Demand-Side Flexibility – Enabled and Enhanced by Information Technologies in Current and Future Electricity Systems

Dissertation

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Das Ziel muss man früher kennen als die Bahn.

Jean Paul (1763 – 1825)

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Copyright Statement

The following sections are partly comprised of content taken from the research papers included in this thesis. To improve the readability of the text, I omit the standard labeling of these citations.

Abstract

Renewable energy sources can contribute to the decarbonization of electricity systems around the world. Due to their weather dependency, however, renewables such as photovoltaic and wind power plants generate electricity intermittently. This makes it a challenge to ensure grid stability, i. e., the required balance between electricity generation and consumption. Flexibility options, such as grid flexibility, storage flexibility, supply-side flexibility, and demand-side flexibility, can all play a part in ensuring that this balance is always guaranteed. A particular potential for flexibility, and one that remains largely untapped, lies on the demand side. Therefore, this doctoral thesis examines demand-side flexibility and the ways in which information technologies could enable and indeed enhance the exploitation of demand-side flexibility in current and future electricity systems. First, this doctoral thesis focuses on how these four flexibility options contribute to grid stability. Subsequently, the focus will shift to the demand-side flexibility of companies in the industrial sector and corresponding prerequisites and opportunities to market demand-side flexibility in current electricity systems. In particular, digital flexibility trading platforms offer great potential to enhance the exchange of information between different stakeholders. However, the use of information technologies in the exploitation and automation of demand-side flexibility requires a standardized communication protocol about flexibility. The purpose of this doctoral thesis, then, is to analyze the possibilities to standardize communication of flexibility while taking into account the degrees of freedom as well as the restrictions on flexibility. Despite the great potential for demand-side flexibility, however, several obstacles currently get in the way of companies leveraging this potential. To reduce or indeed remove these obstacles, this doctoral thesis will consider these obstacles and the ways in which they get in the way of companies. Since renewables have also led to increasing decentralization and the corresponding divergence of markets and physics, there have been certain inefficiencies due to corrective measures. With a view to future electricity systems, this doctoral thesis will illustrate possible design options for future electricity markets that account for the rich potential of information technology to exploit demand-side flexibility. This doctoral thesis is a cumulative work that comprises seven research papers. To summarize, it contributes to a better understanding of (industrial) demand-side flexibility by highlighting the extent to which information technologies can enable and indeed enhance new opportunities to make the demand side more flexible and thus contribute to the decarbonization of current and future electricity systems.

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I Introduction

I.1 Motivation

The climate crisis poses a grave threat to global society, as it challenges the environment as well as humanity. Worldwide, the rise in temperature associated with climate change causes a host of negative consequences for the planet's ecosystems and thus also for human beings (World Meteorological Organization, 2021). In 2015, at the United Nations Climate Change Conference, 195 parties ratified the Paris Agreement to limit global warming by reducing greenhouse gas emissions as a way of mitigating the harmful effects of climate change (Rogelj et al., 2016). The target to turn around global emissions can only be reached if the international community levels off emissions and gets beyond the peak as soon as possible (Rogelj et al., 2016). Another part of the Paris Agreement is the objective to stop the increase in the planet's average temperature well before it reaches 2.0 °C above the pre-industrial level. Indeed, efforts are ongoing to limit this increase to a maximum of 1.5 °C (Rogelj et al., 2016). The Paris Agreement is the first global climate protection accord that is both comprehensive and legally binding. However, the nationally determined contributions that were targeted might not be sufficient to keep global warming well below 2.0 °C. This highlights the need for a much faster decline in global emissions (Raftery et al., 2017).

