Using grid supporting flexibility in electricity distribution networks

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Abstract: The electrical grid is facing several challenges. On the energy generation side is the decentralized power generation in solar parks, wind parks, or residential solar panels, which all result in a time variable power generation. They may generate power while it is not needed. On the load side, there are the challenges of controllable loads and the electromobility with its high demands on the grid. These loads may need power when it is not available or cannot be transmitted by the grid. In addition to these technical challenges, there is the political will in Germany both towards renewable energy generation and towards a smart grid. The orchestration of controllable loads with variable power generation could alleviate these problems. Loads could be orchestrated to use power when it is generated. In this paper two approaches of how to orchestrate the controllable loads considering the variable power generation are described: a centralized and market-driven approach from the research project C/Sells and a decentralized approach from the research project LAGE-EE.

Keywords: renewable energy, smart grid, flexibility, energy trading

1 Introduction

The electrical grid should perform reliable and efficient, especially for the optimal use of the already installed grid. Additionally, there are new challenges for the grid. Due to the uprising use of renewable energy sources, the location of the sources can be scattered all over the area and thus all over the grid [FH19]. Especially in Germany, many solar arrays are built on domestic house roofs. And also, solar parks and wind parks are not necessarily built in strategic positions for the grid, but rather where the wind or the necessary space is available. Due to the nature of these generators, the amount of produced energy can vary quickly, mainly related to the weather. Thus, the energy may be available when it is not needed or where it is not needed, or the generation of energy may stop weather related while it is still needed.

On the energy consumption side are also challenges. Some consumers are, to some degree, flexible in the amount of energy needed and the time when the energy is needed. To coordinate the energy generation and consumption an act [DB16] has been passed in Germany, giving the possibility to control some energy consumers and this in a „smart“

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way. Flexible energy loads raise the challenge of the best regulation mechanism to control them. In addition, an increase of electromobility can be seen [NP18]. This will also significantly increase the load in the grid, especially the maximum power required at times of loading many vehicles. An upgrade of the existing grid, allowing to transport larger electric powers, could solve the described challenges. Nevertheless, each upgrade of the grid is expensive. Therefore, the optimal use of the existing grid should be considered.

A solution to the described challenges can be the smart control or orchestration of both sources and consumers of energy. But then, the question for the best regulation mechanism remains. In this paper two different approaches are presented. Both are developed in research projects at the University of Kassel. In the first research project C/Sells [CS19], a trading-based approach is developed and investigated, to cover not only the technical aspects but also the monetary aspects. This trading aims to optimize the overall energy situation given by time-varying energy production and potentially time-varying energy consumption. So, i.e., energy consumers could be motivated to shift their energy consumption due to financial reasons. This project focusses on the inclusion of loads on a corporate level like cooling warehouses and process ovens. The second research project LAGE-EE [LA19] concentrates on flexible energy consumers on a domestic scale. In this project, a field test is done where heat pumps are controlled by the local electrical parameters of the grid. While the first approach focuses on a centralized and market-driven orchestration, the second approach investigates a decentralized and locally controlled approach.

The remainder of the paper is as follows: First, an overview of the problems of an electrical grid is given. Afterwards, the two approaches from the two research projects are explained in detail. Finally, a conclusion is given.

2 Detailed description of the issues in electrical grids

In this section, an overview of the German grid structure is given. Also, the issue of congestions is explained. This is the basis for the solutions investigated in the R&D projects C/Sells and LAGE-EE. These solutions will then be explained in Section 3 and 4, respectively.

2.1 Structure of the grid

The grid in Germany can be divided into two layers: the transmission network (the upper layer in Figure 1) and the distribution network (the lower layer in Figure 1). The transmission network is used to deliver the energy over long distances from the energy source to the distribution networks. Transmission networks can also be used to transfer energy from a distribution grid to another distribution grid. And they can even cross international borders, to exchange energy between countries.

Distribution networks are the second stage of the grid. They are operated in medium, high and low voltage and connect the transmission networks with the local grids and the residential houses. Almost all wind farms (96%) [BW19], and many solar farms as well as companies with higher energy needs are connected to the medium-high voltage grid. At the low voltage grid, the residential houses and small companies are connected via a local transformer. Also, at this voltage level, the typically large number of residential solar arrays are connected. On the other hand, the large powerplants are only connected to the first layer, the transmission grid.

