Integration of Flexibility into an Energy System with High Shares of Solar PV – Contributions from the Project C/sells

Michael Hinterstocker
FfE GmbH
Munich, Germany
mhinterstocker@ffe.de

Kirstin Ganz
FfE GmbH
Munich, Germany
kganz@ffe.de

Timo Kern
FfE GmbH
Munich, Germany
tkern@ffe.de

Patrick Dossow
FfE GmbH
Munich, Germany
pdossow@ffe.de

Serafin von Roon
FfE GmbH
Munich, Germany
sroon@ffe.de

***Abstract*—Since January 2017, more than 70 project partners are investigating the transformation towards a digital energy system within the project C/sells. Over a period of four years, a combination of theoretical research and development as well as practical application in field trials will be used to investigate and demonstrate the implementation of an intelligent energy supply of the future. The key focus of the project is on the integration of solar PV, since the project region consists of the southern German states of Bavaria, Baden-Württemberg and Hesse with high solar potential.**

The main topics of FfE within the project deal with the integration of flexibility into the system. Firstly, the aggregation and extrapolation of measured consumption data in the low voltage grid allow estimating the grid state and therefore, quantifying the potentially available flexibility. Similarly, the development of forecasting methods for residential consumers enables relevant stakeholders to predict the grid load and consider this for the flexibility activation process.

Another focus is the specification and evaluation of business models and business cases in a future decentralized energy system. The developed tools can be applied to assess the potential economic viability of different concepts for flexibility integration for all relevant stakeholders. Additional analyses of electricity market data and market interaction are required to reliably estimate the behavior of potential market participants. Moreover, technical and regulatory requirements of identified business models are investigated and applied as another criterion for comparison.

The last area of research deals with the problem of incentivizing flexibility by small-scale appliances. For assets such as electrical heating systems or electric cars, models like local flexibility markets are being developed by project partners. These are not appropriate for household appliances though. Therefore, variable electricity rates for residential customers are analyzed as means to tap this additional potential, but also as a potential incentive for owners of the aforementioned assets who are not willing to participate in a flexibility market. The developed simulation model allows optimizing rate parameters based on measured consumption data, leading to recommendations regarding optimal rate structures and price spreads.

Keywords—flexibility, variable electricity rates, energy system analysis, forecasting, extrapolation, electricity markets, PV integration

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I. Introduction

Increasing generation from volatile renewables in the German and the European energy system requires additional flexibility in order to balance production and consumption. Besides conventional flexibility options like pumped hydro storage or battery systems, the ongoing digitization of the energy sector also enables small, decentralized flexibility options to participate in current or future markets and therefore, to monetize their willingness to adapt their production or consumption pattern to external requirements. Local flexibility markets can act as an appropriate incentive for these new market actors and enable use cases like market-based congestion management [1].

These local flexibility markets (or "flexibility platforms") are one of the main research topics within the project C/sells [2]. Three different implementations are being designed, developed and practically tested over the project duration of four years. Moreover, several tools and evaluations by a variety of project partners contribute to the feasibility and realization of these markets and complement the actual core concepts. This paper presents an overview of FfE's fields of research within this context, focusing on tapping the potential of decentralized flexibility options and on the interaction with prospective flexibility markets.

II. Selected Fields of Research

A. Extrapolating Household Load Data

1) Motivation

As already mentioned, one of the main objectives of the overall project is the development of market-based congestion management tools for low and medium voltage level grids. The focus here is on small-scale consumer-side flexibility mainly in the residential sector, such as heat pumps and electrical appliances. A prerequisite for determining both flexibility demand and potential flexibility supply is precise knowledge of the consumption. The rollout of smart metering systems ("iMSys" for "intelligent metering systems") enables continuous monitoring. However, the German rollout has not started yet, so full coverage of residential consumers is not to be expected soon. Therefore, methods for extrapolating low voltage power consumption of households to approximately represent the total load at the local substation are investigated in order to provide input data for calculations on the medium voltage grid level.

