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Dynamic pricing and the flexible consumer – Investigating grid and financial implications: A case study for Germany

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ABSTRACT

Due to the ongoing expansion of renewable energies and the increasing energy demand of household consumers, e.g., due to the electrification of the mobility and heating sectors, grid bottlenecks and voltage band violations in low-voltage grids in Germany are expected to occur more frequently in the future. Dynamic pricing, implemented through digitization, is seen as one option to incentivize flexible and responsive electricity use of household consumers. Flexible consumption of household consumers could make grid utilization more efficient. So far, most studies on the effects of dynamic pricing focus on only one tariff for all household consumers within one low-voltage grid, whereas, in reality, households are free to choose between many different static and dynamic electricity tariffs. As previous studies have shown, the choice of tariff plays a major role in how flexibility is used. To address this research gap, we developed a model which integrates households and their static and flexible consumption and generation units into a home energy management system (HEMS) and minimizes the households' power purchase costs. The model considers a range of dynamic tariffs that are already available today and includes the decision-making of heterogeneous household customers regarding the choice of tariff. Load flow calculations are then used to determine and analyze the effects on a low-voltage grid area. With this methodology including the free choice of tariff we go beyond the state of the art and paint a more realistic picture of the effects of dynamic tariffs on low-voltage grids. Our results show that, even though dynamic tariffs lead to increased peak demand at the level of individual households, peak loads are spread more widely within a grid area as the result of households choosing different tariffs based on economic considerations. Due to these effects, dynamic pricing has positive effects on grid utilization and could reduce the need for grid expansion.

1. Introduction

The energy industry is currently facing major changes, including the expansion of renewable energies and increasing household energy demand due to electric vehicles (EVs), heat pumps (HPs), etc. On the one hand, these changes result in new business models and new ways for household consumers to participate in energy trading, facilitated through digitization, as well as in cost savings through automation in some areas. On the other hand, there will be a significant increase of the load on the electricity distribution grids in Germany [1,2]. Although grid stability in Germany is very high ($SAIDI_{EnWG}$[1] in low-voltage (LV) grids was 2.11 min in 2020, $ASIDI_{EnWG}$[2] in medium-voltage (MV) grids about 8.62 min [3]), the frequency of grid congestion and voltage band violations could increase sharply given the potential for high simultaneity of EV charging as well as heat demand if appropriate countermeasures are not taken. Those effects could especially increase in MV and LV grids, as this is where most heat pumps as well as most of the charging points for electric vehicles are likely to be found. One

Abbreviations: BSS, Battery storage system; CPP, Critical-peak-pricing; DA, Day-ahead; EV, Electric vehicle; HEMS, Home energy management system; HP, Heat pump; HS, Heat storage; iMSys, Intelligent metering system; LV, Low-voltage; MFH, Multi family home; MV, Medium-voltage; RTP, Real-time-pricing; SFH, Single family home; ToU, Time-of-use; WTP, Willingness to pay; WTPM, Willingness to pay more.

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[1] $SAIDI_{EnWG}$: System Average Interruption Duration Index; Indicates the average supply interruption per connected end consumer within a calendar year. Only unplanned interruptions are included in the calculation.

[2] $ASIDI_{EnWG}$: Average System Interruption Duration Index; Indicates the average supply interruption per connected rated services within a calendar year. Only unplanned interruptions are included in the calculation.

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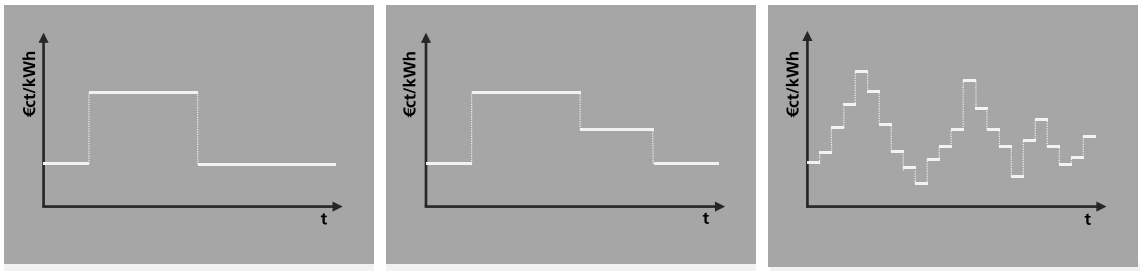

Two-tier Time of Use (2-tier ToU)
Each time period is assigned to a price level. Within one day, two price levels are possible. Price levels and time periods are set for a whole year.

Three-tier Time of Use (3-tier ToU)
Each time period is assigned to a price level. Within one day, three price levels are possible. Price levels and time periods are set for a whole year.

Day Ahead Pricing (DA)
Tariffs based on the day ahead spot market prices. The spot market price can be passed on directly to the customer, but certain min/max limits can also be set. Price levels and time periods are set the day before after market clearing.

Fig. 1. Concepts of dynamic tariffs available on the market in Germany.

promising and in literature much discussed way to handle this increased load and the mentioned simultaneities is to incentivize flexible consumption behavior through dynamic electricity price components ('dynamic tariffs'). This could improve the efficiency of use of the distribution grid, so that grid expansion can be delayed or avoided [4–6]. As cost-reflective pricing is one way to promote the system integration of small-scale power generation plants and flexible loads, regulators, e.g., at EU level, have established the obligation for utilities to offer dynamic tariffs to their customers [7].

Some energy suppliers, therefore, already offer dynamic tariffs for household customers (e.g., 'Tibber' [8], 'aWATTar' [9] or ''Polarstern' [10] in Germany). The tariffs available in Germany are two- or three-tier time-of-use (ToU) tariffs and hourly tariffs based on the day-ahead wholesale market price. An overview over these three pricing schemes is given in Fig. 1. As the rollout of intelligent metering systems (iMSys) advances and home energy management systems (HEMS) are improving, dynamic tariffs can be offered and used to an even greater extent in the future.

As the framework conditions for the use of dynamic tariffs will continue to improve in the future, the question arises, which effects those tariffs are having on the customer's electricity bill and which flexible consumers will opt for a dynamic tariff. For all consumers having a certain degree of flexibility (e.g., through storage or controllable devices) making use of those tariffs, a change in the individual load profile can be expected. Those changes on individual household level can have a systemic effect on LV distribution grids due to the incentivized use of flexibility.

1.1. Literature

Dynamic tariffs for end-users, e.g., based on the wholesale electricity price or on price signals derived from the local grid situation, have been investigated in several existing papers. One major topic is their influence on the load curves of households, electric vehicles, heat pumps, PV home storage systems and other flexible devices. Another important issue is their financial attractiveness for end-users. Going one step further, there is also research on the influence of dynamic tariffs on distribution grids. These three literature strands are relevant for this paper and are presented below.

The effects of dynamic tariffs on household load curves have already been discussed in several studies. Ref. [11] gives a good overview of pilot studies in different countries and reveals that the implementation of ToU tariffs can lower peak demand by about 3–6%. Critical-peak pricing (CPP) can lead to even higher reductions of about 13–20%, or, in combination with enabling technologies, 27–44%. Ref. [12] observed an average peak load reduction of up to 54% for individual households using dynamic pricing schemes.

The financial attractiveness of dynamic tariffs for flexible consumers (end-users with different flexible technologies such as EVs, HPs, or battery storage systems (BSS)) has also already been assessed in several papers: Ali et al. [13] determined potential energy cost savings for direct electric space heating and partial thermal storage using a tariff based on hourly prices of the Nordic day-ahead power market. In Ref. [14], the focus was on smart charging of electric vehicles. The authors found lower charging costs for EV owners using a dynamic tariff. Ref. [15] explored the effect of different dynamic tariff schemes ('Economy 7', which corresponds to a day/night tariff; 'time-of-day' and 'wholesale', a real-time pricing scheme) on the electricity bill and peak load of households, taking into account EVs, vehicle-to-home options, and BSS. The study showed it is possible to reduce a household's electricity bill by up to 85%. At the same time, the peak load increased for all dynamic tariffs considered. A new enhanced ToU (*E*-ToU) approach was considered in Ref. [16]. This tariff varies for different type days and on energy drawn from the grid. The authors analyzed the effects of the *E*-ToU tariff on a PV system with BSS considering two options: *E*-ToU was applied only to power drawn from the grid; and *E*-ToU was applied to power drawn from and fed into the grid. In the latter case, it was shown that the household peak load could be reduced significantly as could the daily electricity costs (average of summer and winter).

The authors of Ref. [17] analyzed four different EV charging strategies in households with a PV system: direct charging, optimizing self-sufficiency, and optimizing electricity costs with a day-ahead pricing scheme with and without including the PV system. When considering the cost of charging, the best result was for the optimizing self-sufficiency case (35% cheaper than in the direct charging case), followed by the optimizing electricity cost case with PV system (approx. 34.9% reduction of the cost of charging). For both cases of price-optimized charging, the results indicated an increase in the 1% quantile of the aggregated grid load of 184% without PV and 125% with PV. In both cases, it is assumed that all households received the same price signal and used the same charging strategy.

