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Impact of Dynamic Electricity Tariffs and Time-of-Use Grid Charges on Households with PV-BESS

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Abstract. This study uses simulation-based analysis to examine how a real-time pricing electricity tariff and time-of-use grid charges affect different residential households with photovoltaic generator and battery energy storage system. The study aligns with other research in terms of general trends. A novelty of this work is the completely reworked methodology regarding the level of detail in which the households are modeled. The findings confirm that economic benefits are achievable through price-based control, especially when combining real-time pricing electricity tariffs and time-of-use grid charges. With a standalone 5-kWh battery system and without a photovoltaic generator they save €153/year on electricity costs on average when just using real-time pricing. If the nominal charging power of the battery inverter is lifted from 2 kW to 3 kW the reference household saves €35/year, whilst the nominal discharge power of 1 kW is sufficient enough to reach the maximum savings for this usable battery capacity. Furthermore, if the time-of-use grid charges are incorporated as well the savings can be increased to €233/year on average. However, in case that an additional 10-kW photovoltaic generator is installed the savings are diminished to €64/year. Depending on the scenario, some households would even pay more than before. Photovoltaic systems reduce the potential savings of real-time pricing electricity tariffs since their generation often aligns with low-price periods. Future research should further explore potential savings for other controllable devices like heat pumps and electric vehicles.

Keywords: PV BESS, RTP ELECTRICITY TARIFF, TIME-OF-USE GRID CHARGES

1. Introduction

Real-time pricing (RTP) or dynamic electricity tariffs and time-of-use (TOU) grid charges offer homeowners a financial incentive to shift their consumption to off-peak times wherever possible. Transmission and distribution system operators (TSOs, DSOs) in particular see this as an opportunity to avoid grid bottlenecks and thus the option to reduce costs for grid expansion measures or redispatch, especially in the future with a high penetration of full electrified appliances [1].

Several case studies as well as pilot projects by manufacturers of photovoltaic (PV) inverters, battery energy storage systems (BESS), and energy management systems (EMS) have already shown that residential customers can achieve economic benefits by switching to RTP tariffs and TOU grid charges, e.g. [2], [3]. The focus lies particularly on controllable consumption devices such as heat pumps and private charging points, but there are also repeated considerations regarding BESS in combination with and without a PV generator [4].

RTP tariffs based on wholesale prices are signals that reflect the overall system status of the grid and market. If based on merit order, low prices usually correlate to high shares of renewable generation and high prices indicate the opposite or in general a high residual load. By making the option of RTP tariffs mandatory for electricity providers, customers' load may increase or decrease to a certain degree at different times. However, balancing the market in this way on the highest system level might lead to conflicts with local grid requirements. For example, low wholesale prices and thus low RTP prices can intensify grid shortages due to avalanche effects as a result of synchronization. To counteract this problem, local price signals are needed, which can be implemented in form of TOU grid charges [4].

German TSOs and DSOs are eligible by law to pass grid expansion and maintenance costs onto customers in the form of grid charges, which are regulated by upper limits. Until recently, this has generally been a fixed value for residential customers. Due to §14a of the *Energiewirtschaftsgesetz* (EnWG) DSOs have direct access to newly built *Steuerbare Verbrauchseinrichtungen* or controllable consumption devices, e.g. heat pumps, charging points, BESS, etc. In the case of a critical grid situation the DSO is entitled to reduce the maximum power drawn from the grid by households by sending a control signal to their smart meter. As a compensation mechanism, the customer is given a choice between the following options [5]:

Module 1 represents a flat reduction in grid fees. Depending on the local DSO, the amount ranges between €110/year and €190/year as of 2023. The reduction is paid only once, even if there are multiple controllable consumption devices at the same market location [6].

Module 2 offers a 60% reduction of the working price of the grid fees. This option requires separate metering of the chosen controllable consumption devices. The base grid fee is just paid once and not multiple times for each device.

Module 3 can only be chosen with Module 1, e.g. it is always a combination of Module 1 and Module 3. This option allows customers use TOU grid charges. Grid operators are obliged to determine times with high and low grid charges for at least two quarters of the year. During this time the working price of the grid charges may indicate grid utilization. Thus, encouraging consumers to shift their electricity consumption of the controllable devices to more favorable times from the local DSOs perspective. Therefore, the TOU grid charges can vary among the DSOs to meet their anticipated grid relieving requirements.