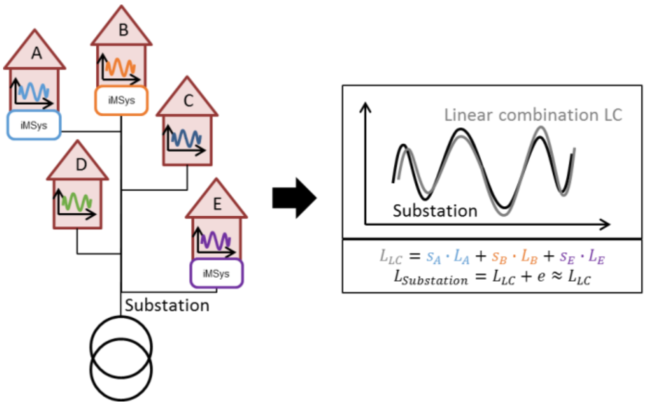

Fig. 1. Illustration of load extrapolation

2) Methods and Results

The presented approach thus aims to achieve a representative approximation of the total grid load at a substation without full knowledge of the individual households' load as displayed in Fig. 1. In a multi-household line, a certain number of households are assumed to be equipped with smart metering systems (initial phase of the smart meter rollout). The load curves of these households are algorithmically combined to calculate a total load profile. In this case, a linear combination of the individual load profiles is used. The scaling parameters are determined in an optimization in such a way that the difference between the measured total load curve and the synthetic extrapolated load curve is minimal. Depending on the initial selection of measurement points, very different aggregated load curves can result, so that the selection of households equipped with smart meter systems is crucial. One way to address this problem is to integrate the selection in the optimization problem as shown in [3]. For large systems, however, this results in very high computation time [4], so alternative methods are investigated. Another option is to preselect the households with heuristics. Therefore, the households which should be measured have to be determined in advance, followed by an optimization of the linear factors for aggregation.

Different approaches to select representative households to recreate a network profile can be applied. These include:

1. Consumers with the maximum yearly energy consumption
2. Consumers with minimal deviation between their load characteristics and the total grid load characteristics
3. Sorting profiles by central moments [4]
4. Approximation with integral transformations [4]

The evaluations reveal that for the available data sets, good results are obtained by selecting the largest consumers. It is the approach of choice when already a certain amount of smart metering systems is available. An advantage of this approach is that no knowledge of the real aggregated profile is required for selection of the measurement points. Furthermore, it fits the German regulation to install smart metering systems dependent on yearly consumption. [5]

The second approach yields good results for small amounts of known load curves. However, the real aggregated load curve has to be available for the selection process. [5] In the third approach, a selection of the profiles is performed using the central moments of the time series as a statistical characterization. The results show that different combinations of the multiple central moments as criteria do not yield better results. Furthermore, the consideration of the central moments also needs knowledge about the aggregated load curve [4]. For the fourth approach, the time-based problem is transformed into the frequency domain to reduce the problem based on periodical behaviour of consumers, since not all frequencies are expected to be relevant. Therefore, two transforms are tested: the discrete fourier transform and the discrete cosine transform. It can be seen that reducing the problem down to 0.45 % of the frequencies for the linear combination of 5 profiles and down to 0.25 % of the frequencies for the combination of 10 profiles evinces the best results [4].

3) Conclusion

Overall, it is shown that load extrapolation can be used to approximately calculate aggregate load curves of low voltage grids. However, whether the accuracy of this load extrapolation is sufficient for application in congestion management processes on the medium voltage level, e.g. in combination with flexibility markets is still to be investigated.

B. Day-ahead Probabilistic Load Forecasting for Individual Residential Customers

1) Research needs

With means of market-based congestion management like local flexibility markets on the low and medium voltage level, the residential sector can contribute to the necessary flexibility supply with e.g. heat pumps and electric vehicles. However, to utilize this flexibility, detailed knowledge about the expected time-resolved electric load of these households is essential in order to avoid causing additional congestion by e.g. load shifting of heat pumps to already existing load peaks. Moreover, forecasting is also crucial for home energy management systems for optimization of local consumption and potential bids on these markets. Data acquired by smart metering systems can be used to analyze the current and historic load characteristics of individual households. Therefore, it provides the necessary basis for load forecasting on the household level. Several methods for day-ahead forecasting are described and evaluated in the following section (detailed analysis in [6]).

There is numerous literature about load forecasting. Most of the research, however, is done for aggregated load and not for individual households (e.g. [7], [4]). Furthermore, the focus of single-household load forecasting in literature is set on point forecasting [8], [9]. Since the load of individual households is highly volatile and stochastic as a result of numerous influencing factors, these forecasting approaches entail the risk to greatly over- or underestimate the load which is potentially problematic when utilized in e.g. grid-related operation or optimization processes (cf. Fig. 2).

