Market Engineering for the Smart Grid

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Learning Objectives

- What is Market Engineering?
- How do Smart Girds impact the energy market?
- How can Market Engineering and the Smart Grid improve energy markets?

1 Energy Market Design in a Changing Environment

In January 2001, California experienced rolling blackouts in their energy systems and an average price of electricity of $250 per MWh. This price was nearly ten times the average price of the previous January in the year 2000 (Woo et al. 2003). What had happened? California had liberalized its electricity market with a zonal setup and with it, had introduced various new market components that were intended to reduce grid congestion, market power and risks for consumers, and at the same time, drive down wholesale electricity prices. There was little experience with designing electricity markets at that time and some market design choices created strategic incentives for individuals to optimize themselves against the market (see Alaywan et al. (2004) for more details on California's design flaws). California was not the last trial and error of power market design. There are constant reports on small power market failures all over the world. This is not surprising as the market design for

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power markets is very complex and it needs to integrate various interests. The peculiarities of the power market have been introduced to you in chapter "Smart Grid Economics". The worldwide transition to more intermittent renewable generation challenges traditional market designs. It leads to generation spikes that can cause congestion (Staudt 2019), reversed power flows on the distribution level (Walling et al. 2008) or even negative electricity spot prices (Kyritsis et al. 2017). The market design needs to be adapted to these changes. At the same time, the Smart Grid introduces new possibilities to measure and control actions at the low voltage level that can help to balance the local infeed of renewable generation. This allows new actors to enter the market, creates active and price-sensitive consumers and provides more detailed market information. It is important to note that when we talk about the power market (in this Chapter we will use power, electricity or energy market synonymously), we are really meaning a multitude of market stages (i.e., sub-markets) such as the wholesale spot and intraday markets or the market for balancing power, for example. Others might be added in the course of the energy transition, such as redispatch markets (Hirth and Glismann 2018). The Smart Grid potentially impacts all of these sub-markets and it might enable the creation of new sub-markets, for example, in the form of peer-to-peer trading in the distribution grid (Mengelkamp et al. 2018). Such markets as well as changes in the existing markets need to be carefully engineered to avoid market failures as in California and to achieve the intended objectives. In this chapter, we therefore, introduce the market engineering framework as a way to systematically describe and engineer existing and new markets. We then describe the impact of the Smart Grid on energy markets and discuss how these changes can be classified.

2 Concept of Market Engineering

As shown by the example of the failed Californian electricity market reform, a market engineer needs to consider a variety of aspects when designing a market that also needs to be continually re-evaluated. A formalization of the components of market engineering in the form of a market engineering framework is provided by Weinhardt et al. (2003a). The designed framework is depicted below in Fig. 1. The framework is originally designed to describe virtual marketplaces but it can be used to formalize all kinds of markets. It is a very powerful tool that forces the engineer to consider different aspects of a market environment when designing the market. In the following, we describe all components of the framework. Note, that the market engineer can only influence the market structure that is comprised of the microstructure, the (IT)infrastructure and the business structure. However, if the market engineer is the regulator or the designer of the traded product, she might also be able to influence the transaction object that is traded on the market. After the explanation of the framework, we provide an illustrative example of the secondary control power market in Germany. Additionally, we describe some desired properties of markets that should be taken under consideration when the market is designed.

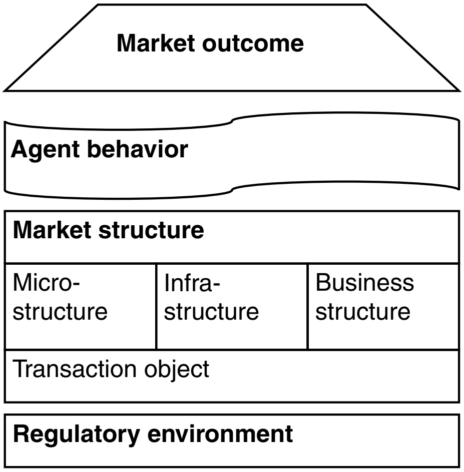

Fig. 1 Market Engineering Framework (Weinhardt et al. 2003b)

2.1 The Market Engineering Framework

Socio-economic and legal environment
This is the foundation for the market engineer. The rules of the market, the traded products, and the participating agents need to comply with laws and regulations. This might include tax law, competition law and so on and so forth. In the electricity market context, there might be specific regulations on the availability of resources or specific limits for the allowed emissions of different substances, for instance.

Transaction object
The transaction object is the product that is to be traded on the designed market. It might be abstract such as any legally tradable physical good as would be the case for eBay, for instance. In the electricity context, it would often be either power or electricity. However, with the Smart Grid, new demand side flexibility resources might become tradeable. A possible product formulation is introduced by Dauer (2016).

Microstructure
The microstructure determines the rules of the market. This can be broadly summarized as the auction design on the designed market. It defines how sellers and buyers submit bids and how a successful trade is found and at what price it is executed. Even a farmers market has a microstructure. Customers that arrive at the market before the produce is completely sold, can perform a successful transaction if they are willing to pay the displayed price.

IT-infrastructure
Today, most markets are virtual. Market places can be accessed on web platforms and bids can be submitted online. This means that markets need an IT infrastructure that determines the access for different participants, the time resolution and needs a

user- friendly design. eBay, for instance, allows access to all registered users within the timeframe of the auction to access and to enter their reservation price using a number field.