On the one hand, Module 3 is designed to balance local generation and consumption imbalances directly onsite. On the other hand, it is used to provide an incentive for off-peak consumption. These measures give the grid operator not only an option to influence the power consumption in emergencies to a certain extent but also market-based control, thereby theoretically reducing the need for grid expansion due to market-driven behavior of customers [7].

While numerous studies using simulation-based analysis have already examined the influence of the presented price signals on the distribution grid [1], [2], [3], there is a lack of comprehensive results regarding the economic efficiency for various end-customer use cases. Even when the financial viability for residential customers is examined, it is a fixed set of technical parameters and system sizing [4], [8], [9], [10], [12], [14]. Different conditions result in individual scenarios, and the variability of key system parameters such as power consumption and nominal BESS charging and discharging power increases the complexity of the analysis.

Research questions: This paper investigates the impact of an RTP electricity tariff and TOU grid charges on 27 households through the simulation of one operational year for different scenarios. The following central questions are addressed:

1. In which scenarios do the households benefit financially from switching to RTP electricity and TOU grid charges?
2. Which system parameters have the largest influence on the potential savings?

2. Model Description and Input

This section describes the simulation model that was used to obtain the results and answer the proposed research questions. Afterwards, the model input is presented and to some extent analyzed. A simulation model for a residential PV-BESS called simbat is used [15]. So far, the BESS in the model is controlled to optimize self-consumption. For this work, the model is extended to be able to control the BESS to incorporate price signals, such as RTP tariff and TOU grid charges.

Conventional control strategies for PV-BESS follow a surplus-charging principle, where the battery is charged immediately when PV generation exceeds electrical load. When there is no solar surplus, the battery covers these loads within the limits of its discharge capacity and its current state of charge (SOC). However, this control strategy does not take any price signals into account, which is why the BESS is only charged by the electricity generated by the PV itself, and the storage system does not prioritizes discharge times.

Therefore, the implemented model predictive control searches within a rolling-horizon ideal forecast of the combined time series of RTP tariff and TOU grid charges for low-price time frames. The controller uses the load consumed in the coming hours, the initial SOC at the current time, and a perfect forecast of PV generation to check in advance whether grid charging in the current time step offers an economic advantage. The price spread between the points of charging and upcoming discharge period must reach a certain threshold to compensate the conversion and storage losses. In this study a minimum of 19% is needed, due to the chosen inverter efficiencies of 91.9% (Inverter - charging), 91.8% (Inverter - discharging), and 96% (Battery). Within the discharge periods, the EMS prioritizes loads during times of high electricity costs in order to minimize grid procurement costs.

To compare the financial gains of the different system configurations and scenarios, a key performance index (KPI) is needed. In addition to common figures such as the share of self-consumption or the degree of self-sufficiency, economic approaches are often used for the evaluation [16]. The most obvious comparison is that of annual **grid procurement costs** C_{G2AC}, which are determined as follows:

$$C_{\mathrm{G2AC}} = \sum_{\mathrm{t}} E_{\mathrm{G2AC}}(t) \cdot p_{\mathrm{G2AC}}(t) = \sum_{\mathrm{t}} P_{\mathrm{G2AC}}(t) \cdot p_{\mathrm{G2AC}}(t) \cdot \Delta t \qquad (1)$$

The variable E_{G2AC} describes the energy drawn from the grid and p_{G2AC} the price of electricity at each moment. The energy sum is calculated with the power drawn from the grid P_{G2AC}. Furthermore, the step size of the simulation Δt is needed to quantify the energy sums. A step size of 15 min is chosen for the simulation as a compromise between the accuracy of the results and the computing time of the simulation, which is quite important due to the many parameter variations. As the focus of this study lies on price signals with a minimum time step of 15 min, the chosen Δt is adequate, as smaller step sizes are mainly needed for efficiency characterisations of BESS [17]. The savings on electricity costs C_{diff} are calculated to quantify the economic benefit from switching to the RTP electricity tariff from a fixed tariff:

$$C_{\mathrm{diff}} = C_{\mathrm{G2AC,36ct}} - C_{\mathrm{G2AC,dyn}} \qquad (2)$$

$C_{\mathrm{G2AC,36ct}}$ describes the grid procurement costs for a system with a fixed €0.36/kWh-tariff without any grid charge reduction. In comparison, $C_{\mathrm{G2AC,dyn}}$ describes the electricity costs for the same household but with the RTP tariff. In the following the achievable cost savings of the reference system or all households through the switch to the RTP tariff are just referred to as **savings**. The usage of TOU grid charges is defined in certain scenarios, e.g. if a household is using them in a scenario the variable $C_{\mathrm{G2AC,dyn}}$ also includes them.

