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Energy systems based on renewable energy sources require increasing demand side flexibility. Also, changes in the underlying cost structure, i. e., decreasing variable costs and increasing infrastructure investments, and varying customer needs should be reflected in the setup of future markets, including retail markets and electricity providers' tariffs. While various studies focus solely on tariffs with variable energy prices to leverage residential demand side flexibility, we incorporate tariffs with a variable capacity price component in our analysis. The latter enables electricity providers to offer more differentiated tariffs, considering individual customer needs and a balanced cost allocation. To compare the impact of different tariffs on residential demand side flexibility, we develop a bottom-up load model. This model not only simulates but also optimizes residential load profiles according to different tariffs. In order to account for behavioral aspects, the model is calibrated based on data from a large-scale field trial. Our results show that tariffs with variable energy prices induce larger demand side flexibility, but the impact of tariffs with variable capacity prices is more predictable and reliable from a supplier's point of view. To enable sustainable business models, politics should change regulations rewarding demand side flexibility and facilitating the technical implementation.

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Energy systems based on renewable energy sources require increasing demand side flexibility. Also, changes in the underlying cost structure, i. e., decreasing variable costs and increasing infrastructure investments, and varying customer needs should be reflected in the setup of future markets, including retail markets and electricity providers' tariffs. While various studies focus solely on tariffs with variable energy prices to leverage residential demand side flexibility, we incorporate tariffs with a variable capacity price component in our analysis. The latter enables electricity providers to offer more differentiated tariffs, considering individual customer needs and a balanced cost allocation. To compare the impact of different tariffs on residential demand side flexibility, we develop a bottom-up load model. This model not only simulates but also optimizes residential load profiles according to different tariffs. In order to account for behavioral aspects, the model is calibrated based on data from a large-scale field trial. Our results show that tariffs with variable energy prices induce larger demand side flexibility, but the impact of tariffs with variable capacity prices is more predictable and reliable from a supplier's point of view. To enable sustainable business models, politics should change regulations rewarding demand side flexibility and facilitating the technical implementation.

Keywords

Residential bottom-up load model; variable energy prices; variable capacity prices; load shifting potential

1 Introduction

Many energy systems tend to rely on an increasing share of power generation from renewable energy sources (RES) (cf. Ambec and Crampes 2012). This results in a higher decentralization of generation facilities, a higher fluctuation of power generation and an increasing uncertainty regarding the available power at a specific point in time. As power supply and demand in energy systems must be balanced at all times, the before-mentioned changes require the system to react flexibly on fluctuations in demand and supply (cf. Bertsch et al. 2016). Furthermore, these changes influence the underlying cost structure of the system. The increasing use of RES for power generation leads to decreasing variable generation costs. Contrariwise, the investment in power infrastructure increases as a result of an enormous amount of RES capacities, grid reinforcements and partly also conventional back-up power plants. Consequently, the fix costs become more important in future energy systems necessitating the reflection of these systematic changes in electricity tariffs as well. On the one hand, electricity tariffs should consider the temporal fluctuations of RES generation, i. e., incentivizing or at least not penalizing consumption during high RES availability. On the other hand, electricity tariffs need to appropriately include the underlying system costs.

Moreover, the availability and utilization of self-produced energy, e. g., from photovoltaic (PV) systems, allows traditional consumers like households to reduce their electricity consumption from central providers. However, based on current regulations, an increasing self-consumption of those consumers reduces their contribution to system costs while still allowing them to benefit from the security of supply provided through the central generation and grid structure (cf. Simshauser 2016). In order to ensure a fair system cost allocation according to the individual needs of different consumers, future electricity tariffs should allow for an appropriate price differentiation. In this context, smart grid technologies can enable electricity providers to offer more sophisticated services, allowing not only for a fair cost allocation but also to create tariffs fitting to the individual needs of different customers (cf. Oren 2010).

In the context of this paper, flexibility of energy systems shall be defined as the ability to balance demand and supply in order to avoid shortages in the system. These shortages can refer both to generation as well as transportation or distribution shortages. Generation shortages can occur in case of little RES generation and high energy demand. Transportation shortages can arise in case of high RES generation leading to an overload of the power grid (cf. Jacobsen and Schröder 2012). Both shortage situations may negatively influence the economic welfare as either a specific energy demand cannot be fulfilled or a surplus of available energy from RES must be curtailed in order to avoid system outages (cf. Jacobsen and Schröder 2012; Henriot 2015). Flexibility in energy systems can be provided both from the supply and the demand side. On the supply side, the generation capacity of power plants can be controlled, though most plants using RES cannot provide additional power in case of exceeding demand. On the demand side, customers can provide flexibility through demand side management or, often synonymously used, demand response (cf. Broberg and Persson 2016; Clastres and Khalfallah 2015).

While in traditional energy systems with a large share of conventional power plants, flexibility was mainly delivered through the supply side, the increasing utilization of RES promotes the need for demand side flexibility (cf. Broberg and Persson 2016; Clastres and Khalfallah 2015). In the industrial sector, demand side flexibility is already partly leveraged through contracts allowing for direct load control, capacity prices in industrial electricity tariffs and their possibility to actively participate in balancing markets (cf. Krzikalla et al. 2013). In the residential sector, however, demand side flexibility is hardly leveraged even though various studies indicate a high potential for demand response (cf. dena 2010; Klobasa 2009; Krzikalla et al. 2013). Accessing this untapped potential increases the economic welfare by reducing the curtailment of RES generation (cf. Schermeyer et al. 2014) and, in the long term, the amount of backup generation capacity through peak load power plants and the need for grid expansion (cf. Broberg and Persson 2016; Kostková et al. 2013).

To access residential demand side flexibility, customers need some kind of incentive in order to adapt their consumption to system requirements. For this purpose, residential electricity tariffs with variable price components can be used. The majority of recent research projects focuses on electricity tariffs with variable energy prices, e. g., time of use pricing or real time pricing, in order to alter residential electricity consumption (see Faruqui and Sergici 2010; Hillemacher 2014) but also tariffs with variable capacity prices, e. g., curtailable load tariffs, attract the attention of research (see Hayn et al. 2015a; Ruiz et al. 2014; Woo 1990). When analyzing the impact of tariffs on residential demand side flexibility, all reviewed studies focus exclusively either on tariffs with variable energy prices or tariffs with variable capacity prices. The main contribution of this paper is the comparative analysis of tariffs with variable energy prices and variable capacity prices, as well as a combination of both approaches and their impact on residential demand side flexibility. Therefore, a residential bottom-up load model is developed which combines a technical bottom-up simulation approach with different optimization problems allowing for the analysis of tariffs with variable energy and/or capacity prices.

The underlying concept of tariffs with variable capacity prices used in this paper is described in (Hayn et al. 2015a) in detail. Basically, the tariff represents a curtailable load tariff allowing an electricity provider to curtail the power consumption of an individual household in case of shortages on a contracted guaranteed power level. Besides the power level also the frequency of curtailments, i. e., the number of curtailments per time period, their duration and the advance warning time are assumed to be individually agreed between provider and household. Referring to concepts from service research, these main elements can be described as service level indicators and related service level objectives. Within this paper, the impact of such tariffs on residential electricity demand is analyzed. The two key questions to be answered within this paper are, how different tariffs alter the general power consumption behavior of households and, more specifically, how these tariffs influence the power consumption of households in times of shortages.

The remainder of this paper structures as follows: Section 2 briefly differentiates this paper's bottom-up model from selected existing bottom-up models. Section 3 describes the model. In section 4, the main results of different scenarios focusing on the impact of residential electricity tariffs on demand side flexibility are highlighted and discussed. Section 5 concludes.

2 Related work

A large number of residential load models was developed so far following either a top-down or a bottom-up approach (see Grandjean et al. 2012; Swan and Ugursal 2009). For the analysis of the impact of different residential electricity tariffs on demand side flexibility, technical bottom-up models are most suitable as their high level of detail makes it possible to simulate different household types as well as a large number of different appliances both being relevant with regard to households behavior towards different tariffs (cf. Hayn et al. 2014b). Within the methodology of bottom-up modeling, technical bottom-up models offer the highest level of detail. In order to simulate households' reaction on different tariffs, several additional aspects need to be considered in the model. As residential demand in general and the load profiles of individual appliances in particular fluctuate continuously, a high temporal resolution is advisable. Additionally, differences between seasons and weekdays should be considered since those aspects influence residential electricity demand (cf. Fünfgeld and Tiedemann 2000). Finally, the model needs to be capable to represent regional specifics, i. e., country specific appliance and household distributions as well as appliance utilization rates.

The overview in Table 1 includes only technical bottom-up models allowing for the analysis of demand side management effects. Besides the main objective of the reviewed models, key aspects of the models are highlighted, e. g., the geographical focus and the level of detail regarding household and appliance differentiation. Descriptions of more residential bottom-up load models can be found, for instance, in Gottwalt 2015, Grandjean et al. 2012, Swan and Ugursal 2009.