Business structure
The business structure is the business model of the market operator. It determines her revenue model. For example, participants might pay an access fee and a fraction of each transaction to the market operator. If the market operator is not a private company but the regulator, the business structure relates not to revenue but some other metric that is to be achieved. One example is the resiliency of the electrical grid that is strengthened through the procurement of reserve power.

Agent behaviour
The microstructure, the IT infrastructure and the business structure form the overall market structure. It can be influenced by the market engineer to achieve eventual goals of the market, be it efficiency, reliability or profit maximization, among many others. However, the structure does not directly translate into a market outcome. It defines a set of rules and regulations that influence agents on the market. The market result then depends on the behaviour of agents that act within this set of rules. For instance, a very complicated framework might discourage participation and therefore, the ultimate outcome cannot be achieved. The market structure of eBay, for instance, encouraged agents to submit their bids last second in order to impede other people from being able to outbid them. This even led to according software artefacts that would allow people to follow this strategy more conveniently.

Market outcome
The market outcome results from the agent behaviour. Usually, the market engineer has a set of objectives for the market outcome as previously described. These objectives can then be evaluated against the actual outcome. For instance, the German government has introduced a market mechanism for the assignment of feed-in tariffs to large renewable generation units. They are assigned through an auction that is performed multiple times per year. The objective is to reach the expansion goals for renewable generation while using the cheapest technology at the most suitable locations in terms of total generation. In the year 2019, almost no new wind projects were proposed, which is supposedly caused by increasing opposition within the population and other regulatory issues. As this is not caused by the market design, which is suitable, the government is currently evaluating a change to the legal environment. This is possible as the government has a further reach than normal market engineers. The performance of a market is difficult to measure because it depends on the desired properties of the market. Therefore, we introduce possible performance critieria of a market in Sect. 2.2.

Case study: Market design of the German secondary reserve market
To illustrate, how the market engineering framework can be used to describe and design markets, we provide the example of the secondary control energy market in Germany. This market is operated by the TSOs in Germany, who need to procure reserve power in order to balance the grid in case of unforeseen events or forecasting

errors and it serves well as an example because its setup is rather complex. The secondary reserve is activated after the primary reserve power. The costs for the power provision are covered through grid tariffs by all consumers. The actual cost of activating the secondary reserve is distributed among the market participants that caused the disruption of the balanced grid operation. The socio-economic and legal environment for reserve power is constituted by the law on grid access (in German *Stromnetzzugangsverordnung (StromNZW)*). There are of course many other laws to consider, for example, the law on energy markets (*Energiewirtschaftsgesetz (EnWG)*). However, it often suffices to describe only the most important regulation. The transaction object on the secondary reserve power markets is multi-dimensional. It is composed of a quantity, a power and an energy price, it can be positive or negative (meaning that power can be added to or taken from the system), and it is differentiated by the time of day in four-hour blocks. The quantity is the offered amount of power that can be activated to balance supply and demand in the energy system. The power price dimension provides the payment that is required to be paid to contract that offer. It is paid regardless of an activation to provide balancing power. The energy price, on the other hand, is only paid if the participant is actually required to provide energy. Positive and negative secondary reserve power is procured separately. Furthermore, the products are divided into four-hour blocks in which they have to be provided. Therefore, the transaction object has 5 dimensions. The microstructure has multiple stages: in the first stage, the TSOs acquire reserve capacity and in the second stage they procure reserve energy. The capacity stage serves as a form of insurance, ensuring that enough reserve energy is available. Reserve energy can be thought of as a transaction object with a capacity price bid of zero. On the reserve capacity market, the bids are accepted in increasing order until the required capacity is reached. Then, in the reserve energy market, the participants that have been accepted at the reserve capacity stage have to participate, but other market participants are also allowed to submit bids. The required reserve energy is then also acquired in increasing order. The TSOs use a web interface as IT infrastructure. The business structure for the TSOs is to generate a competitive environment and to procure the secondary reserve at a minimal price. They, therefore, do not have a revenue objective but they do have a financial objective. In the past, the agent behaviour was often strongly influenced by the market structure, because the bids for reserve power and energy were submitted simultaneously and accepted only based on the capacity price. Therefore, there was no more competition for the energy price. This lead to situations where suppliers bid very low power prices but the energy prices skyrocketed, which then occasionally lead to very high reserve energy prices. Consequently, this mechanism was redesigned. This is a very good example of how market engineers react to the market outcome by trying to change the agent behaviour through a redesign of the market structure. As the market design changed only very recently, it remains to be seen whether it has an effect on the market outcome.

2.2 Market Properties

There is a variety of market properties and quality measures that can be considered when markets are designed. In the previous example, the objective of the market operators is to achieve minimal costs because they are both, the market operators and the consumers on the market. Often, a market engineer needs to consider the interests of both, supply and demand on a market, which results in properties that take all stakeholders into account. These properties are sometimes conflicting, sometimes they are complementary. The following concepts are extracted from Wurman (1999, pp. 15–19) as it provides a neat overview but many concepts are originally explained by Mas-Colell et al. (1995).