The traditional energy flow in the German grid was top-down, starting from the power plant over extended transmission networks and ending in the residential houses or the industry. In this traditional flow all the generators would only be in layer 1 in Figure 1 and all the loads in layer 2.

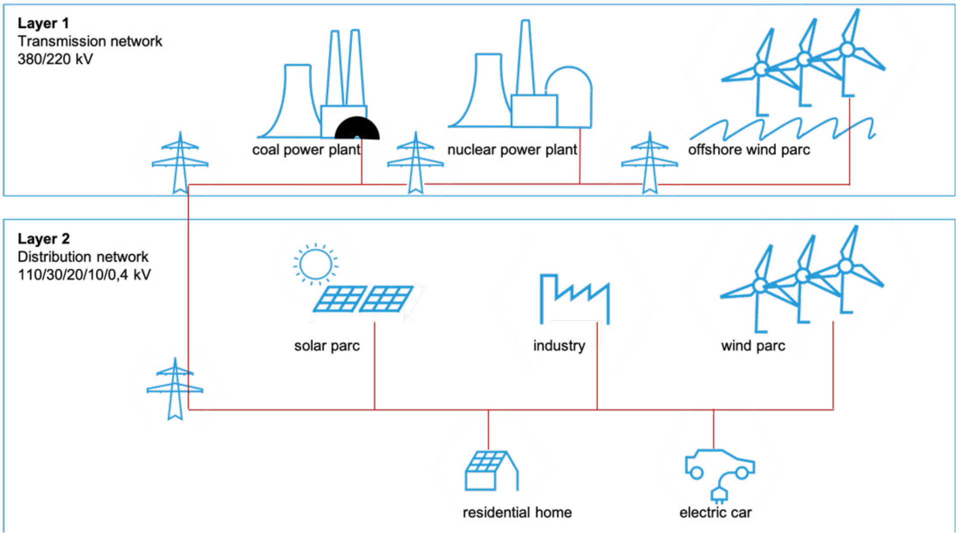

Figure 1: German grid, energy flow and layers [VU15]

2.2 Congestions

The traditional setup of the grid in Germany was load oriented. The energy was produced in large powerplants and distributed from the transmission networks over the distribution networks to the local consumers. The distribution of load over time was approximately known, and the energy generation was planned, scheduled, and controlled to the needs of the customers.

The traditional grid setup has changed over the last years. Many private households have installed solar arrays on their roofs. In addition to this, wind and solar parks have been installed in many locations. They all feed energy into the grid. Unfortunately, the amount of energy feed into the grid is depending on the weather and the time of the day and year. Also, a change in energy needs is expected due to the rising number of electro mobiles and heat pumps. These two developments lead to the risk of energy congestions. Energy congestion means, that the grid is not able to support as much energy transport. Congestions can occur either on the energy consumption side, as well as on the energy production side.

Congestions induced by the energy production side occur when there is too much energy produced but not needed in the local grid, and it cannot be fed back into the upper network layers. This is illustrated in Figure 2 at ‘House 2’. The voltage rises over the upper border V_{max}. To stabilize the grid the generation of energy is reduced by the solar inverter of House 2 until the grid is in the allowed electrical parameters again.

Congestions induced by the energy consumption side occur when not enough energy can be transported to the consumer. A scenario covering this hypothetical situation is the homecoming of employees in the evening with their electric cars. They all connect their vehicles to the grid and want to charge them. If many residents of a single street or a village arrive at a similar time, congestion of energy may occur, because the installed grid may not be able to deliver the energy needed to charge all vehicles fast and at the same time. A Congestions of this kind is illustrated in Figure 2 under the SME. As a result of such a situation the voltage in this location of the grid drops under the minimum V_{min}.