In comparison to existing developments, our model offers several enhancements. First, the developed model is able to demonstrate the effect of residential tariffs with variable energy and capacity prices as well as a combination of both. Additionally, the maximization of self-produced PV energy (self-consumption) can be modeled. Second, the model is calibrated with empirical data from a large scale field trial with more than 1,000 participating households for the simulation of manual demand side flexibility. More information on the field trial is given in Hillemacher 2014. Using empirical data on the probability of manual load shifting improves the model's ability to simulate real life behavior of households instead of considering only technical restrictions of electric appliances. Third, the developed model creates weekly profiles instead of daily ones offering the possibility to shift the utilization of appliances across daily limits, e. g., for dish washers. As most reviewed models create only daily profiles, this option does not apply for these.

The strongest similarities regarding the methodological modeling approach exist with the model developed by Gottwalt et al. 2011. The major improvement of their approach is seen in the consideration of tariffs with variable capacity prices. Furthermore, the underlying data base was enhanced, using empirical distribution functions for the utilization of different appliance types in order to determine their start time instead of calibrating the model with empirical load profiles (see Prior 1997). However, as already mentioned, we calibrate the likelihood of manual demand side flexibility with empirical data. Consequently, the outcome of the model relates closer to the demand side flexibility achievable in reality instead of a purely theoretical potential. Additionally, we implemented typical load profiles for different appliance types in the model based on Stamminger 2008.

Table 1 Overview on selected technical residential bottom-up load models with demand side management

Source	Objective	Geographical focus	Details (households)	Details (appliances)	Demand side management	Simulation horizon	Seasons	Weekdays	Temporal resolution	Photovoltaic	Electric vehicles	Others
Gobmaier 2013	Development of future residential load profiles	GER	Socio.	n. s.	EP, PVS	1 year	3	3	15 min.	yes	yes	
Gottwalt 2015	Evaluation of demand side flexibility based on variable energy prices	GER	n. s.	8 types	EP, PVS	12 weeks	partly (SH, BL)	partly (BL)	15 min.	yes	yes	BAT
Gottwalt et al. 2011	Evaluation of demand side flexibility based on variable energy prices	GER	Socio.	14 types	EP	1 year	yes	yes	15 min.			
Huang et al. 2011	Evaluation of the profitability of electric vehicles[a]	USA	n. s.	28 types	EP	1 day	2	2	1 h.		yes	
Maier et al. 2014	Evaluation of the maximization of photovoltaic self-consumption	AUT	8 arche-types	12 classes	PVS	1 year	3	3	1 min.	yes	yes	HP
Michalik 1997	Evaluation of load shifting potential with hot water appliances	AUS	24 arche-types	17 types	EP	1 day	1	1	15 min.			
Paatero and Lund 2006	Evaluation of load shifting potential as a function of grid frequency	FIN	Socio.	17 types	Grid	1 year	3	2	1 h.			
Ruiz et al. 2014	Evaluation of demand side flexibility based on variable capacity prices	ESP	n. s.	5 types	CP	1 day	partly (SC)	n. s.	15 min.			
Widén et al. 2012	Combination of existing models and enabling for demand side management	SWE	Socio.	9 types	EP, PVS	1 day	partly (L)	2	1 min.	yes		
Own model	Evaluation of demand side flexibility based on variable energy as well as capacity prices	GER	Socio.	17 types	CP, EP, PVS	1 year	3	3	15 min.	yes		

[b] Model based on Paatero and Lund 2006

Abbreviations: BAT = Battery; BL = Base load; CP = Capacity price; EP = Energy price; HP = Heat pump; L = Lighting; n. s. = not specified; PVS = Photovoltaic self-consumption; SC = Space cooling; SH = Space heating; Socio. = Socio-demographic characteristics

As relates to the content, the strongest similarities exist with the model developed by Ruiz et al. 2014 as their model is the only one able to describe the effect of residential tariffs with variable capacity prices. However, even here, differences exist. On the one hand, different electricity tariffs are modeled. First, the impact of tariffs with variable capacity prices is considered differently. While Ruiz et al. 2014 minimize the electricity bill by applying a capacity price function, i. e., households receive a bonus payment if their power consumption remains below or above a certain threshold, our applied tariff with variable capacity prices curtails households' power consumption to a pre-defined household specific level in shortage situations. Hence, the approach from Ruiz et al. 2014 is more similar to tariffs with variable energy prices just applying the price incentive on power instead of energy. Second, as already mentioned, our model is able to simulate both variable energy and variable capacity prices which is its major enhancement. On the other hand, the modeling approach significantly differs, e. g., the longer simulation horizon of one year in our model versus one day and the representation of seasonal and diurnal differences in household's energy consumption.

3 Modeling approach

To illustrate the work flow of the developed model, Fig. 1 shows a simplified flow diagram for the model. The model combines a simulation with an optimization approach, allowing us to reflect household specific differences regarding electricity consumption on the one hand, and model rational household or appliance reactions on external price or control signals on the other hand. After reading the required input data, e. g., the number of simulated households I, their distribution of sizes and appliances, all individual households are generated and described with specific characteristics. Then, weekly load profiles with a 15 minutes resolution for every week $w \in W$ for each household $i \in I$ are simulated. Concatenating these profiles over all weeks creates a yearly profile for each household. The accumulation of these across all households is used to determine relevant energy consumption indices. Finally, the load profiles and indices are written as output files for further analysis.

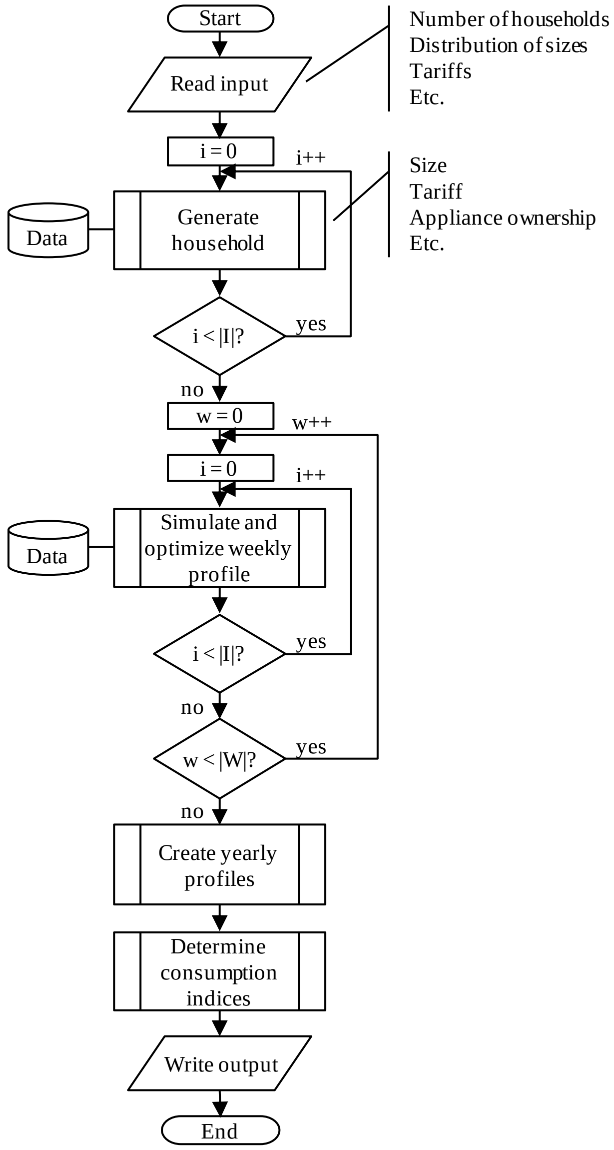

Fig. 1 Simplified flow diagram of the model

The model is able to reflect the reaction of households on external price or control signals. For instance, households can shift their power demand according to tariffs with variable energy prices. Therefore, the tariff structure, i. e., which price applies at what time, must be given as an input to the model. Control signals can be used to indicate shortage situations to the households, through which the supplier activates pre-defined power consumption limits. Both, the power consumption limits and the point in time at which the activation takes place, are exogenous model parameters.

The main method of the model covers the simulation and optimization of weekly load profiles. Within this method, firstly the number of appliance utilizations in a specific week and the related start times are simulated for every household. The simulated start time represents the point in time when the household would, under normal circumstances, use the appliance. Subsequently, the optimization regarding the owned tariff takes place. When using tariffs with variable energy prices, the start times or energy consumption of appliances at a specific point in time are optimized, if possible, to minimize the related costs. For tariffs with variable capacity prices, the optimization ensures that the used power does not exceed the pre-defined limit. In case the limit is exceeded, a penalty term applies. Objective of the optimization is to minimize these penalties. If a household owns a tariff with variable energy and capacity prices, both optimizations are performed. After the optimization, the final weekly load profile of the household is created based on the final start times and energy consumption of all appliances.