- **Efficiency**: There are different definitions of efficiency. One could, for example, argue that an efficient solution is such that it maximizes the utility of all agents. However, a more common definition of efficiency is Pareto efficiency. A market leads to a Pareto efficient solution if in that solution, no agent can improve her utility without reducing the utility of another agent.
- **Equilibrium**: There is a variety of different possible equilibria. However, a market engineer might wish to build a market such that some form of equilibrium state can be achieved. One common definition is that of a Nash equilibrium in which no player wishes to deviate given the rational strategy of the opponents. A dominant strategy in this sense would be a strategy that is optimal for a player regardless of the actions of her opponents.
- **Stability**: Formally, this concept means that agents will not choose a strategy that is not allowed by the designed mechanism that would increase the overall utility of the agents. A solution is, therefore, stable because no agent has any incentive to work around the mechanism to improve her position. Therefore, any stable solution is also Pareto efficient but not vice versa.
- **Individual Rationality**: A mechanism is individually rational if it is stable for each individual agent. That means that every agent would enter the mechanism and not try to work around it. In essence, it means that an agent cannot be worse off by participating in the mechanism.
- **Convergence**: This implies that if an equilibrium exists, it will eventually be reached by the mechanism.
- **Incentive Compatibility**: A mechanism is incentive compatible if it is the dominant strategy for each agent to reveal her true type. This is understood the easiest when considering an auction. Every agent has a valuation for a given good. In an incentive compatible mechanism, each agent has the incentive to report the true valuation to the auction operator. Every other strategy potentially leads to a worse payout.
- **Privacy preservation**: This simply means that the mechanism should not allow agents to learn relevant private information about other agents that could be used in future executions of the mechanism.

- **Computational Costs**: The necessary communication, the number of necessary messages and the computational complexity of associated algorithms of the mechanism should be kept to a necessary minimum.

There might be other desirable market properties that are not included here. For instance, in some markets, perceived fairness might be an important factor. However, not all of these properties do necessarily have to be addressed. However, if a mechanism has no equilibrium, for example, there needs to be some form of decision rule that determines market results. Ultimately, designing markets is an engineering task that should be pragmatically executed to achieve the desired outcome.

3 The Smart Grid and Energy Markets

The Smart Grid as such does not change the market. In essence, it is merely a layer of communication infrastructure that creates the opportunity to communicate signals in real-time or near real-time between market participants. Additionally, analyzing this data can help in making investment decisions in the system that increase its efficiency (see also chapter "Smart Grid Analytics"). Through these signals, the Smart Grid can indirectly influence demand and supply curves by allowing new actors to participate in the energy market and by allowing consumers to react to market signals. Figure 2 shows a reduced causal model for an efficient market outcome. The numbers 1 to 3 indicate the components that can be influenced through the installation of a Smart Grid. In essence, the market outcome is influenced by supply and demand curves which are efficiently integrated through a market design. Supply curves are influenced by the amount of competition in a market. More competition forces participants to bid their actual marginal costs of generation (Bompard et al. 2007). The demand curve is particularly influenced by the demand elasticity. One peculiarity of the electricity market is that demand is often very inelastic. This can lead to inefficiencies due to price caps, too few options of the demand side to participate in the market or regulation on market power abuse (Cramton and Ockenfels 2016). Therefore, increasing demand elasticity can increase the efficiency of electricity markets (Bompard et al. 2007). The Smart Grid can impact the supply side by allowing new actors to participate in the market. Small generators, storage units or electric vehicles, among others, can be aggregated and controlled through signals communicated through the Smart Grid. This increases competition, and therefore, leads to more competitive behaviour causing a more efficient market outcome. At the same time, the demand side is enabled to react to price signals through automated energy agents that operate storage capacity, heat pumps or electric vehicles. This increases price elasticity through changed time preferences in consumption. Furthermore, market information can lead to changes in the long run. Information on price development and individual consumption can cause consumers to switch their supplier contracts to time-variable tariffs and consumers might invest in storage or PV panels because they are able to estimate the effects of preferential self-consumption more easily.