Venkatesan et al. [4] explored consumer behavior towards demand response by considering different types of consumers. The authors incorporated the different consumer types into an analysis of the IEEE 123 node test feeder, assuming all consumers were given a 24-h real-time pricing (RTP) tariff scheme. They showed that demand

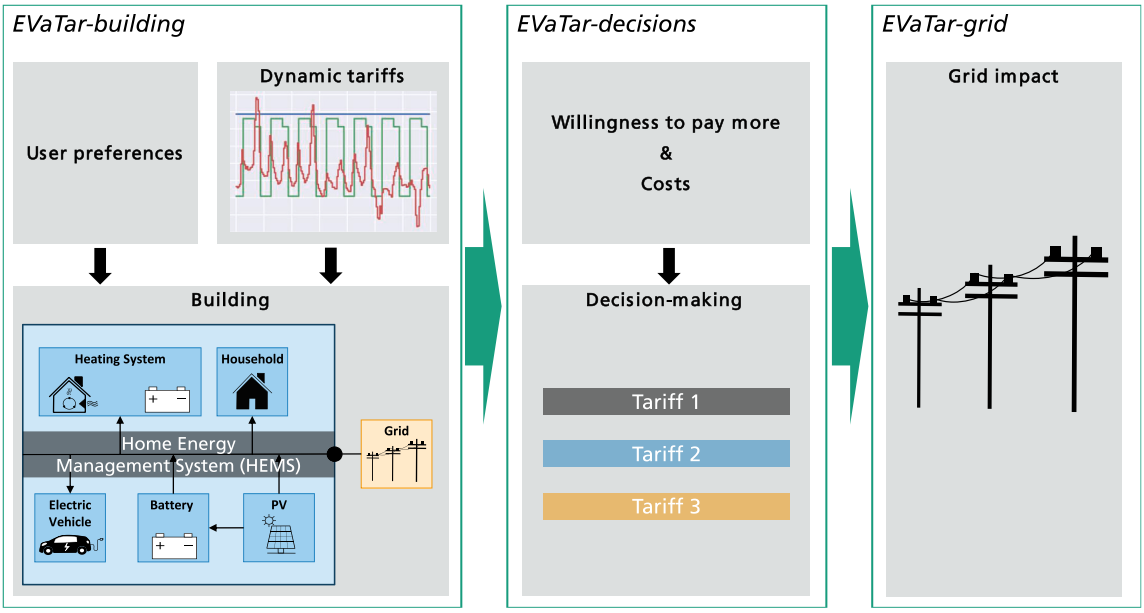

Fig. 2. Structure of the simulation model *EVaTar* and its modules.

response during peak hours helped to boost the node voltages. Ref. [18] considered the effects of time-of-use and time-of-export[3] tariffs for households with batteries and heat pumps. The authors aggregated the load of 100 households to assess the effects on a MV/LV substation level and assumed all households had the same pricing scheme (3-tier ToU). Their results showed the formation of a rebound peak in the evening hours, when all batteries started charging during the off-peak price band. In a second step, the authors examined the effects of staggered off-peak price bands. This helped to reduce the rebound peak in areas with a high number of BSS. Boulaire et al. [19] analyzed the potential benefits of household and community batteries for individual households but also for the transformer of a LV grid using an agent-based model. They considered a 2-tier ToU and a static tariff already available on the market (in Queensland, Australia). Their results showed that a community battery would lead to a slight increase of peak load at the MV/LV transformer. Ref. [20] investigated the impact of a 3-tier ToU tariff combined with a grid tariff with demand charge (€/kW) The technologies considered were electric water heating, PV and BSS. Power flow analysis was conducted for three different residential LV distribution grids. The results showed an increase in line loading of the head feeder of each grid when applying the ToU tariff. The demand charge of the grid tariff was only able to counteract that effect to a small extent. Furthermore, the ToU tariff was shown to have negative effects on the voltage level of the grid nodes. In this paper, as well as in the others described above, it was assumed that all households react to the same tariff within a grid. In Ref. [21][4], households within the CIGRE LV benchmark grid (European configuration) with different technologies such as EVs, heat pumps and PV systems were presented with different price incentives. It was shown that, for all dynamic pricing schemes, there was an increase in grid restriction violations compared to the static tariff case. Again, all household consumers within the grid area were presented with the same tariff scheme for each scenario.

1.2. Research gap and research questions

Overall, as outlined above, dynamic tariffs appear to be financially attractive for the participants. Researchers have also analyzed the implications of dynamic tariffs for the grid and obtained mixed results. On the one hand, there are positive implications, e.g., the peak demand of households decreases in pilot studies of households without flexible devices. On the other hand, there are negative implications for LV grids if households have a higher share of flexible technologies. A common denominator of the studies presented above is that they model both the attractiveness and the grid implications of tariffs sequentially, i.e., each case study assumes only one type of tariff per scenario. This is, however, not a realistic assumption: In reality, end-users that have selected different tariffs are located within one grid area. The systemic impact of price-responsive pricing is affected by the sum of the tariff choices and the decision-making of all consumers within the grid, not just by the design of a specific tariff or the economic attractiveness of this tariff to an individual consumer. This is due to the fact that, in Germany (and most of Europe), customers are free to choose a tariff and, due to the heterogeneity of households and occupants, it is unlikely that all end-users within a grid area will select the same tariff.

Decision-making behavior within this study refers to the decision to actively use the flexibility of EVs, heat pumps and PV battery storage systems (e.g., via a HEMS). This can be achieved by choosing an electricity contract with a dynamic tariff and benefiting specifically from price differences over the course of the day. These decisions are not based on purely financial aspects, but also on personal preferences, knowledge and understanding of the technologies and tariffs offered, and other, sometimes idealistic reasons [22].

Essentially, this means that the perceptions of a tariff's attractiveness will vary because households are heterogeneous both in terms of their demand patterns and the technical equipment they have at their disposal. As a result, different tariffs are likely to coexist within one distribution grid, leading to a different/new grid situation.

These observations give rise to the following research questions:

- Are the dynamic electricity tariffs available on the market today financially attractive to flexible consumers and prosumers?
- When considering the variety of tariffs available to flexible consumers, do dynamic electricity tariffs have a positive impact on the distribution grid after all?

[3] A time-of-export tariff offers the possibility to penalize the export of electricity from PV systems in specific hours of the day and to incentivize the export of electricity in other hours of the day.

[4] The first author of this paper also co-authored Ref. [21].

We attempt to answer these research questions by presenting a model-based but more realistic insight into the effects of dynamic tariffs on low-voltage grids. This is achieved by considering the free and thus heterogeneous choice of tariff that household customers have in reality: The model integrates consumer decision-making, gives customers a set of different static and dynamic tariff options, and investigates the cumulated effect their individual decisions have on a low-voltage grid.

The following chapter describes the methodological approach used to answer the questions (Section 2). Section 3 presents the underlying assumptions of the case study. Section 4 gives an overview of the electricity tariffs considered, their effects on the load profiles and decision-making behavior of households, as well as their effects on the distribution grid. The paper finishes by discussing the results (Section 5) and presenting the conclusions (Section 6).

2. Method

Depending on the electric devices available in a household, their flexibility and whether a household has a PV system, dynamic tariffs lead to changes in consumption behavior, i.e., in the load profile of a household. The model *evataraTar* ('**E**fficient **Va**riable **Tar**iffs', developed by the first author) is used to map the reaction of flexible consumers to dynamic tariffs. An overview of the model structure consisting of three modules is shown in Fig. 2. The model allows the simulation of inflexible and flexible load shares in households and models a HEMS. Within the HEMS, the household's electricity purchase costs are minimized by optimizing the operation of the BSS, the charging of EVs, and the electricity consumption of heat pumps (*EVaTar-building*). User preferences regarding the charging of EVs can also be mapped (see Section 2.1). In addition, the decision-making behavior of household consumers with regard to the choice of electricity tariff is depicted (*EVaTar-decisions*). This considers the electricity procurement costs determined in *EVaTar-building*, investments, and the willingness to pay more (WTPM) of individual groups (see Section 2.2).

By coupling this model with the open-source model pandapower [23], it is possible to perform load flow calculations for low-voltage power grids. In this way, the effect of dynamic tariffs and the resulting changes in grid load and grid feed-in on the load of the distribution grids can be mapped and investigated (*EVaTar-grid,* see Section 2.3).

The individual modules are described below.

2.1. Modeling of households (EVaTar-building)

Buildings in the model consist of at least one household. In addition, EVs, PV systems and battery storage systems as well as heating systems consisting of a heat pump and a heat storage tank (HS) can be represented. The building is connected to a low-voltage grid and can draw electricity from it or feed electricity generated by a PV system into it. More information on the structure and energy flows of a building within *EVaTar* can be found in Ref. [24].