Table 2 Overview on used data

Data	Description	Source
Household distribution	Statistic distribution of number of occupants in households in Germany (household size) [in %]	Destatis 2013
Appliance distribution	Statistic distribution each appliance type for different household sizes (saturation) [in %]	Destatis 2013
Appliance stock	Number of appliances of each appliance type available in 100 households for different household sizes [in units]	Statis Destatis 2013
Average household electricity consumption	Average electricity consumption of households for different household sizes and the respective standard deviation [in kWh]	RWI and forsa 2013
Average appliance electricity consumption	Average electricity consumption as percentage of total residential electricity consumption [in %]	Bürger 2009
Average appliance utilization	Calculated average utilizations per year of active appliances for different household sizes [in use times]	Cf. Gottwalt et al. 2011
Simplified appliance load profiles	Simplified load profiles of all appliance types in 15 minutes steps for an average use cycle [in W]	Stamminger 2008
Average appliance peak load	Average peak load of appliance types [in W]	Beer 2009; Stamminger 2008
Daily appliance electricity consumption	Share of yearly electricity consumption of active appliances distributed to each weekday for winter and summer [in %]	Prior 1997
Hourly appliance electricity consumption	Share of abovementioned daily electricity consumption of active appliances distributed to each hour of a day [in %]	Prior 1997
Average heating days per season	Average number of heating days in Germany for different seasons [in days]	IWU 2014
Average days with hot water consumption	Average number of days per year when households require hot water [in days]	Beer 2009
PV generation profiles	PV generation time series for different system sizes for the year 2011 [in W]	Cf. Bertsch et al. 2014
Load shifting potential	Relative load shifting potential under tariffs with variable energy prices [in %]	Hillemacher 2014
VDEW H0 standard load profile	Standard load profile representative for household samples with more than 150 households [in W]	Fünfgeld and Tiedemann 2000

The main criterion for the differentiation of households is their size (cf. Hayn et al. 2014a). Based on their size, households are randomly equipped with different electric appliances and have a different user behavior regarding the number of utilizations as well as heat and hot water requirements. Additionally, each household uses a specific electricity tariff. The considered appliance types are fridges, freezers, washing machines, tumble dryers, dish washers, stoves, TV, DVD/video, audio, PC/laptop, telecommunication appliances, lighting, circulation pumps, night storage heating, direct hot water heating, hot water heating with storage and a residual category. Appliances with significantly fluctuating power demand during their utilization, e.g., fridges and washing machines, are characterized through simplified load profiles (cf. Stamminger 2008). In the following, these general appliance types are indicated by the index $\dot{g}$ and the respective set $\dot{G}$. When referring to a specific appliance of a household and not to the general appliance type the index g is used. The mentioned appliance types can be clustered in the following sets: $\dot{G}^{Active}$ covers all appliances with active participation of people, i. e., washing machines, tumble dryers, dish washers, stoves, TV, DVD/video, audio, PC/laptop and lighting. $\dot{G}^{Heat}$ includes night storage heating, direct hot water heating and hot water heating with storage, $\dot{G}^{Cold}$ combines fridges and freezers. Within each set, appliances may be available for load shifting, i. e., either smart appliances or appliances that can be manually shifted such as washing machines or dish washers. The set of shiftable appliances is marked by the superscript index $Flex$.

The model makes use of several data during the simulation in order to reflect the characteristics of German households. Besides statistical information on the distribution of household sizes and different appliance types (cf. Destatis 2013), the main input data are cumulated distribution functions (CDF) used to determine the start time of appliances. The CDF consider seasonal and diurnal variations in appliance utilization as well as hourly ones (cf. Prior 1997). For validation and calibration purposes of the simulated load profiles without demand side management, the VDEW H0 standard load profile is used (cf. Fünfgeld and Tiedemann 2000), for load profiles with demand side management, data from the already mentioned field trial are considered (cf. Hillemacher 2014). The full overview of used data is given in Table 2.

3.1 Load profile simulation

The first step of the model consists of the creation of household objects, each described through a household's size, i. e., the number of occupants, the equipment with electric appliances, their specific utilization rates and an electricity tariff. Furthermore, each appliance is characterized with a specific peak load determining its electricity consumption during utilization. Mathematically, this definition of household objects is based on pseudo random numbers combined either with the inverse function of the cumulative distribution function (quantile function), e. g., for the household's size, or with Bernoulli-experiments, e. g., for the ownership of different appliance types. Several characteristics of a household object are dependent on the household size, for instance the ownership of different appliance types, the number of owned appliances per appliance type and the utilization rate of different appliances. The underlying data for this differentiation stems from empirical studies and statistical data from Germany (see Table 2). If the corresponding data from other countries is at hand, it is easy to adapt the model accordingly allowing for the generation of load profiles for households of the respective country.

The simulation of individual load profiles takes place on a weekly basis, taking seasonal and diurnal variations in the probability of appliance utilizations into account. The start time of each utilization of a household's appliance is allocated to a specific 15-minutes time step of a week based on empirical quantile functions per appliance type (cf. Prior 1997). Subsequently, the appliance specific load profile is allocated to that start time. By aggregating the power consumption of each appliance in every time step of a week, the household's load profile can be constructed (see Fig. 2 for an example of a summer weekday). A more detailed description of the simulation approach is given in Hayn et al. 2014b, differing only in minor points from the final model presented in this paper.

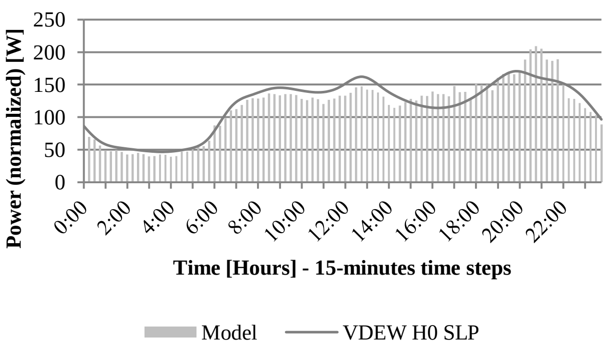

Fig. 2 Visualization of modeled load profile of 1.000 households and VDEW H0 standard load profile of a summer weekday

Standard load profiles are accepted as good approximations of cumulated load profiles for more than 400 households (cf. Esslinger and Witzmann 2012). The correlation coefficient of the simulated load profiles for an increasing number of simulated households with the developed model is given in Table 3. While individual households show only a low correlation to the VDEW H0 standard load profile (SLP), the correlation coefficient strongly increases when analyzing more households (see also Fig. 2). Also the root mean square error (RMSE) supports the increasing fit of the simulated load profiles with an increasing number of households.

Table 3 Indices for the comparison of simulated load profiles to the VDEW H0 standard load profile

Number of simulated households	Correlation with VDEW H0-SLP	RMSE [in W]
1	0,203	162,3
10	0,652	52,8
100	0,895	22,7
1.000	0,929	17,5
10.000	0,931	17,1

3.2 Optimization with variable energy prices

The developed model is not only able to simulate the effect of residential tariffs with variable energy prices but also the effect of self-consumption of self-produced power from PV systems, though the latter is not in focus of this paper. In both cases, the energy price for households is time-dependent as PV power is only available with a limited amount at certain points in time. The model assumes that the household knows for the entire simulated week at what time which price is valid and how much power from its PV system can be used. We are aware, that in reality this knowledge might rather be on a day-ahead basis. However, the effect of this information discrepancy is mostly negligible as neither the initial start time of the individual appliances relies on this knowledge, nor can any appliance be shifted by more than 24 hours. Hence, the model implicitly applies a day-ahead logic. Based on this knowledge, the household aims at minimizing its electricity bill by shifting utilizations of certain appliances. Only certain types of appliances allow for demand side flexibility, either when they are equipped with a thermal storage or when they operate rather independently from household's occupants once started (cf. Klobasa 2009; Moser et al. 2015). The former are smart fridges, freezers, electric heating systems and hot water systems with storage reacting automatically on price signals. The latter are dish washers, washing machines and tumble dryers which can either react automatically to price signals in case of smart appliances or can be shifted manually in their utilization by household occupants delaying their start time. For each appliance, type specific restrictions constraining their flexibility are considered. These are summarized in Table 4.

Table 4 Overview on appliance specific load shifting restrictions

	Load shifting range		Time of day restrictions
	Earliest start	**Latest start**	
Fridges[a]	Up to 1 hour earlier	Up to 1 hour later	None
Freezers[a]	Up to 1 hour earlier	Up to 1 hour later	None
Dish washers	Simulated start time[c]	Up to 12 hours later[b]	None
Washing machines	Simulated start time[c]	Up to 4 hours later[b]	Not later than 10 p.m. [b]
Tumble dryers	Simulated start time[c]	Up to 4 hours later[b]	Not later than 10 p.m.[b]
Night storage space heatings[c]	Simulated start time	Up to 24 hours later	None
Hot water heatings (Storage)[c]	Simulated start time	Up to 24 hours later	None

[a] Cf. Klobasa 2009
[b] Cf. UBA 2011
[c] Own assumptions

An optimization takes place for every shiftable appliance utilization within one week. Shiftable appliance utilizations are those of smart appliances and those for which households are willing to react on price signals manually. The probability for manual load shifting is derived through calibrating the model with measured data from the field trial already mentioned. The probability takes seasonal, diurnal and hourly differences into account. The objective of the optimization is to minimize the energy costs.