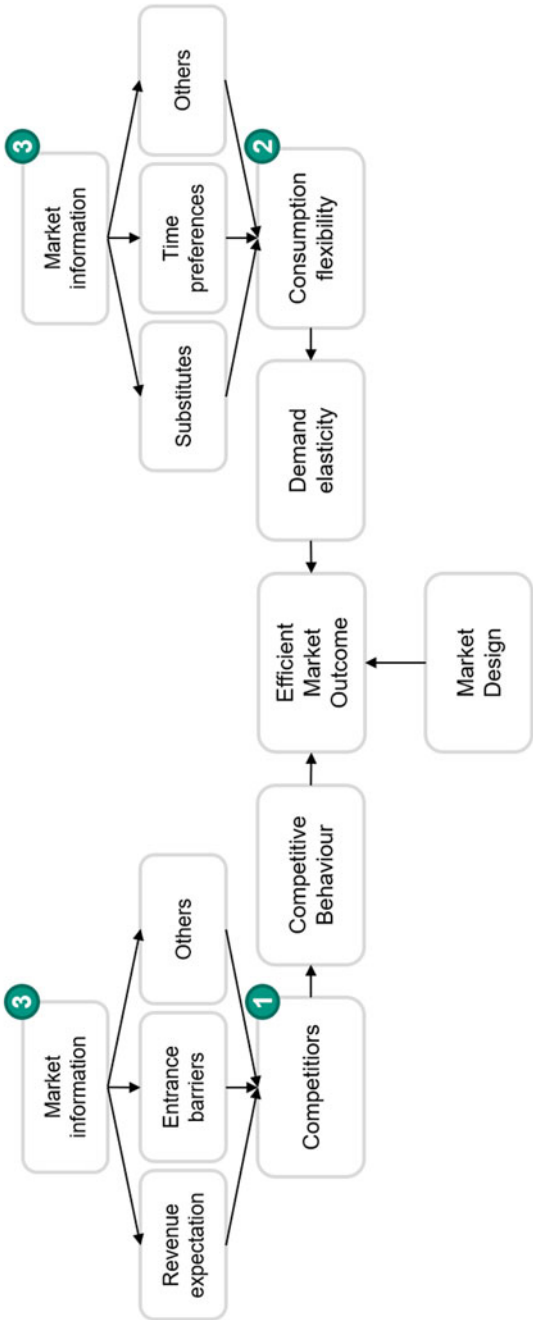

Fig. 2 Causal model of market outcome

The purpose of markets always is the coordination of supply and demand through signals. In the long run, these markets are intended to incentivize the investment in resources that can increase the efficiency of the market. For example, in the housing market, an increase in demand leads to increasing rents. This signals scarcity and might incentivize people to rent smaller apartments or to share apartments but might also cause people to sublet parts of their house as the high rents make this more attractive. This might lead to coordination mechanisms such as websites that connect people who are looking for shared apartments. The high rents make it more attractive to build and sublet apartments. This extends the offer and increases the amount of rented apartments. Information is an important factor in this process. If the level of apartment rents is not public knowledge, market participants might not be able to interpret them correctly. Similarly, in the electricity market, an increasing demand might cause increasing prices. This might lead to energy efficiency measures causing some people to be able to share their PV generation with their neighbours. Online platforms can help in finding tariffs that reward off-peak electricity use or such platform can connect neighbourhoods into microgrids that share their generation. In the medium term, this price signal would cause private households to install more PV capacity on residential roofs or to invest in storage capacity to maximize preferential self-consumption. Similarly, as for the housing market, the market signals and information need to be communicated to consumers. The Smart Grid is the infrastructure that allows all of these market signals to be efficiently communicated and similar solutions as on the housing market to be implemented for the electricity market in the distribution grid.

The intention of this chapter is to introduce changes to the market caused by the implementation of the Smart Grid. The areas that benefit from the Smart Grid can broadly be divided into the three areas highlighted in Fig. 2. These three areas can then be differentiated into market operation and market evolution where market operation describes the short-term opportunities created by the Smart Grid that affect supply and demand in operation, while market evolution encapsulates the mid- to long-term efficiency increases in the market. Therefore, in the following sections, we introduce examples of market improvements potentially caused by the Smart Grid along the value chain of generation, distribution and consumption. The examples are depicted in Table 1. We discuss the impact of the Smart Grid in particular examples and what part of the Market Engineering framework is impacted.

Table 1 Market developments triggered by smart grid developments

	Market operation		Market evolution
	Competitors	Consumption flexibility	Market information
Generation	Virtual power plants	Net metering	Hardware investment
Distribution	Congestion markets	Peak pricing	Community storage
Consumption	Smart energy communities	Real-time pricing	Tariff recommendation platforms

4 Market Operation

Market operation naturally refers to anything that can be adapted quickly and without long lead times. Such quick wins of the Smart Grid can be the activation of market participants through communication, control and the transmission of market signals. The Smart Grid is in essence the infrastructure to quickly transmit information and instructions regarding the electricity system. This information can be a price that is a signal to a generation or flexibility asset to be activated or it can simply be a price signal that causes a response of consumers. In the following sections, we first introduce examples of how the Smart Grid enables new resources to enter the market and how it enables new markets to form. This is followed by new forms of tariff designs that will increase the temporal flexibility of the demand side (see also chapter "Demand Side Management").

4.1 Competition

The increasing availability of real time data through the Smart Grid enables operators to coordinate a number of resources for different purposes. Such purposes might be frequency stability, congestion relief or the exploitation of temporal price differences. Coordinating these resources and allowing them to enter the market increases competition. While the market design might not change, the agent behaviour might change because of the increased competition. In the following, three new market developments are described which are enabled by the Smart Grid and relate to an increase in competition.