The simulation model needs different inputs: Irradiation and temperature data from the German Weather Service (DWD) of 2024 [18] is used to simulate the PV generation. German day-ahead wholesale electricity prices for the same period [19] are the basis for the RTP electricity tariff which is synthesized with average values of taxes, levies, etc. for German residential households according to [20]. Furthermore, electrical load profiles of 27 real German households and TOU grid charges from 14 German DSOs are used. All simulation parameters and a comprehensive description of the simulation model are available online [21].

Electrical load profiles are essential for simulating household consumption behavior. Since peaks in electrical consumption often occur only in very short time windows, high-resolution electrical profiles are essential for analyzing load fluctuations in households [22]. The data basis for this study is provided by the publicly available data set of several residential load profiles from multiple single-family households by Schlemminger et al. . Eleven households are excluded from the analysis due to larger measurement gaps or system changes during the measurement period, which is why only 27 households from the data set are used for the investigation in this work. The operating year 2019 is selected because a full year is required and the data of 2019 contains a larger number of plausible load profiles compared to 2020. The households examined consumed between 1146 kWh/year and 5490 kWh/year in 2019 and showed peak loads between 5.2 kW and 11.6 kW. The median consumption was 2946 kWh/year.

Figure 1 (left) shows the average daily progression of the electrical profiles regarding their share of the annual consumption. The daily consumption is strongly influenced by the presence and usage behavior of the homeowners, e.g., work (office, home office, shifts). Typical load profiles are often characterized by increased consumption in the evening hours and low consumption during the night. The prediction interval and interquartile range (IQR) are shown to demonstrate the variety of the 27 profiles. A reference profile is chosen which represents the group best regarding consumption (3133 kWh/year), daily, weekly and seasonal progression.

Figure 1 (right) supplements the previous graph by showing the average seasonal progression. The median of all profiles clearly shows the trend of lower consumption in the summer months and higher consumption during winter [24]. However, the IQR range clearly shows how the seasonal progression can vary depending on the electrical load profile. Seasonal differences can often be explained by certain household equipment and length of use over the course of the year. Small electrical heating units or saunas often increase consumption during the heating season, whereas air conditioning leads to increased consumption in the summer months. The data set used for this work lists electrical consumption for heating with heat pumps in a separate data series, which is not included in this analysis. Accordingly, the higher consumption in the winter months can be attributed to other consumers or adjusted user behavior.

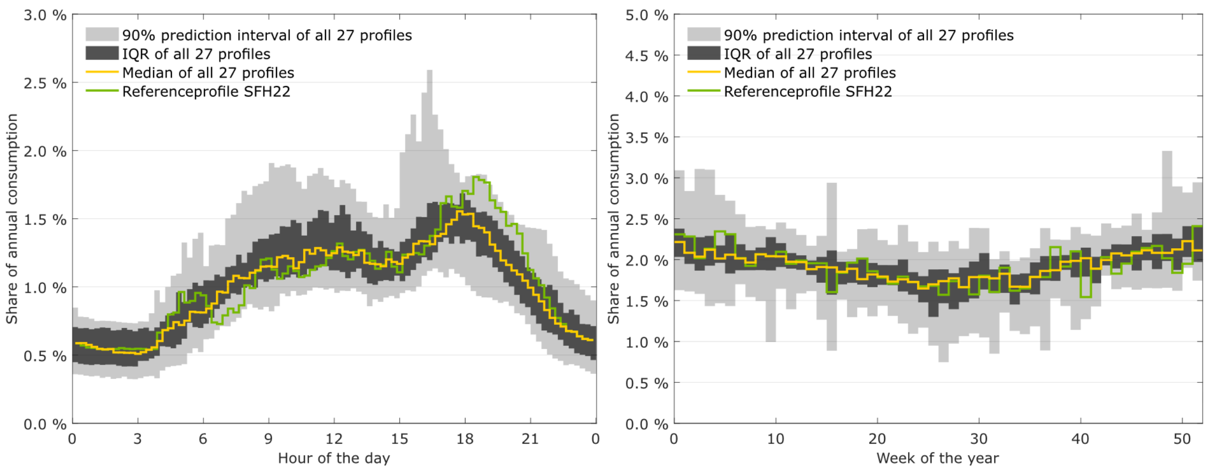

Figure 1. *Daily (left) and seasonal (right) progression of the reference load profile, as well as all 27 load profiles and their median*