The linear (integer) optimization problems are solved with IBM ILOG CPLEX for appliances with thermal storage and with exhaustive enumeration for appliances with active participation of occupants but independent operation (dish washers, washing machines, tumble dryers). In the latter case, a solver does not have any computational advantages due to the non-linear structure of tariffs with variable energy prices and the problems are rather simple since the only decision variable is the specific start time of an utilization. In the former case, however, the decision variable is the specific power consumption of an appliance at every point in time leading to more complex optimization problems, thus necessitating a solver. This difference results in two different optimization problems – one for dish washers, washing machines, tumble dryers, i. e., active appliances, and one for appliances with thermal storage.

The objective function and the related cost function for shiftable active appliances $G^{FlexActive}$ are given in formulas (1) and (2). The decision variable in the optimization is the specific start time t of each utilization $u \in U_{w,g}$ of an appliance g in a week w. The lower and upper bound ($t^{min}_{w,g,u}$ and $t^{max}_{w,g,u}$) for the start time, i. e., the shifting range, depend on the appliance specific restrictions given in Table 4. The costs of a specific utilization $c_{w,t,g,u}$ are cumulated over its duration $D_{\dot{g}}$, where g is of type $\dot{g}$. The costs are influenced through the given energy price from the tariff $\varphi^{Tariff}_{w,(t+d)}$, where d counts through the duration of an appliance utilization, and the power used from a PV system $q^{PV}_{w,(t+d),g,u}$ which is available at a cheaper price φ^{PV}. The usable power from a PV system is restricted through its at a specific point of time initially available power $\nu_{w,t}$ reduced by the already simulated power consumption $\tilde{q}_{w,t,g,u}$ of other appliances (cf. constraint (3)). Since the covered appliances follow a specific load profile, their power consumption during the utilization can be determined through a load factor $\psi_{\dot{g},d}$ and the appliance peak load λ^{max}_{g}. As the price is given per energy unit, the power consumption is converted to its corresponding energy consumption in the specific 15-minutes time step.

$$\min_{\substack{t \in \{t^{min}_{w,g,u},\dots,t^{max}_{w,g,u}\} \\ \forall g \in G^{FlexActive}, u \in U_{w,g}, w \in W}} c_{w,t,g,u} \tag{1}$$

$$c_{w,t,g,u} = \frac{1}{4} \sum_{d=0}^{D_{\dot{g}}-1} \left(q^{PV}_{w,(t+d),g,u} * \varphi^{PV} + \left(\psi_{\dot{g},d} * \lambda^{max}_{g} - q^{PV}_{w,(t+d),g,u} \right) * \varphi^{Tariff}_{w,(t+d)} \right) \tag{2}$$

$$\forall\, t \in \{t^{min}_{w,g,u}, \dots, t^{max}_{w,g,u}\}, g \in G^{FlexActive}, u \in U_{w,g}, w \in W$$

$$q^{PV}_{w,t,g,u} = max\left(0, min\left(\nu_{w,t} - \sum_{g \in \tilde{G}} \sum_{u \in \tilde{U}_{w,g}} \tilde{q}_{w,t,g,u}\,, \lambda^{max}_{g}\right)\right) \tag{3}$$

$$\forall\, t \in \{0,1,\dots,|T_w|\}, g \in G^{Flex}, u \in U_{w,g}, w \in W$$

Shiftable appliances with thermal storage ($G^{FlexHeat}$ and $G^{FlexCold}$) follow a different optimization approach, represented through the objective function and the related cost function in formulas (4) and (5). In this case the decision variables are the used power from a PV system $q^{PV}_{w,t,g,u}$, if available, and the power used from the grid $q^{Grid}_{w,t,g,u}$. Combined with the specific price φ^{PV} and $\varphi^{Tariff}_{w,t}$ respectively the utilization costs can be determined. Divergent from the previous optimization problem, the utilization is not dependent on a specific start time. While cold appliances are continuously in use throughout a week and their optimization takes place on an hourly basis, heating appliances are optimized on a daily basis, depending on if they are used on a specific day or not.

$$\min_{\substack{\left(q^{PV}_{w,t,g,u}, q^{Grid}_{w,t,g,u}\right) \\ \forall g \in G^{FlexHeat} \cup G^{FlexCold}, u \in U_{w,g}, w \in W}} c_{w,g,u} \tag{4}$$

$$c_{w,g,u} = \frac{1}{4}\left(\sum_{t=t^{min}_{w,g,u}}^{t^{max}_{w,g,u}} q^{PV}_{w,t,g,u} * \varphi^{PV} + q^{Grid}_{w,t,g,u} * \varphi^{Tariff}_{w,t}\right) \tag{5}$$

$$\forall\, g \in G^{FlexHeat} \cup G^{FlexCold}, u \in U_{w,g}, w \in W$$

The given optimization problem is subject to several constraints. Independent from the specific appliance type, the power consumption from the grid may not exceed the peak load λ^{max}_g of the specific appliance. Additionally, other constraints need to be considered depending on the optimized appliance type.

Fridges and freezers are implemented with a short shifting range of plus/minus one hour. The main constraint in this case is that within every hour $h \in H_w$ in week w the initially simulated power consumption $\tilde{q}_{w,g,h}$ needs to be covered during the optimization time span from $t^{min}_{w,g,h}$ to $t^{max}_{w,g,h}$ through power used either from the PV system $q^{PV}_{w,t,g,\mathrm{h}}$ or from the grid $q^{Grid}_{w,t,g,\mathrm{h}}$ (see equation (6)).

$$\sum_{t=t^{min}_{w,g,h}}^{t^{max}_{w,g,h}} \left(q^{PV}_{w,t,g,h} + q^{Grid}_{w,t,g,h}\right) = \tilde{q}_{w,g,h} \tag{6}$$

$$\forall\, h \in H_w, g \in G^{FlexCold}, w \in W$$

Due to this hourly approach, consecutive optimizations overlap. In order to adhere to the appliance specific minimum and maximum loads λ^{min}_g and λ^{max}_g, an additional constraint is considered. The sum of the already set power consumption from previous optimizations $\ddot{q}_{w,t,g}$ and the two decision variables of the current optimization $q^{PV}_{w,t,g,h}$ and $q^{Grid}_{w,t,g,h}$ must remain within the appliance specific load limits (see constraint (7)).

$$\lambda^{min}_g \le q^{PV}_{w,t,g,h} + q^{Grid}_{w,t,g,h} + \ddot{q}_{w,t,g} \le \lambda^{max}_g \tag{7}$$

$$\forall\, t \in \{0,1,\dots,|T_w|\}, h \in H_w, g \in G^{FlexCold}, w \in W$$

For shiftable heating appliances $G^{FlexHeat}$, the power consumption throughout a day a is optimized. The main constraint in this case is that the minimum required heat $e^{min}_{w,t,g,a}$, from the beginning of the day until the current time period, of a household is supplied by the appliance at every point in time of that day. Therefore, the cumulated power consumption of the appliance, from the starting point of the optimization $t^{min}_{w,g,a}$ to the current time step t, must be greater or equal to the minimum required heat (see constraint (8)). Again, similar to the optimization of fridges and freezers, the sum of used power from a PV system and from the grid must remain within the appliance specific load limits.

$$\frac{1}{4}\sum_{j=t^{min}_{w,g,a}}^{t} \left(q^{PV}_{w,j,g,a} + q^{Grid}_{w,j,g,a}\right) \ge e^{min}_{w,t,g,a} \tag{8}$$

$$\forall\, t \in \{0,1,\dots,|T_a|\}, g \in G^{FlexHeat}, a \in A_{w,g}, w \in W$$

The described optimization results in cost minimal load profiles for every shiftable appliance in a specific week. This profile replaces the initially simulated one and will be used in case of an additional optimization with variable capacity prices which will be described in the next section.

Based on the described optimization with variable energy prices, the model is calibrated with data from the already mentioned field trial in order to reflect manual load shifting of households appropriately. In the field trial, a time of use tariff with three price steps was used from very low (SNT), to low (NT) to high (HT) (cf. Hillemacher, 2014). Additionally, around 25% of the participating households were equipped with smart appliances, mainly smart freezers, some smart dish washers and washing machines and few smart tumble dryers. The objective of the calibration is to represent the load shifting behavior, observed in the field trial, appropriately within the model. It is assumed, that the observed load shifting behavior based on a time of use tariff holds true for real time tariffs as well, which will be analyzed in the scenarios in section 4.

In Fig. 3, the indicated range represents the minimum and maximum load shifting potential achievable within the model using the abovementioned configuration from the field trial. The minimum is achieved when only the existing smart appliances react on the given price signals, the maximum when, in addition, all households manually shift all utilizations of their dish washers, washing machines and tumble dryers to the optimal start time.