Worldwide, energy systems have to reduce their greenhouse gas emissions to contribute to the required decarbonization, i. e., the reduction of greenhouse gas emissions. Generally speaking, there are three options to decarbonize energy systems: to avoid the use of energy, to increase energy efficiency, and to use Renewable Energy Sources (RES) instead of fossil energy carriers (Pacala and Socolow, 2004). Since electricity as a form of energy has a wide range of applications, many countries have begun this decarbonization effort by focusing most of their attention on increasing the share of RES in their electricity systems. A further reason to do so is the fact that an increasingly decarbonized electricity sector may also contribute to the decarbonization of the heating and transportation sectors by means of sector coupling, i. e., using electricity stemming from RES in these sectors. In some countries, such as Norway, electricity already supplies most of the heat for warm water systems as well as for room heating (Seljom et al., 2011). Here, the increase in the RES share of electricity contributes directly to the decarbonization of the heating sector. Furthermore, hydrogen generated by electricity from RES, so-called "green" hydrogen, could become a potent means of decarbonizing this sector (Nastasi and Lo Basso, 2016), and the possibilities of a shift to green hydrogen go even further (Glenk and Reichelstein, 2019). For instance, emission-intensive industries, such as the steel industry, could use green hydrogen instead of hydrogen produced from natural gas or coal (Kazi et al., 2021). In the transportation sector, electricity can help reduce the use of fossil fuels in automobile, airplane, ship, and train transportation. Electricity from RES can either serve as a direct substitute, e. g., in battery electric vehicles, or it can be used to produce synthetic fuels (Vliet et al., 2011). Either way, the decarbonization of the electricity sector plays a leading role in the decarbonization of energy systems (Blazquez et al., 2018), which is why this doctoral thesis focuses on the electricity sector.

In 2020, the COVID-19 pandemic led to a decline in emissions in many countries, in effect short-term decarbonization (Le Quéré et al., 2020). Policymakers imposed various restrictions, such as contact restrictions and the partial shutdown of public life, to limit the spread of COVID-19 (Wilder-Smith and Freedman, 2020). The unintended consequences of these restrictions included a lower electricity demand, fewer transportation movements and, therefore, decreasing emissions in the energy sector (Research Paper 1; Le Quéré et al., 2020; Bompard et al., 2021). This emission reduction, however, is likely to be no more than a short-term effect (López Prol and O, 2020).

To achieve long-term decarbonization, a thorough transformation of the electricity sector would appear to be necessary. A point worth repeating in this context is that a key element of this transformation is the expansion of RES in electricity systems. This involves a transition from conventional power plants, such as nuclear and fossil fuel, to RES. As an industrial nation, Germany has decided to retire all of its nuclear power plants by the end of 2022 (Rogge and Johnstone, 2017). By 2038, Germany has further planned to shut down all of its lignite and hard coal power plants (Oei et al., 2020). Given the fact that, in 2019, nuclear, lignite, and hard coal power plants provided almost a third of the German net electricity supply (Fraunhofer ISE, 2020), there is an urgent need for compensation with new electricity generation capacities, namely RES.

A transition to RES also implies a shift from a small number of centralized conventional power plants to a large number of decentralized RES, i. e., from power plants located close to electricity consumers to new ones further afield (Alanne and Saari, 2006). This decentralization increases the need for a grid infrastructure adequate to the task of transporting electricity to consumers (Research Paper 7). Much like hydropower and biomass power plants, photovoltaic (PV) and wind power plants offer major potential for electricity generation with marginal electricity costs near zero (Blazquez et al., 2018). As for the controllability of various RES technologies, hydropower and biomass power plants can adjust their electricity generation to the demand within a broad range of technical capabilities. In contrast to such relatively controllable electricity production, that of PV and wind power plants depends on weather conditions and is thus intermittent. In other words, PV and wind power plants offer rather low possibilities to adjust their electricity feed-in according to demand. In the literature, this is known as "non-dispatchable renewable power generation" (Muratori et al., 2014).