2) Methodology

For single-household load forecasting, interval instead of pure point prediction is proposed. Two approaches are compared: a probabilistic prediction approach based on point prediction, which is subsequently transformed to an interval prediction in a second step, and a direct interval prediction approach. The point forecast methods are reference-based and use data from recent days as well as load profiles generated from historical data as input data to forecast the load of the next day. The direct interval forecast methods utilize only historical data. A naïve forecast considering the load of the last 24 hours is applied as a benchmark.

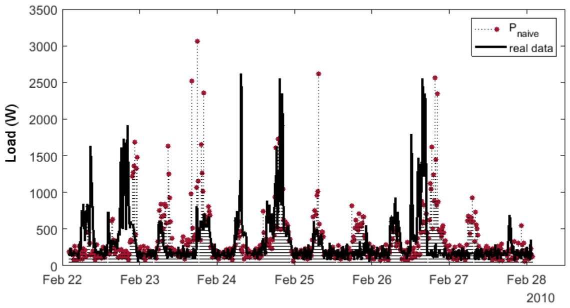

Fig. 2. Real data and point prediction for a single household

3) Results and Discussion

These two approaches with different modifications are compared and analyzed for a case study of 74 households in Germany for one year. The evaluations reveal that independently of the method, high interval widths result due to very volatile load patterns. Regarding the level of fulfilment, the direct interval prediction methods show a more stable result. The variation of the level of fulfilment between the different households differs by about 6 % in comparison to more than 10 % for most point-based methods. Furthermore, the computation time for point-based methods is considerably high, while the direct interval prediction is quick and needs less data. One advantage of the point-based method is the point prediction itself, when this is required as an additional output. All developed point prediction methods outperform the benchmark for all error measures.

There are differences between the various point-based methods and the several direct interval methods, however, the trend described above is seen clearly independent of the specific modification.

As a next step, a comparison to alternative forecast methods based on artificial neural networks is intended. Furthermore, a detailed analysis about the performance of every single household is planned. This contributes to the research question whether specific load patterns and characteristics indicate forecasting performance.

C. Developing a Business Case Guideline

1) Motivation

One of the most common blind spots of scientific research is the lack of perception of the need for practicability concerning new and innovative ideas [10]. When it comes to questions like profitability and distribution markets, operational strategies are seldom developed prior to the product due to scientific habits of overestimating technical solutions. The absence of a business strategy often causes promising research projects to be abandoned even if the technological solution is in place.

In the context of the project C/sells, entirely new and unprecedented flexibility options and flexibility markets are projected to be entering the German electricity market. These are discussed on a technological level in great detail and with great attention. To avoid the hazard of developing a product, which might be of use for the energy system but lacks ability to produce revenue, it was decided to focus some of the scientific work on the relevant aspects of business models and the development of concrete business cases [11].

The aim of the presented work is to establish a comprehensive methodical procedure, which enables the structured development of viable business cases for flexibility options in today's energy markets. After conducting the methodical procedure presented through a guideline, the business case should be presentable to the person in charge to come to a substantiated decision.

2) Preceding Work

Prior to the work presented here, several steps were taken to ensure a uniform and comprehensible basis:

- It has been agreed on a consistent business model language to be used within the C/sells project based on [12],
- Three descriptive tools have been selected and modified to discuss business models in the context of flexibility,
- Workshops have been organized with a consortium of partners with the aim of testing the selected business model tools in terms of usability and expediency.

These three steps constitute the foundation of knowledge on which the presented work builds. The developed so-called value network consists of three business model tools:

- Value Creation Design
- Value Proposition Design
- Business Model Design

All three tools are based on existing business tools invented by Osterwalder et al. [13], [14], and were modified for the special context of business models in the context of decentralized flexibility. Their usability has been proven by the series of workshops conducted with several diverse groups of partners.

3) Business Case Development Procedure

The development of a universally valid guideline to elaborate business cases in the context of flexibility options is based [15]. Minor adjustments and modifications are made to shift the focus on market potentials as well as risks and chances. Both aspects are commonly discussed late in the scientific process.

The business case guideline features seven main components:

1. Business idea
2. Market and competition
3. Marketing
4. Organization and contributors
5. Chances and risks
6. Finance planning
7. Summary

These components are gradually analyzed for the particular business case, which is advised to be conducted in a workshop format. The business case guideline thus provides the workshop structure based on the previously described value network. As a result of this procedure, two decision-making slides are produced, which summarize the business case in the shortest possible way, so that persons in charge can judge the proposal.

