Project Report L18-3: Demonstrating the optimal prediction of user behaviour for the virtual energy community

09/2022

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SPARCS

Dissemination level		
PU	Public	X
CO	Confidential, only for members of the consortium (including the Commission Services)	

Deliverable administration

No & name	**Annex to D4.3** **Report on the implemented demonstrations of solutions for energy positive blocks in Leipzig**				
Status	Draft/Working/Released	**Due**	M36	**Date**	2022-09-30
Author(s)	*Hendrik Kondziella, Karl Specht, Tim Mielich, Thomas Bruckner (ULEI)*				
Description of the related task and the deliverable. Extract from DoA	**T3.4 Integration of Community Energy Storage (CES) and Community Demand Response (CDR) (ULEI, LPZ, LSW) M1 – 36** This subtask takes on the task of understanding and predicting the behaviour of energy system participants. The reliable integration of the planned "community energy storage" (CES) and "community demand response" (CDR) represent possible business cases for a successful system transformation at the municipal level. The mathematical optimisation model, as a mixed-integer linear programming, will allow a policy-oriented, technology-based, and actor-related assessment of varying energy system conditions in general, and innovative business models in particular. The integrated multi-modal approach is based on a novel six layer-modelling framework, which builds on existing high-resolution modelling building blocks.				
Participants	ULEI				
Comments					

V	Date	Authors	Description
0.1	30/09/22	HKo	First draft
0.2	07/10/22	HKo	Review

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Partners

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EXECUTIVE SUMMARY

This study analyses the optimal customer behaviour as reaction to flexible electricity tariffs. In addition, the demand-side management measures are evaluated in combination with a Virtual Power Plant (VPP) to show its impact on the design of positive energy districts (PED). The research question is divided into three parts, which illustrate the technical, economic, and environmental aspects of the potential of residential demand response. Regarding the methodology, a techno-economic energy system model is proposed that optimises both, the customer cost and the utility's margin. The building blocks of the energy system model are depicted in Figure 1. These components are equipped with parameter estimates for two time-steps representing the short-term (e.g. 2025) and long-term (e.g. 2045) developments. It is assumed, e.g., that the absolute amount of customers within the virtual energy community is increasing to about 50,000 households in the long-term as well as the particular share of customer group 2. This second cluster is supposedly activating a higher potential for load shifting by its electric heating appliances. Aside from the long-term development of model parameters, the differing load shifting potential of the customer groups is represented by two distinct scenarios (*Acceptance* vs. *Reluctance*).

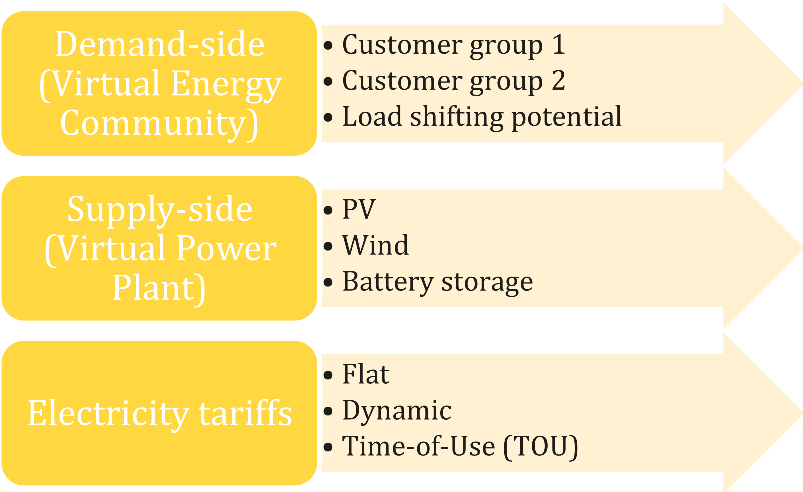

Figure 1: Building blocks of the modeling approach.

Regarding the technical potential of Residential Demand Response (RDR), the parameter combinations within the *Acceptance* scenario provided the highest potential for load shifting. Furthermore, the VPP oriented tariffs, which integrate the state of zonal and local conditions for RES generation, likewise achieved to reduce the market dependency observably. By encouraging load shifting, the Annual Mismatch Ratio (AMR) of the local energy system, describing the hourly imbalances, is improved.

With respect to the economic outcome, the results distinguish between general welfare, and the specific actors. Over all scenario combinations, a welfare gain by using customer flexibility is achieved in comparison to a static case without load shifting. This welfare gain is attributed to the cost reductions of the residential customers that were observed over all scenario combinations of the *Acceptance* and *Reluctance* scenarios. However, the amount of avoided costs differed significantly between the various tariffs and residential

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customer groups. Over both groups and time-steps, the dynamic "VPP (HD)" tariff provided the best cost savings whereas the two-stage TOU-tariff ranged at the lower end of the spread. While the cost savings of group 2 were significantly higher than the savings of group 1, the calculated volatility of cost reduction would be presumably not sufficient to cover the costs for smart metering respectively.

Subsequently, it is deduced that the price volatility has to be increased to cover the costs for smart metering. An increase in spot market volatility or more drastically a change in taxation from per-unit to an ad-valorem taxation system could provide promising results (Blaschke, 2022) In contrast to the customer side, the utility lost some of its margin when changing from a static to more dynamic tariff schemes. Nonetheless, the utility was able to increase the energy autonomy of the local system. Accordingly, RDR proved to be a potential component of the flexibility options of the utility and therefore to some extent able to replace conventional power plants for the provision of residual load. Potential economic benefits of the flexibility provided by RDR within this system regarding the residual load and balancing group management are not considered and are subject to future research.

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1. Introduction

As part of Leipzig's lighthouse demonstrations, an open standard based Information and Communication Technology (ICT) platform is developed and implemented (Sparcs project, 2021, task 4.3). The main goal is to upgrade the interaction between energy production, storage capacity and the consuming entities to a virtually connected community. It provides the prerequisites for peer-to-peer energy trading, energy communities, a citywide decentralized virtual power plant, and the link to heat and power sectors (see L9-1). The virtual power plant (VPP) integrates alternative power generation like solar energy, and combined heat and power (CHP) with weather and demand forecasts. On the basis of (almost) real time data, the energy consumption and generation can be balanced. Consequently, the platform has to implement real time forecasting and optimisation methods. Additionally, it is planned to simulate the integration of an energy storage in this local energy structure to demonstrate that the ecological end economic efficiency can be further increased (Sparcs project, 2021). With the established distributed cloud-centric ICT system, intelligent energy management is enabled. Therefore, externally controlled « Smart plugs » will be installed in various living units for proving economies of scale for larger installations on a citywide level. By this, efficient demand side management will be demonstrated via the monitoring and controlling of energy consuming devices. This solution enables customers to actively participate in the energy market and thereby increase the share of RES for their energy consumption (Sparcs project, 2021). Moreover, the reliable integration of the envisaged "community demand response" (CDR) is thought of as a possible business case for a successful transformation of the municipal energy system. The target design of the virtual energy community by the end of the demonstration phase of SPARCs is visualised in Figure 2. Although the platform is not in operation yet, this study aims to provide insights into the impact of active customers on the energy system by a modelling approach.

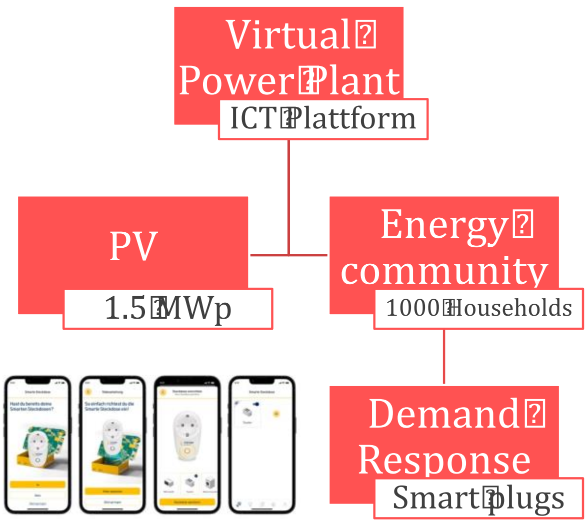

Figure 2: Existing design of the virtual energy community by the end of the demonstration phase. (Source: ULEI and LSW)

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1.1 Purpose and target group

To address the issue of load fluctuations and to provide flexibility, academia and practitioners have been discussed Demand Response (DR) and Virtual Power Plants (VPP) as counter measures. Such concepts are seen as approaches, which are able to provide aggregation potentials in the electricity system (Ma et al., 2017). DR is used as a load control technology for responding to energy consumption, e.g., to manage grid stress and congestion. One way to achieve effective load consumption using DR is by load shifting. This means that the load of certain appliances is shifted to other periods without affecting the consumer's comfort (Talpur et al., 2020). On the other hand, a VPP can be described as virtual entity that is composed of physical devices such as Renewable Energy Sources (RES), gas turbines, energy storage, and flexible loads using advanced information technology and software systems. The VPP is set to participate in the managing of the power system and respective electricity market (Liu et al., 2018).

So far, only a few studies have investigated the economic and ecological potential of residential demand response (RDR) in combination with a VPP. To fill this gap, this work aims to

(1) develop a model of a municipal energy system (including market players) for the years 2025 and 2045;

(2) evaluate the future technical, economic and ecological potential of the respective municipal energy system scenarios; and

(3) determine the particular future economic potential of the different actors in the energy system, e.g. the energy community.

By this way, the results contribute to efforts of energy providers regarding the development of innovative business models, which are based on an active management of the demand-side. In addition, grid operators can also benefit since the model outcome also comprises highly resolved load flows.

1.2 Research questions

The distinct research questions that are necessary to evaluate the potential of RDR in combination with a VPP are split into three steps. The first step focuses on the technical viable potential of residential demand in combination with a VPP in a municipal setting. Secondly, the attention is devoted to the future economic potential of the modelled energy system. Furthermore, it is to be assessed what ecological benefits can be achieved within the varying scenarios. Finally, the third step analyses the respective future economic potential of the various actors of the municipal energy system for which RDR is being applied.