Next to the load profiles, the price signals in the form of RTP electricity tariffs and TOU grid charges are additional inputs. **Figure 2** (left) shows the day-ahead electricity wholesale prices for 2024. They are the main component of the RTP tariff, levies stay consistent per kWh and the taxes amplify the signal as they are calculated by percentage. A comparatively higher wholesale price is particularly noticeable between 6:00 a.m. and 9:00 a.m. and between 5:00 p.m. and 9:00 p.m. The daily local maximum price is often around €0.20/kWh. Between late morning and early afternoon, prices often fall below €0.10/kWh on many days. This diurnal characteristic is not constant throughout the year, but adapts to the seasonally fluctuating times with available PV energy. In January, February, November and December, this trend is less noticeable compared to the rest of the year.

Furthermore, several days with comparatively higher electricity wholesale prices are seen from November to December, resulting from cold temperatures in combination with low electricity generation from renewable sources such as PV and wind energy. When renewable sources cannot generate sufficient energy, gas-fired power plants that can be activated very quickly are increasingly started up. Due to the declining available capacity of nuclear and coal power plants in Germany, gas turbines are increasingly stepping in [25]. This is one of the main drivers of expensive wholesale electricity prices [2].

Compared to RTP tariffs, TOU grid charges after Module 3 §14a (EnWG) are clearly defined each year. **Figure 2** (right) illustrates the three grid charge levels for 14 German DSOs indicated by the colors. The DSO names are listed in **Table 1**. For each DSO, there are three levels, but to enable a better comparison between DSOs the absolute price of the grid charge is indicated in the form of a color bar. 13 of the 14 DSOs offer a low charge during the night and morning hours to encourage customers to use their controllable devices during these times. The exception is the operator Netze BW (Nr. 11), who only offers low grid charges between 10:00 a.m. and 2:00 p.m. A possible reason might be the high levels of PV generation in its grid, and the resulting oversupply of solar energy, especially at midday.

***Table 1**.* Full names of the DSOs which TOU grid charges after Module 3 §14a have been analyzed

Nr.	Name of DSO	Nr.	Name of DSO
1	Stadtwerke Greifswald	8	SH Netz
2	Wesernetz	9	Stadtwerke Bayreuth
3	Stadt- und Überlandwerke Luckau-Lübbenau	10	Energienetze Offenbach
4	Gera Netz	11	Netze BW
5	Stadtwerke Hameln	12	Sachsen Netze
6	Bayernwerk Netze	13	Stromnetz Berlin
7	EV Inselsberg	14	Hamburger Energienetze