4) Business Case Workshops

To test the usability of the developed business case guideline for the purpose of flexibility options, business case development workshops are conducted. Arising needs for change are incorporated into the guideline design in an iterative manner, so that the final guideline can be employed for most energy-related business cases and flexibility options in particular.

5) Main Findings and Implications

The most striking and appreciable outcomes of the conducted workshop of business case development are presented here. The following list provides findings, which are both instructive and beneficial for further development:

- Stating the business idea in only two sentences is highly difficult but also highly reasonable to prevent misunderstanding and further discussion
- Limiting the target group as far as possible is sensible to focus one's attention on the core business
- Defining a distinguishing business feature improves motivation and success prospects
- Analyzing the market yields previously unknown results in terms of revenue potential
- Discussing matters of internal organization uncovers necessary additional expenses
- Identifying upcoming risks is highly difficult but essential at the same time
- Establishing a broad but simplified finance plan is valued by participants of non-economic backgrounds
- Summarizing the workshop results on two decision-making slides is both handy and appreciated

Thus far, the business case guideline has been proven to be highly useful in the workshop format. The established structure helps to avoid misunderstandings and hence improves efficiency in the cause of a business case development process. Through the help of additional upcoming workshops the discussed findings can be confirmed and complemented.

D. Evaluating Situation-dependent Opportunity Costs of Flexible Assets

1) Introduction

In addition to local flexibility markets or redispatch, flexible assets have the opportunity of trading at short-term electricity markets [16]. Sufficient forecasting of revenues in all available markets is a crucial factor to a successful integration of these flexible units into the energy system, since it enables reasonable decisions about the marketing option of choice. This is important for the analysis of local flexibility markets, as it allows estimating both expected liquidity and bid prices. This chapter discusses an approach to analyze the opportunity costs of units that distribute e.g. in local flexibility markets or evaluate a schedule change because of redispatch [17]. Therefore, it focuses on the continuous intraday market in Germany.

2) Previous Approach

The price development of the continuous intraday price affects the potential revenues of flexible asset. Continuous, quarter-hourly intraday prices, modelled in a simplified way as Brownian motion, result in normally distributed values with a mathematical expectation value of the intraday auction price and a standard deviation [18].

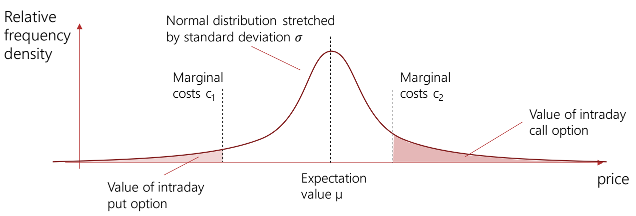

Fig. 3. Evaluation of the value of intraday options

Based on [18], the value of intraday options, meaning potential intraday revenues, depends on four different parameters:

- The expectation value of the continuous intraday price μ at time of evaluation of the option
- The standard deviation σ of the continuous intraday prices
- The marginal costs c for a power output of an asset
- The amount of power to be distributed

The unit-specific and statistical parameters result in the value of intraday options as illustrated in Fig. 3. If marginal costs of an asset c_2 are higher than the intraday auction price, it will not distribute its electricity at this market.

Yet, there is still a chance for higher continuous intraday prices as the prices are assumed to be normally distributed around the expectation value. Distributing electricity with these higher continuous intraday prices will lead to revenues.

The nearer the expectation value gets to marginal costs, the higher the value of the intraday call option will get. If otherwise marginal costs of an asset c_1 are lower than the price in intraday auction trading, it will sell its electricity at these markets. Consequently, a continuous intraday price that is lower than the marginal costs will lead to revenues resulting from the purchase of electricity instead of producing itself. Possible revenues weighted with their probabilities lead to the value of the intraday put option.

3) Methodological Improvements

The shape of the normal distribution determined by expectation value and standard deviation is crucial for the value of intraday options. Relating the deviation between continuous prices and expectations of intraday auction to daytimes and day-ahead forecasts of residual load (defined as the difference of load and renewable generation) results in a situation-dependent standard deviation displayed in Fig. 4. It shows the comparison of standard deviations for the deviation of continuous intraday price and intraday auction price based on different specifications.