Research question 1: *How does the future technical potential of residential demand response in combination with a virtual power plant vary for differing municipal energy system scenarios for the years 2025 and 2045?*

The starting point of the first research question is to lay out the municipal energy system model, which is described more thoroughly in Section 3. Following, the emphasis of the modelling is to generate data points relating to the technically viable potential of RDR. These points are used to identify the maximum amount of optional load shifting over the

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forecasted year. Furthermore, the scenario design in Section 3 offers details on the key variables differentiating the developed scenarios. The aforementioned variables are adjusted to construct various conceivable futures. With this, a foundation is provided for the investigation of the economic and ecological potential of RDR. The second research question moves from a purely technical perspective to a substantial economic one.

Research question 2: *How is the future economic viability of residential demand response and what ecological potential does it yield for the years 2025 and 2045?*

The second research question builds on the results from the first one to deduce the economic potential of the future municipal energy system for varying scenarios and differing variables. By applying RDR combined with a VPP, energy consumption can be shifted intelligently so that curtailment of RES production can be evaded. Moreover, spot market price peaks are avoided and the share of decentralized RES production is increased. Evaluating these processes allows a deeper analysis of the economic impact of RDR. Besides, the aggregated results of the analysis allow conclusions regarding the ecological potential of the application of RDR. The ecological potential is derived from the amount of avoided carbon dioxide emissions. With the last research question, the focus of the analysis shifts from an overall economic perspective to the actor-level one.

Research question 3: *Regarding the various actors in the municipal energy system, how is the respective future economic potential to be determined applying residential demand response, for the years 2025 and 2045?*

The usage of RDR must be economically worthwhile for all actors. Without their interest in participating in a more flexible municipal energy system all technical viable potential for RDR is inaccessible. Therefore, it is within this research question to determine the individual economic output for the various actors with regard to the different energy system scenarios. Overall, the aggregated results from the research questions aim to highlight the possibility of transforming the future municipal energy system to a more decentralized and flexible one.

1.3 Structure

This report is subdivided into three thematic sections. The first block forms the foundation (Sec. 2). The subject is introduced, followed by a presentation of the technologies of interest – DR and VPP. This section is concluded by an overview of application-oriented smart city projects. Thereafter, the main part of this research consists of the methodology and analysis (Sec. 3). The first part is dedicated to the scenario modelling in which the framework of the model is illustrated and the model setup described. Within the model framework, the energy system design is outlined and the optimization approach explained. In Sec. 4, the optimization results are presented for the main scenarios followed by a comparison of the outcomes of a sensitivity analysis. Finally, we evaluate the technical, economic and ecological perspective and conclude this report in Sec. 5.

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2. THEORETICAL FOUNDATIONS

The first part of these fundamentals introduces DR and VPP. The DR model is defined, its program classification described, pricing preferences outlined, and shifting potentials identified. Following, the second part gives a short overview over some European applied research projects.

2.1 Demand response

DR is seen as a promising techno-economic solution to transform electricity demand towards more flexibility. The terminology of it is varying. Consequently, this work uses the definition of (Albadi & El-Saadany, 2007) who defines DR "as the changes in electricity usage by end-use customers from their normal consumption patterns in response to changes in the price of electricity over time". All deliberate modifications to consumption patterns of electricity of final consumers that are planned to change the timing, level of demand, or the total electricity usage can be seen as a part of DR. For a more precise description of price changes, hourly, daily or seasonal variable tariffs can be used. Furthermore, two ways of proceeding in changing their consumption behaviour, which are adoptable by the customers, are load curtailment and load shifting (Scheller et al., 2018). Thus, DR and battery energy storages in urban areas are able to provide a similar opportunity for load flexibility (Hu et al., 2017). The principle of load shifting can be described in the way that temporary load reductions are balanced out by load increases in other periods. In contrast, load reductions are not compensated in case of load curtailment. Logically, both procedures create certain discomfort for customers by implementing consumption changes. As acceptance of DR programs by the customers is crucial for the success of demand side flexibility spreading, this study aims to reduce the discomfort for residential customers originating from DR as far as possible. Accordingly, it is assumed that RDR is solely performed by load shifting, due to its lesser impacts on customer comfort.

2.1.1 Demand response programs

DR programs intending to animate end-use customers to participate are classified in different categories. The main categories are price-based and incentive-based programs, which are depicted in Figure 3. Moreover, the subdivisions of these main categories are illustrated with some exemplary DR program types. Thus, incentive-based programs are divided into classical and market-based programs. Within classical incentive-based programs, like direct load control, participating customers allow an external scheduler to control their energy consumption. For this discomfort the program participants receive payments. Naturally, the extent to which the load is controlled externally needs to be determined in a contract between the two parties (Albadi & El-Saadany, 2007; Gärttner, 2016). In market-based programs, participating customers receive money contingent on the amount of load reduction during pivotal conditions. Therefore, in the case of emergency DR participants are rewarded with incentive payments for load reductions during periods of reserve shortfalls. Otherwise, in the capacity market programs, customers help to replace conventional energy generation by supplying load reductions of a predetermined quantity (Scheller et al., 2018).

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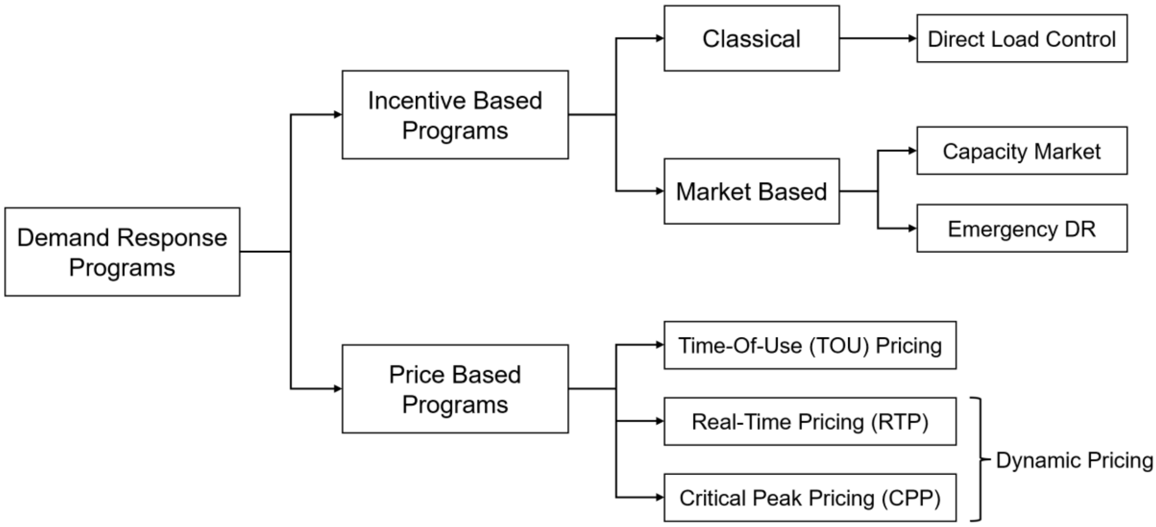

Figure 3: Classification of Demand Response programs. Adapted from (Albadi & El-Saadany, 2007).

The other main category of DR programs are the price-based ones, which are related to this study. In these programs, the variable (wholesale) electricity price is transferred to residential customers through fluctuating variable electricity tariffs based on the spot market prices. The basic idea is to flatten the demand curve by charging high prices during peak periods and lesser prices in off-peak periods. (Scheller et al., 2018) also distinguish between time-of-use pricing and dynamic pricing options. Time-of-use (TOU)-pricing is described as the basic type of price-based programs. In these programs, the day is subdivided into different blocks, which have stepwise rates of electricity prices per unit consumption. These price rates for the different periods are based on historical or forecasted electricity spot market prices. Consequently, the tariffs during peak periods are higher, but lower during periods with low demand. In addition, seasonal price fluctuations as well as variations of prices between weekdays and weekend can be designed for TOU tariffs (Albadi & El-Saadany, 2007). In contrast to the fixed blocks of time in TOU pricing, in dynamic pricing schemes the hourly electricity tariff is fixed at short notice and reflects the spot market price. As the name of real-time-pricing (RTP) implies, the information of these prices is provided one day ahead or, in the literal sense, constantly on hourly basis either. In attenuated form, critical peak pricing tariffs provide their customers in advance with information about the different applied price levels. Thus, the communication on when these price levels are effective is real-time oriented. Here too, the name of the tariff option shows its advantage as it allows utilities to raise prices significantly during times of extreme stress on the network (Scheller et al., 2018).

2.1.2 Load shifting potential

The consumption of electricity in the residential sector is usually depending on a variety of appliances with a comparably small energy demand. Not all of the various household appliances are suitable for DR. Therefore, three groups of appliances are characterized in

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Table 1. The essential parameters for the DR potential are the control mode, and generated discomfort. Therefore, only groups are considered with semi-automatically or automatically controlled appliances (Gärttner, 2016). The shifting distance and discomfort level of that group of appliances, which need user interaction, can be classified as medium. The shifting period can be assumed with up to twelve hours for dishwashers and up to four hours for washing machines and tumble dryers. Thus, these appliances yield some negative implications for the costumers when used for DR. Unlike processes of electrical cooling or heating generation and storage, the consumers must have to actively change their behaviour when using washing machines, tumble dryers and dishwashers in everyday life (UBA, 2011). Consequently, the load shift potential of this group of devices is controversial. To take this uncertainty and the consumers' discomfort with semi-automatically controlled appliances for DR into account, as a premise, a maximum of 50 % of loads from this appliance group can be shifted (Scheller et al., 2018).

Table 1: Characterisation of household appliance groups. Adapted from (Gärttner, 2016).