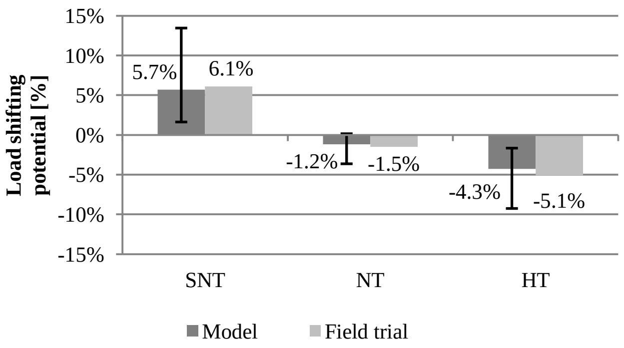

Fig. 3 Comparison of the modeled load shifting potential to the results from a field trial (cf. Hillemacher, 2014)

In order to avoid an overestimation of the load shifting potential, three aspects need to be considered in the calibration. First, few households in the field trial had an additional battery storage leading to an increased load shifting potential which is not covered in the model. Second, the model setup used for the calibration may differ from the real situation in the field trial, e. g., the distribution of household sizes and electric appliances. Third, the results from the field trial may be biased due to the voluntary participation of the households having an increased interest in this topic and maybe a higher willingness to react on price signals (cf. Hillemacher 2014). Consequently, following a more conservative approach, the calibration should result in a slightly lower load shifting potential from the model than observed in the field trial.

The calibration takes place through the definition of probabilities for hourly Bernoulli distributions of every season weekday combination ranging from zero (no manual load shifting at all) to one (full manual load shifting). In Fig. 3, the columns show the achieved load shifting potential with the finally chosen Bernoulli distributions of the model in comparison to the observed load shifting potential within the field trial. Based on the underlying likelihood, the model determines for every utilization of dishwashers, washing machines and tumble dryers if manual load shifting takes place. The hourly probabilities are given in Table A.1 in the appendix.

3.3 Optimization with variable capacity prices

Similar to the optimization with variable energy prices, the optimization with variable capacity prices is influenced through the use of a related tariff and the existence of a PV system. Again it is assumed that households know for one week in advance at what time how much power from their PV systems is available and at what time and for how long a curtailment will occur. The considered appliance types remain the same as in the optimization with variable energy prices having the same shifting restrictions already presented in Table 4. This time, however, the optimization does not take place for single appliances but for every shortage situation during the week considering all appliances in use during the shortage. The mixed integer linear problems are solved with the IBM ILOG

CPLEX solver. The maximum available power level of households $\gamma_{w,t}^{max}$ depends on the contracted guaranteed power level $\gamma_{w,t}^{Tariff}$ and, if available, additional power from a PV system $\nu_{w,t}^{max}$ at a specific point in time (see equation (9)).

$$\gamma_{w,t}^{max} = \gamma_{w,t}^{Tariff} + \nu_{w,t}^{max} \; \forall \; t \in \{0,1,\dots,|T_w|\}, w \in W \tag{9}$$

The objective of the optimization is to remain below the maximum power level in every shortage situation s announced by the electricity provider, given as exogenous input for the model. Therefore the utilizations of all shiftable appliances can be optimized within the lower and upper bound of a shortage ($t_{w,s}^{min}$ and $t_{w,s}^{max}$), both depending on the considered appliances shifting ranges. In order to reduce possible negative impacts on households' comfort, appliance types are prioritized based on a penalty term $\tau_{\dot{g}}^{Flex}$. Whenever possible, smart heating appliances $G^{FlexHeat}$ are used first, then smart fridges and freezers $G^{FlexCold}$ and finally shiftable active appliances $G^{FlexActive}$. If a household is not able to remain below its maximum available power level during a shortage situation, a much bigger penalty term τ^{Tariff} is applied. In this case, it can be chosen if the model shall allow the household to consume more power than contracted or if the power consumption is reduced on the contracted power level after the optimization. The former represents a possible tariff structure where customers would have to pay a penalty price when exceeding their power level during shortages. The latter represents a tariff where technical restrictions hinder households in exceeding their power level. In reality the latter would mean for households that they would need to provide additional demand side flexibility, e. g., by switching of other appliances than considered as shiftable in this model.

The objective function (10) includes two binary decision variables $b_{w,t,s}^{Tariff}$ and $b_{w,t,s,g,u}^{Flex}$ linking this function with the main constraints of the optimization problem. The first decision variable is part of a big-M constraint turning one if the cumulated power consumption of all appliance utilizations exceeds the maximum available power level $\gamma_{w,t}^{max}$ at any point in time during the duration of the shortage from $t_{w,s}^{min}$ to $t_{w,s}^{max}$ (see constraint (11)). Otherwise $b_{w,t,s}^{Tariff}$ is null.

$$\min_{\substack{\left(b_{w,t,s}^{Tariff}, b_{w,t,s,g,u}^{Flex}\right) \\ \forall\, s \in S_w, w \in W}} \left(\sum_{t=t_{w,s}^{min}}^{t_{w,s}^{max}} \left(\tau^{Tariff} * b_{w,t,s}^{Tariff} + \sum_{g \in G^{Flex}} \sum_{u \in U_{w,g}} \tau_{\dot{g}}^{Flex} * b_{w,t,s,g,u}^{Flex} \right) \right) \tag{10}$$

Subject to:

$$\left(\sum_{g \in G} \sum_{u \in U_{w,g}} q_{w,t,g,u} \right) - \gamma_{w,t}^{max} \leq b_{w,t,s}^{Tariff} * M^{Tariff} \tag{11}$$
$$\forall \; t \in \left\{t_{w,s}^{min}, \dots, t_{w,s}^{max}\right\}, s \in S_w, w \in W$$

The second binary variable of the objective function turns one if an appliance utilization is changed during the optimization in comparison to the initially simulated load profile. For heating appliances as well as fridges and freezers a deviation from the initially simulated power consumption $\tilde{q}_{w,t,g,u}$ can exist through an over- or under-consumption at a specific point in time. Consequently, the binary variable equals the sum of two other binary variables $b_{w,t,s,g,u}^{Flex+}$ for the over- and $b_{w,t,s,g,u}^{Flex-}$ for the under-consumption (see equation (12)). The related big-M constraints to penalize the corresponding deviation are given in (13) and (14).

$$b_{w,t,s,g,u}^{Flex} = b_{w,t,s,g,u}^{Flex-} + b_{w,t,s,g,u}^{Flex+} \tag{12}$$
$$\forall \; t \in \left\{t_{w,s}^{min}, \dots, t_{w,s}^{max}\right\}, g \in G^{FlexHeat} \cup G^{FlexCold}, u \in U_{w,g},$$

$$s \in S_w, w \in W$$

$$\tilde{q}_{w,t,g,u} - q_{w,t,g,u} \leq b^{Flex-}_{w,t,s,g,u} * M^{Flex}_{\dot{g}} \tag{13}$$

$$\forall\, t \in \{t^{min}_{w,s}, \dots, t^{max}_{w,s}\}, g \in G^{FlexHeat} \cup G^{FlexCold}, u \in U_{w,g},$$

$$s \in S_w, w \in W$$

$$q_{w,t,g,u} - \tilde{q}_{w,t,g,u} \leq b^{Flex+}_{w,t,s,g,u} * M^{Flex}_{\dot{g}} \tag{14}$$

$$\forall\, t \in \{t^{min}_{w,s}, \dots, t^{max}_{w,s}\}, g \in G^{FlexHeat} \cup G^{FlexCold}, u \in U_{w,g},$$

$$s \in S_w, w \in W$$

For shiftable active appliances, the specific start time of the utilization $t^{Start}_{w,g,u}$ is the determining factor for its power consumption since, after the start, a fixed load profile is followed. To reflect this appliance behavior appropriately in the optimization problem, every step of the load profile is represented with a dedicated binary variable $b^{Profile}_{w,t,s,g,u,d}$ during the shifting range of the appliance utilization. This variable is set to one if, at a specific point in time t, the specific value of the appliance load profile at position d is used. In combination with a load factor $\psi_{\dot{g},d}$ of that specific position λ^{max}_{g} and the appliance peak load, the power consumption can be calculated accordingly (see equation (15)).

$$q_{w,t,g,u} = \sum_{d=0}^{D_{\dot{g}}-1} b^{Profile}_{w,t,s,g,u,d} * \psi_{\dot{g},d} * \lambda^{max}_{g} \tag{15}$$

$$\forall\, t \in \{t^{min}_{w,s,g,u}, \dots, t^{max}_{w,s,g,u}\}, g \in G^{FlexActive}, u \in U_{w,g}, s \in S_w, w \in W$$

Constraint (16) connects the single steps of the load profile, constraint (17) ensures that every step of the appliance load profile is used only once per utilization. Finally, constraint (18) is used to avoid a temporal overlap of two utilizations of the same appliance.