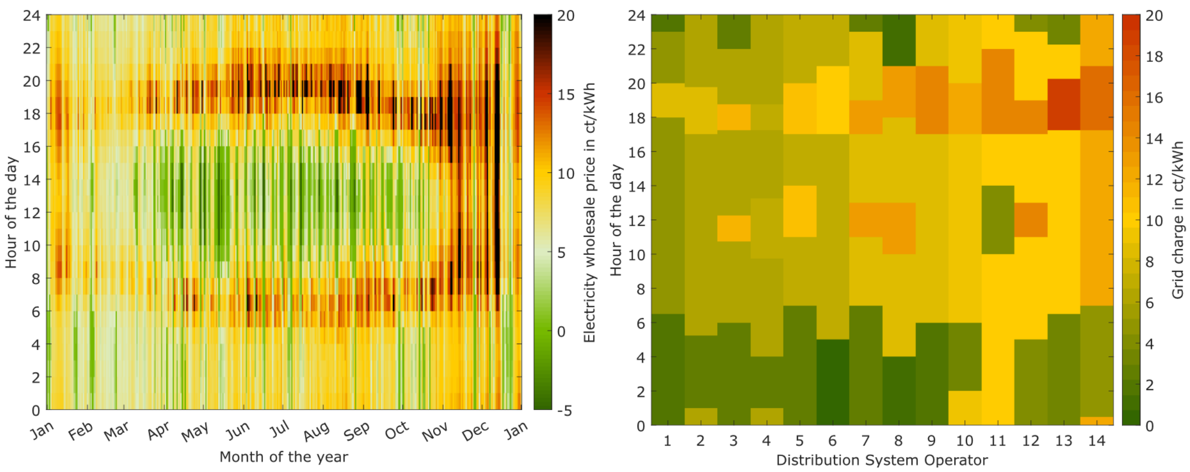

Figure 2. *Daily and seasonal trends in German wholesale electricity prices in 2024 (left) and TOU grid charges after Module 3 §14a of the EnWG for 14 German distribution system operators (right)*

3. Results

In this section the simulation results are presented. Firstly, the price-based control strategy is shown and exemplarily analyzed for one day. Secondly, the impact of certain system parameters and scenarios on the achievable RTP savings is explored.

The operation of the implemented price-led control is illustrated and analyzed. **Figure 4** (left) shows the ideal (lossless) system behavior for an exemplary day. The following findings can be identified from the simulation results:

- The PV-BESS charges between 2:00 a.m. and 3:00 a.m., as a low price of €0.28/kWh is identified by the EMS. The BESS charges enough energy from the grid to cover all loads until the surplus of PV generation occurs.
- The storage unit then discharges to cover all household loads as the RTP cost rises. This allows the system to avoid grid consumption during this time period which would add up to about 0.55 kWh.
- Thanks to the morning grid charge, the system with price-based control can cover the loads during evening and nighttime not only until 6:30 p.m. (which would be the case with self-consumption control), but until 10:30 p.m. and thus saves €0.17 on this particular day.

When the battery is charged from the grid at low prices, the charging power might influence the possible savings, low-priced time windows could be quite short. **Figure 4** (right) illustrates this dependency. It shows the achievable cost savings of the reference profile through the use of the RTP tariff depending on the charging and discharge capacity of the 5-kWh-BESS. The household can save between €20/year and €69/year, with savings change most significantly up to charging powers of 3 kW. By increasing the charging power from 2 kW to 3 kW, the reference household saves an additional €35/year. Higher charging power is not necessarily required with this specific storage capacity, as the power of the inverter is sufficient to take advantage of the short low-priced windows to fully charge the battery.

The influence of the discharge power of the battery storage is clearly noticeable up to just under 1 kW. The reference household often requires power outputs below 1 kW, so a higher discharge power is not significant for the achievable cost savings. In general, the cost savings in the parameter range studied are achieved with a nominal discharge power of just under 2.8 kW. Optimal system combinations in terms of cost savings are close to the isoline of 4 kW of charging power per 1 kW of discharge power.