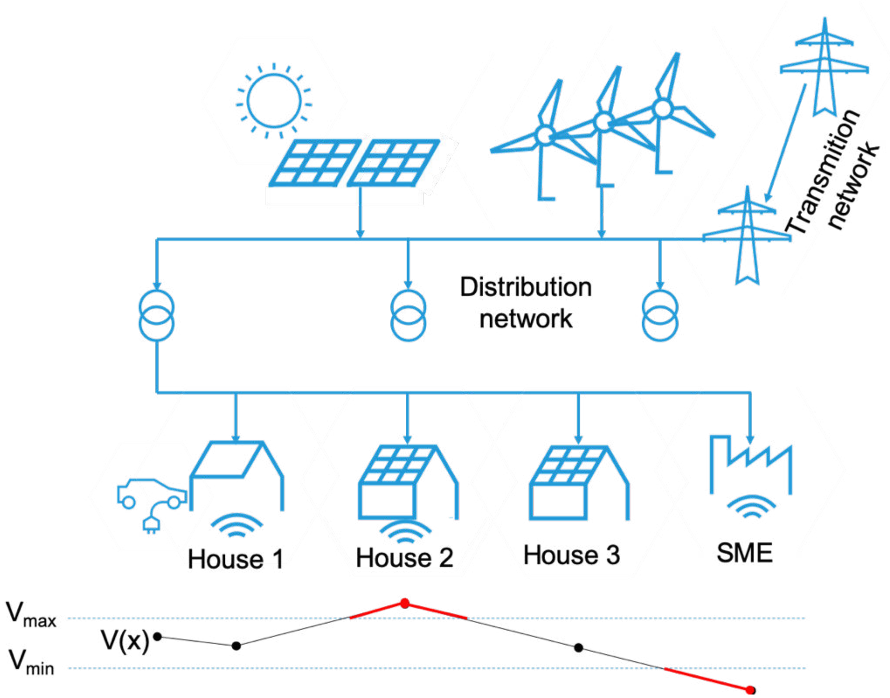

Figure 2: Congestions in the distribution Network

2.3 Grid expansion

One way to solve this issue of congestions is an upgrade of the power grid. The power transmission capacities of the grid mainly depend on the capacities of the installed technical infrastructure like power lines and transformers. A change of the installed infrastructure to an infrastructure with a higher capacity can solve the issue of congestion caused by too much power generation or too much power consumption. However, an upgrade of the already installed technical infrastructure has to be considered carefully because of the high costs resulting from it. Besides this, it would also be uneconomical to install power lines with a larger capacity when the full capacity is only used rarely. Most of the time it would only be used as it is already used today, and there is no need for a change during this time.

2.4 The use of flexibilities to stabilize the grid

The German government agency of regulation (Bundesnetzagentur) defines flexibilities in the context used in this paper: "On an individual level flexibility is the modification of generation injection and/or consumption patterns in reaction to an external signal (price signal or activation) in order to provide a service within the energy system. The parameters used to characterize flexibility include the amount of power modulation, the duration, the rate of change, the response time, the location etc." [BN17]

Flexibilities can be used to stabilize the grid. They can be controlled to generate more or consume less power when there is a congestion of energy generation. And when there is an oversupply they can be controlled to generate less or consume more power. This can be done in many locations in the grid simultaneously, depending on the local requirements of the grid.

The control of flexibilities can be done by different approaches. Two approaches are described in the next two sections.

3 The approach of regional flexibility markets: C/Sells

The research project C/Sells investigates on the future energy grid setup of Germany. One particular focus is the use of flexibilities to solve congestions in the grid. The flexibilities which may help to solve a congestion have to be chosen out of the available flexibilities. In this research project the flexibilities get chosen via a market-based mechanism. The underlying market mechanisms are investigated, and several mechanisms are tested. This investigation is supported by a test done in a simulation and a field test.

The flexibilities considered for a market in this project are on a corporate level like cooling warehouses and process ovens. However, the same underlying principals can be used to enable other participant on a smaller or larger scale.

In the next subsection the market platform is described. Then the structure of the market and the traded products are described in more detail. In the last subsection the forecast mechanism to predict congestions is described. This forecast is needed to trigger the allocation of flexibilities and therefore the market process.

3.1 Market based use of flexibility

The general idea of a flexibility market is the procurement of a required flexibility via market mechanisms. This is done to enable a transparent and non-discriminatory allocation of a flexibility. A platform is needed for the market. This market platform in connection with its participants is shown in Figure 3 .