This limited controllability of RES is also worth mentioning when discussing the challenge that electricity systems must generate electricity to meet demand at all times (Research Paper 6). More specifically, certain physical characteristics of electricity systems require that electricity generation and consumption are always in balance, at least within a given tolerance range. Electricity grids are fitted with several safety mechanisms that equalize imbalances to ensure grid stability, i. e., a reliable electricity supply. Yet as soon as an imbalance exceeds the given tolerance, (local) failures may occur. Within an interconnected electricity grid, for instance, that of the European Network of Transmission System Operators for Electricity (ENTSO-E), failures can affect the entire interconnected grid. As far as interconnected grids are concerned, then, the transition to more RES is not only a national but an international challenge. To summarize, the shift to decarbonized electricity systems multiplies the number of decentralized RES (Alanne and Saari, 2006). In turn, this causes intermittent electricity generation that poses various challenges to (interconnected) electricity systems (Brouwer et al., 2016).

To ensure the required balance of electricity generation and consumption, it is essential that electricity generation, transportation, and consumption become more flexible. To provide a unifying definition of flexibility in electricity systems, Degefa et al. (2021) drew on a range of previous attempts to define it as follows: "*The ability of power system operation, power system assets, loads, energy storage assets and generators, to change or modify their routine operation for a limited duration, and responding to external service request signals, without inducing unplanned disruptions*". Meanwhile, Lund et al. (2015), Müller and Möst (2018), and Papaefthymiou et al. (2018) classify the following flexibility options in slightly different terms: grid flexibility, storage flexibility, supply-side flexibility, demand-side flexibility. Furthermore, Papaefthymiou et al. (2018) emphasize the role that markets play in facilitating the exploitation of such flexibility. There is also some disagreement as to whether, for instance, sector coupling measures like power-to-gas constitute a separate flexibility option (Lund et al., 2015; Heffron et al., 2020). Power-to-gas, however, represents a form of storage and demand-side flexibility. With a view to classification, this doctoral thesis will thus focus on the four flexibility options outlined above, which is in accordance with Degefa et al.'s 2021 definition of flexibility.

Demand-side flexibility has particular and yet untapped potential (Sauer et al., 2019; Heffron et al., 2020), which is why it forms the focus of this doctoral thesis. In the past, flexibility on the supply side was the most important of the four flexibility options (Papaefthymiou et al., 2018). Meanwhile, RES have changed this by virtue of their minimal costs. In some countries, this change is expedited by their prioritized feed-in. RES are thus replacing conventional power plants in the merit order – the order in which the different generation capacities satisfy the electricity demand (Sensfuß et al., 2008; Heydarian-Forushani et al., 2017). Moreover, the regionally planned shutdown of conventional power plants makes the need for new flexibility measures even more urgent (Papaefthymiou et al., 2018). After all, the intermittent electricity generation of RES requires a great deal of flexibility (Kondziella and Bruckner, 2016). Heydarian-Forushani et al. (2017) and Papaefthymiou et al. (2018) describe this development as the "flexibility gap". A combination of various flexibility options would, therefore, appear to be the best strategy for the ongoing integration of intermittent RES.

What is called for, then, is not a choice between the four flexibility options. Instead, it is necessary to combine all of them. It is also necessary, however, to bear their respective advantages and disadvantages in mind (Research Paper 1), since it is a challenge to efficiently integrate multiple flexibility options within an electricity system (Zöphel et al., 2018). In the following pages, the focus will be on efficient integration of demand-side flexibility, and here Information Technology (IT) plays a major role in enabling and enhancing this integration for a decentralized demographic of flexible consumer – in the short as well as in the long term (Research Paper 3; Research Paper 4; Goebel et al., 2014).

I.2 Research Aim

In recent years, electricity systems have been afflicted by a rise in the number of actual and potential power failures. This reinforces the need to safeguard the necessary flexibility in electricity systems, which is why the first research aim of this doctoral thesis is to analyze how flexibility options contribute to grid stability, i. e., the balance of electricity generation and consumption. The COVID-19 pandemic created unique circumstances that led to an increased share of RES in pan-European electricity systems (Research Paper 1). These unprecedented circumstances reveal multiple insights into the behavior of the German and European electricity systems with special regard to the four flexibility options, namely grid flexibility, storage flexibility, supply-side flexibility, and demand-side flexibility. In the context of this pandemic, it is possible to examine the individual contribution of each flexibility option to grid stability and improve our understanding of their interrelations.