We assume that the building has a HEMS with perfect foresight that actively intervenes in operating the building and its energy-using technologies in order to minimize the electricity purchase costs. The associated objective function is given in Equation (1):

$$\min \sum_{t=0}^{t_{max}} E^t_{grid,\ building} \cdot c^t_{electricity\ price} - E^t_{PV,\ grid} \cdot c_{feed-in\ remuneration} \tag{1}$$

Here, $E^t_{grid,\ building}$ stands for the energy drawn from the grid in an hour t in kWh. $c^t_{electricity\ price}$ is the electricity price applicable in this time unit in €ct/kWh. $E^t_{PV,\ grid}$ stands for the energy fed into the grid from the PV system in an hour t in kWh. $c_{feed-in\ remuneration}$ stands for the time-independent feed-in remuneration in €ct/kWh. The energy drawn from the grid $E^t_{grid,\ building}$ is defined as follows (Equation (2)):

$$E^t_{grid,\ building} = E^t_{building,\ H} - \alpha^i_{PV} \cdot E^t_{PV,\ building} - \alpha^i_{BSS} \cdot E^t_{BSS,\ building} + \alpha^i_{EV} \cdot E^t_{building,\ EV} + \alpha^i_{HP} \cdot E^t_{building,\ HP}, \forall t \in T, \forall i \in I \tag{2}$$

where α represents a binary variable that defines whether a technology is available in the building i; $E^t_{building,\ H}$ is the household's inflexible electricity demand in an hour t in kWh; $E^t_{PV,\ building}$ represents the energy supplied to the building by the PV system in an hour t in kWh; $E^t_{BSS,\ building}$ stands for the energy supplied to the building by the battery storage system in an hour t in kWh; $E^t_{building,\ EV}$ is the energy supplied from the building to charge the EV in an hour t in kWh; and $E^t_{building,\ HP}$ defines the energy supplied from the building to the heating system in an hour t in kWh.

We considered two different operating strategies of the building:

- *No HEMS, inflexible demand:*
  - Battery storage system: The battery operation is based on simple rules. The electricity from the PV system is first used to meet the electricity demand of the building (including the electricity demand of the EV and the heating system). If a generation surplus remains, it is used to charge the battery storage. Further surpluses are fed into the grid. As soon as the building's electricity demand exceeds PV generation, electricity is drawn from the battery to cover the household's energy demand.
  - Electric vehicle: Continuous charging of the EV is started immediately after arrival until a state of charge of 100% is reached or the EV is driven again.
  - Heating system: The heating system is operated in an inflexible way, so that it meets the heat demand at any given point in time.
- *HEMS, flexible demand:*
  - Battery storage system: The operating strategy allows flexible and predictive operation in terms of dynamic tariffs. This means that the battery system is included in the building's HEMS and thus used to minimize the building's overall energy procurement costs (see Equation (1)).
  - Electric vehicle: Controlled charging is possible. This means that the EV is integrated into the HEMS. We assume that EV owners can enter their preferences into the HEMS, i.e., they can specify the minimum range or the minimum energy stored in the battery at the time of departure $E_{min,\ departure}$ and the minimum energy level $E_{min,\ charge}$ at which they want to start charging their vehicle at the latest.
  - Heating system: The heating system is integrated into the HEMS and can supply flexibility using the heat storage tank.

For both operating strategies, the electricity demand of household appliances is considered to be inflexible and is defined exogenously in the form of a household load profile. Furthermore, the PV system can be used within the model to supply the various appliances in the building, charge a battery storage system or feed electricity into the grid. Its generation is also considered to be inflexible.

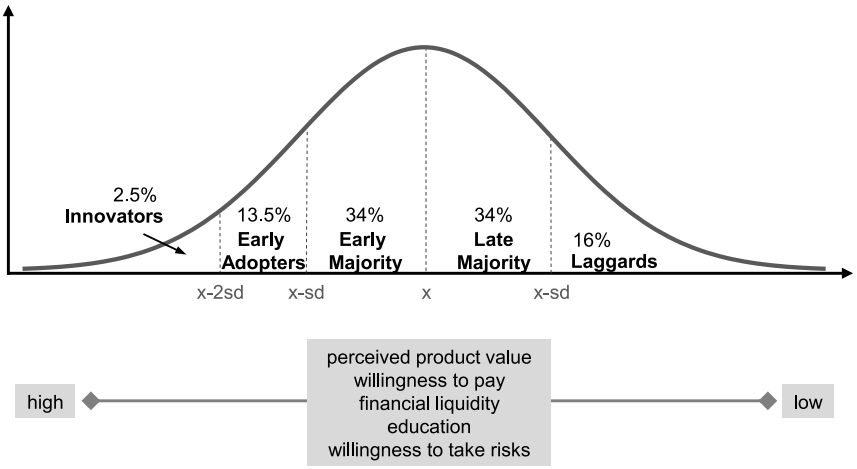

Fig. 3. Schematic representation of the relationship between types of adopters and their location on the adoption curve with defining characteristics according to Rogers [25].

2.2. Decision-making behavior regarding the electricity tariff (EVaTar-decisions)

To map the decision-making of flexible consumers regarding the choice of an electricity tariff, one key factor are the financial aspects of dynamic tariffs. In addition to the perception of economic benefits, other behavioral drivers such as perception of environmental values, status and prestige, self-sufficiency or interest in innovative technologies play a key role in the adoption of new technologies. In order to take into account the heterogeneity of households regarding those behavioral drivers of the adoption of new, innovative technologies such as a HEMS, we use the 'diffusion of innovations' theory of E. Rogers [25]. This theory is often used to describe the market diffusion of new technologies and states that consumers can be divided into five adopter categories: innovators, early adopters, early majority, late majority, and laggards. A schematic representation of the relationship between the types of adopters and their location on the technology adoption curve according to Rogers can be seen in Fig. 3. The adopter categories differ in their behavioral drivers as well as their willingness to pay (WTP) for non-financial values. The adopter categories are linked to socio-economic characteristics and personal variables (e.g., social status, financial liquidity, education). Innovators are the most innovative and risk-taking adopter category and tend to be quick to adopt new technologies. Furthermore, innovators have the highest WTP and/or WTPM amongst the five adopter categories. Early adopters are also quick to adopt new technologies but less risk-taking than innovators. They do have a high degree of opinion leadership. A significantly longer adoption time can be seen within the category of the early majority. Individuals in the category late majority adopt a new technology later than the average individual in a society. The last category are laggards, who usually tend to be focused on 'traditions' and therefore are last in adopting a new technology. The characteristics and behavioral drivers are usually determined through household surveys. Using these characteristics and variables, each household can be assigned to one of the adopter categories.

Based on the adopter category and the survey results, a WTPM results for each household, which is included in the decision-making behavior. A positive WTPM means that some households are willing to pay more compared to the status quo (for instance static tariff without HEMS) due to their attitude towards new technologies. A negative WTPM means the opposite.

In order to model the decision-making behavior of households regarding the choice of an electricity tariff, we first determine the electricity costs incurred within a year for each available electricity tariff. We assume that all households initially use a static tariff without HEMS. The cost of a dynamic electricity tariff thus includes the capital expenditure for a HEMS, derived from distributing the initial investment to individual years using the annuity method (see Section 3.2), in addition to the electricity costs incurred within the timeframe of one year. On top of this purely financial consideration, we include a WTPM for the different adopter groups. With that included, we first find the dynamic tariff which would result in the lowest costs for the household within the year under consideration, taking into account the annualized investment costs for the HEMS C_{HEMS} (Equation (3)):

$$\min \left(\left(C_{HEMS} + \begin{bmatrix} C_{electricity\ costs,\ tariff\ 1} \\ C_{electricity\ costs,\ tariff\ 2} \\ \vdots \\ C_{electricity\ costs,\ tariff\ n} \end{bmatrix} \right) \cdot (1 - WTPM) \right) \tag{3}$$

The overall electricity costs $C_{electricity\ costs,\ tariff\ n}$ in €/yr. with a tariff n for each household can be calculated as (Equation (4)):

$$\begin{aligned} C_{electricity\ costs,\ tariff\ n} = & \sum_{t=0}^{t_{max}} E^{t}_{grid,\ building,\ tariff\ n} \cdot c^{t}_{electricity\ price,\ tariff\ n} \\ & - E^{t}_{PV,\ grid} \cdot c_{feed-in\ remuneration,\ tariff\ n} + C_{standing\ charges,\ tariff\ n} \\ & + C_{metering\ point\ operation} \end{aligned} \tag{4}$$

where $C_{standing\ charges}$ are the tariff's annual standing charges in €/yr. and $C_{metering\ point\ operation}$ depicts the annual costs for metering point operation in €/yr.

Having determined the dynamic tariff with the lowest costs (including the WTPM), we check whether this option is cheaper than the static tariff option. If it is, the household chooses the dynamic tariff. If the static tariff is cheaper, the household will choose the static tariff and remain inflexible in their electricity consumption.