Appliance group	**Examples**	**Characterization**		
		Control mode	**Shifting distance**	**Discomfort**
User interaction	Dishwasher, washing machine, tumble dryer	Semi-automatic	Medium	Medium
Cooling	Fridge, freezer	Automatic	Low	Low
Heating	Electric heating (with buffer storage)	Automatic	High	Low

The cooling and heating equipment is controlled automatically. Therefore, load shifts of these applications create minimal discomfort for customers. Their filling and the respective temperature interval (e.g. 2-6 °C) determine the storage capacity of refrigerators and freezers. The time shift potential depends not only on the storage capacity but also on the specific cold losses (insulation). It is in the range of 0.5 h to 2 h (UBA, 2011). Depending on the quality of insulation of the built-in thermal buffer storage, electric heating systems provide a high shifting distance. This means that loads from these systems can be shifted over much longer periods than basic household appliances. Due to the fact, that the market share of electric heat pump systems has increased up to around 50 % of new buildings in Germany in 2020, it can be assumed, that the relevant share of electric heating systems consists of heat pumps (bwp, 2021). Hence, in this work an electric heating system is defined as an electric heat pump coupled with a thermal buffer storage providing heat and hot water to end-use customers.

To get a profound understanding of the total load flexibility by residential customers, the previously identified DR compatible appliances need to be further specified. To identify their load shift potential, the consumption share and penetration level of these appliances are of especial interest. The penetration level indicates the percentage of households that

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are equipped with a certain appliance. In Table 2 an overview of the input specifications and control options of household appliances is given.

Table 2: Input specifications and control options of household appliances suitable for DR[1].

Appliance	Penetration level (%)	Consumption share (%)	Control option
Refrigerator	99.8[2]	9.0[3]	Automatic
Freezer	48.0[4]	7.1[5]	Automatic
Dishwasher	72.3[4]	3.7[5]	Semi-automatic
Washing machine	96.1[4]	3.6[4]	Semi-automatic
Dryer	42.7[4]	2.4[6]	Semi-automatic
El. heating system	10.8[5]	49.0[6]	Automatic

As Table 2 shows, the consumption share of flexible household appliances excluding electric heating systems is 25.8 % of the overall residential electricity consumption. Nevertheless, as mentioned before, the discomfort of shifting load from semi-automatically controlled appliances limits the potential of these appliances. In consequence, it is very probable that even if all technical requirements for DR are met, not all loads from these appliances will be actually shifted. Given the presumption of a 50 % potential from semi-automatic appliances, the total share is reduced to around 21 %. The table also points out the huge consumption share for the case of electric heating systems, and consequently, a much higher share of flexible electricity consumption of those household types. The total electricity consumption differs significantly depending on the existence of an electric heating system. Accordingly, the consumption share of household appliances is calculated with respect to a total electricity consumption of 2,500 kWh_{el}, whereas the share of the electric heating system is determined with respect to a considerably higher overall electricity consumption of 6,500 kWh_{el} (Scheller et al., 2018). The penetration level of electric heating systems is assumed to be 10.8 % for the year 2025 and 41.9 % in the year 2045. This is based on the strong increasing share of installed electrical heat pumps in new buildings (Winiewska et al., 2021).

[1] Adapted from Gottwalt et al. (2017)

[2] Statistisches Bundesamt (Destatis) (2020)

[3] Bürger (2009)

[4] Bürger (2009)

[5] Winiewska et al. (2021)

[6] Scheller et al. (2018)

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2.2 Overview of European smart city projects

Since this work aims to analyse the potential of RDR in combination with a VPP, it is of utmost interest to give an overview of the current applied research projects in the smart city area in Europe. For this purpose, it seems to be beneficial to narrow the sample group to the 18 lighthouse projects from the *SCALE* (European Smart and Lighthouse Cities Amplified) initiative. The city-led initiative has the objective to bring stakeholders, policy makers, industries, researchers and citizens collaboratively together to develop more inclusive and resilient smart cities. These should be able to respond and to adapt to the dynamic evolvement of climate change by utilizing innovative and carbon-neutral technologies and implementing green policies (European Commission).

The project *GrowSmarter* aimed to highlight twelve smart city solutions, which were split into three areas of action. The area of interest for this study is the low energy district, within which three blocks were classified: building energy retrofitting, energy consumption visualization platforms, and local energy generation with smart management (Sola et al., 2020). One of the quintessential perceptions is that the economic feasibility and upscaling of local energy generation highly depends on national regulation. The smart management of energy flows from on-site production via solar energy generation to heat pumps and battery storages demonstrate a possibility to integrate buildings in local energy communities, by this means, utilizing building flexibility. It is stated that related end user benefits would increase if national regulation includes demand response aspects. This might push-start the scalability potential of smart home services. Moreover, (Sola et al., 2020) conclude that applying the tool for demand response at an overall building level boosts the tool's replication potential. In addition, the current lack of flexibility to trade with energy and unpredictability of law changes hinder the scalability of local renewable electricity generation in cities.

The Concluding Report states that the collection of electricity consumption data by the home energy management system (HEMS) enables functionalities, which are able to increase energy efficient residential behaviour (Sanmartí & Sola, 2019). This includes incentives for residents in the form of cost-reflective prices, and the possibility to apply demand response services. However, the costs for the installation and procurement of specific appropriate hardware is hindering the economic feasibility and its upscaling, which needs to be paid by the HEMS providers. The report likewise states that the development of the best technologies is outpaced because regulation is slower than technology development. Actually, the monetized value of HEMS could easily justify the participation in the demand response market. Thus, Time-of-Use (TOU) tariffs would enable users to receive substantial cost savings in contrast to fixed rate tariffs by shifting their consumption to advantageous times. The greatest impediment for progress is seen in the current lack of flexibility to trade with energy and the unpredictability of changes in regulations. This state of legal uncertainty obstructs the scale-up of distributed renewable electricity generation at communal level. While the regulatory framework for demand response in Europe is evolving, further development is needed. The report also

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suggests a regulation-free zone to verify hypotheses in the area of local renewable energy generation and consumption in the urban environment.

The *Triangulum* smart city project has analysed the potential of demand response as a resource in the spinning reserve (SR) electricity market (Safari et al., 2019) define SR "as the arrangement of capacity, which is synchronized to the power grid". In addition, it has the ability to react promptly to serve load and to be available within ten minutes. As demand response can be seen as a possible solution for easing network and market problems, the paper proposes a bidding strategy for smart building aggregators. Based on a self-scheduling method, the bidding strategy is to provide "Negawatt" demand response resources. In that sense, a "Negawatt" describes the theoretical amount of energy conserved by scaling down consumption. It was observed that the total amount of consumed energy per day is decreasing for the studied smart buildings. Moreover, the smart building aggregator was generating a daily profit.

A sustainable energy management system (SEMS) was monitored and analysed in the *Sharing Cities* lighthouse project. It works by linking assets like solar panels, heat pumps, household appliances, and electric vehicle charging points together while collecting data from them to forecast energy use. In combination with external data such as weather forecasts, the levels of demand and production are predicted. Based on that information, it is possible to control and operate energy assets across the network efficiently (Sharing Cities, 2020). Furthermore, a residential demand response service was integrated. The residents across the test borough installed an app and connected to a CT clamp on their electricity meter. Live information about the electricity use was delivered, and monthly alerts encouraged them to reduce their electricity consumption for some hours. As motivation for participation, the users allocated points based on their reduction in comparison to their baseline. At regular intervals, these points can be converted into charity donations or vouchers. Overall, the app was designed to create a competition within communities or groups regarding energy savings.

The *IRIS* project has tested a Smart Energy Management System (EMSs). Energy consumers, producers and storage providers are interconnected through the district energy system (van der Ree et al., 2019). To transform the district energy system into a smart one, among other things, the transformer stations are equipped with additional special measuring sensors. By this equipment, the real time detection of the electricity flows can deliver crucial input for the aggregator to use flexibility for keeping the maximum flow in the range of acceptable values. The project will assess the value to the transmission system operator (TSO) as well as to the distribution system operator (DSO) of flexibility delivered. In addition, the exploitation of flexibility resources will be investigated to minimise local grid congestion and to sell flexibility to the TSO.

The *STARDUST* project demonstrates the potential of demand response (DR) and its viability in residential buildings connected to district heating (DH) (Ala-Kotila et al., 2020). Some impact indicators such as saved energy, peak load control, emission cuts and saved energy costs were analysed to identify an optimal DH production profile and advantageous options for end-user. The study finds that the conducted field test successfully shows the techniques for implementing DR in DH. By using a building-specific DR system combined with the heat storage capacity of a DH network, the heat consumption can be managed in a way that energy from peak power plants is decreased. While several methods exist for reducing power peaks, all showed some reliability issues,

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thus limiting their usability. Apart from this, the paper demonstrates that significant peak power reductions are possible using reliable methods. In addition, no special instruments, connections, or close co-operation and synchronisation among user and DH supplier are needed. The study recommends that DR requirements are included in energy efficiency guidelines.

3. Research concept

An essential part of this study is the application of a techno-economic model as a mean to assess the potential of RDR in combination with a virtual power plant. By this means, technical, economic as well as ecological benefits of the implementation are to be evaluated. In the following, the approach is further outlined. First, the applied methodology regarding the energy model is described thoroughly, comprising the energy system design and the optimisation approach of the used modelling framework (IRPopt). Subsequently, the model setup embraces the concrete features of the techno-economic model, e.g., the data collection process, the scenario design and the applied sensitivity analysis.

3.1 Model framework

The goal of this modelling exercise is to appraise the potential of RDR in combination with a VPP in a municipal energy system setting. In particular, the study investigates the technical, the economic, and the ecological potential. Thus, a specific section of a municipal energy system for the hypothetical years 2025 and 2045 was modelled, laying the focus solely on electricity. This section includes electrical energy generation, storage, demand, an interconnection to the electricity market, a VPP as layer of control, and their interconnections. The electrical energy originates mainly from rooftop solar power. For projecting parameters of the year 2045, it is assumed that the VPP and RDR are widely implemented in the municipal energy system then. Consequently, by a switch to 100 % RES combined with an increased demand for electricity managed by the VPP, the sources for the generation of electrical energy are likely to be diversified and therefore some wind power plant capacity is included.

The model also contains a cumulative energy storage in the form of a battery system. The main function of the storage in the model is to provide flexibility to counteract temporal displacements of energy production and consumption. Moreover, the final energy demand for electricity is split into two different groups of residential demand types. These customer groups are aggregated to represent the cumulated demand of different residential consumption patterns. Lastly, the VPP as the virtual control layer is implemented as the managing unit for commencing DR actions like load shifting. Therefore, the VPP is the centrepiece of information and control, and thus, responsible for the adequate management of the energy flows within the system. A graphical depiction of this energy system including the interconnections drawn is provided in Figure 4.