For this purpose, a price deviation is defined:

> *id_diff_3h:* Average price of all transactions in continuous intraday trading within three hours before delivery minus intraday auction price

Regarding the standard deviation in dependence of the daytime, there is a slight situational dependence. At night time, there is a lower standard deviation resulting in more certain continuous intraday prices. However, a large difference in the standard deviation between individual, successive quarter hours can hardly be explained by fundamental energy-economical reasons. A much better dependence factor is the residual load forecast.

The residual load forecast combines the influencing factors of wind and solar generation forecasts as well as load forecast. Standard deviations vary from 10.2 to 22.0 €/MWh for *id_diff_3h*. Intraday price deviations between continuous and auction trading are much more uncertain for very low and very high residual load forecasts than for moderate residual load forecasts.

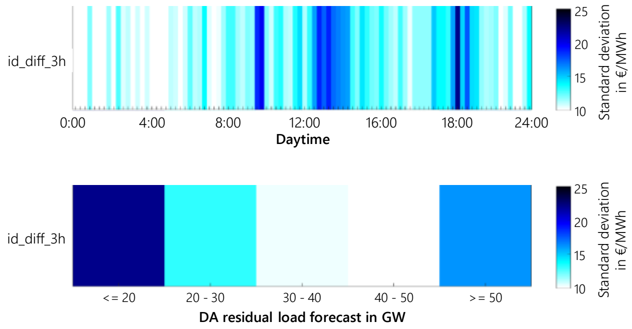

Fig. 4. Comparison of standard deviation for intraday price deviation based on daytime and residual load forecast

In Weber et al. [18], the expectation value of quarter-hourly continuous intraday trading assumes the intraday auction price at the time of the auction. This is a reasonable assumption because otherwise there would be opportunities of making arbitrage profits. If there was a positive expectation value, meaning a higher mean continuous intraday price compared to the mean auction price, traders would consistently buy at intraday auction and sell in continuous intraday trading to generate profits on average.

Nevertheless, the expectation value of continuous intraday trading dependent on the different specification of considered dependence factors is analyzed to support or reject this hypothesis. Fig. 5 therefore shows the expectation value of *id_diff_3h* for different daytimes and residual load forecasts separated in the factors specifications. An expectation value of zero, displayed in black, represents a continuous intraday price that is equal to the average auction price. Positive expectation values, shown in red, and negative expectation values, displayed in green, point out a mean price deviation between continuous the intraday price and the intraday auction price.

For different times of day, there seems to be a random expectation value. Some quarter hours have positive deviations, while others have negative ones. The influencing factor residual load forecast once again is a representation of wind and solar generation forecast as well as load forecast. The expectation value is around 2.2 €/MWh for low residual loads and -1.1 €/MWh for high residual loads for *id_diff_3h*. In Germany, curtailment of wind power plants correlates to the amount of wind power generation. Therefore, a reasonable explanation for systematic higher continuous intraday prices for high wind generation, and consequently low residual loads, is the decreased electricity generation offered, resulting from curtailed wind power plants.

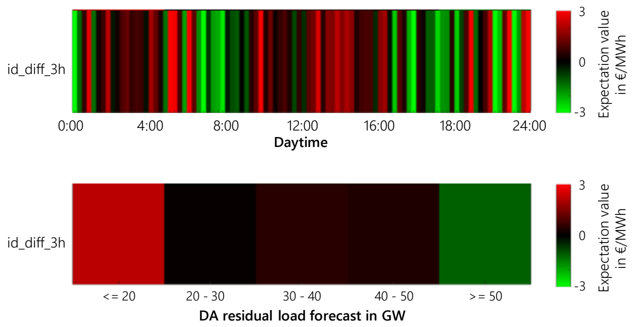

Fig. 5. Comparison of expectation value for intraday price deviation based on daytime and residual load forecast

Based on situation-dependent standard deviations and expectation values of intraday price deviations, realistic opportunity costs of flexible assets can be determined. These opportunity costs of the continuous intraday market added to the marginal costs of a power plant, consisting of fuel and carbon costs, lead to realistic marginal costs of the corresponding power plant and therefore an optimized evaluation of offering electricity at other markets. Our approach consequently promotes flexible assets to maximize their profit and even grid operators to evaluate realistic opportunity costs for power plants offering redispatch.