2.3. Modeling the grid impact (EVaTar-grid)

After the choice of tariff has been determined for each household, the resulting load and generation profile of each household were used to model the grid impact. Each household is connected to a grid connection point of the distribution grid. Assigning the selected households to grid connection points is randomly based. To obtain more robust results, this random-based assignment was repeated 50 times for each scenario (Fig. 4).

A load flow calculation was performed for each of the resulting grid scenarios. The load flow calculations were performed with the open

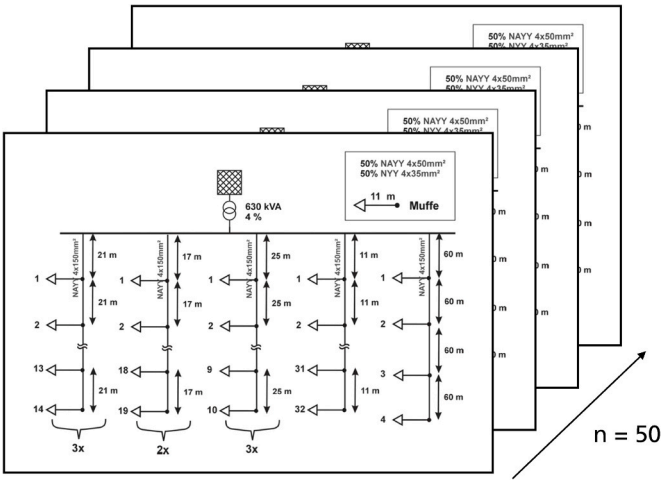

Fig. 4. Iterations of random-based assignment of households to grid connection points in the representative suburban grid 'Vorstadt Kabel 1' by Kerber [26].

source model pandapower [23]. The results of the load flow calculations were analyzed regarding the minimum and maximum voltage band deviation, the maximum occurring line and transformer loading as well as the maximum power drawn from the higher grid level.

3. Case study

In our case study, a suburban low-voltage grid was selected and defined for the grid analyses. Households with various technology options (EVs, HPs, BSS, PV rooftop systems) are located within this grid and different dynamic tariffs are offered to the household customers. The decision to choose one of the tariffs is determined for each household. Subsequently, the effects on the load profiles of the households as well as on the load of the distribution grid are analyzed using the relevant indicators. For comparison reasons, as a reference we also considered the case where all households have a static tariff. For consistency, we used data for the city of Karlsruhe (Southern Germany) for the year 2019. These include weather data, PV generation time series, heat demand time series, grid charges, and electricity price time series. A more detailed description of the individual aspects of the case study is given below.

3.1. Low-voltage grid

The reference grid for our investigations is the suburban grid 'Vorstadt Kabel 1' by Kerber [26]. The grid is defined as a representative grid for suburban areas in Germany [27]. The topology is shown in Fig. 4. The grid has 146 grid connection points, to each of which one household (single-family home or two-family home) is connected in our case study.

3.2. Households and technologies considered

3.2.1. Households

We used load profiles from a sample of more than 300 households from a smart meter field study conducted in Austria and Germany [28] to reflect the heterogeneity of household load profiles.

3.2.2. Electric vehicles

For EVs (availability at home and energy demand while driving), we used a dataset [29] computed with the vehicle diffusion model *ALADIN* [30–32]. This model uses vehicle usage data from Ref. [33]. EV profiles were assigned to each household based on the socio-demographic data also collected in this field study.

3.2.3. PV systems

An optimized sizing of a PV system for a household is out of scope of this study, therefore we assumed an installed capacity of 8.1 kWp for households with a PV system. This corresponds to the average installed capacity of PV systems in Germany in 2017 [34]. To create the PV generation profile for the year 2019 and the city of Karlsruhe, we used the simulation tool *Renewables.ninja*.[5]

3.2.4. Battery storage systems

We assumed a battery capacity of 7.8 kWh for households with BSS. This corresponds to the average useable battery capacity installed in Germany (2017) [34]. We chose a fixed value, as the determination of the optimal size of a BSS is out of scope of this study.

3.2.5. Heating systems

The size of the heat pump was selected depending on the heated area of the respective building. The size of the heat storage tank was selected so that it can store the energy supplied by the heat pump running at maximum operation for 2 h. A heat demand profile for the year 2019 was taken from 'HotMaps' [35] for the city of Karlsruhe (DE12) and scaled to 236 kWh/m^2/yr. For consistency, we used ambient temperature for the same year (2019) and also for the city of Karlsruhe. Weather data, including ambient temperature, were taken from the Climate Data Center of the German Weather Service (Deutscher Wetterdienst) for station ID 4177 [36].

3.2.6. Home energy management system

The time horizon within the model is one year. Therefore, we annualized the investment in a HEMS. We assumed costs of € 1500 for the HEMS (incl. installation), a lifetime of 10 years and an interest rate of 2%; the resulting annual payment is 167 €/yr.

3.3. Willingness to pay more (WTPM)

Within the smart meter field study, the load profiles of households used within this paper were measured as well as two household surveys were conducted. From those surveys, each household was assigned to adopter categories according to Rogers [25] in Ref. [37]. The WTPM for purchasing a PV home storage system was determined for these categories using the given information on the households as well as a market

[5] Renewables.ninja is available at [44] For more information, please refer to Refs. [45,46].

Table 1
Willingness to pay more of the adopter categories according to Rogers [25] taken from [37].

Innovators	Early Adopters	Early Majority	Late Majority	Laggards
60%	10%	0%	−5%	−10%

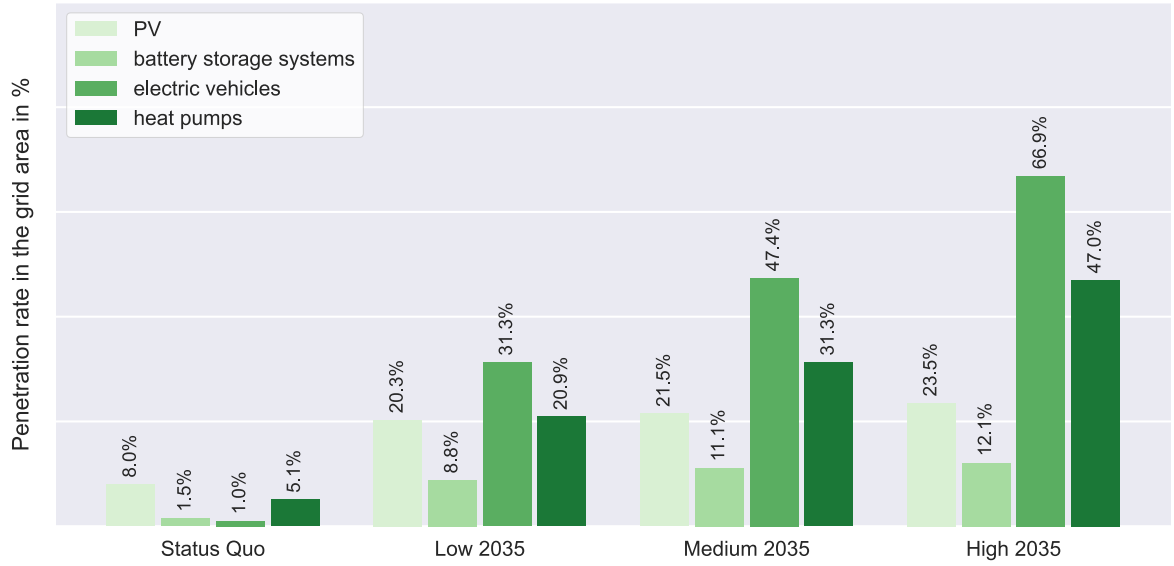

Fig. 5. Scenarios investigated with regard to the diffusion of technologies in the households considered (based on [38]).

research survey and a prosumer model (Table 1). Further information on the households and derived WTPM can be found in Ref. [37]. Due to a lack of data on the WTPM for HEMS and dynamic electricity tariffs, we further assumed that the WTPM for PV battery storage systems is also valid for the purchase of a HEMS.

3.4. Technology scenarios

Four different technology penetration scenarios were defined in the case study: a status quo scenario reflecting the current penetration of rooftop PV, home battery storage, EVs, and HPs, and three future scenarios for the year 2035 (Low, Medium and High), which are based on the scenario framework of the German Network Development Plan for Electricity (2021) 2035 [38]. Our Low 2035 scenario corresponds to the scenario NEP A 2035, our Medium 2035 scenario corresponds to the scenario NEP B 2035, and our High 2035 scenario corresponds to the scenario NEP C 2035. For the penetration of PV systems, the installed PV capacity and number of PV systems of 2018 is taken from MaStR[6] database for all PV systems with an installed capacity below 15 kW. The penetration is then calculated for the Status Quo scenario by dividing the number of installed PV systems by the total number of single- and multi-family homes (SFH/MFH) in Germany [39]. For the future scenarios, it is assumed that the average PV system size and the ratio of PV rooftop systems to PV ground-mounted systems is constant. Therefore, we can derive the number of PV systems from the installed PV capacity given in the NEP scenarios. Regarding the penetration rate of BSS and HS, we assume that approximately 90% of all BSS and HS will be installed in SFH/MFH. For EVs, we assume that around 75% of all EVs have private owners. The penetration rates for all four scenarios are shown in Fig. 5. A penetration rate of 10% means that 10% of all household within the given grid area do have the according technology. The figure shows a strong increase of EVs and HPs in all scenarios for the year 2035 and large differences between the three scenarios for these technologies. The differences are smaller for PV rooftop systems and battery storage systems.