Depending on the different scenario design decisions, the mixed-integer problem (MIP) is modelled via an objective function considering the financial flows of chosen market

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actors, time series and energy sectors, rested on the energy flows of the technical components. Hence, maximising the total profits of the individual actors is the main goal of the modelling exercise. Subsequently, the model optimises in two steps, one being from an aggregated customer perspective (customer optimisation) and the second one from the utilities' perspective (organization optimisation).

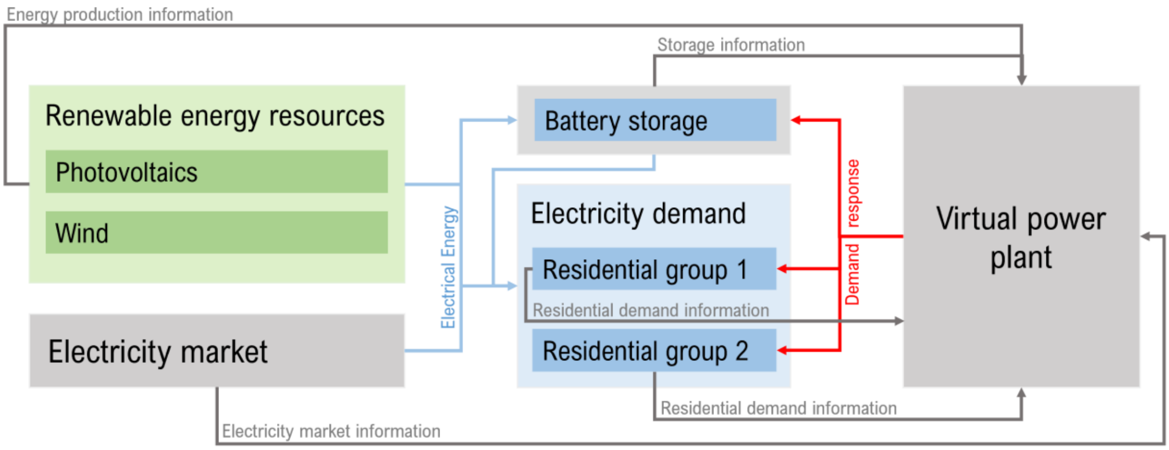

Figure 4: Representation of the main elements of the energy system model, and its interdependencies.

3.2 Scenario design

To illustrate the potential of RDR in combination with a VPP, three scenarios are developed and applied. The scenarios are characterised as *Reference*, *Reluctance,* and *Acceptance,* which are differentiating between the load shift potential and the load shift horizon. Subsequently, the scenarios alter these parameters for two predefined customer groups.

Firstly, the *Reference* scenario was generated for 2025 and 2045. The limitations or favourable assumptions of the other scenarios do not apply for this one. In addition, this scenario neglects the existence of DR in the residential sector. A likewise conservative scenario titled *Reluctance* is characterized in particular by noticeable resistance to the use of new technologies in the private sector. Hence, the load shift potential in the residential sector is limited. However, various different electricity tariffs are being applied. Lastly, the scenario *Acceptance* describes a development, in which behavioural changes take effect in large parts of the customers that create a noticeable participation in RDR programs.

The varying load shift potential and load shift horizon of the different scenarios are presented in Table 3. Since scenario *Acceptance* describes a very positive development, the parameter values for this scenario mark the upper boundary. Therefore, in this scenario the values for the load shift potential are 20 % for the residential customer group (1) without an electric heating system, and 70 % for the customer group (2) equipped with one. For this study, the values for this parameter are not subject to changes over time.

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Table 3: Assumptions on the scenario-based parameters.

Year	Shifting parameters	Residential customer group 1		Residential customer group 2	
		Reluctance	Acceptance	Reluctance	Acceptance
2025	Load shift potential	10 %	20 %	35 %	70 %
	Load shift horizon	1.5 h	2.5 h	1.5 h	2.5 h
2045	Load shift potential	10 %	20 %	35 %	70 %
	Load shift horizon	1.5 h	2.5 h	2.5 h	4 h

Both, the values for the load shift potential and the load shift horizon are average values taking the distinct shares and characteristics of all DR capable appliances into account. Apart from this, the size of the customer groups depends on the penetration level of electric heating systems in the building stock. As described in sec. 2.1.2, the share of electric heating systems is increasing from approximately 10 % in 2025 to around 40 % in 2045 (Winiewska et al., 2021). Leaning on the SPARCs project, 1000 households are provided with electricity via the VPP in 2025, and in consequence, 900 of them are part of residential customer group 1, whereas 100 belong to group 2. While the scenarios for 2025 describe a more experimental stage, it is assumed that the VPP of the municipal utility has increased its size substantially in 2045 (Olumoroti, 2022). Therefore, the total number of households within the VPP amounts to 50,000 in 2045, though the ratio between the two customer groups changes. As mentioned in chapter 2.1.2 the penetration level of electric heating systems is assumed with 41.9 % in the year 2045.

3.3 Relevant model data

3.3.1 Customer load profile

The first group (residential load 1 - RL1) is based on a standard load profile of an average household in a city living in an apartment building, whereas the second group (residential load 2 – RL2) is characterised by living in single-family homes with heating and hot water provided by an electrical heat pump with a thermal buffer storage. The load profile for RL1 is taken from (Stromnetz Berlin GmbH, 2022). The load profile for RL1 is up-scaled to the yearly electricity consumption of an average two-person household in an apartment building, which amounts to 2,500 kWh (Weißbach & Wagener, 2021). For the load profile of RL2, a yearly electricity consumption of 6,500 kWh is the foundation for the upscaling of the standard load profile (co2online, 2022). The basic load profiles and of the heat pump system were interlaced to add up to the overall yearly electricity

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consumption of 6,500 kWh. The load profile for the heat pump system scaled up to a yearly average consumption of 4,000 kWh (energis-Netzgesellschaft mbH, 2022).

3.3.2 Electricity tariff design

Four different electricity tariffs were applied, ranging from very static to highly dynamic ones. These tariffs all consist of a fixed utility margin and a fluctuating price component. A summary of the tariff designs can be seen in Table 4.

Table 4: Artificial electricity tariffs for the model-based analysis.

Tariff	Description
FT	Constant electricity price (yearly average spot market prices + margin)
HD	Tariff with hourly changes in price (hourly average of spot market prices + margin)
VPP_{TOU}	Tariff with two price zones per day: low-cost (8:00-16:00) and high-cost (16:00-8:00) (zonally average of spot market prices + margin)
VPP_{HD}	Tariff with hourly changes in price (hourly demand-supply ratio with reflecting prices time series based on hourly average of spot market prices + margin)

The Flat tariff (FT) provides the customers with a fixed price for every time step of the survey period. Accordingly, the constant electricity price is derived from the yearly average spot market prices plus the utilities' margin. The second tariff (HD) is a highly dynamic pricing scheme, in which the fluctuating price component reflects the electricity spot market price per time step. Subsequently, the electricity price for the customer changes hourly, based on the spot market price for this time step and the fixed margin.

The third tariff, described as VPP_{TOU}, is a time-of-use pricing scheme, and therefore, it consists of two tariff zones over all days. The concept behind this pricing model is that at least in the year 2025, the utilities' own PV produces most of the electricity consumed within the VPP framework. Naturally, PV electricity is generated over the course of the day. To reflect these periodic fluctuations in supply, two tariff zones were recognized. The first one is the low-cost period, ranging from 8:00-16:00 and the second one, the high-cost period ranging from 16:00-8:00. For comparability, the price comprises of the zonally average spot market prices for each tariff zone and the fixed margin for the utility.

The fourth tariff (VPP_{HD}) is a highly dynamic pricing scheme with a fluctuating price component. However, the price variation is not directly related to the hourly changing spot market prices over the year. Instead, the electricity production of the generation units per time step are juxtaposed with the residential demand in respective time steps. For every hour of the forecasted year, the deviation between the anticipated on-site electricity production and the residential demand is considered. These values indicate periods, in which demand exceeds the supply or vice versa. The goal of the VPP is to be as self-sufficient as possible, and therefore, to produce most of the electricity in the nearer region. Due to the volatility of RES, the demand must be shifted to hours where supply exceeds demand to minimise the amount of time steps in which the supply is not

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sufficient. The calculated ratios are linked to spot market prices to ensure comparability with the other tariffs. In concrete, the hourly market prices are ordered and the highest price is matched with the highest demand-supply ratio. The matching is executed for every time step, leading to a new market price-based time series, which reflects changes in the demand-supply ratio. In addition, the tariff design has to take into account the two different load profiles of the residential customer groups. Both are aggregated to a merged time series while considering the different sizes of the groups. Following this process, a new demand-supply ratio time series is created, which reflects the demand flows of both customer groups. Beyond that, the supply time series for the year 2045 consists of the merged load profiles for the PV and Wind generation units of the energy system. The resulting tariff is illustrating the fluctuating price component and the fixed utility margin of the end-customer price.

3.3.3 Electricity generation capacity

For the initial phase of the energy community, PV is the only source of on-site power supply. The installed capacity of PV amounts to 1.5 MWp. It is assumed that the utility is not the owner of the generation units. Accordingly, the utility has signed a power purchase agreements (PPA) with PV and Wind power plant operators over a predetermined amount of power output. This means that the utility commits to purchase the power output of the generation capacity according to its anticipated load profile. Since the model is deterministic, the utility is able to plan with a given generation load profile and a fixed price per MWh, e.g., 41 €/MWh for PV.

In 2045, the energy community increased substantially, and therefore, the installed capacity of PV is raised to 50 MWp. Due to missing figures for the prices of power purchase agreements in the long-term, and the uncertainty of future projections, it is assumed that the price level remains constant. Due to the raising electricity demand, a diversification of RES is anticipated. Hence, an installed capacity of 25 MW of wind power is available. As mentioned before, a PPA with a price of 39 €/MWh is contracted. In addition, a battery storage complements the technical configuration with a capacity of 15 MWh.

Table 5: Assumptions on the electricity generation and storage capacity.