$$b^{Profile}_{w,t,s,g,u,d} = b^{Profile}_{w,(t-1),s,g,u,(d-1)} \tag{16}$$

$$\forall\, t \in \{t^{min}_{w,s,g,u}, \dots, t^{max}_{w,s,g,u}\}, g \in G^{FlexActive}, u \in U_{w,g},$$

$$d \in \{1, \dots, D_{\dot{g}} - 1\}, s \in S_w, w \in W$$

$$\sum_{t=t^{min}_{w,s,g,u}}^{t^{max}_{w,s,g,u}} b^{Profile}_{w,t,s,g,u,d} = 1 \tag{17}$$

$$\forall\, g \in G^{FlexActive}, u \in U_{w,g}, d \in \{0, \dots, D_{\dot{g}} - 1\}, s \in S_w, w \in W$$

$$\sum_{u \in U_{w,g}} \sum_{d=0}^{D_{\dot{g}}-1} b^{Profile}_{w,t,s,g,u,d} \leq 1 \tag{18}$$

$$\forall\, t \in \{t^{min}_{w,g,u}, \dots, t^{max}_{w,g,u}\}, g \in G^{FlexActive}, s \in S_w, w \in W$$

If the utilization of an active appliance is delayed during the optimization, the start time changes and consequently the first step of the appliance load profile takes place at a different point in time. The corresponding binary variable $b^{Profile}_{w,t^{Start}_{w,g,u},s,g,u,0}$ is linked to the penalty binary variable $b^{Flex}_{w,t^{Start}_{w,g,u},s,g,u}$ for active appliances (see constraint (19)), with $t^{Start}_{w,g,u}$ being the previously simulated start time.

$$1 - b^{Profile}_{w,t^{Start}_{w,g,u},s,g,u,0} \leq b^{Flex}_{w,t^{Start}_{w,g,u},s,g,u} \tag{19}$$

$$\forall\, g \in G^{FlexActive}, u \in U_{w,g}, s \in S_w, w \in W$$

Other constraints considered in the optimization with variable capacity prices relate to the minimum heat and cooling requirements and are very similar to those already explained in the previous section. Therefore, they are not explained in detail again. After the optimization, the already created weekly load profiles of the household are adapted accordingly and the next week can be simulated until a full year load profile is available.

4 Results and discussion

The described model is used for a comparative analysis of the impact of different electricity tariffs on residential demand side flexibility. Therefore, four different scenarios will be defined, evaluated and discussed in the following.

4.1 Scenario description

The model offers a wide range of setup options, e. g., with regard to the simulated household characteristics, the share of smart appliances in households and the applied electricity tariffs. As the objective of this paper is to analyze the impact of different tariffs on residential demand side flexibility, the scenarios must be identical except regarding the applied tariff.

The reference for the following analysis is a scenario with a classic electricity tariff without any variable price components representing the status quo for most German households. For the tariff with variable capacity prices, the service level objective for three out of four service level indicators, i. e., the guaranteed power level, the frequency of curtailments and the duration, must be defined for different household sizes as the household size is a major impact factor for residential electricity demand (cf. Hayn et al. 2014a). Furthermore, since households shall only be curtailed in case of shortage situations, it must be defined when these shortage situations occur. As this is an exogenous parameter to our model, we use hourly EEX prices of 2011 as a reference. Based on these prices, ten shortage situations with a maximum duration of four hours are defined in every month at times when the EEX prices are the highest. The frequency of ten shortages per month with a maximum duration of four hours is taken from the results of a representative survey with more than 1,000 German households indicating that this combination of service level objectives is accepted by the majority of households (cf. Hayn et al. 2015b). The survey results additionally indicate that households have different needs for supply security – some households have a higher, some have a lower need for supply security. Hence, based on the survey results and some sensitivity analyses with the model, the guaranteed power levels for different household sizes are set as shown in Table 5. With regard to the shown values it must be kept in mind that the model operates on a basis of 15-minutes time steps. Thus, higher inrush currents that might occur from specific electric appliances or other peaks become leveled in the model, leading to an underestimation of peak loads.

Table 5 Guaranteed power levels for different tariff options

	Lower need for supply security	**Higher need for supply security**
1-person-households (HH1)	2.000 W	4.000 W
2-persons-households (HH2)	2.500 W	4.500 W
3-persons-households (HH3)	3.000 W	5.000 W
4-persons-households (HH4)	3.000 W	5.000 W
5 or more-persons-households (HH5)	3.500 W	5.000 W

In order to achieve consistent scenarios, the tariff with variable energy prices is based on the same EEX data and information on the composition of average German residential electricity prices, given in Table A.2 in the appendix. By substituting the average value for generation by the hourly EEX value, a real-time-price tariff with hourly values is constructed. The chosen methodology ensures consistency in the effects of the tariff with variable energy and variable capacity prices since curtailments and high energy prices coincide.

Besides the tariffs, further setup options must be defined for the scenarios. In all scenarios 1,000 households are simulated reflecting the German distribution of household sizes as well as the corresponding equipment with electric appliances (cf. Destatis 2013). Only appliances for electric hot water and space heating are excluded for two reasons. First, only a minority of German households uses electric appliances for hot water and space heating. Second, the high power consumption of these appliances would require different tariffs with variable capacity prices which are not in scope of this paper. Even today's residential standard load profile is not valid for households with electric space heating (cf. Fünfgeld and Tiedemann 2000). PV systems are also not included in the analysis as the resulting self-consumption alters the simulated load profiles disguising the impact of tariffs.

The model is able to reflect manual and automatic reaction of households on price or control signals. For an automated reaction, smart appliances are required. Results of our model concerning the effect of different shares of smart appliances in combination with the time-of-use tariff used of the already mentioned field trial are illustrated in Fig. 4, also differentiating the effect with and without hot water and space heating appliances. Every household owning at least one smart appliance is denominated as a smart household.

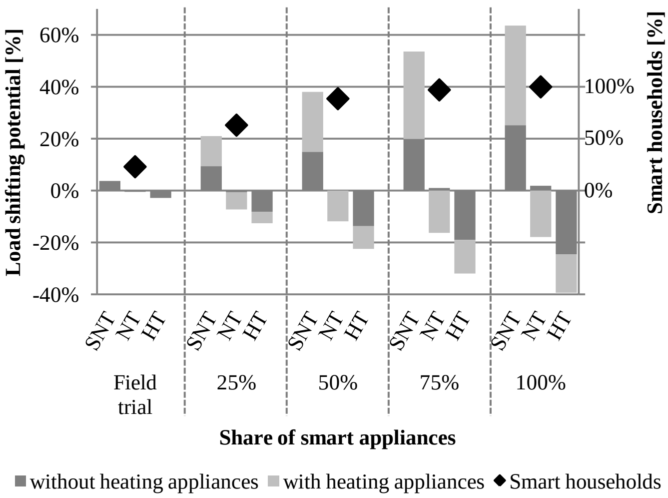

Fig. 4 Sensitivity analysis for the impact of smart appliances on demand side flexibility

In the field trial, about 25% of smart households participated. With an increasing share of smart appliances, the number of smart households increases as well, leading to a higher load shifting potential (cf. Fig. 4). Especially the utilization of smart hot water and space heating appliances allows households to significantly increase their demand side flexibility, due to the associated thermal storages and the high energy consumption of these appliances. As residential electricity tariffs with variable price components are nowadays hardly available, we analyze potential future scenarios. Therefore, we assume a share of 50% smart appliances, representing a possible scenario in the mid-term future. As a consequence, around 95% of all simulated households own at least one smart appliance.

The results of the conducted survey indicate that around 75% of the participants are willing to use a tariff with variable capacity prices (cf. Hayn et al. 2015b). However, for the purpose of this paper, we assume that all households use the same tariff within one scenario. Besides the reference scenario without variable price components, three more scenarios are analyzed. One scenario with variable energy prices, one with variable capacity prices and one with variable energy and capacity prices. Fig. 5 shows in a simplified morphologic box the chosen model setup for the four scenarios.