We assumed that households are more likely to adopt a technology if they belong to a more innovative adopter group. In other words, the group of innovators are quicker to adopt the considered technologies than the group of laggards. As the technologies are being randomly distributed to the households, some households will have more than one of the technologies available. More detailed information is shown in Table 2.

4. Results

The results of the analyses of the case study scenarios are presented below. First, the investigated tariff structures are presented and compared (Section 4.1). Then, the influence of the dynamic electricity tariffs on the load profiles of households is considered (Section 4.2). Based on this, the possible cost savings of households and the effects on their decision-making behavior are derived (Section 4.3). The final aspect is the impact on the grid if households are considered to have a free choice of tariff (Section 4.4).

4.1. Tariffs

The case study considers dynamic electricity tariffs already available today and includes one static and two dynamic electricity tariffs. The amount of the grid charge component to be paid was adjusted to the Karlsruhe grid area. Fig. 6 gives a graphical representation of the tariffs considered for an exemplary week in summer and in winter.

[6] https://www.marktstammdatenregister.de/MaStR, date of data evaluation: 19.8.2021.

Table 2
Number and share of households with different technologies (- only household, - PV system, - BSS, - EV, - HS) for all four scenarios (deviations from 100% result from rounding errors).

	Status Quo	Low 2035	Medium 2035	High 2035
	133 (91,1%)	90 (61,6%)	72 (49,3%)	47 (32,2%)
	6 (4,1%)	4 (2,7%)	0 (0%)	0 (0%)
	0 (0%)	0 (0%)	0 (0%)	0 (0%)
	0 (0%)	21 (14,4%)	23 (15,8%)	24 (16,4%)
	0 (0%)	1 (0,7%)	5 (3,4%)	5 (3,4%)
	0 (0%)	0 (0%)	0 (0%)	1 (0,7%)
	1 (0,7%)	2 (1,4%)	3 (2,1%)	1 (0,7%)
	3 (2,1%)	4 (2,7%)	2 (1,4%)	0 (0%)
	1 (0,7%)	0 (0%)	0 (0%)	0 (0%)
	0 (0%)	3 (2,1%)	17 (11,6%)	40 (27,4%)
	1 (0,7%)	8 (5,5%)	8 (5,5%)	11 (7,5%)
	1 (0,7%)	13 (8,9%)	16 (11,0%)	17 (11,6%)

4.1.1. Tariffs considered

Static electricity tariff

The static electricity tariff is composed of a standing charge of 11.82 €/month and the unit rate of 29.87 €ct/kWh.

3-tier time-of-use tariff (ToU)

We chose the 'E.ON SmartStrom Öko' tariff [40] as our first dynamic tariff. This is a time-of-use tariff with three (time-dependent) price levels for the unit rate. The High Tariff I (HTI) is applied between 6 a.m. and 4 p.m. at a unit rate of 29.60 €ct/kWh. The slightly cheaper High Tariff II (HTII) is applied from 4 p.m. to 9 p.m., at a unit rate of 29.13 €ct/kWh. The Low Tariff is applied between 9 p.m. and 6 a.m., at the unit rate of 25.09 €ct/kWh. The standing charge is 15.62 €/month.

In addition, there are costs for the smart meter (7.50 €/month) plus the annual investment costs for the HEMS (see Section 3.2).

Hourly pricing based on the day-ahead price of EPEX spot DE (DA)

The second dynamic electricity tariff considered is the 'HOURLY' tariff of aWATTar Deutschland GmbH [41], which is based on the day-ahead price of EPEX Spot DE. The unit rate consists of the hourly prices of EPEX Spot DE (limited to max./min. ±20 €ct/kWh), a flat rate of 0.25 €ct/kWh and all other taxes, levies and charges. The standing charge amounts to 8.73 €/month.

Here, too, there are additional costs for the smart meter of 5.44 €/month plus the annual investment costs for the HEMS.

4.1.2. Analysis and comparison

For a better classification of the results described below, it is necessary to analyze the electricity tariffs considered. Table 3 shows the minimum and maximum unit rates that occur in the year for all three tariffs considered, as well as the arithmetic mean and the median. The lowest unit rate occurs in the case of the ToU tariff (low tariff phase between 9 p.m. and 6 a.m.). The minimum value for the DA tariff is higher by 0.53 €ct/kWh. The maximum occurring prices of the dynamic tariffs are lower than the value of the static tariff. Consequently, the static electricity tariff - without considering the investment in the HEMS - is presumably the most expensive for all households. On average, the DA tariff is the cheapest (1.01 €ct/kWh cheaper than ToU). Considering only the electricity procurement costs, it is reasonable to assume that the DA tariff is the cheapest for most households.

4.2. Effects on household load profiles

At this point, the impact on household load profiles is only considered for the High 2035 scenario. All households with a flexibility option are included in the analysis. The relevant variables identified are the maximum feed-in power, the maximum power drawn from the grid, and the standard deviation of the load. Fig. 7 shows the changes to these three variables for the dynamic tariffs considered compared to the static tariff without HEMS. In each case, all flexible consumers are depicted and households are additionally grouped by technologies (EV, HP, BSS).

There are no significant changes in the maximum feed-in power. For households with BSS, the maximum feed-in power can be reduced by 1.5%.

The analysis of the maximum power drawn from the grid shows larger changes. On average across all flexible consumers, there is an increase of 11% for the ToU tariff, and around 15% for the DA tariff. For households with an EV or a BSS, the changes are also in the range of 11% (ToU) and 14–15% (DA). For households with a heat pump, there are significantly higher changes of about 17% (ToU) and about 20% (DA). This is mainly due to the installed capacity of heat pumps, which run at full capacity during flexible operation when electricity prices are favorable and fill the heat storage tank. In addition, many households that own a heat pump also have an EV, further increasing the maximum power drawn from the grid when the EV and HP respond to favorable electricity prices.

This higher change in maximum power drawn from the grid for households with heat pumps is also reflected in the change in the standard deviation of load (up to 27%). Notable in terms of the standard deviation of load are households with BSS, where the change compared to the static tariff is lower than in the other household groups (by around 9% for ToU and around 11% for DA). This difference is due to the fact that the BSS enables a time-delayed use of the cheaper electricity generated by the PV system and thus reduces the energy drawn from the grid in hours with high electricity demand (especially in the evening).

4.3. Impact on household electricity costs/decision-making behavior

An analysis of the electricity costs (incl. the annualized investment in HEMS) of households with flexibility shows that cost savings are possible with both the ToU and DA tariffs. However, these savings are on average 8.3% higher for the DA tariff than for the ToU tariff, which is why the discussion below focuses on the cost savings under the DA tariff compared to the static tariff. Fig. 8 gives an overview of the cost savings normalized to household electricity consumption for all flexible consumers by scenario and technology group. Maximum, minimum, and average values are shown in each case.

It can be seen that there are cost savings for all flexible consumers in the Status Quo and Low 2035 scenarios compared to the static tariff. For the Medium 2035 and High 2035 scenarios, there are individual households for which the DA tariff would involve additional costs. However, on average, there are cost savings in all scenarios. These range between 3.5 and 4.9 €ct/kWh. The largest average cost savings are for households with heat pumps (4.7–4.9 €ct/kWh). This is partly due to their availability; as stationary heat storage units, their flexibility can be used at any hour of the day, making optimal use of low-price phases.