The demand side, in particular, has a significant flexibility potential in the industrial sector (Sauer et al., 2019), which makes it the focus of this doctoral thesis. For many companies in the industrial sector, the flexibilization of their electricity consumption has become a new objective alongside others, such as energy efficiency (Wohlfarth et al., 2020). In current electricity systems, however, companies are only partially exploiting the potential for demand-side flexibility. It is, therefore, the aim of this doctoral thesis to analyze the prerequisites as well as the opportunities for companies to exploit this potential in full. Here, IT might play an important supporting role. As suggested by Ashour Novirdoust et al. (2021), IT can increase the transparency of electricity systems for network operators as well as for those generating and gathering information. One way in which this can be facilitated is the use of smart meters – meters that digitally capture electricity consumption. Moreover, IT supports multiple applications that facilitate the fast exchange of information, respectively the acquisition and sharing of knowledge among various actors in the electricity system (Sučić and Capuder, 2016; Hirth et al., 2018; Ketter et al., 2018). What is more, IT provides the foundation for automated systems and agents that, for instance, control electricity generation/consumption or trade electricity automatically (Ibrahim et al., 2020). Hence, this doctoral thesis investigates not only the potential to run digital flexibility trading platforms as an IT application but also the potential for a standardized communication protocol about flexibility, both of which are intended to make the demand side more flexible.

While demand-side flexibility is a comparatively new objective for some companies, there are further obstacles that get in the way of companies using their full potential for demand-side flexibility potential. Olsthoorn et al. (2015) investigate German companies of the industrial sector and analyze what obstacles hinder companies from exploiting their flexibility potential. Olsthoorn et al. (2015) present their study with regard to the categories of Cagno et al. (2013), according to which the relevant obstacles are technological, information, regulatory, economic, behavioral, organizational, and competency issues. Their results reveal that disruption of operations has a particular impact on product quality, and uncertainty about cost savings throws up major barriers for companies that might otherwise explore or invest in demand-side flexibility. Another aim of this doctoral thesis is, therefore, to deepen the insights of Olsthoorn et al. (2015) by investigating precisely how these obstacles get in the way of companies using or investing in demand-side flexibility. A detailed understanding of current obstacles will facilitate potential mitigation and more effective countermeasures.

The current development of various corrective measures to ensure grid stability within a more decentralized electricity generation structure reveals the need to adjust electricity market designs. To address this need, the following pages provide an analysis of possible design options for the design of a future electricity market. Such a design ought to account for technological developments not only in IT but also in flexibility options (Ashour Novirdoust et al., 2021). Particular attention must, therefore, be dedicated to the potential of IT to enable and indeed enhance the exploitation of demand-side flexibility in future electricity systems.

The overall purpose of this thesis, then, is to provide insights for researchers and practitioners alike, especially those at work in the industrial sector and those who wish to invest in demand-side flexibility or exploit its full potential. Further parties this doctoral thesis wishes to benefit are policymakers who might jointly manage a successful energy transition in electricity systems with an increasing share of RES.

I.3 Structure of this Thesis and Embedding of the Research Papers

This doctoral thesis has a composite structure in which seven papers contribute to the stated research aim. Figure 1 illustrates the embedding of the seven research papers in this doctoral thesis.

After this introduction (Section I), Section II deals with the role of flexibility in current electricity systems. In general, it is necessary to consider flexibility with regard to not only national but international, i. e., interconnected, electricity systems. Therefore, Subsection II.1 investigates how flexibility contributes to a stable grid in interconnected electricity systems. Doing so with a view to how the COVID-19 pandemic has created a unique situation for electricity systems means that this thesis takes advantage of an unprecedented opportunity to reveal new insights into how each of the four flexibility options, and particularly demand-side flexibility, contributes to a secure electricity system.