Year	Characteristics	Photovoltaics	Wind	Battery storage
2025	Installed capacity	1.5 MWp	x	x
	Price in €/MWh	41	x	x
2045	Installed capacity	50 MWp	25 MW	15 MWh
	Price in €/MWh	41	39	10

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4. RESEARCH RESULTS

The following chapter illustrates the results of the scenario analysis, beginning with a description of the modelling process and the evaluation framework. Subsequently, the optimization results are analysed from a technical, economic and ecological point of view. Finally, a sensitivity analysis is carried out and the results being assessed.

4.1 Evaluation of the basic scenarios

As described in section 3.2, the technology-based scenarios are intertwined with different electricity tariffs to cover a broad variety of economic circumstances. For the *Reference* scenario, only the flat tariff is applied (see Table 6). Similarly, the flat tariff was not applied for the other scenarios as this electricity pricing does not incentivize load shifting. The outcome of the RDR scenarios are compared for the variable electricity tariffs with the flat one. Finally, 14 scenario-tariff-combinations are to be optimised by IRPopt.

Table 6: Relevant combinations of scenarios and electricity tariffs.

			Electricity tariff			
		Year	**FT**	**HD**	**VPP_TOU**	**VPP_HD**
Scenario	**Reference**	2025	x			
		2045	x			
	Acceptance	2025		x	x	x
		2045		x	x	x
	Reluctance	2025		x	x	x
		2045		x	x	x

4.1.1 Analysis of the technical potential of residential demand response

Dependency of electricity imports

Regarding the variables, which simplify the state of the electricity grid, only the external supply from the spot market varies. The absolute change in purchased and sold electrical energy by the VPP in 2025 and 2045 is illustrated in Table 7. In 2025, the delta is evenly balanced between purchases and sales. In 2045, the quantities differ due to the utilisation of the battery storage in combination with self-generation capacity. The electricity trade flows decreased in both scenarios in 2025. For comparison, the purchases within the basis scenario (flat tariff) amounts to 2,034 MWh (2025) and to 113,862 MWh (2045) whereas sales totals 730 MWh (2025) and 13,846 MWh (2045).

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Table 7: Model results: changing energy flows due to Demand Response compared to the *Reference* scenario.

		Scenario *Acceptance*			Scenario *Reluctance*		
Year	**2025**	**HD**	**VPP (TOU)**	**VPP (HD)**	**HD**	**VPP (TOU)**	**VPP (HD)**
Change in electricity purchases [MWh]		-18.74	-53.36	-85.11	-2.60	-2.54	-23.07
Change in electricity sales [MWh]		-18.74	-53.36	-85.11	-2.60	-2.54	-23.07
Year	**2045**	**HD**	**VPP (TOU)**	**VPP (HD)**	**HD**	**VPP (TOU)**	**VPP (HD)**
Change in electricity purchases [MWh]		2,590.19	-4,214.89	1,966.37	-69.92	-1,845.16	-614.66
Change in electricity sales [MWh]		2,606.26	-4,202.51	1,871.67	-53.84	-1,845.23	-707.63

When integrating RDR to the system in 2025, the effects are straightforward, which show a decrease in trade flows, reaching the lowest for the tariff VPP (HD). As expected, the numbers were noticeably smaller over all tariffs for the scenario *Reluctance*. In contrast, the market interactions are increased in 2045 for scenario *Acceptance* combined with tariffs HD and VPP (HD). The utility is applying the increased flexibility of the battery storage given those tariffs, which are at least partly correlated with the spot market, and therefore highly dynamic. Hence, the load shifts of the residential customers were in the case of the HD tariff completely, and for the VPP (HD) tariff partly induced by the spot market. This led to load shifts to periods with lower or negative spot market prices, and increased purchases in these time steps.

The increased quantity of electricity sold in two scenario combinations can be explained with gained surplus from RES at high price periods due to the load shifting. Contrary to the highly dynamic tariffs, the VPP (TOU) electricity tariff delivered a significant decrease in market interactions. The static structure of this tariff with two price levels, which are oriented at the own RES generation, led to a lower interaction with the spot market. Similar market dynamics were observed in mitigated form in the scenario combinations of the *Reluctance* scenario.

Key performance indicators of the energy system

Another technical aspect of interest is the degree of self-sufficiency. Some key performance indicators (KPI) were developed in the literature for assessing the quality of an energy positive neighbourhood (EPN). Some of these indicators are suitable for measuring the balance between local energy supply and demand. The **On-site Energy Ratio (OER)** describes the relation between the annual energy supply from (local) RES and the annual (residential) energy demand (Ala-Juusela et al., 2016). Due to the definition of the OER, it does not depend on the load shifting, and thus, remains constant for all scenario-tariff combinations. Therefore, the OER is 0.55 in 2025, and 0.51 for the year 2045.

Besides the total annual energy balance, it is essential to assess the matching of supply and demand in terms of timing. Thus, the **Annual Mismatch Ratio (AMR)** was calculated

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(Ala-Juusela et al., 2016). The AMR represents the average amount of imported energy into the system. It is composed of relative mismatches per hour over the course of the year, which show the difference between supply from own (local) RES in comparison to the (residential) demand. Accordingly, it highlights the periods when demand exceeds the supply from renewables. Smaller numbers for the AMR denote that the RES supply is closer to meet the demand. The AMR for the Reference scenario was 0.7 in 2025, which is slightly reduced to 0.69 with RDR measures. Table 8 displays the AMR of the scenarios in 2045. All dynamic electricity tariffs reduced the AMR in comparison to the *Reference* scenario. Given the smaller load shifting potential in the *Reluctance* scenario, the AMR is likewise reduced only marginally.

Table 8: Calculation of the Annual Mismatch Ratio (AMR) in 2045.

	Reference	**Acceptance**			**Reluctance**		
	FT	**HD**	**VPP (TOU)**	**VPP (HD)**	**HD**	**VPP (TOU)**	**VPP (HD)**
Annual Mismatch Ratio	0.54	0.47	0.48	0.46	0.52	0.53	0.52

Load shifting potential

The impact of the scenario combinations on the amount of shifted load over the period of one year can be seen in Table 9. The numerical entries represent the total amount of shifted load of both residential customer groups. For comparison, the total demand over one year of all 1,000 participating households amounted to 2,900 MWh in 2025, whereas the electricity consumption of 50,000 households is expected with 205,000 MWh. The *Acceptance* scenario yields larger numbers of load shifting, in particular in the case of the VPP (HD) electricity tariff.

Table 9: Total annual amount of load shifting.

		Acceptance			**Reluctance**		
Year	**2025**	**HD**	**VPP (TOU)**	**VPP (HD)**	**HD**	**VPP (TOU)**	**VPP (HD)**
Shifted load [MWh]		702.94	580.82	710.92	363.90	378.50	373.75
Year	**2045**	**HD**	**VPP (TOU)**	**VPP (HD)**	**HD**	**VPP (TOU)**	**VPP (HD)**
Shifted load [MWh]		76,370.31	66,785.29	80,040.25	39,103.03	35,625.86	40,796.21

Figure 5 illustrates the annual load shift per household for the years 2025 and 2045. The numbers nearly doubled over all scenario combinations over time. This is induced by the changing composition of the two customer groups and their respective load profiles. For the year 2045, it was assumed that the share of households equipped with an electrical heat pump increased significantly. As heat pumps (with buffer storages) provide a great potential for load shifting, the average shifted load per household over all households increased visibly. Furthermore, the difference in shifted load between the two residential

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customer groups was noticeable. Although the predefined load shift potential of residential customer group 1 aggregates to 50 % of the one of group 2, the actual quantity reached around 10 % of the load shift of residential group 2 over all scenario combinations. This can be explained by the impact of a lower load shift horizon.

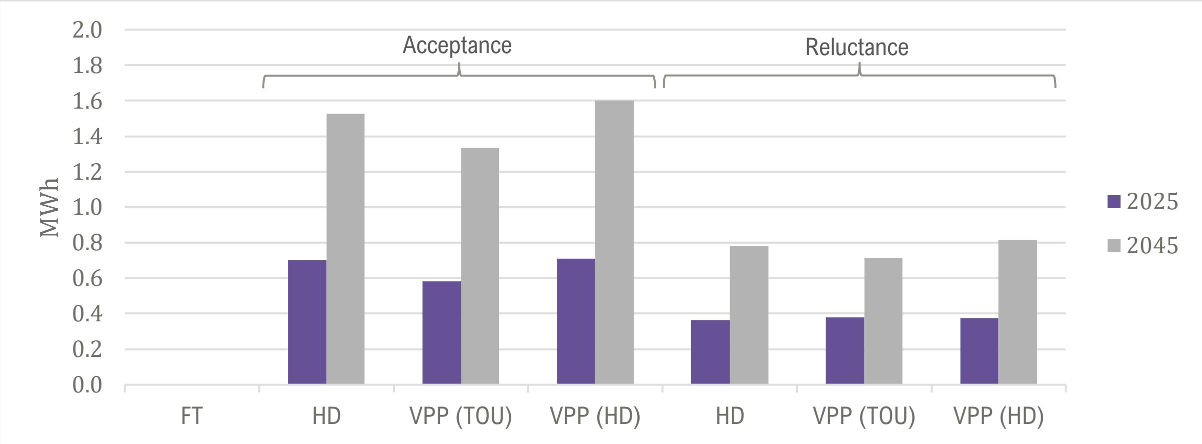

Figure 5: Annual load shift per houshold according to different variable electricity tariffs.

4.1.2 Economic evaluation

In the following, the economic impacts of RDR for customers as well as the utility-side are going to be outlined. Table 10 illustrates the relative change in electricity costs per customer compared to the FT for the *Reference* scenario. Moreover, the analysis also makes the distinction between the residential customer groups, and the years 2025 and 2045. As expected, for both years and customer groups, the highest cost reduction was achieved with the VPP (HD) tariff. For the residential customer group 2, an overall higher cost reduction was observed. In 2045, the cost reductions for both residential customer groups were significantly stronger. Accordingly, the cost reductions in comparison to the FT in the basis scenario nearly doubled over all other scenario combinations.

Table 10: Model results: Change in electricity costs per customer with Demand response compared to a fixed tariff.