Virtual power plants. Virtual power plants are one of the major concepts enabled by the Smart Grid. The term describes a connection of different distributed energy resources (DER) that act together imitating a conventional power plant. The combination of these resources then jointly forms a virtual power plant. The resources can be anything from renewable capacity such as PV panels or wind turbines as well as active demand response, electrical storage or electric vehicles. A very good description of this concept and its characteristics is provided by Pudjianto et al. (2007). The authors distinguish between the capacity and the energy effects of DER. They argue that energy generation from DER can replace generation from conventional power plants. However, their capacity does not replace conventional capacity, thus leading to over-provision of capacity. Through combinations into virtual power plants, DER become visible from a capacity perspective and can be actively relied upon by system operators. If you think back to the introduced example of the secondary control reserve market: DER might participate at the energy market but they could never participate in the capacity market because their generation is uncertain. The authors already point out that this concept can only be implemented with improved information and communication technology. Virtual power plants are closely related to the concept of sector coupling. Sector coupling describes the integration of different forms of energy usage. This typically includes among others the power, heat and transportation sectors. A combination of DER and electric vehicles to create virtual power plants is described by Schuller et al. (2015). Technologies that enable sector coupling are power-to-gas electrolyzers, electric vehicles, vehicle-to-grid services or heat pumps, just to name a few. Sector coupling allows for electrification of energy usage that has traditionally relied on fossil energy sources such as space heating or transportation. This requires, however, a drastic increase in renewable generation capacity to ensure further decarbonization. On the other hand, it facilitates the integration of fluctuating renewable energy because the concept comes with more storage ability. It is easier to store heat energy than electric energy. Strong market penetration of electric vehicles will lead to large mobile battery storage capacities. Therefore, sector coupling will champion the concept of the virtual power plants because it finally creates flexibility in the electricity system that can then be combined with fluctuating renewable generation to make its capacity "visible." This will require much more coordination that can only be ensured through the Smart Grid. On the market side, this potential will be coordinated by aggregators who contract different resources in the market to combine them into a capacity product. These aggregators will have to combine the resources such that they can optimally position them in the different electricity markets. The optimal composition of these portfolios is described by Gärttner et al. (2018). These developments might not necessarily change the market. However, from a market perspective, it might be important to change the rules such that this flexibility can be integrated profitably. For instance, consumption of self-produced electricity might be exempt from certain fees to encourage the installation of decentralized resources and the electrification of the residential heat and transportation sector, which, in turn, increases the system's flexibility. This means that the Economic and Legal Environment needs to be adapted before such markets can become reality. This is out of the hands of the market engineer, but it sharpens our understanding of the situation. Ultimately, a shift in this foundation can create new market actors that increase the efficiency of the overall market through increased competition which leads to changing agent behaviour.

Congestion markets. Virtual power plants as described in the previous paragraph can be marketed on existing power markets such as the wholesale market or reserve power markets. Their flexibility is compensated either for consumption in cheaper time periods or for the balancing of short-term fluctuations. Another increasingly important aspect is grid congestion, both in the transmission, but more importantly, in the distribution grid. Transmission grid congestion is a growing concern in Europe (Lang et al. 2020). Another problem on the horizon that is still a rare event at the moment is distribution grid congestion. Such situations have been occurring infrequently when PV or wind energy is fed into the low voltage grid while consumption is low and the capacity is not sufficient to transmit the energy to the high voltage grid (Schermeyer et al. 2018). In the future, it is possible that similar situations might occur in the other directions when many electric vehicles try to charge at the low voltage level at the same time, or if the market penetration of heat pumps increases. This might be resolved through market-based solutions (Flath et al. 2014). Such markets might be implemented using the Smart Grid by providing short-term price signals that incentivize households to charge their electrical storage, electric vehicles or heat storage in times of local congestion. However, the design of such markets is very controversial. Proponents argue that market coordination might increase the investment in flexibility potential such as electrical storage (Huber et al. 2018). Opponents argue that such markets create gaming opportunities and will increase the costs for congestion management (Hirth et al. 2019). This discussion only shows that the solution to the problem of regional congestion is yet to be found. New markets and products are necessary which are enabled by the Smart Grid to reward regional flexibility when needed. Regional congestion or flexibility markets are ultimately another platform for virtual power plants to market their flexibility. For such markets, all components need to be defined. First, the Economic and Legal Environment needs to be adjusted to allow for such markets. However, the European Commission requires member states to implement market-based congestion management solutions (Hirth et al. 2019). Then, the transaction object needs to be defined. This could be energy in a consecutive market after the spot market clearing as discussed in (Hirth et al. 2019). However, it might also be capacity similar to the secondary reserve power market. Then, the market structure needs to be defined. We leave this as an exercise for the readers. Your objective is to achieve an efficient market outcome that mirrors a nodal pricing optimization with competitive bids by the participating agents.

Smart energy communities. An emerging concept that has attracted much attention from researchers and practitioners is that of citizen energy communities or local energy markets. In such markets, the participants trade their own generation peer-to-peer with their neighbours (Mengelkamp et al. 2017). Some countries encourage this through specific regulations. The rationale is that local balancing of supply and demand relieves the grids and that it increases the incentives for the residential population to participate in the transition to more renewable generation. The European Commission has issued a directive to support citizen energy communities which they define as "a legal entity which is based on voluntary and open participation, effectively controlled by shareholders or members who are natural persons, local authorities, inducing municipalities, or small enterprises and microenterprises. The primary purpose of a citizen's energy community is to provide environmental, economic or social community benefits for its members or the local area where it operates, rather than financial profits. A citizen's energy community can be engaged in electricity generation, distribution and supply, consumption, aggregation, storage or energy efficiency services, charging services for electric vehicles or provide other energy services to its shareholders or members." (European Union 2019). The rise of the concept of citizen energy communities is closely tied to the advent of blockchain technology as a means to allow for the creation of markets that operate without central intermediary. This concept was first introduced commercially through the Brooklyn Microgrid (Mengelkamp et al. 2018). This has sparked a variety of local energy market pilots (Weinhardt et al. 2019). Currently, the value of such designs is mostly symbolical: The trading of local energy might make the transition to renewable generation more tangible for the population and the associated regulated financial incentives lead to the consideration of decentral, green technology. In the long run, these markets might become important platforms for the coordination of demand and supply in a local area that respects constraints with the higher voltage grids. Citizen energy communities are of course highly dependent on Smart Grid technology. They can only be realized if participants can record their production and consumption in real time. From a market engineering perspective, this concept is highly interesting. As households are virtually unable to forecast their demand, it is impossible to trade ahead of time. Therefore, both control and market clearing need to happen in real time. This is a challenge for the microstructure of the market as well as for the IT infrastructure. Possible solutions are proposed in Wörner et al. (2019) or Richter et al. (2019).