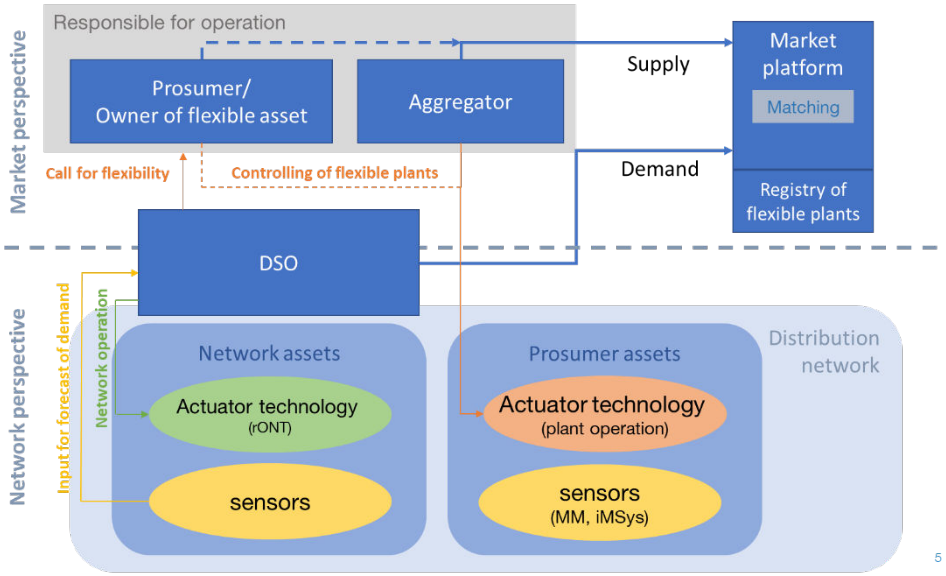

Figure 3: Concept of the market platform

The lower part of Figure 3 shows the network perspective. The classic network operation comprises the handling of active network infrastructure and will be based more on different kinds of sensors (e.g., smart meters) in the future. The data of these sensors can be used to monitor and predict the state of the network (see also Section 3.3). With this information, the network operator can identify problems and can determine the demand for flexibility. The demand for flexibility gets transmitted to the market platform.

The market platform is also the place, where owners of flexible assets can bid their flexibility. Flexible assets can be, for example, households with battery storage, industrial companies with flexible demand, flexible power plants, or aggregators that bring a pool of different power plants to this market.

The demand for flexibility and the bidden flexibilities are matched on the market platform. The output of the market platform is a list of flexibilities that can solve the expected problem with the lowest possible cost.

The network operator can decide if and when he actually wants to use a flexibility from the list of flexibilities. If the predicted situation occurs, he can request a flexibility from the list. The activation of a particular infrastructure on the other hand, is the responsibility of the supplier of the flexibility.

3.2 Structure of the market and traded products

We also implemented a prototypical regional flexibility market for a sub-network of the project partner EnergieNetz Mitte, a DSO (Distribution System Operator) in northern Hesse. The market processes are structured, as shown in Figure 4.

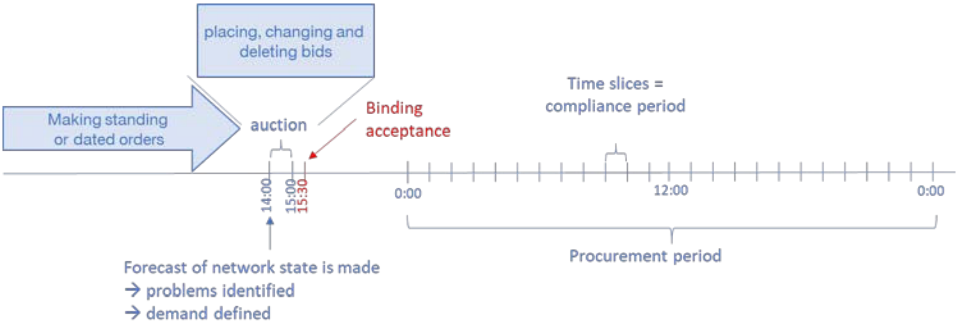

Figure 4: Structure of the market process

The trading process is organized in a day-ahead auction, which takes place between 2 and 3 pm. Until the start of this auction, the network operator must define the demand for flexibility. Suppliers can place, change, and delete their bids until the end of the auction. It is also possible to automate the placement of bids by placing automatically repeating standard bids. After the auction, the winner is determined, and a list of the relevant bids is generated. This list is the output of the market.

The traded products of our market contain the option for the system operator to request the flexibility if actually needed. Therefore, the decision of activation is delayed to the trading of flexibility. One bid of a flexibility product belongs to one hour of the next day, because the trading is organized in a day-ahead auction. If traded, the flexibility supplier must maintain the flexibility in the auctioned time slot. The activation of the flexibility is realized in a short time, e.g., 2 hours, before delivery.

We designed various products that aim to fulfill different requirements for the demand side as well as the supply side. The products of our market are defined in this paragraph and summarized in Figure 5. The main product is a positive or negative power. This is the standard product when talking about flexibility. It leads to the adoption of the production or consumption schedule of the supplier. In connection with this product, we designed three different 'quota' products for different technologies (PV, wind, e-mobility).