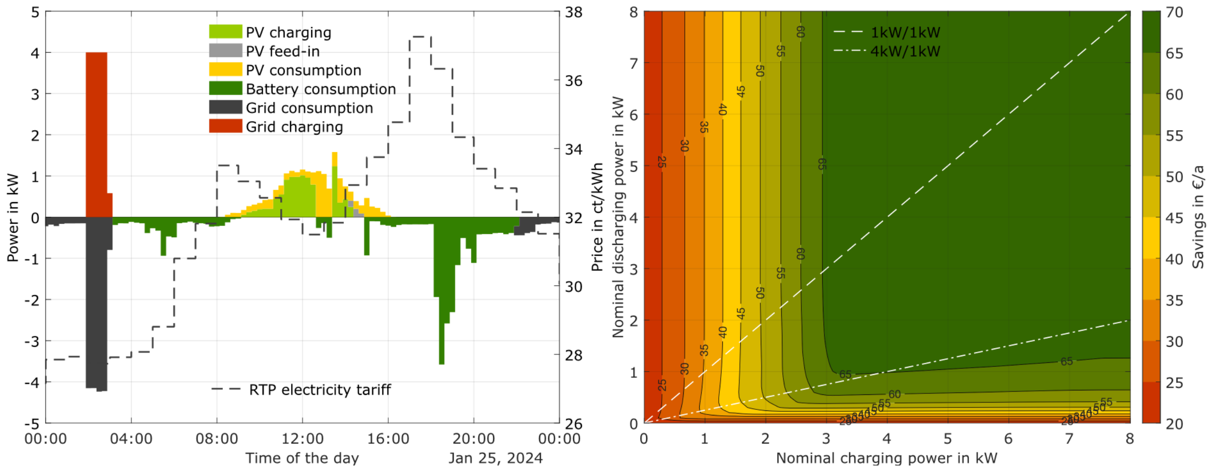

Figure 3. *Ideal system behavior on an exemplary day with the price-led system control based on threshold values (left) and influence of the charging and discharge capacity of the BESS on the savings of the reference household (right)*

The results above refer to households that only use the RTP tariff; the TOU grid charges have so far been neglected and the combination of both is therefore analyzed in the subsequent section. **Figure 4** (left) shows the cost savings achieved by the 27 households with a 10-kW-PV generator and 5-kWh-BESS through the combination of RTP tariff, flat grid charge reductions after Module 1 and TOU usage after Module 3 for 14 exemplary German DSOs.

The savings range from €3/year for one of the households with Stadtwerke Greifswald to just under €155/year for a household in the area of Stadtwerke Bayreuth. The small range of cost savings for households using Netze BW is particularly interesting. The savings within the households differ by just under €20/year. The reason for the comparatively low absolute values is the low range between low and high grid charges after Module 3 of this individual DSO. Furthermore, of the 14 DSOs examined, Netze BW is the only one that does not include a low-price time window at night or in the morning, but the only one offering lower grid charges at midday. Due to PV generators of the households, the low-priced periods can almost only be utilized for storage during the winter, which is why the savings for all households are comparatively low. A possible reason for the DSOs choices is the low wind capacity in the grid area as well as the energy-intense and in shifts around the clock working industry.

For the scenario analysis, the DSO Stromnetz Berlin is chosen, the system retains a 5-kWh-BESS and for certain scenarios a 10-kW-PV generator. **Figure 4** (right) summarizes the range of cost savings achieved by the 27 households examined for the use cases analyzed in this chapter. Households with only a BESS benefit significantly more from the use of the RTP electricity tariff than households with a combined PV generator. Households with BESS that use the combination of RTP and grid charge reduction through Module 1 and Module 3 (Scenario 4) see the greatest financial advantage. On average, these households save €233/year compared to the fixed tariff without a reduction in grid fees. If they just use the RTP tariff without the grid fee reduction they save between €49/year and €324/year (Scenario 1), averaging €152/year. In comparison, households with a PV-BESS only achieve a guaranteed financial advantage when using Module 1 (Scenario 6) or Module 1 and Module 3 (Scenario 8). On average, the savings for these two use cases are €48/year and €64/year.

By using Module 2, all systems with a PV-BESS (Scenario 7) incur higher grid procurement costs, with the median additional cost being €114/year. If these households are not entitled to compensation for grid fees and only use the RTP tariff (Scenario 5), some households may achieve savings, while others will pay more. On average, however, the savings are negative at around €4/year. Even households with a standalone BESS that use RTP and Module 2 (Scenario 3) might have to pay more compared to the Status Quo, in the worst case €39/year.