If these cost savings - viewed purely in economic terms - are combined with the WTPM described in Section 2.2. the result is the decision-making behavior regarding the electricity tariff shown in Fig. 9. It can be seen that the ToU tariff is not chosen by any of the flexible consumers, as the cost savings here are lower than with the DA tariff. In the Status Quo and Low 2035 scenarios, all households with flexibility choose the dynamic DA tariff. In both the Medium 2035 and High 2035 scenarios (higher shares of flexible households), a few flexible consumers opt for

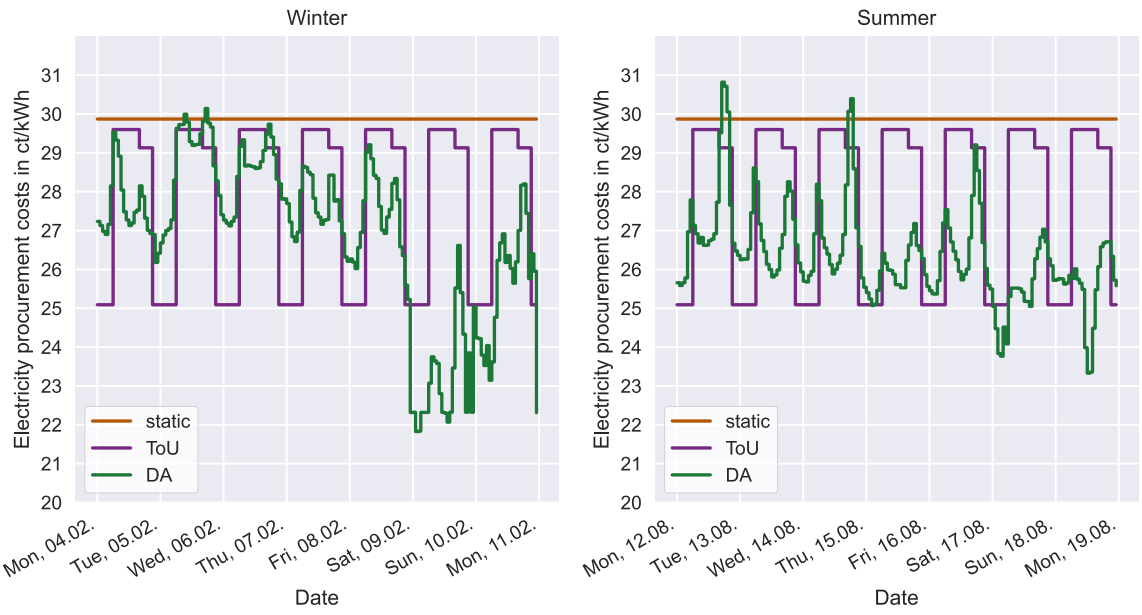

Fig. 6. Considered electricity tariffs for one example week in winter and one example week in summer (ToU - Time-of-Use tariff, DA – hourly day-ahead tariff).

Table 3
Overview of the three electricity tariffs considered within this case study.

	Min.	Max.	Mean	Median
Static electricity tariff (static)	29.87 €ct/kWh	29.87 €ct/kWh	29.87 €ct/kWh	29.87 €ct/kWh
3-tier Time-of-Use tariff (ToU)	25.09 €ct/kWh	29.60 €ct/kWh	27.81 €ct/kWh	29.13 €ct/kWh
Hourly day-ahead tariff (DA)	25.62 €ct/kWh	28.22 €ct/kWh	26.80 €ct/kWh	26.72 €ct/kWh

the static tariff. Due to the higher penetration rates of the flexibility options, households assigned to the Late Majority adopter group are also flexible in these scenarios. Households from the Late Majority group have a lower yearly energy consumption than more innovative adopter groups. At the same time, in order to opt for the dynamic tariff, for these households, the cost savings must again be higher than for the more innovative adopter groups due to their lower WTPM. This leads to some of these households choosing not to use the HEMS and a dynamic tariff.

4.4. Grid impacts

This section compares two cases for all technology scenarios outlined in Section 3.4: in the first case all households use the static tariff, in the second case we consider free choice of tariff. For each case and each scenario - as already mentioned in Section 2.3 - 50 iterations with random assignment of households to the grid connection points are performed. Fig. 10 shows the maximum voltage deviation occurring in the grid in both negative and positive directions across all iterations. Negative voltage deviations arise from electrical loads, while positive voltage deviations can arise from feed-in from PV systems. When analyzing the impact of the DA tariff on the maximum feed-in power of households (cf. Section 4.2), it was shown that the use of dynamic tariffs has hardly any effect. Analogously, the maximum positive voltage deviation also changes only minimally. The comparison of the maximum negative voltage deviation occurring in the grid shows improvements with a free choice of tariff, especially in the future scenarios. There are hardly any changes in the status quo scenario. If a permissible voltage band of ±4% is assumed in the low voltage grid (based on [28]; red dashed line in Fig. 10), the number of hours in which this grid restriction is violated can be determined (see Table 4). It can be seen that, for the future scenarios, there are significantly more hours with voltage band violations in the case of a free choice of tariff than in the case of using the static tariff. This suggests a higher utilization of electric equipment if the grid is expanded.

With regard to the thermal load of lines and the transformer, notable differences can be observed between the two cases investigated (Fig. 11). For the lines, an improvement of the maximum thermal load can be shown for all scenarios with a free choice of tariff. Here, this improvement in the thermal load of the lines increases with the number of flexible households in the grid area. The maximum thermal load limit assumed here is 100% [42] (red dashed line in Fig. 11). Again, the Medium 2035 and High 2035 scenarios show that the number of hours per year in which the thermal load limit is exceeded is significantly higher in the free choice of tariff case than in the static tariff case (Table 5). There are also improvements in transformer thermal loading with free choice of tariff in all scenarios. However, the number of hours with thermal overload of the transformer is also higher with free choice of tariff than in the static case (Table 6). As for lines, the load limit is 100% [42]. These figures also indicate that, assuming the grid is expanded, there is a higher utilization in the free choice of tariff case than in the static tariff case.

Fig. 12 shows the change in the maximum active power drawn from the higher grid level when comparing the free choice of tariff case with the static tariff case. A reduction of the active power consumption by up to 11% is shown (Medium 2035 scenario). This reduction in active power consumption may have positive effects on the higher grid level, as the grid load at this level then decreases. Furthermore, a lower annual maximum power has the effect of reducing the grid charges within the low-voltage grid.

5. Discussion and outlook

The methodology presented and the analysis of the influence of free choice of tariff for flexible consumers results in a more realistic assessment of the influence of dynamic tariffs on a LV distribution grid and therefore adds value to the ongoing discussion in this research field. In the following, the results will be discussed regarding the important contribution of this study, the comparison to previous research in this field, as well as the limitations of this study.

Under the conditions outlined in this study, the dynamic electricity tariffs lead to substantial cost savings for most of the flexible consumers

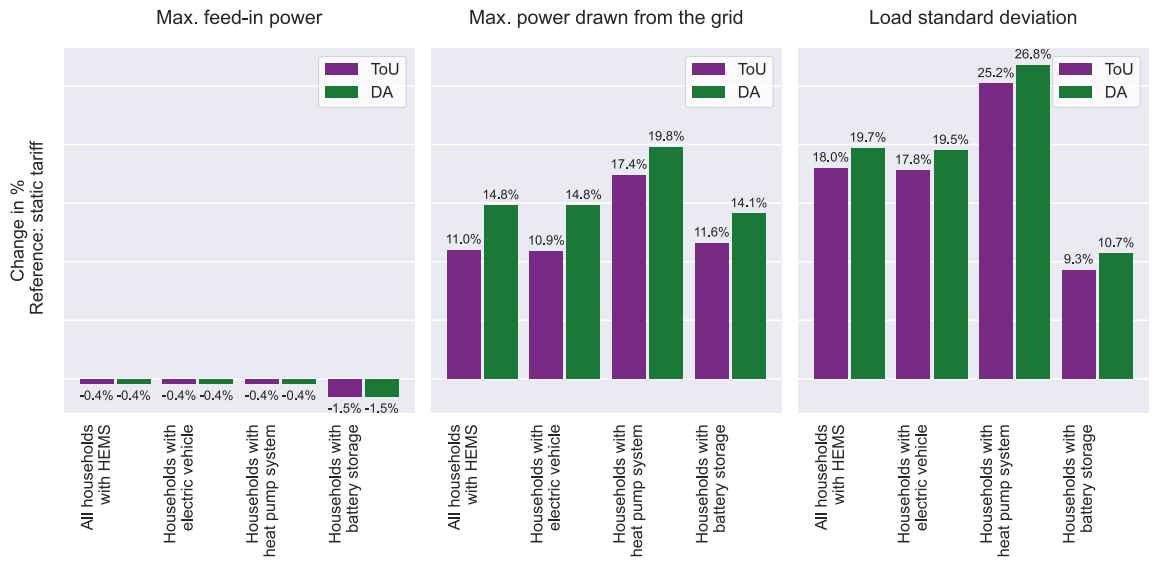

Fig. 7. Changes in maximum feed-in, maximum grid draw, and standard deviation of load for households with HEMS installed in conjunction with a dynamic tariff in the High 2035 scenario. Reference case: static electricity tariff without HEMS. (ToU - Time-of-Use tariff; DA – hourly day-ahead tariff).