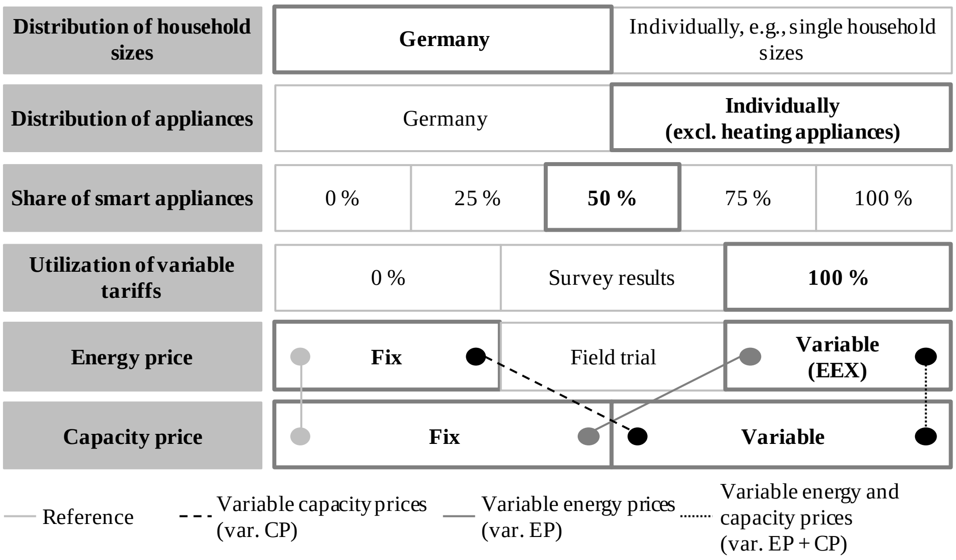

Fig. 5 Morphologic box for the model setup of the four scenarios

4.2 Scenario analysis

As the defined scenarios differ only with regard to the applied tariffs they can be used to analyze the impact of different residential electricity tariffs on demand side flexibility. In this context, two questions are of major interest:

- How do different tariffs alter the general power consumption behavior of households?
- How do these tariffs influence the power consumption of households in times of shortages?

Fig. 6 shows the box-plot per scenario for the power consumption of 1,000 simulated households during one simulated year. Referring to the first question it becomes obvious that variable energy prices have a significant impact on residential power consumption while the impact of variable capacity prices is negligible. Tariffs with variable energy prices lead on the one hand to more extreme peak values but on the other hand to a smaller interquartile range and median compared to the reference scenario. This means that the related load profile is smoothened during most times of the year but showing extreme values at certain times. In contrast, the impact of tariffs with variable capacity prices is only visible in the absolute values being too small to be visible in the chart. Briefly stated, tariffs with variable capacity prices slightly reduce the maximum power consumption when used in combination with variable energy prices.

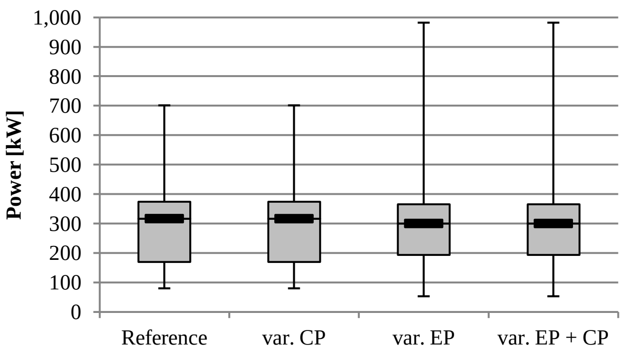

Fig. 6 Box plots for the power consumption of 1,000 simulated households

The described results can be explained through the different tariff structures. While tariffs with variable capacity prices, as used within this paper, only influence households' power consumption during shortages, which is for a maximum of 40 hours per month and only aiming at power reduction, the applied tariff with variable energy prices constantly incentivizes households to adapt their power consumption in both directions. Additionally, tariffs with variable energy prices always incentivize all households in the same way while in tariffs with variable capacity prices only those households are constrained that initially intended to use more power than contracted as their guaranteed power level. In the chosen setup of power levels this is only a fraction of the total number of simulated households, hence the visible effect is smaller.

Since the objective of the used tariff with variable capacity prices is to reduce residential power consumption during shortage situations, the following analysis considers only those time steps at which a shortage situation has been simulated. Fig. 7 shows the box plot per scenario for the change in power consumption during those shortages of 1,000 simulated households. The maximum power reduction of tariffs with variable capacity prices is approximately -6%, varying in a very narrow interquartile range around the median of -2%. In very rare situations a minimal power increase can be observed. This phenomenon occurs mainly during long shortages when load shifting activities result in small power increases in single time steps of the shortage still obeying the effective power levels.

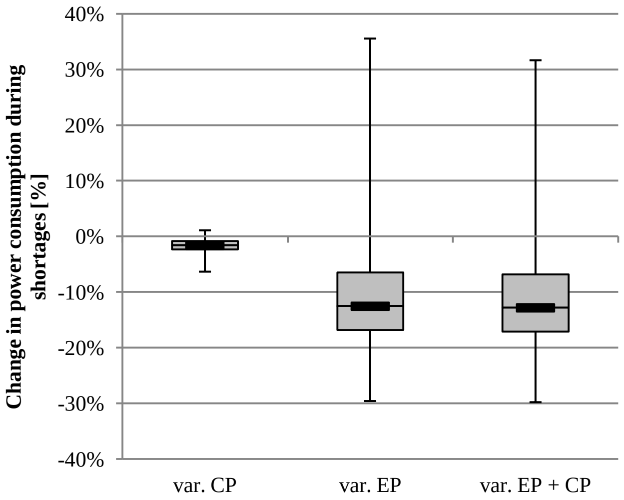

Fig. 7 Box plots for the change in power consumption during shortages of 1,000 simulated households

The maximum power reduction of tariffs with variable energy prices exceeds the one of tariffs with variable capacity prices with almost -30% by far. Even the median, with almost -13%, is about twice as big as in the former case. However, two drawbacks are shown in the figure as well. First, in some situations, tariffs with variable energy prices lead to strong power increases of more than +30% during shortage situations aggravating the criticality. Second, the interquartile range is much bigger for tariffs with variable energy prices resulting in a higher uncertainty about the effective power reduction in shortage situations.

The power increase occurs again during long shortages over several hours. Since the energy prices vary on an hourly basis, even small price reductions during the shortage result in lower energy costs incentivizing the households to shift appliance utilizations to that point in time. As all households react simultaneously on price signals in the model these power increases appear. Even though this effect occurs only in about 5% of all time steps in shortage situations, it can still be critical for energy systems, when the majority of power shall be provided through renewable energy sources. Combining variable energy and capacity prices slightly improves the described drawbacks, but the impact of variable energy prices still predominates (cf. Fig. 7).

Fig. 8 shows a specific example for a summer Sunday with two shortage situations highlighting the impact of the analyzed tariffs on demand side flexibility. The selected day is characterized through a comparably high electricity demand in the reference scenario. In the upper part of the figure, the load profiles of the four scenarios as well as the energy price and shortage situations are shown. The lower part zooms in on one shortage situation showing the change in power consumption per 15-minutes time step. The results described beforehand are supported by this figure. The scenarios with variable energy prices lead to a much stronger decrease in power consumption in the first hour of the shortage, but result in a small increase in one time step of the second hour. The scenario with variable capacity prices shows only a power reduction of about -2% but this potential is rather constant over time.

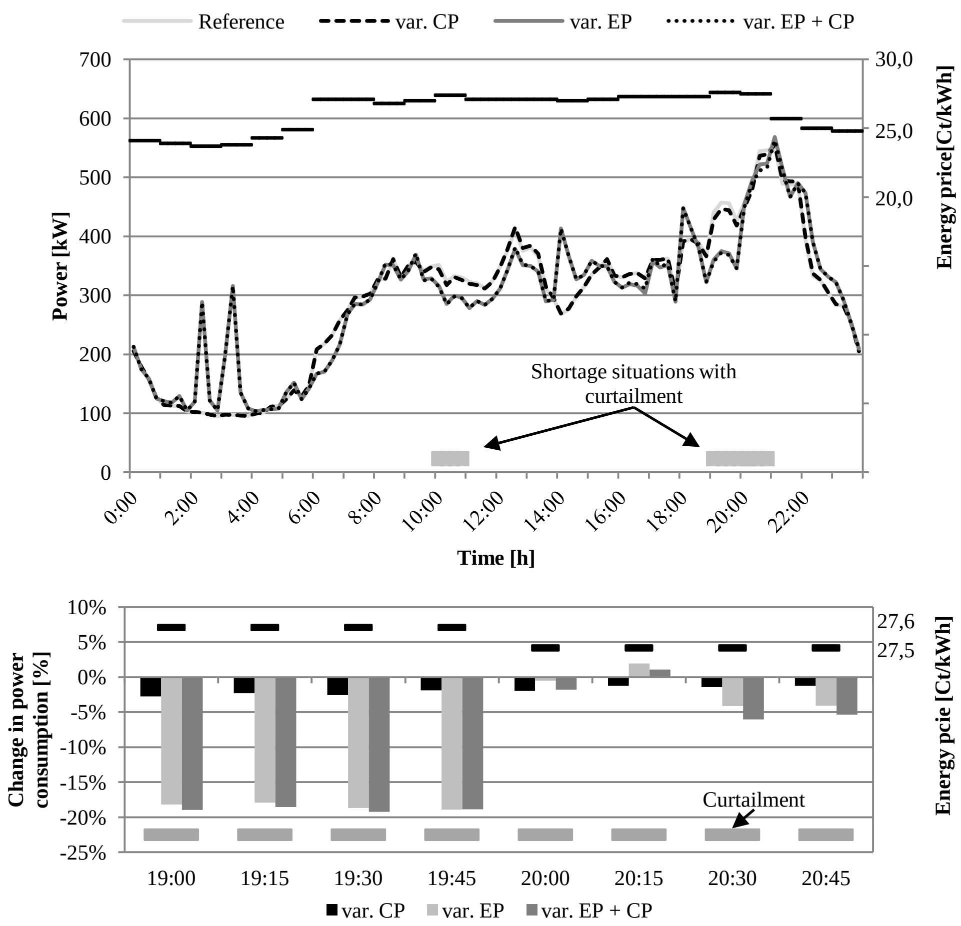

Fig. 8 Load profiles and changes in power consumption on a summer Sunday with shortages situations and high energy demand

4.3 Discussion

The presented results show that electricity suppliers can influence residential demand through different tariffs. The specific impact of tariffs on demand side flexibility is, however, strongly dependent on the characteristics of the used tariff.