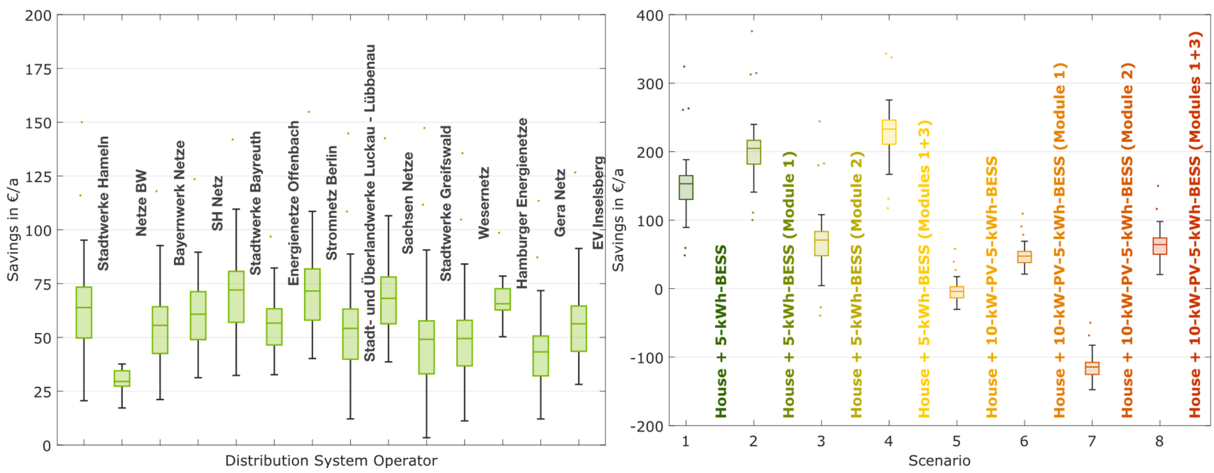

Figure 4. *Savings for the 27 households when choosing Module 1 in combination with Module 3 for 14 DSOs (left) and range of savings through the use of the real-time pricing electricity tariff for the 27 households for different scenarios in terms of installed technologies and regulations (right)*

4. Summary and Discussion

The simulation-based analysis of residential households with PV-BESS that use RTP electricity tariffs and TOU grid charges after §14a of the EnWG shows that many of the examined households in different scenarios are able to achieve financial gains compared to the status quo with a fixed electricity tariff. But there are a few system configurations and scenarios where the choice to use the named price signals is a financial disadvantage for some or even most households.

By using a 5-kWh BESS without PV, the households save on average €152/year compared to the fixed electricity tariff. Conversion losses have a significant impact on the quality of energy management and system control. The benefits of the RTP tariff decrease with the installation of a PV generator, since it mainly generates electricity during periods when the dynamic tariff is favorable. By varying the charging power and battery storage capacity, the highest savings can be achieved with a ratio of storage capacity to nominal charging power of 1 kWh to 0.65 kW.

By using the RTP tariff and combining Module 1 and Module 3, the reference household can achieve savings of €74/year. Depending on the DSO, the households examined can save between €3/year and €155/year. The lowest reductions are achieved by a household supplied by Stadtwerke Greifswald, while the highest savings are achieved by a system located in the grid area of Stadtwerke Bayreuth. In general, households without a PV generator but with a BESS benefit most from the use of the price signals: By combining RTP tariff, flat grid charge reduction (Module 1) and TOU grid charges (Module 3) the maximum savings are above €400/year.

A comparison of the results of this paper with the current research in this field reveals some significant deviations, but generally the same trends [10], [13], [14]. Several studies focus on the effects of price signals for residential homes on the distribution grid, which are not examined in this study [2], [3], [4], [26]. Furthermore, only a few identified studies include the costs for the needed measurement hardware and necessary control boxes in their cost analysis, which makes the savings achieved through the RTP tariff in other studies appear significantly higher. Not all studies consider a full year in their simulation of use cases [26], [27]. This means that seasonal effects on system behavior are ignored, which can lead to distorted results, especially in households with PV systems.

Nevertheless, a critical view of the methodological approach used in this paper is necessary. In general, it should be noted that the generalizability of the results is minimized by the small sample size of only 27 real household electrical load profiles. Also, reference must be made to the performance of the energy management system implemented in this study. Since it is difficult to calculate the maximum theoretical cost savings, the quality of the energy management system cannot be directly assessed. In general, the implemented price-based control approach proves to be effective; however, even a small improvement can make the use of RTP tariffs and TOU grid charges much more financially attractive for various applications.

The results of this study have raised new questions that should be analyzed in more detail in future research:

- What are the benefits of RTP electricity tariffs and TOU grid charges for households with other controllable consumption devices such as heat pumps and electric vehicles?
- To what extent can the quality and efficiency of the energy management system be improved by using state-of-the-art optimization methods?

Data availability statement

The simulation results will be published with the model, but are available earlier on request.

Underlying and related material

The used simulation model is currently developed further to incorporate the option to add heat pumps and electric vehicles. The model will be published with the conclusion of the research project “KLIMTEC” as an open-source simulation model.

Author contributions

Lucas Meissner: conceptualization, methodology, software, simulation, writing – original draft. Joseph Bergner: conceptualization, methodology, writing – review & editing. Volker Quaschning: conceptualization, supervision.

Competing interests

The authors declare that they have no competing interests.

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