to those of the scenarios Status Quo, Dynamic, and Restrictive. Interestingly, in scenario Standard Load Profile, the lack of diversity in household load profiles reduces the effect described in Section 4.4. The residential storages increase the expected operating hours of conventional power plants to a lesser extent than in scenarios Status Quo, Dynamic, and Restrictive, thus reducing the incentive to invest in CCGTs. Instead, more utility storage is built in the last years of the simulation period. Overall, the impact of the residential battery storages on the utilities' investments remains small, even under a higher diffusion rate.



(a) No Storage **(b) High Diffusion** **(c) Standard Load Profile**

Fig. 7. Installed capacities of conventional power plants as well as utility and residential storage (sensitivity analyses). The figure shows the absolute values (top) and the deltas with respect to the case without residential battery storage diffusion (middle/bottom). Both, in scenario High Diffusion and Standard Load Profile, the residential battery storages replace rather small amounts of peak load capacity, whereas some additional medium load power plants and utility storages are built. *Abbreviations:* CCGT—combined cycle gas turbine, OCGT—open cycle gas turbine.

Finally, Table 10 presents the curtailment volumes under the two sensitivity scenarios. In scenario High Diffusion, much less curtailment needs to be carried out than in scenario Status Quo. This is caused by the 50% higher residential battery storage volumes. However, curtailment can still be reduced even more in scenarios Dynamic and Restrictive, despite the much lower amount of residential storage. This confirms our previous finding that the operational strategy may be more crucial in this regard than the installed residential storage volumes. The results of scenario Standard Load Profile are similar to those of scenario Status Quo.

Table 10

Market-related curtailment of renewable electricity generation (sensitivity analyses). The values show the arithmetic mean over the simulation years 2020–2050. In scenario High Diffusion, the 50% higher residential storage capacity reduces curtailment stronger than in scenario Status Quo, whereas the reduction in scenario Standard Load Profile is similar to scenario Status Quo.

Scenario	All countries [TWh/a]	thereof Germany [TWh/a]
No Storage	15.00	5.33
High Diffusion	14.64 (−2.4%)	5.02 (−5.8%)
Standard Load Profile	14.75 (−1.6%)	5.16 (−3.1%)

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