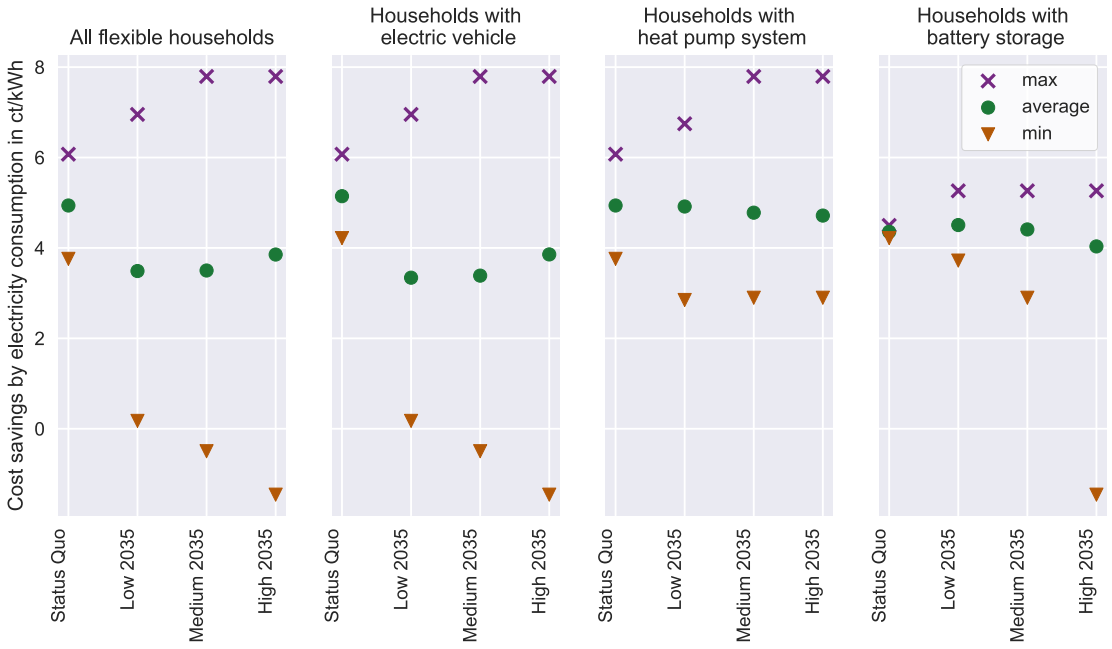

Fig. 8. Cost savings when using the DA tariff; average, minimum, and maximum values across all households with flexibility for the scenarios considered; investments for HEMS are included.

(on average between 3.5 and 4.9 €ct/kWh, which corresponds to a reduction in the electricity bill of 11,7–16,4%). This result was obtained under the assumption of perfect foresight in terms of the load and generation for the home energy management system. In reality, of course, the results of using a home energy management system are less optimal due to forecasting uncertainties and - as a consequence - cost savings are lower. Nevertheless, that dynamic electricity tariffs are financially profitable for household customers has also been demonstrated in other scientific studies [13–17], where the foreseen possible cost savings reach as high as 85% [15]. On an individual household level, our study shows, that dynamic tariffs can lead to an average increase of the maximum power drawn from the grid of 11.0% (ToU) and 14.8% (DA). An increased peak load when applying dynamic tariffs can also be found in Ref. [15]. Our approach considers the free choice of electricity tariffs of household customers by integrating this aspect explicitly in the model. It thus goes one step further than the state of the art by modeling the effects of dynamic tariffs on distribution grids in a more realistic manner. Our results indicate that peak loads within a LV distribution grid can be reduced due to the heterogeneous choice of tariff and the resulting mixing effects in households' peak loads. This contradicts the results of studies with scenarios with only one electricity tariff for all household customers within a grid area, where an increase in peak loads is predicted (as seen e.g., in Refs. [17,18,20,21]). Including the more realistic point of the free choice of tariff for flexible consumers does give new insights into the topic. Furthermore, it should be noted that the tariff options used are based on research from the beginning of

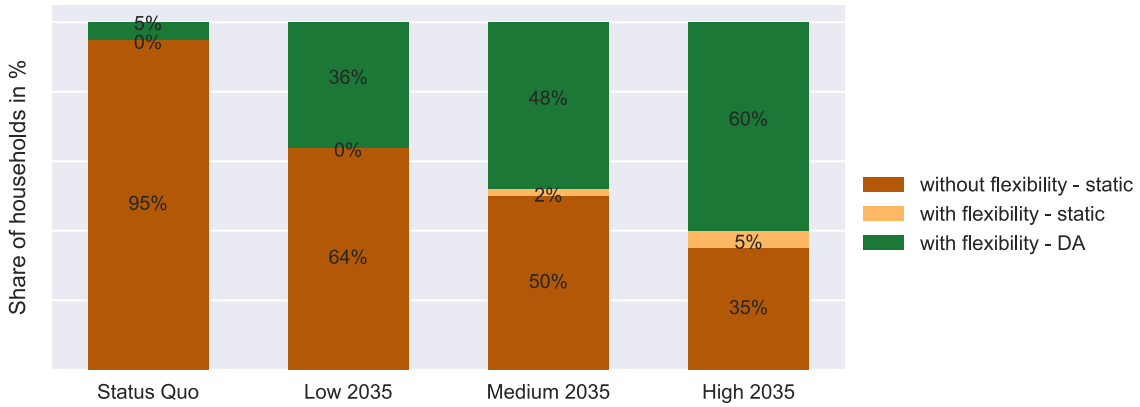

Fig. 9. Shares of households without flexibility with static electricity tariff (brown), with flexibility choosing the static electricity tariff (ochre), and with flexibility choosing the dynamic electricity tariff (hourly day-ahead tariff, DA) (green).

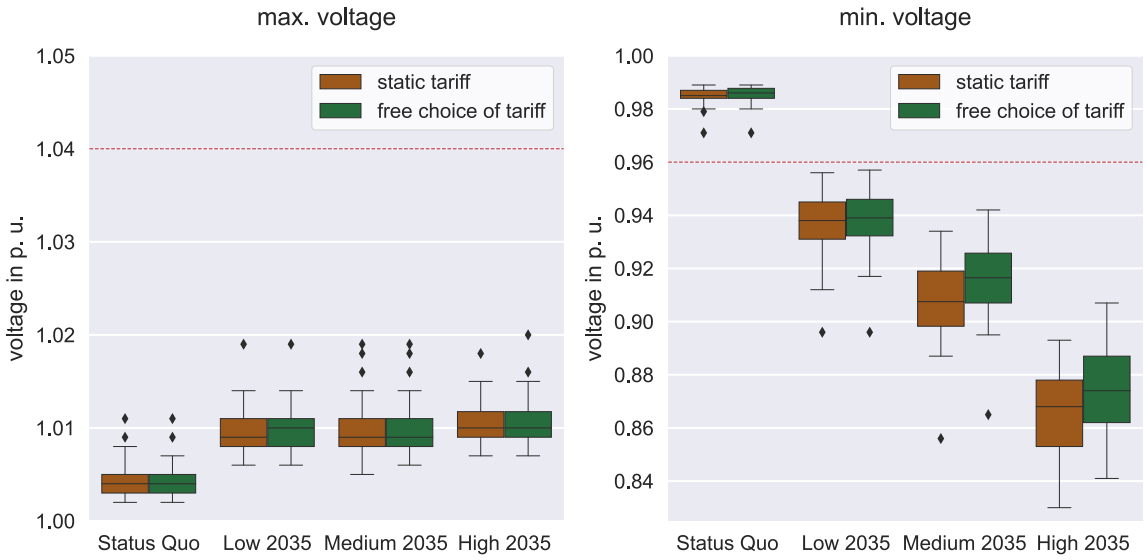

Fig. 10. Maximum negative and positive voltage deviation for the cases static tariff and free choice of tariff over all four technology scenarios (values for all iterations).

Table 4
Number of hours per year with voltage band violation for the cases static tariff and free choice of tariff in the considered scenarios (mean value over all iterations).

	Status Quo	Low 2035	Medium 2035	High 2035
Static	0 h/yr.	11.4 h/yr.	90.8 h/yr.	426.6 h/yr.
Free choice of tariff	0 h/yr.	86.5 h/yr.	229.0 h/yr.	649.1 h/yr.

2021. Since then, the average price level on the spot market has risen sharply and there are now larger price spreads over the course of a day. This will increase the attractiveness and have an influence on the design of dynamic electricity tariffs in the future. Our approach also represents the heterogeneity of households by using measured load profiles of different adopter groups and considering a great range of technologies such as PV systems, electric vehicles, heat pumps with heat storage and battery storage systems. As a consequence, the results in terms of household load profiles and cost savings represent a good range of households and adopter groups in the single- and two-family household sector.

The household customers were divided into adopter categories according to Rogers and each group was assigned an individual willingness to pay more. Due to a lack of data availability, values taken from another study on the willingness to pay more for a PV battery storage system were applied to a home energy management system. The willingness to pay more for a home energy management system could show other values than the one for a PV battery storage system. Therefore, a survey of the willingness to pay more for home energy management systems and dynamic tariffs could improve the quality of our findings and could be integrated into the existing model. In addition, it would be possible to map the decision-making behavior of households not only using their willingness to pay more, but also including a threshold for the minimum electricity cost savings that would have to be possible for customers to even consider switching tariffs.

Comparing the mean values of the energy price of the two existing dynamic tariffs considered in the paper shows that the DA tariff is lower than the time-of-use tariff. This results in a shift towards the DA tariff, regardless of the tariff structure. Since the focus of this paper was on the analysis of existing dynamic tariffs, the use of the two mentioned tariffs is nevertheless considered appropriate and legitimate. In further research - where the focus is not on actually available tariffs - the price level (annual average) of the tariffs should be aligned to ensure better comparability.