		Acceptance			**Reluctance**		
Year	**2025**	**HD**	**VPP (TOU)**	**VPP (HD)**	**HD**	**VPP (TOU)**	**VPP (HD)**
Residential Customer Group 1		-1.77%	-0.65%	-3.15%	-0.59%	-0.17%	-1.40%
Residential Customer Group 2		-6.45%	-2.27%	-8.84%	-2.29%	-0.59%	-2.66%
Year	**2045**	**HD**	**VPP (TOU)**	**VPP (HD)**	**HD**	**VPP (TOU)**	**VPP (HD)**
Residential Customer Group 1		-3.93%	-1.26%	-4.25%	-2.25%	-0.32%	-2.22%
Residential Customer Group 2		-14.73%	-8.77%	-15.40%	-5.00%	-2.23%	-5.45%

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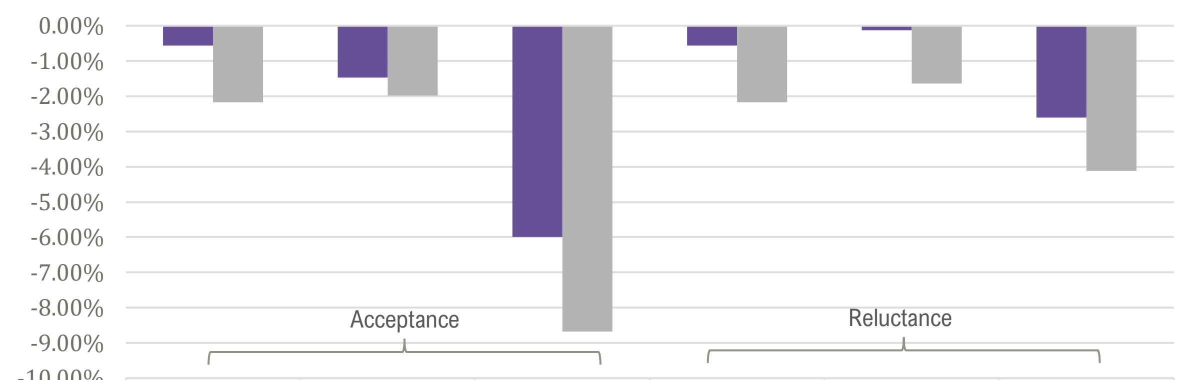
Regarding the economics for the utility, different effects of demand response tariffs must be evaluated:

- Revenue losses due to behavioural change of electricity consumption of the customer groups.
- Gains from an optimisation of the purchasing strategy (cost reduction).

The net effect is presented in Figure 6 as percentage change compared to the *Reference* scenario. Based on the assumptions of the tariff design, the net effect is negative for the utility. The highest reduction of profit for the utility was recorded in 2045 with the VPP (HD) electricity tariff in the *Acceptance* scenario with nearly 9 %. Also for the year 2025, the VPP (HD) tariff generated the by far largest profit decrease with around 6 %. Clearly, the cost reduction of the customers (Table 10) equals the loss in revenues for the utility. In parallel, the utility can improve its purchasing strategy and reduce the decrease in revenue. Given the rational behaviour of the customers and the perfect foresight of the model, the total effect remains negative for the utility.



	HD	VPP (TOU)	VPP (HD)	HD	VPP (TOU)	VPP (HD)
2025	-0.56%	-1.47%	-5.99%	-0.56%	-0.13%	-2.61%
2045	-2.17%	-1.98%	-8.67%	-2.17%	-1.64%	-4.12%

Figure 6: Monetary net effect of Residential demand response for the utility compared to a fixed tariff for both customer groups.

4.1.3 Reduction of CO_2 emissions

As long as the German electricity sector is not decarbonised, a carbon footprint has to be considered for the residential consumption within the municipal energy system. RDR measures can reduce carbon emissions if it induces a direct consumption of local RES. Subsequently, when the load is shifted to hours with a greater share of own generation, the supply from the spot market can be reduced, and consequently, the (local) CO_2 emissions are decreasing. The carbon intensity of the German electricity mix was used for the calculation of the CO_2 emissions savings in comparison to the *Reference* scenario. The specific greenhouse gas emissions in CO_2 equivalents (CO_2eq) per kilowatt-hour of electricity is specified with 485 g/kWh in 2021 (UBA, 2022). It is assumed that the yearly average reduction of specific greenhouse gas emissions of generated electricity of around 2 % continues until 2025. Hence, the specific greenhouse gas emissions in 2025 are

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anticipated to be 448 g/kWh. Based on the reduction in market purchases per scenario, the calculation is presented in Table 11.

Table 11: Savings in CO_2 emissions due to Residential demand response measures.

	2025					
	Acceptance			Reluctance		
	HD	VPP (TOU)	VPP (HD)	HD	VPP (TOU)	VPP (HD)
Change in market purchases [MWh]	-18.74	-53.36	-85.11	-2.60	-2.54	-23.07
CO_2 emissions savings [t]	8.4	23.9	38.1	1.2	1.1	10.3

4.2 Sensitivity analysis – Increasing RES capacity and battery storage

The sensitivity of the initial results is evaluated by increasing the RES generation. This strategy can facilitate the implementation of positive energy districts based on the OER. This relevant KPI is now assumed to be one for both years. In a first step, the RES curtailment in case of negative spot prices is not allowed (Sensitivity 1). Then, the battery storage (Sensitivity 2), and the installed RES capacity (Sensitivity 3) are increased to match the yearly residential demand. Accordingly, the upscaling factor for the year 2025 was 1.6 to increase the annual electricity provision to 2,908 MWh. For the year 2045, the factor was 1.76 to reach 107,000 MWh from PV and 98,400 MWh from Wind power plants. The sensitivity analysis is applied for the *Reference* and the *Acceptance* scenarios only.

The results of the sensitivity analysis are discussed from the perspective of the import requirements of the local energy system. Figure 7 illustrates the percentage change in market supply in comparison to the standard settings. Thereby, the purple-colored bars depict the percentage decrease in market purchases according to the increased power generation capacity compared to the original settings (Sensitivity 3). In addition, the grey and red bars represent the changes in comparison to the two previous sensitivities of sensitivity 1, or 2, resp. There are no red bars given for the 2025 scenarios since the battery storage is only active in the year 2045.

In 2025, the reduction in market supply was nearly two times as high in comparison to the original settings (Sensitivity 3) than versus the non-curtailed version (Sensitivity 1). This is related to the already higher level of utilised on-site generation given the non-curtailment restriction. In 2045, the decrease in market purchases was significant compared to all previous settings, reaching levels between minus 30 and minus 40 %. Similar reduction rates arise when compared to the settings with increased battery capacity. Here, the higher battery capacity is utilised to exploit the spot market volatility. Regarding the battery usage indicators, the number of cycles did not increase compared to the settings from the previous chapter, though the energy throughput increased over all four tariffs about around 10 %.

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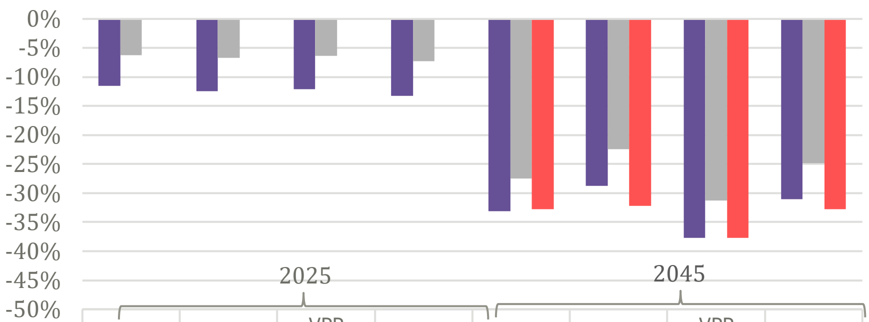

	FT	HD	VPP (TOU)	VPP (HD)	FT	HD	VPP (TOU)	VPP (HD)
	2025				2045			
Change in market supply compared to original scenario settings	-11%	-12%	-12%	-13%	-33%	-29%	-38%	-31%
Change in market supply compared to Sensitivity 1	-6%	-7%	-6%	-7%	-27%	-22%	-31%	-25%
Change in market supply compared to Sensitivity 2	0%	0%	0%	0%	-33%	-32%	-38%	-33%

Figure 7: Sensitivity analysis – change in market supply in comparison to different strategies to increase the local RES generation for the *Reference* and the *Acceptance* scenario of the years 2025 and 2045.

Given the OER being set to one, the AMR changed as well. In 2025, an AMR of around 0.61 was observed over all four tariffs. The *Acceptance* scenario yields a negligible impact on the AMR values. Due to the limited load shift horizons, evening and night-time demand cannot be easily shifted to high generation times of PV. Therefore, with PV being the only RES and no battery storage available, the AMR improving possibilities are finite. This converts when the RES are diversified as in the year 2045. Assuming sufficient electricity generation from Wind and PV, the AMR observed significant reductions compared to previous settings due to the higher load shift potential, which is leading to a decrease in AMR values compared to the FT of 0.05 to 0.08 (see Table 12).

Table 12: Annual Mismatch Ratio (AMR) for sensitivity 3 (Increased RES capacity and storage) in 2045.

	Reference	**Acceptance**		
	FT	**HD**	**VPP (TOU)**	**VPP (HD)**
AMR (with OER = 1)	0.32	0.27	0.26	0.24

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5. Conclusions

After the presentation of optimization results and their analysis from a technical, economic and ecological point of view, we now discuss the different perspectives in more depth. The outline of this section is oriented at the same structure, starting with a technical perspective followed by economic and ecological views, respectively. Thus, the outline of sec. 5.1 follows the structure of the research questions, which were split into three steps.

5.1 Summary of results

5.1.1 Technical perspective

Given the design of the energy system model, only the spot market interaction varies on the supply-side between the different scenario combinations. Subsequently, we derive the impact of the different electricity tariffs on the market supply. In Figure 8, the market interactions in 2025 are summarised for the original scenario settings and the sensitivities. To improve the clarity the figure, only the *Reference* and *Acceptance* scenario are displayed.