'Quota' products do not contain the change of a specific value of electric power, but the limitation of production or consumption of these assets, in contrast to the standard power products. These products respect the difficulty of predicting the production or consumption of individual small plants. At last, we take into account the possibility of solving voltage problems with reactive power.

To solve a congestion problem the location of the flexibility is crucial. The more fare away it is from the location of the problem, the less useful it will be to solve it. Therefore every product specification contains a location information. The location Information is not position on the surface of the earth like in GPS, but rather the information to which knot in the net the flexibility is connected. This distance is also used for the valuation of a specific offer.

Underlying problem	(power) congestion		Voltage problem				Superior
	Can be solved with						
Technical good	Power				Reactive power		Standardized
Direction	+ (Generation)		- (Consumtion)		+ (capacitive)	- (inductive	
Activation condition	Secure maintenance with short term activation						
Predictability	Exact defined	Quota PV Wind	Exact defined	Quota E-Mob	Exact defined		
Time slices	24 One-hour-time slices						
Individual local component	Defined with grid node						Technical based
Prices	Asking price (€/kW, €/kWh)						Indi-vidual

Figure 5: Traded products on the C/Sells market

3.3 Forecasts

In regional energy markets, knowing future power grid states is crucial. Typically, the market operator uses information about future grid states to trigger an auction period. After the auction, a plan on how to balance out possible faulty grid states is created. Before the actual need to implement the balancing plan, another forecast for the power grid state is triggered. This forecast, also called short term forecast, is performed with more current information about the power grid, therefore, also more accurate about the grid state prediction.

Hence, for regional energy markets, we need two types of forecast:

- For planning: long term forecast, 12h to 36h into the future.

- For implementation: short term forecast: up to 6h into the future.

The power grid state is dependent on each individual state of the components in the power grid.

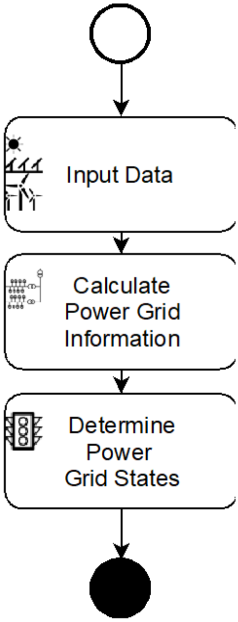

Figure 6: The data analysis chain to obtain power grid states

Mainly the power grid state is obtained after calculating the load flow calculation for the specific grid. Afterward, the results of the load flow allow determining the capacity for each component. Based on the capacity the BDEW (Bundesverband der Energie- und Wasserwirtschaft) [BD01] in Germany proposed limits to define different power grid states.

To be able to forecast the power grid state, we can forecast each of the outputs of three blocks seen in Figure 6:

1. energy production and consumption,
2. load flow results, or
3. grid state estimation.

Each of these approaches increases the difficulty of the problem, as the machine learning algorithm needs to abstract more information about the power grid.

E.g., for Approach 2 the load flow calculation, as well as the power grid layout, needs to be abstracted, and Approach 3 needs to abstract the maximum capacity of the components within the power grid.

Approach 1:
Forecasting energy production and consumption is a straight forward solution to obtain information about the future power grid states. The challenge in this approach is that the number of different forecast models, as an individual forecast for each production and consumption node in the power grid is needed.

Approach 2:
Forecasting the load flow results is a challenge similar to forecasting the energy production and consumption. Each component in the power grid, e.g., each line or transformer, needs to be forecasted, increasing the number of individual forecasts. Additionally, the load flow calculation is added as a preprocessing step.

Approach 3:
Forecasting the state of the power grid is as challenging as forecasting the load flow results. If we use a traffic light system as proposed by BDEW [BD01], the actual forecasting problem changes to a classification problem with three labels.

4 A decentralized control of flexibilities – LAGE-EE

LAGE-EE is a funded research project with a focus on the local management of loads to keep the grid stable. The local management can be useful when there are many residential solar arrays installed in an urban area. The solar arrays can increase the voltage level to a point where the attached solar inverter limits the energy generation because no more energy can be transferred into the grid without violating the stability. On the other hand, there are controllable loads such as heat pumps or electric water heaters. The approach in LAGE-EE is to control such loads locally based on the grid parameters.