4) Applications

In the project C/sells, the average revenue forecasts for continuous intraday trading are applied to model opportunity costs for flexibility options dispatching at a local flexibility market. In further studies, acting at continuous intraday trading will be analyzed as a use case for electric vehicles that are able to charge bidirectionally. In addition to the analyzed quarter-hourly, average revenues for continuous intraday trading, in these studies we will also consider hourly continuous intraday trading [19].

E. *Variable Electricity Rates for Residential Customers*

1) Project Context

As described in the introduction, one of the main research areas within the project are local flexibility markets. These provide means for integration of decentral flexibility options like electrical heating systems, electric vehicles or residential battery storage systems, but are not suitable for smaller household appliances, which might nevertheless provide a non-negligible contribution to smart flexibilization of consumption. In order to also pose appropriate incentives for optimized operation schedules of these kinds of appliances, variable, e.g. time-dependent, electricity rates are a possible solution [20]. Therefore, a simulation model is developed which allows

- estimating the reaction of residential customers to various rate structures and price spreads,
- optimizing rate parameters and
- quantifying potential benefits for the energy system.

The overall objective here is to incentivize load shifting with the purpose of increased integration of renewable energy, i.e. the reduction of grid-induced curtailment. As a result, recommendations for future rate design and respective regulation are elaborated.

2) Load-shifting Potential

Different pilot projects show that variable rates are mostly well accepted by a majority of customers, but partly yield contradictory results regarding the reaction to these rates. Complementing previous research, a survey among 130 household customers was conducted to determine the selection criteria for electricity rates, the preferred rate structures and price spreads as well as the actual reaction of customers to variable rates.

The results suggest that, in addition to monetary factors, particularly the comprehensibility of the rate structure and its integrability into the customers' everyday life are important selection criteria. The participants show strong interest in variable electricity rates, particularly rates with three price levels and a price spread around 30ct/kWh, but want to be informed about the electricity price schedule at least one day before. The willingness to shift consumption largely depends on the potential monetary savings and varies considerably within the group of participants. However, a large majority of them accept automatic control of their appliances. These results allow modelling and simulating the expected impact of variable rates in the energy market and thus, the potential benefits for the energy system [21, [22].

3) Regulatory Setting

Utilizing this potential by variable electricity rates requires mapping flexibility demands to sufficiently large price differences in order to cause changes in behavior. It is analyzed whether this is possible in Germany's current regulatory setting and which approaches for improvement are to be recommended. The analyses show that in the current regulatory setting, only the amount for procurement and sales of the energy supplier can be potentially designed in a variable and flexible way in order to pose an incentive for residential customers for behavioral changes. This evinces two main disadvantages: the potential spread is restricted by external factors and other stakeholders in the energy system have no means of influencing the final retail prices.

Possible improvements of the system include three different approaches. The first one is the regulatory introduction of price signals from other stakeholders to the energy supplier, providing an opportunity for e.g. grid operators to react to their specific requirements. This could be also achieved by flexible design of further price components like grid fees or EEG levy. As a last option, the implementation of new price components, e.g. a flexibility bonus, yields highest flexibility for customized rate structures. Therefore, further development of the regulatory environment in one or more of these directions is recommend in order to tap the full potential of residential flexibility. [23]

4) Simulation of Customer Behavior

Based on measured load data in high temporal resolution, the time-dependent load shifting potential of residential electricity customers can be assessed. This enables the simulation of their reaction to variable retail electricity rates, and consequently the evaluation of the suitability of these rate structures for the described purpose. [24]

Since the goal of the whole model is not only to assess the suitability of a given rate structure but to find the optimal structure by optimization of the parameters, this simulation is part of the objective function in a mathematical optimization problem. The parameters of the rate are optimized regarding the maximum possible value of curtailment reduction. With suitable choice of all simulation parameters, this potentially yields a recommendation for applicable rates in the considered region. [25]

III. Summary

The described areas of research within the scope of the project demonstrate the variety of activities, which contribute to the overall goals of developing mechanisms for integration of decentral flexibility options into a future digitized energy systems. The developed methods support the implementation and application of local flexibility markets by providing appropriate input data, by analyzing market environment and potential market effects and by complementing the set of instruments with suitable incentives for smaller appliances. In conclusion, these contributions prove to be important components of the overall concept of the project C/sells, leading to a blueprint for the future energy system.

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