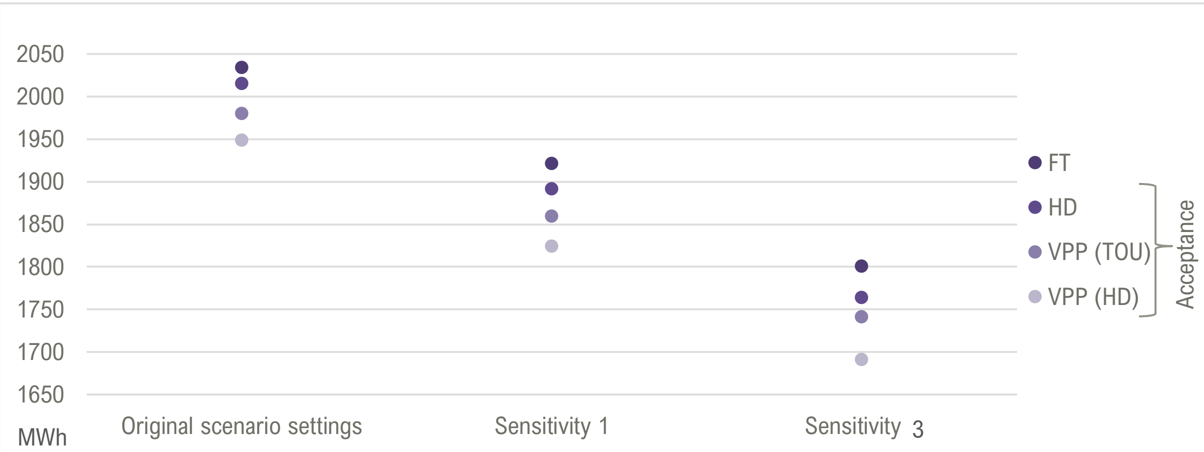

Figure 8: Comparison of total market supply for the original scenario setting, sensitivity 1 (non-curtailment condition), and sensitivity 3 (increased RES capacity) in 2025.

It shows that the market dependency decreased stepwise when implementing a non-curtailment restriction (Sensitivity 1), and a higher generation capacity (Sensitivity 3). By these measures, the own RES generation is increasing and therefore, the dependency from market purchases decreases. Apart from that, all scenario combinations with applied load shifting from residential customers observed less market purchases than the *Reference* scenario. The structure of the HD, VPP (TOU) and VPP (HD) tariff incentivised the residential households to shift their demand from high-cost periods to ones with lower costs, in particular for scenarios combined with a VPP (HD) tariff. Here, the different structures of the tariffs come into play. The HD tariff is solely oriented at the spot market and follows its dynamics while not regarding the load profiles of the own power generation. The structure of the two VPP tariffs allowed them to take the generation of

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own RES into account. Hereby, it was incentivised to shift load to time periods with higher own generation. This is reflected by the stronger decrease in market supply. As the VPP (HD) tariff is a dynamic tariff, it has more potential for load shifting than the static VPP (TOU) tariff.

The trend in market dependency in 2025 is straightforward but changed for scenarios in the year 2045. Now, scenario combinations with a FT did not record the highest market purchases over all settings. While the distance between the FT and the two dynamic tariffs was marginal for the original setting and sensitivity 1, it enlarged with an increased battery capacity in sensitivities 2, and 3. Furthermore, adding only a higher battery capacity (Sensitivity 2) intensified the market interactions over all tariffs compared to sensitivity 1. Beyond the model results of Sensitivity 2, the different settings observed the same pattern than in the year 2025 – a higher contribution of on-site RES generation reduces market purchases. However, in contrast to 2025, in 2045 the VPP (TOU) recorded the lowest market interactions due to the static structure of the tariff that led to a smaller utilisation of the market price fluctuations, and therefore, less market purchases.

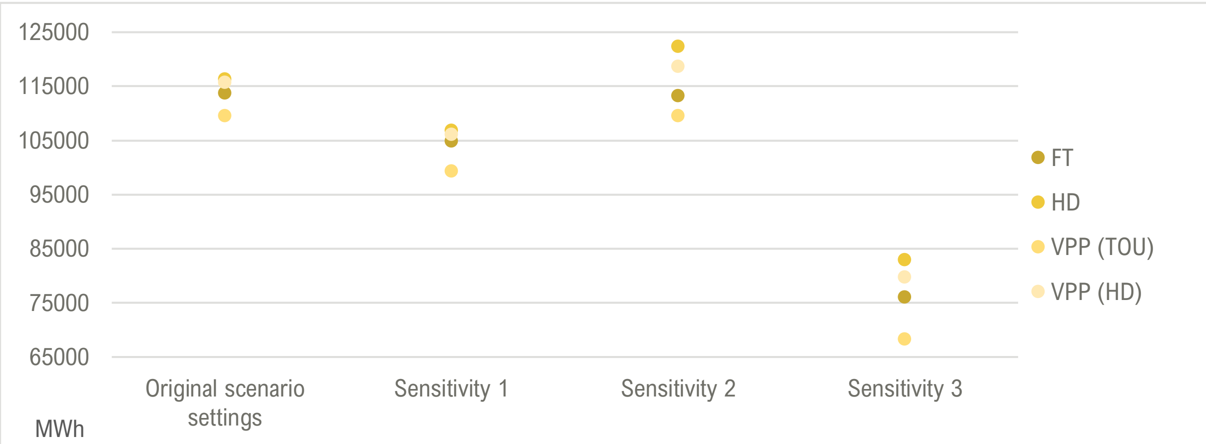

Figure 9: Comparison of total market supply for the original scenario setting, sensitivity 1 (non-curtailment condition), sensitivity 2 (increased battery storage), and sensitivity 3 (increased RES capacity and battery storage) in 2045.

The model results also showed that OER and AMR ratios are reciprocal. It is reasonable that the AMR decreases as long as the OER increases but has not reached one. However, scaling up the on-site generation to gain OER values over one does not automatically mean a reduction of the AMR value since the variable profiles of the generation units limit the further improvement of the AMR. This is observed in scenarios of the year 2025. While the increase of on-site generation capacity reduced the AMR in general, the load shifting potential had only minor effects on the AMR in comparison to the *Reference* scenario. This can be attributed to the specific generation profile of PV, limited to daytime and the non-shiftable demand at evening and nighttime (household appliances with non-shiftable load).

This picture changed in 2045. Although the OERs are below the numbers in 2025, the average AMR is better off due to the diversified power generation sources comprising

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Wind and PV. Since these RES have complemented load profiles, the potential to meet the hourly demand increases automatically. As Figure 10 demonstrates, the increase in power generation capacities reduced the AMR of the scenario combinations for the sensitivity settings. Hereby, the increased capacity led to an improved capability of covering the demand at more time steps to a higher degree. These diversified total generation profiles also allowed for reductions of the AMR within the different system settings. Thus, scenario combinations with load shifting capability decreased their AMR compared to the *Reference* scenario for all system settings, with the VPP (HD) tariff showing the strongest improvements. This underlines the potential of RDR for improvements of the self-sufficiency.

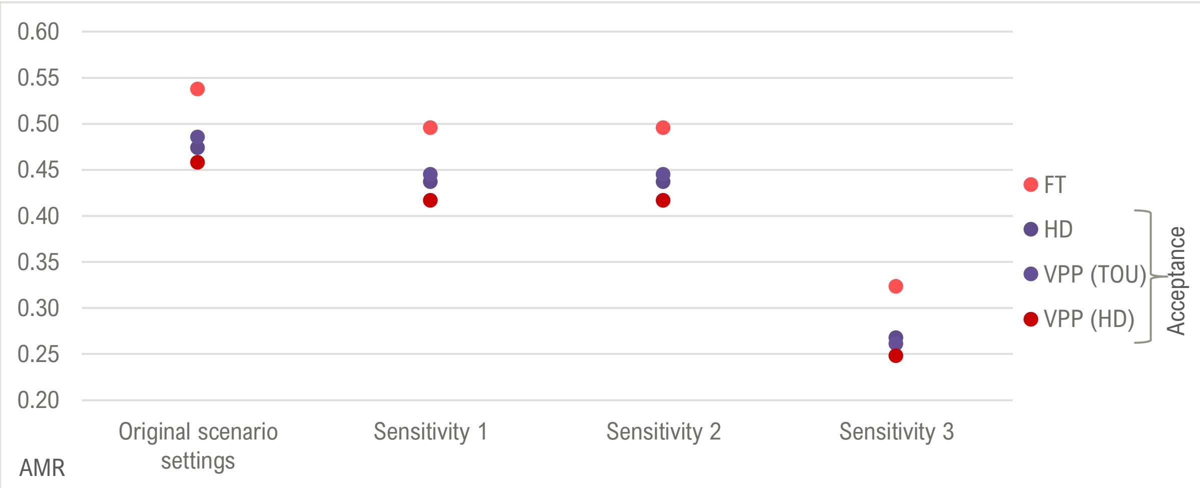

Figure 10: Sensitivity of the Annual Mismatch Ratio in 2045.

5.1.2 Economic evaluation

The economic results show that within the limited consideration of costs and revenue sources the FT provided the highest profit for the utility. Since the utility had to purchase significantly more energy at the spot market than it was able to sell, the total market outcome is negative over all scenario combinations. An exception marks the Sensitivity 3 with increased generation capacity, when the sales and purchases were balanced. Nonetheless, even in this case the total market outcome was largely negative because surplus power generation had to be sold often at low prices, whereas power purchases had to be made at high-cost periods. On the other hand, the dynamic electricity tariffs which induces customer load shifting enables the utility to reduce the market losses. However, the residential customers are also able to reduce their electricity costs via load shifting – the optimised trading balance cannot outweigh this loss in revenues for the utility. The avoided costs of the end customers surpass the loss in profit considerably over all scenario combinations. Accordingly, the general economic outcome of the system is valued to be positive for the scenario combinations when compared to the *Reference* scenario.

Regarding the private customers, the amount of cost savings differs significantly between the various tariffs. Figure 11 gives an overview of the yearly cost reduction range of electricity tariffs compared to the FT for the two residential customer groups in 2025 and

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2045. It shows that the potential cost savings of residential group 1 are noticeably smaller than for residential group 2. The smaller monetary outcome is related to the substantially lower amount of shifted load of households of group 1.