The parameter used in LAGE-EE is the local voltage of the grid. A controller has been developed, which is installed in the residential home. It measures the voltage, and when it is during a certain time interval in one of the narrow bands close to the min and max borders of the voltage, the regulation algorithm starts to control the loads.

The loads controlled in the project are mainly heat pumps in residential homes. Heat pumps convert electrical and thermal energy into heat. They achieve a much better efficiency (like a lever) by additionally using temperature differences between inside and outside a building or tapping into the earth. In principle they can also be used for cooling. Here heating is further considered. This heat is used for heating and hot water. Usually, a hot water storage tank is attached to the heat pump, sometimes also one for the heating. And the building itself can also store thermal energy.

Thermal storages can be used to be more flexible in energy consumption. The thermal storages are usually operated within an upper and a lower border. If the room temperature or the temperature in the storage tank approaches the lower border the heat pump is started. When the temperature reaches the upper border the heat pump is stopped. However, the borders can usually be shifted slightly up or downwards. And the heat pump can also be started when the temperature is well between the borders, although this might be unusual. This border and timing shifts enable the heat pump to be more flexible in energy consumption.

Modern heat pumps have already a self-optimized energy consumption function. When solar arrays on the roof produce energy and the energy cannot be feed into the grid because of regulation issues, the heating is started, or thermal storages are directly heated with the excess energy. However, this is only done in one household, not considering the neighborhood. The approach of LAGE-EE comprises a whole neighborhood of several houses and heat pumps, this for the case that locally generated energy gets locally consumed.

The approach in this subsection also helps with the aspired growth rate in number as well as usage of heat pumps. This is part of the political agenda for the use of renewable energy in Germany. Heat pumps are one way to use renewable energy. Thus, many heat pumps get installed into the grid, where traditionally the heating in Germany is done with oil and natural gas [BU15]. The grid is able to supply the heat pumps, as their electric requirements are in within the specifications of the domestic electrical supply. Nevertheless, there can be a problem when several heat pumps start at a similar time in one part of the grid. The controller investigated in LAGE-EE can also help to prevent this problem as the starting of the devices is shifted until the grid is within its specific borders. When the grid is in this state, there is enough electrical energy to start several heat pumps.

The monetary aspects of this approach are also investigated in LAGE-EE. First, the electrical grid in a certain area was simulated. Scenarios were developed for different kinds of future expansions in solar arrays and heat pumps. These scenarios were used in the simulator to calculate the amount of time the grid is not in its specific borders, and the amount of time the energy generation from the solar arrays had to be limited. Afterwards, the potential of buildings and water storage tanks to store energy were investigated. The additional energy losses due to the higher upper border (which also produces higher losses in storages) were simulated. In this simulation also different kinds of buildings were simulated. Also, the avoided grid expansion was considered. Thus, the pricing for the electrical flexibility could be calculated. Models of a dynamic pricing and a flat fee were investigated.

5 Conclusion

The energy generation in Germany is changing towards renewable energies. This changes also the usage of the electrical grid and raises some challenges. Power is no longer only generated in some big plants but rather scattered all over the country. The part of the grid built to supply residential homes is now used to feed energy from PV power plants back into the grid. Wind and solar parks are built which have a fluctuating power generation, depending mainly on the weather. The residential heat and hot-water supply changes to electricity. And the use of electric cars increases, which have a demand for high load currents over a short period.

The use of flexible generation and loads can alleviate several of these challenges. In this paper, two approaches to control flexibilities have been presented, both based on research projects of the University of Kassel. The first approach was using a market mechanism that leads to a transparent and non-discriminatory allocation of flexibilities to be used to stabilize the grid. This new product changes the traditional approach, where only power generation was traded on stock markets. Now also flexibilities can be traded. This may be especially useful for industries utilizing processes that can be shifted in time and also for aggregated smaller loads. In this project also a prototypical regional flexibility market is developed which is also put to a field test.

The second presented approach aimed at a more local stabilization of the grid. It is working decentralized by only measuring electrical properties of the grid at residential homes. The approach is controlling loads like heat pumps based on the local electrical values of the grid. A field test is done in this project to evaluate the simulation-based findings and the regulation algorithm of this approach. Although monetary aspects like the use of excess energy, prevented grid updates and cost increases due to energy losses are considered, the algorithm itself is not considering the price of the energy.

Both approaches can solve some upcoming challenges of the electrical grid by using new financial incentive systems and smart control technologies of the grid. However, future investigations will have to ensure the reliability of these approaches in order to adapt the legal framework to enable such approaches.

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