Since the study of household decision-making behavior was

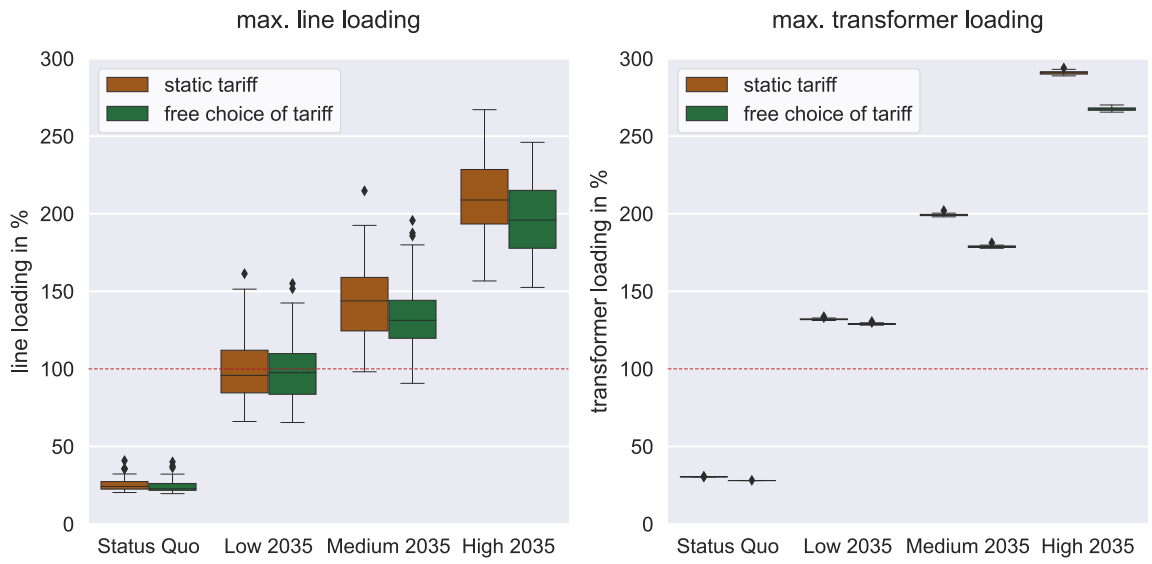

Fig. 11. Maximum thermal load for lines and transformer for the cases static tariff and free choice of tariff over all four technology scenarios (values for all iterations).

Table 5
Number of hours per year with thermal overload of the lines for the cases static tariff and free choice of tariff in the considered scenarios (mean value over all iterations).

	Status Quo	Low 2035	Medium 2035	High 2035
Static	0 h/yr.	1.3 h/yr.	2.4 h/yr.	18.2 h/yr.
Free choice of tariff	0 h/yr.	23.7 h/yr.	50.8 h/yr.	146.7 h/yr.

Table 6
Number of hours per year with thermal overload of the transformer for the cases static tariff and free choice of tariff in the scenarios considered (mean value over all iterations).

	Status Quo	Low 2035	Medium 2035	High 2035
Static	0 h/yr.	2.0 h/yr.	2.0 h/yr.	337.4 h/yr.
Free choice of tariff	0 h/yr.	39.2 h/yr.	110.9 h/yr.	535.3 h/yr.

conducted under current conditions, it was assumed that the active management of flexibility options does not entail implications for the higher-level power system. Therefore, households within this study can be considered 'first movers'. However, based on the attractiveness of dynamic tariffs shown within the paper, it can be assumed that a growing number of flexible consumers will opt for such tariffs in the future. As a consequence, effects on electricity markets are likely and thus also on the attractiveness of dynamic tariffs (e.g., through so-called cannibalization effects). In future studies, the free choice of tariffs implemented in this paper and the associated mapping of consumers' decision-making behavior should be complemented by considering potential repercussions between flexible households and the electricity markets.

New technologies such as electric vehicles, battery storage systems and heat pumps are expected to be adopted most rapidly in suburban areas, which is why a suburban low-voltage grid was chosen for this case study. As low-voltage grids in Germany exhibit a high degree of heterogeneity and electrification will advance in all areas, further analyses with more and different grid types (rural, urban) could lead to a better assessment of the observed mixing effects.

Furthermore, hourly resolved time series were used due to data availability. Especially in low-voltage grids, the voltage quality is evaluated in 10-min averages according to DIN EN 50160 [43]. An adjustment of the time resolution would therefore make the results even more precise.

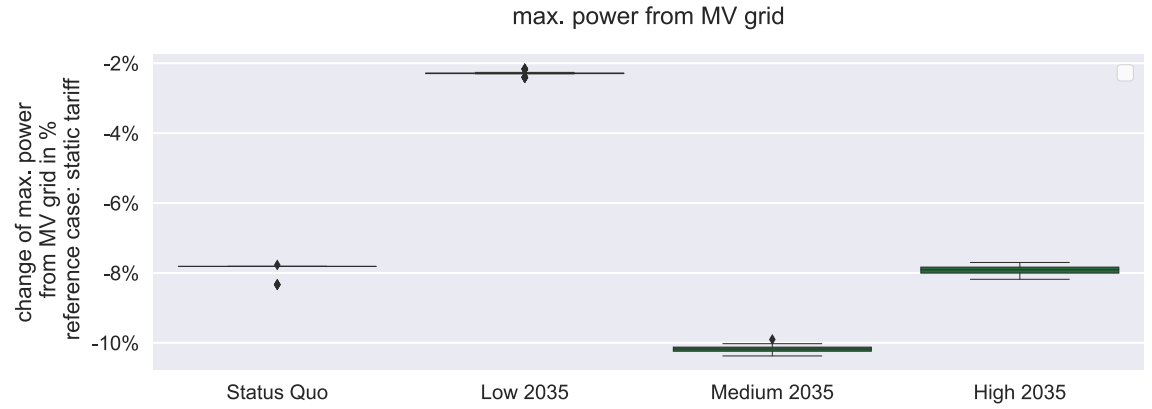

Fig. 12. Changes in the maximum active power drawn from the higher-level grid for the free choice of tariff case over all considered scenarios (values for all iterations).

6. Summary and conclusions

End-users in Germany can choose freely between multiple electricity tariffs, both dynamic and static. However, the current literature on dynamic tariffs only examines the impact of single, isolated tariffs on grids and end-users and does not reflect reality. Our study contributes to closing this research gap: We defined a more realistic scenario with several tariffs available within a grid area and investigated the resulting decision-making of flexible consumers concerning the choice of tariff. To account for the heterogeneity of household customers, we applied the 'diffusion of innovations' theory by Rogers and combined this with a willingness to pay more in the individual adopter categories. To go one step further, we analyzed the effects on the grid from flexible consumers optimizing their energy consumption behavior based on heterogeneous price signals.

Our results show that the dynamic electricity tariffs already available today can be financially attractive for household customers with flexibility: Considering the willingness to pay more of all adopter groups, more than 90% of all flexible consumers would select the tariff based on the day-ahead spot market price. This tariff offers greater benefits to all households than a 3-tier ToU tariff, even though the latter still has economic advantages when compared to a static tariff.

Our results demonstrate that, if household customers with flexibility are given the choice between various static and dynamic tariffs, they will select different tariffs depending on the individual benefits they stand to gain. We further show that, even though dynamic tariffs lead to an increase of certain households' peak loads, the diversification of tariffs in an area is still favorable for the grid, since it results in lower thermal loads and lower voltage band deviations (in terms of magnitude) in the grid due to the mixing effects of different tariff schemes. Despite the fact that there are more hours with violations of grid restrictions with free choice of tariff, with respect to grid expansion, this would mean that less expansion measurements might be necessary due to the lower maximum grid load. Additionally, the utilization of the expanded grid would be higher. This finding should have implications for distribution grid planning. Our study goes beyond the current state of the art as it allows for the selection and coexistence of multiple tariffs within one distribution grid. With this novel methodological approach, we generated results that are closer to reality than previous studies.

While this work focused on the effects of heterogeneous household customers and their individual decision-making on financial attractiveness and grid load, further research is planned to also examine the required grid expansion. This could integrate the perspective of the grid operators more strongly into the economic evaluation and would also allow for a quantification of the effects on local grid charges. Even though the tariffs applied in this study were based on incentives from a centralized market, which does not necessarily reflect the local grid situation, we were still able to demonstrate that dynamic tariffs reduced the grid load due to the above-mentioned mixing effects. Comparing these results to other demand response options such as peak load shaving or dynamic grid charges, however, could improve the understanding of possible future pricing options.

Credit author statement

Judith Stute: Conceptualization, Methodology, Software, Validation, Formal analysis, Data Curation, Writing – Original Draft, Writing – Review & Editing, Visualization, Funding acquisition. **Matthias Kühnbach:** Writing – Review & Editing, 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.

Data availability

The authors do not have permission to share data.

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