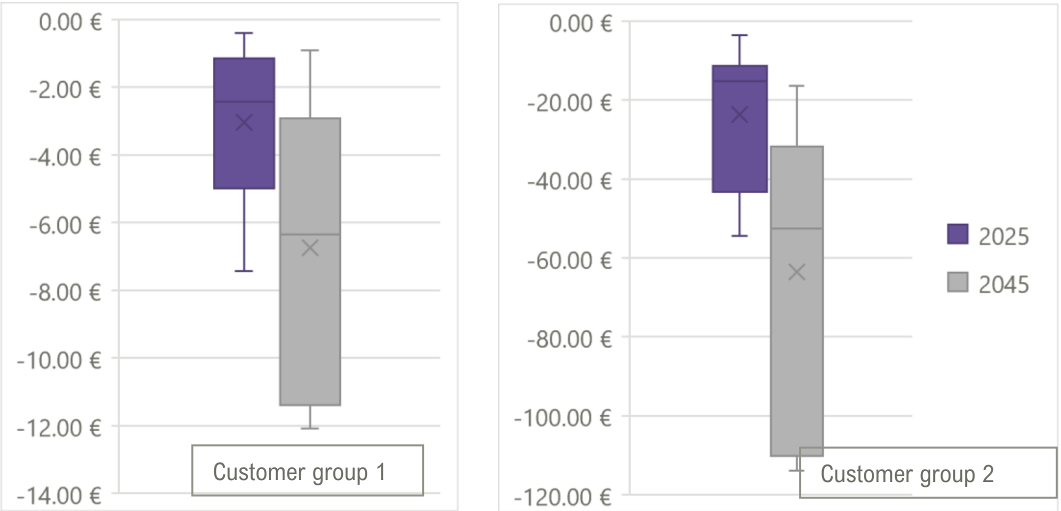

Figure 11: Rang of annual cost savings when applying dynamic electricity tariffs compared to a fixed tariff.

This study assumes that the load shifting of the households is controlled automatically by smart systems. The associated costs of this equipment need to be covered additionally. For the utilisation of the necessary smart devices, meters and controllers, an investment and operating costs are required. The annually fixed recurring costs for smart metering are ranging between 30 € and 90 € (Blaschke, 2022; Liebe et al., 2015).

5.2 Impacts

Given the optimistic assumptions of the *Acceptance* scenario, some scenario combinations are able to cover the occurring costs for smart metering in 2045 for residential customer group 2. In 2025, the two groups cannot yield sufficient savings neither. Hence, households have no monetary incentive to switch from the FT to other electricity tariffs assuming current price volatility and taxation system. (Blaschke, 2022) focuses on dynamic tariffs oriented at spot market prices similar to the HD tariff of this study. In his study, he increases the price volatility in a constant per-unit taxation system and derives the potential savings compared to the FT. A relatively small increase in price volatility enables the customer group with over 6,000 kWh yearly consumption to cover the smart metering costs. For small consumption households, the increase in price volatility would need to be enormous. Switching to dynamic tariffs is not applicable for small households. This conclusion is altered, if the taxation and levy system would be transformed to an ad-valorem regime. The current per-unit system implies per kWh charges regardless of the actual spot market prices. Within this taxation system, (Blaschke, 2022) indicates that

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potential savings would be high enough to cover the smart metering costs even for the households with smaller consumption.

5.3 Other conclusions and lessons learnt

If the utility aims to maximize profits with the VPP system, the FT or HD tariff provide the best potential. However, if the utility has the goal to increase the degree of self-sufficiency and to create a carbon neutral district, a VPP (HD) oriented tariff scheme is to be favored. Regarding the simplified consideration of the cost accounting of the utility, the economic results must be viewed with caution. Since RDR is also a flexibility option for the utility to replace conventional power plants for the provision of residual load, further economic evaluations are necessary. However, the available potential and deployment are limited by time availability and technical restrictions. This means that RDR provides less flexibly than other flexibility options. Nevertheless, it complements and replaces them in some places. This is why RDR plays a central role in the design of the energy system and in the system integration of renewable energies (Ladwig, 2018). The future economic potential of RDR is unfold in case of customer group 2 by running, e.g., an electric heating system with heat pump. Hereby, the higher consumption of electricity as well as the longer load shift horizon have a positive effect on the results. This leads to considerable gains, especially with dynamic tariffs. Furthermore, tariffs that are solely oriented at the spot market prices are reducing the independency of the energy system. Accordingly, the degree of energy autonomy can be increased by electricity tariffs, which are based on both, the residential demand pattern and on the generation profiles of the utilities RES.

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APPENDICES

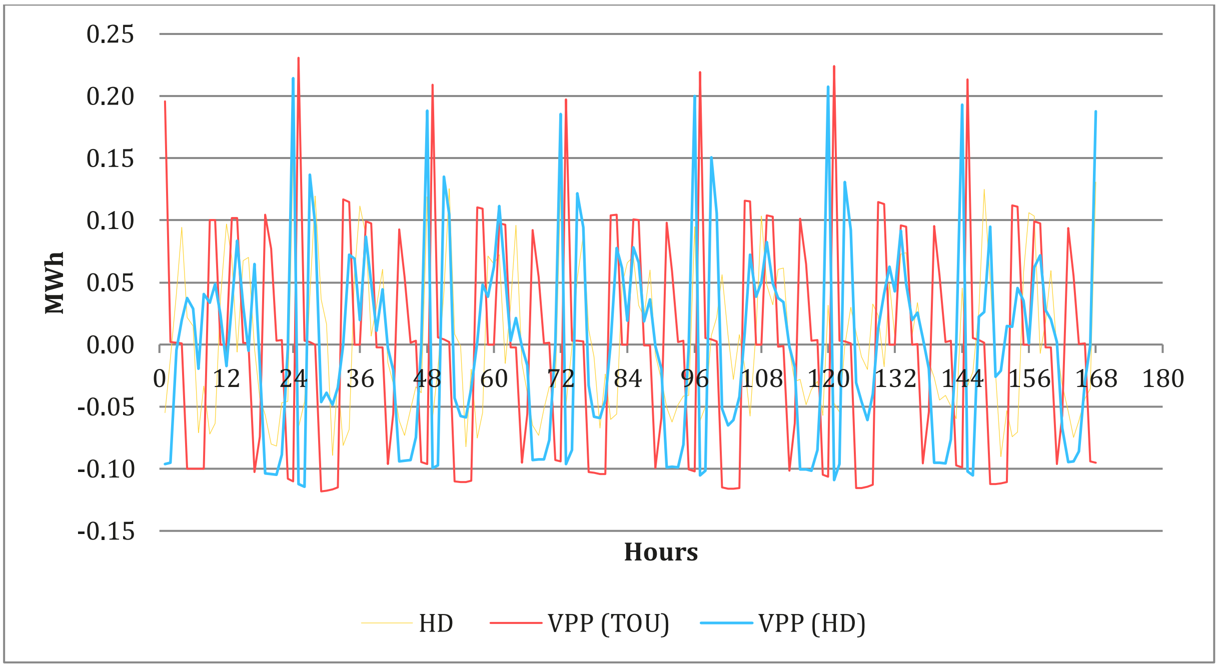

Figure 12: Load shifting based on different tariff schemes in 2025.

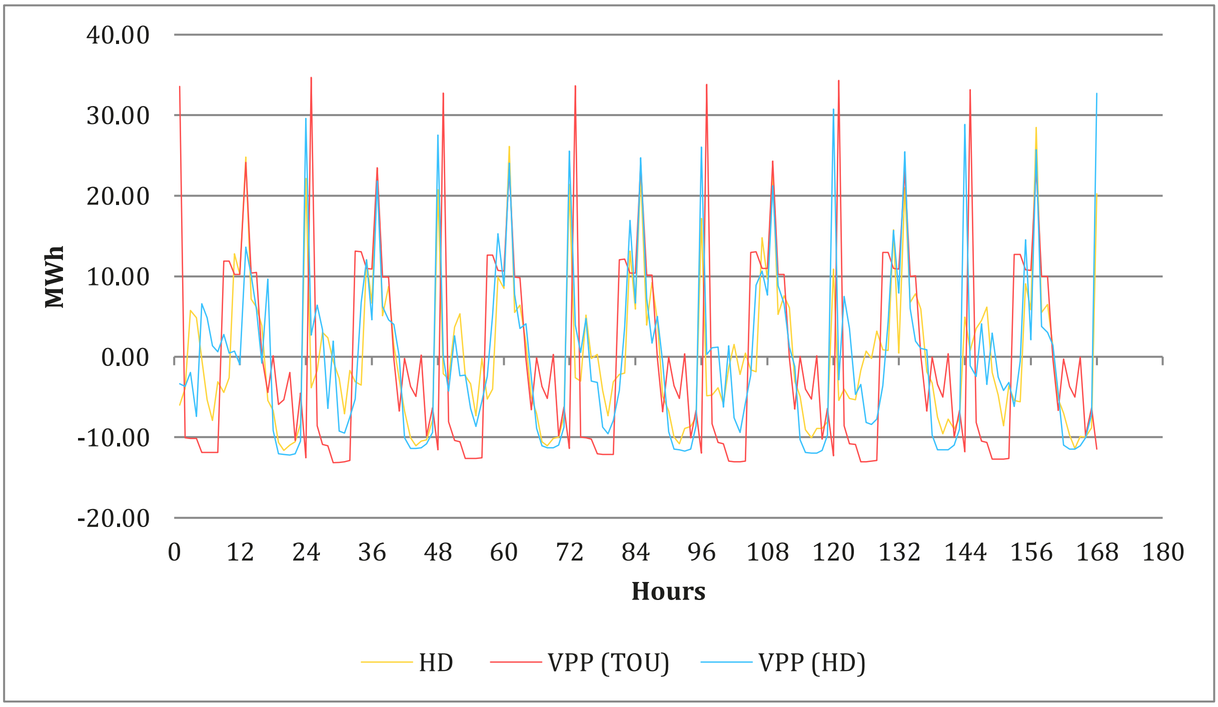

Figure 13: Load shifting based on different tariff schemes in 2045.

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