4.2 Consumption Flexibility

The previous section outlines the active inclusion of new resources such as virtual power plants or markets for new resources that add flexibility to the system. This implies active bidding of participants on market places such as the wholesale markets or in peer-to-peer energy markets. Similar effects might be achieved through unilateral market signals to consumers in the form of specific tariffs. Such tariff options can have a temporal and a spatial component. Real-time tariffs signal the marginal cost of production for electricity at any given time. This might incentivize automated consumers such as heat pumps or electric vehicles to consume when cheap electricity is available. The famous case of a washing machine that starts when energy is cheaply available is, however, more unlikely to have a substantial impact: The very small cost-saving potential hardly justifies any active behavioural change. Besides real-time prices, there is a variety of pricing and regulation concepts that a regulator or utility can introduce to change residential behaviour. The most prominent ones are discussed in the following paragraphs.

Net metering. Net metering is a concept that is especially present in retail energy markets in the United States. However, a similar concept is commercially available in Germany in combination with electrical storage and labelled as the ”electricity cloud”. The German regulator has recently proposed a similar concept in relation to self-consumption. In essence, it means that self-generated energy can be fed into the grid at any time for the current retail price. In case of a flat tariff, this means that the grid essentially serves as a battery storage for prosumers. They can feed their excess generation into the grid at any time and their electricity meters run backwards. Then, they consume the same amount at any later time and their electricity meters run forward again. More detailed explanations are provided by Eid et al. (2014). This concept is often criticized because the cost for balancing the infeed is left for the system operators and occurring costs need to be distributed across all consumers even those without their own generation. So far, the concept has not been further developed. However, it might have the potential of serving as an incentive mechanism for the integration of fluctuating renewable generation. For instance, a household with a PV power plant could be given specific times when feed-in is calculated towards an account that can then be used at other specific times. Therefore, the load serving entity could incentivize a local feed-in management that is beneficial to the system through an efficient tariff. Such a tariff design could incentivize households to add technology that allows a shift of consumption to other times or small storage units that could shift generation at least by a little. In this case, the grid would be used as a battery but in a way that is beneficial for the overall system. From a market engineering perspective, it could be attractive to devise a platform that collects and matches supply offers and net metering tariffs between prosumers and electricity suppliers.

Peak pricing. Another tariff concept is peak pricing. Its underlying idea is to distribute system costs to those consumers who cause the need for system expansions, like grid reinforcements or generation capacity investments (in countries with capacity markets) (Burger et al. 2020). Therefore, consumer prices are much higher during system peak times. This is useful because existing electricity distribution and transmission has no marginal price. Only the need for expansions causes additional costs. Fixed charges and volumetric electricity rates, however, do not incorporate these costs. The Smart Grid could enable consumers to react to peaks quickly to avoid surcharges. This could be used in a variety of ways: Charges could be increased during peak times. On the other hand, feed-in tariffs could be lowered during times of excessive supply. Peak pricing on a local level could help to avoid local congestion and reduce the need for grid expansions. A corresponding example is provided by Flath et al. (2014) to residential EV charging. In some markets, critical peak pricing is already a common concept. Especially, if applied regionally in low voltage grids, it will support the integration of fluctuating renewables and new appliances with high energy consumption. This concept does not necessarily change the market, but it certainly increases demand flexibility. This increases the elasticity of the demand curve, and therefore, increases the efficiency of the electricity market leading to better protection against blackouts among other things (Cramton and Stoft 2005).

Time-variable tariffs. Net metering and peak pricing are special cases of time-variable tariffs that might include additional spatial components. That means that prices do not only vary with time but they might also vary depending on the location of the consumption. Time-variable tariffs include electricity prices that vary by time, signalling that electricity consumption causes different costs at different times. If expensive conventional power plants need to be ramped up to cover the last few kilowatt-hours of demand, then this is reflected in the price signal of time-variable tariffs (Burger et al. 2020). There are many forms of these tariffs. Probably the easiest form is that of a night and day tariff. Electricity is then usually cheaper at night because the overall consumption is lower and the generation occurs through less expensive power plants. These tariffs have a long history and can be realized through analogue technology using two different electricity meters that measure the consumption during the day and at night. Besides such simple time-of-use tariffs with two levels, time-variable tariffs can also include more granular price signals, e.g. with three price levels or even hourly levels. Furthermore, prices could vary across weekdays or seasons. Commonly, such tariffs are set in advance by the utility, communicated to the customer, and only updated on an annual basis. The most granular form of a time variant electricity tariff constitutes real time pricing, where price signals are calculated and communicated in real time. More elaborate time-variable tariffs become possible through Smart Grid technology as consumption is recorded in real time and because it allows the communication of signals from the grid to the consumer who can use automated appliances that react to the signals as described by Dauer et al. (2016). However, as electricity is a basic necessity for all households, it should be considered that such changes in tariff design can have adverse socio-economic consequences, for example, for low-income households. A very good discussion on different tariff designs and their socio-economic effects is given by Burger et al. (2020). The described forms of time-variable tariffs reward flexibility directly if it is executed. However, the communication of available flexibility might also be of value to system operators and utilities. Such flexibility can be actively used to balance suddenly increasing or decreasing generation as in case of a passing cloud. Tariffs can be used to incentivize the communication of such flexibility. One such tariff design is deadline differentiated pricing which is described by Salah and Flath (2016), among others. This design rewards consumers if they provide a later deadline for a stated consumption goal. It allows operators to react to the actual generation and schedule different demands more efficiently. One possible use case is a parking garage with solar panels. Electric vehicles can then provide their desired state of charge at any given time in the future. If the parking garage operator is given longer deadlines, it is easier for her to ensure full satisfaction of demand through self-consumption of the generated solar power. This again requires communication between the consumer and the generator and an exact record of consumption which can all be facilitated through the Smart Grid. A market engineer can design platforms that serve as intermediaries between suppliers and consumers. Consumers can enter their flexibility potential which is then offered to suppliers that can react with tailored offers of time-variable tariffs that range from real time pricing to simple flat-rate tariffs. Here, the IT infrastructure that translates flexibility into tariff offers, is the most complex market component (see vom Scheidt et al. (2019) for an initial approach).