Tariffs with variable energy prices always incentivize all participating households at the same time. Hence, the achievable change in power consumption is higher. The main drawback lays in the occurrence of unwanted power peaks during shortage situations due to the simultaneous reaction of households and smart appliances on small price changes. Additionally, the fluctuation of demand side flexibility varies more. Both effects make it more difficult for electricity providers to predict households' power demand. To overcome the mentioned issues of tariffs with variable energy prices, either a more sophisticated price signal needs to be created or the operating mode of smart appliances needs to be adjusted accordingly to avoid unwanted power peaks.

Also, the setup of tariffs with variable capacity prices influences the measurable demand side flexibility. Even though all households in the corresponding scenario use such a tariff, only those households are curtailed in their power consumption which have a higher demand than covered through their guaranteed power level. With the current set of power levels, the probability for a household to be curtailed by the model is very low. Therefore only a small number of households contributes to the shown effects. Lowering the guaranteed power levels would increase the number of households being curtailed, hence increasing the change in power consumption. However, due to the 15-minutes temporal resolution and the related underestimation of power peaks, we do not recommend this approach. The main advantage of tariffs with variable capacity prices is the high predictability and reliability of the achievable change in power consumption during shortage situations allowing electricity providers to use the resulting demand side flexibility in their planning. Besides these quantified advantages, tariffs with variable capacity prices additionally allow for a fair allocation of system costs based on the individual customer needs for security of supply. Furthermore, the tariff design with curtailments only in shortage situations avoids the penalization of system-conducive behavior of households in case of excess supply from RES.

In tariffs with variable energy and capacity prices, the impact of the former still predominates the simulated load profiles. The chosen power levels still allow households to increase their power demand in accordance with lower energy prices even in shortage situations without being curtailed. However, an improvement with regard to unwanted power peaks can be achieved. Also the non-quantified advantages mentioned before are still valid.

The described results underlie certain limitations due to the chosen model and tariff setup. The main limitation of the model is its temporal resolution of 15 minutes as lower temporal resolutions result in an underestimation of peak loads. Increasing the temporal resolution, e. g., to one minute or even seconds would help to better simulate appliance peak loads such as inrush currents which are leveled with lower temporal resolutions. Consequently, the actual power demand of households can exceed the model results. Furthermore, the model includes only 17 different appliance types, therefore not covering the full range of available appliances in households. Including additional appliances has the potential to further increase the reliability of the modeled load profiles. Finally, the used data for the seasonal, diurnal and hourly appliance utilization is based on a field trial from the 1990s. Thus, changes in daily routines of the last 25 years are not considered. To overcome the mentioned model limitations, more detailed data needs to be available.

5 Conclusions and outlook

Within this paper, we have developed a model capable to simulate the impact of different electricity tariffs on residential demand side flexibility. With regard to the tariffs, both variable energy prices and variable capacity prices are considered in the analysis, hence enhancing existing modeling approaches. Additionally, households' behavior regarding manual load shifting was calibrated for the developed model based on data of a large scale field trial. To analyze the impact of different tariffs on residential demand side flexibility, four scenarios with different tariff setups were compared. While the reference scenario has no variable price components, all other scenarios incentivize households to change their electricity consumption behavior. We have used one scenario based on a tariff with variable energy prices only, one based on a tariff with variable capacity prices only and one based on a tariff with a combination of variable energy and capacity prices. Our results show, that variable energy prices induce a much higher demand side flexibility than variable capacity prices. However, with regard to the predictability and reliability of the resulting impact on demand side flexibility, tariffs with variable capacity prices are superior to those with variable energy prices. Moreover, tariffs with variable capacity prices allow electricity providers to introduce tariffs that take customer needs for security of supply and the related impact on energy system costs into account. As the curtailment in these tariffs is limited to shortage situations only, a penalization of system-conducive behavior of households, e. g., in case of excess power supply from RES, is avoided.

Going forward, two research areas are of major interest with regard to the addressed topics of this paper. First, it needs to be analyzed how new tariffs, both with variable energy as well as with variable capacity prices, can be integrated into energy markets. Therefore, a thorough evaluation of possible business cases, from a provider and a customer point of view, is required, considering new retail market designs rewarding demand side flexibility. Second, which relates to the first research area, the impact of different tariffs on entire energy systems should be quantitatively reviewed. By incorporating residential demand side flexibility in energy system models, the impact on generation, transportation and distribution capacities can be assessed. Especially from a provider's point of view, this is very relevant in order to evaluate the potential benefits of new electricity tariffs.

From a policy perspective it becomes obvious that the regulatory framework in the energy sector needs to be adjusted in order to allow electricity providers to develop sustainable business models. One the one hand, politics can facilitate the roll-out of new tariffs by including required technical specifications in guidelines for advanced metering systems. For instance, in Germany the technical guideline TR-03109 of the Federal Office for Information Security could be adapted, specifying the need for a technical curtailment function in advanced metering systems. On the other hand, residential demand side flexibility needs to be rewarded. Politics needs to change existing regulations in order to increase the incentive for residential customers and electricity providers providing demand side flexibility.

Appendix

Table A.1 Hourly probabilities for the Bernoulli distributions of manual load shifting

	Winter			**Summer**			**Transition**		
	Mo.-Fr.	Sa.	Su.	Mo.-Fr.	Sa.	Su.	Mo.-Fr.	Sa.	Su.
0	10%	10%	10%	10%	10%	10%	10%	10%	10%
1	10%	10%	10%	10%	10%	10%	10%	10%	10%
2	10%	10%	10%	10%	10%	10%	10%	10%	10%
3	10%	10%	10%	10%	10%	10%	10%	10%	10%
4	10%	10%	10%	10%	10%	10%	10%	10%	10%
5	20%	20%	20%	20%	20%	20%	20%	20%	20%
6	20%	20%	20%	20%	20%	20%	20%	20%	20%
7	50%	40%	40%	30%	30%	30%	30%	30%	30%
8	50%	40%	40%	30%	30%	30%	30%	30%	30%
9	50%	40%	50%	30%	30%	30%	30%	30%	30%
10	50%	40%	50%	40%	30%	40%	40%	30%	40%
11	50%	40%	50%	40%	30%	40%	40%	30%	40%
12	50%	50%	50%	40%	30%	40%	40%	30%	40%
13	50%	50%	50%	40%	30%	40%	40%	30%	40%
14	50%	50%	50%	40%	30%	40%	40%	30%	40%
15	50%	40%	50%	40%	30%	40%	40%	30%	40%
16	50%	40%	50%	40%	30%	40%	40%	30%	40%
17	40%	40%	40%	30%	30%	30%	30%	30%	30%
18	40%	40%	40%	30%	30%	30%	30%	30%	30%
19	30%	30%	30%	20%	20%	20%	20%	20%	20%
20	30%	30%	30%	20%	20%	20%	20%	20%	20%
21	20%	20%	20%	20%	20%	20%	20%	20%	20%
22	10%	10%	10%	10%	10%	10%	10%	10%	10%
23	10%	10%	10%	10%	10%	10%	10%	10%	10%

Table A.2 Composition of average German residential electricity prices in 2011

Price components	**Value 2011**	**Unit**	**VAT relevant**
Concession feeds	1,790	Ct/kWh	Yes
Surcharge under EEG	3,530	Ct/kWh	Yes
Surcharge under KWKG	0,030	Ct/kWh	Yes
Electricity tax	2,050	Ct/kWh	Yes
Surcharge under section 19 StromNEV	0,000	Ct/kWh	Yes
Surcharge for offshore liability	0,000	Ct/kWh	Yes
Generation, sales, transport	13,800	Ct/kWh	Yes
Net electricity price	21,200	Ct/kWh	Yes
Value-added tax (VAT)	19	%	No
VAT absolute	4,028	Ct/kWh	No
Gross electricity price	25,228	Ct/kWh	No
Net network tariff	20	%	Yes
Net network tariff absolute	5,046	Ct/kWh	Yes
Generation, sales	8,754	Ct/kWh	Yes
Generation (Average spot price)	5,112	Ct/kWh	Yes
Sales	3,642	Ct/kWh	Yes

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