5 Market Evolution

In the previous section, we introduce ways for the Smart Grid to be used to improve the operation of electricity markets. Real-time signals can be used to incentivize the activation of additional resources, thus increasing competition or they can cause appliances to react to price signals, thereby increasing the demand elasticity. Both measures increase the efficiency of the market and thus improve the market outcome. In this section, we discuss the process of adaption that occurs in the medium and long-term through market incentives. These adaptions then have an effect on the short-term operation of the electricity system and increase its efficiency through the described channels. Such adaptions in terms of investment are supported by the Smart Grid through the provision of time series data (compare chapter "Smart Grid Analytics") or through the possibility of coordination that makes the investment in shared resources possible. The increasing information availability can also allow retailers to develop new business models (compare chapter "Business Model Design") to increase customer satisfaction. Such models often include coordination mechanisms. Thus, the role of the market engineer is to develop market mechanisms that are provided as part of holistic solutions that increase the efficiency of the energy market. Three applications of market mechanisms are described in the following. This is by no means an exhaustive list and readers are encouraged to find more applications and share them with us (or get rich by themselves).

Hardware investment. Private households and industrial consumers can benefit from the investment in generation and storage hardware. While industrial consumers are aware of their consumption, private households usually undertake such investments either because feed-in tariffs allow for a broad estimation of amortization times or because of a combination of standard load profiles and a broad gut feeling that such investments will pay off. The fact that this is already possible is underlined by several startups in this field such as sonnen and their battery solutions in Germany. The Smart Grid and the resulting information availability allow private consumers to estimate the benefits of additional power hardware more precisely. This can lead to more accurate recommendations for private households which might include alternative tariffs or the marketing of such hardware that is described in the previous section. Such recommendations can be given on an individual level or platforms can enable the connection of several households in a neighbourhood. Local PV generation or storage solutions might be more attractive if the corresponding consumption profiles fit well together. Such a platform is described by Golla et al. (2020). The capacity of these investments might later be traded at other markets by the provider, the utility or the customers themselves. For instance, sonnen already markets a virtual connection of their residential battery storage systems at the primary control market (Angenendt et al. 2020). Various developments are possible in this field which is very attractive in terms of future business models. Providers could also offer the hardware for reduced rates in turn for the permission to use consumption data for other purposes such as advertising. This field will, therefore, become a very diverse market without products that can easily be defined as the transaction object in the market engineering framework. This is further discussed in chapter "Case Studies in the Smart Grid Sector".

Community storage. One specific use case of hardware investment is the shared use of resources by multiple households (Golla et al. 2020). This is especially attractive for storage as it can increase the used capacity if combined with residential PV capacity either in times of low PV generation or if residents are unable to perform one full cycle per day with their storage capacity due to their low consumption. Sharing storage capacity can incentivize the investment in more capacity, which in turn supports the energy transition through local balancing of supply and demand and thereby reduces the transmission and distribution requirements of the electricity grid. Some initial studies have been performed, for instance, by Barbour et al. (2018). The exact product and market definition of community storage capacity is still subject to further research. This is an interesting field for market engineers: The market has two perspectives, that of consuming from the storage as well as that of charging the storage. The transaction object could be storage capacity over time, but it could also be simply electricity that is consumed from the storage. The design needs to balance the interests of storage and PV owners, PV owners and simple consumers. Everyone, who benefits the system somehow needs to benefit from the participation in the market to ensure individual rationality. However, to which extent individuals benefit is subject to further analysis and even depends on the subjective understanding of fairness of the participants. The necessary market design includes all aspects of the market engineering framework and it is an interesting task to come up with different designs.

Tariff platforms. As in the previous section, we can differentiate the market evolution between adapting hardware and reacting to price signals. For market evolution, the latter means a change of the residential electricity tariff. While current electricity tariffs are usually rather simple and do not reflect spatial and temporal costs of electricity, this might change in the future. However, it is difficult to choose an elaborate electricity tariff without in-depth knowledge of the personal future consumption patterns, especially if no smart meter is installed. Smart Grid technology allows retailers to recommend tariffs more precisely. Knowledge about appliances in the household can be used to quantify demand response potential. The exact appliance endowment can be characterized using non-intrusive load monitoring, a data science technique that uses exact load profiles to identify individual appliances (Zoha et al. 2012). Furthermore, personal load curves can be used to assess the consumption profile with regards to system peaks and real-time prices. This way, platforms can recommend changing electricity tariffs for individual households. This can go hand-in-hand with recommendations for new appliances such as energy management systems. These can react flexibly to market signals and charge electric vehicles or a heat storage in times beneficial for the user. A market engineer can design complex markets, where the installation of appliances in combination with specific tariffs leads to benefits for the consumer. This might evolve into a Smart Grid market platform, another step further from mere tariff recommendation. Such recommendations have already been studied in vom Scheidt et al. (2019). The authors assess different electricity tariffs and the possibility to predict the optimal tariff based on consumption data of only one month. However, they do not use sophisticated tools, but simply assess what would happen if the best tariff for that month was to be adopted. In markets with a large variety of tariffs and tariff-hardware bundles, it will be important to provide a product that supports customers with their decision or even takes away their risk in return for some concessions like giving up the control over their heat pump. Therefore, the design of the transaction object will play an important role when it comes to tariff platforms.

6 Summary

In this chapter, we describe market engineering as an important task for the energy system. We introduce the market engineering framework as a tool that can be used to describe existing markets and to design and engineer new markets for innovative transaction objects. Furthermore, we describe a set of important market characteristics that need to be taken into consideration when markets are designed. These fundamentals are important to understand how the Smart Grid can support changes in market designs and how it can be leveraged to introduce new markets that increase the efficiency of the electricity system. We describe neuralgic points that influence the market result and are affected by the Smart Grid. Finally, we provide examples of how the Smart Grid changes the electricity market and describe the role of the market engineer within these changes. The provided examples can be classified along the electricity value chain and the market aspect influenced by the Smart Grid. The value chain is classified into generation, transmission and distribution and retail. The influence of the Smart Grid is divided into increasing competition, fostering consumption flexibility (which can be understood as effects on market operation) and providing market information which mainly impacts the market evolution. We provide examples in each category, which are in no way exhaustive. Readers are encouraged to add to these lists and to send us suggestions to enter an academic discussion. The Smart Grid adds functionality, especially in the areas of appliance control, communication of market signals and through increased data availability that can support new products. There is a variety of opportunities that can be leveraged and the coming years will show which areas evolve the quickest.

7 Exercises

Competitors. Imagine the following setup of two prosumers with PV panels and some additional non-flexible demand. There is also an electric vehicle with a capacity of 6 kWh that is fully charged at the beginning of this period and which can be charged and discharged fully within one timestep. It has a need for 6 kWh by the end of the period. There is a CHP plant that can generate electricity at 10 cents per kWh. Self-

Table 2 Local energy system

Timestep	1	2	3	4	5	6
PV1	0	0	1	4	1	0
Consumption1	1	2	3	1	1	2
PV2	0	0	1	8	2	0
Consumption2	0	1	2	2	1	1
Consumption rest	0	1	4	1	3	1

consumed PV electricity has marginal costs of zero and no charges. It is rewarded with 5 cents per kWh if fed into the grid through a feed-in tariff. This is also paid if the renewable generation needs to be curtailed. Detailed information on the generation and consumption in the electricity system is provided in Table 2.

1. PV prosumer 1 combines his PV panel with the electric vehicle through vehicle-to-grid technology to form a virtual power plant. What is her maximum revenue during the period given the consumption she can replace?
2. Assume that the transmission capacity of the community to the higher voltage level is 5. Assume that the electric vehicle acts at a congestion market. What is its maximal revenue of the electric vehicle without increasing the system costs?
3. Assume that an energy community can act as one entity and self-consume locally generated PV. What is the global cost benefit of the community compared to the case of individually acting agents? How would you distribute this gain?

Flexible Demand

1. Assume the same prosumer profiles as in Exercise 1. What is the system benefit in terms of reduced need for curtailment payments if net metering was performed such that 8 cents per kWh were paid as feed-in tariff in the first and last period and no feed-in tariff at all in period three and four?
2. Assume that during the daily peak each kWh costs an extra 5 cents. Assume further that consumer 1 and consumer 2 can shift one kWh freely during the period and that the remaining customers can shift 2 kWh freely. Ignore the electric vehicle. Construct the final load profile for the entire period.
3. Assuming that each consumer can shift two units of their load into the next timestep and that every consumer can shed one unit of load over the entire period. The real time prices per timestep are given as p_t. Formulate the optimization problem of shifting load optimally for each consumer given that the electric vehicle belongs to consumer 1.

Market Information

Pecan Street gibt es nicht mehr kostenlos

1. Download the SCiBER power consumption data set (https://im.iism.kit.edu/sciber.php) and choose one consumer at will. Then use the renewables.ninja tool to generate a PV generation curve (https://www.renewables.ninja/). Use one month of consumption and PV generation data to calculate the benefit of a PV panel and a 5 kWh storage unit that costs 8,000 $. Then evaluate the payback of the investment over the remaining period. How long is the amortization period? Assume grid electricity costs of 20 cents/kWh.
2. Use the introduced market engineering framework to design a market for a community storage unit. You can freely design the transaction object.
3. Using the SCiBER data, calculate the optimal tariff for each household assuming the tariff options from (vom Scheidt et al., 2019) with each month of the data. Then, compare the results with the global optimum over the entire data. Construct a confusion matrix that shows which tariff was and which should have been recommended.

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