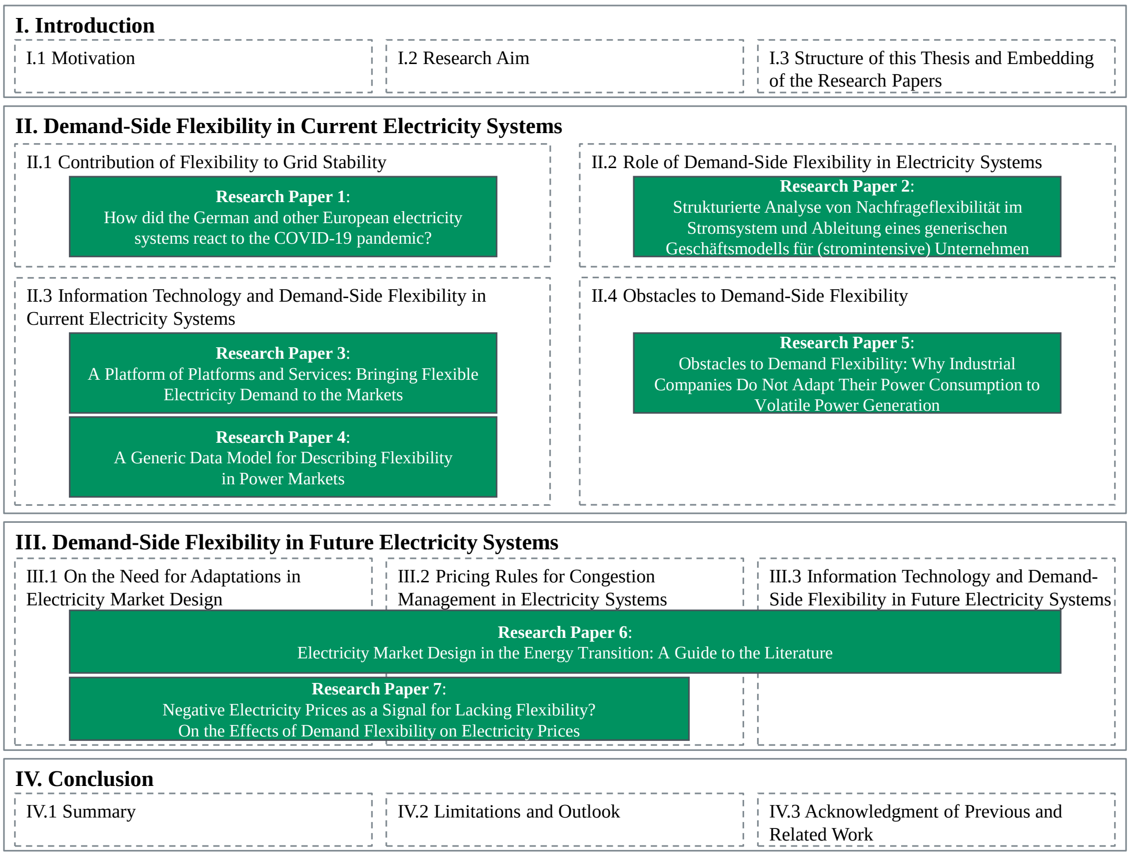

Figure 1: Structure of this doctoral thesis. Own illustration.

Due to its high electricity consumption, the industrial sector has considerable potential for flexibility. Hence, Subsection II.2 focuses on the demand side as the central application of the four flexibility options and analyzes the prerequisites as well as the possibilities for companies in the industrial sector to monetize demand-side flexibility.

Subsection II.3 deals with the short-term possibilities of IT to enable and expedite the exploitation of flexibility on the demand side. The particular focus of this subsection is the potential for this to be achieved on digital flexibility trading platforms. In view of the increasing use of IT in electricity systems, their success is largely predicated on the standardization of communication. Therefore, this subsection also presents possible modeling approaches for demand-side flexibility that provide the foundation for a standardized communication protocol.

On some electricity exchanges, however, the number of hours with negative electricity prices has increased over the past years (i. e., electricity consumers receive money for using electricity). Since many industrial companies struggle to exploit or invest in demand-side flexibility, Subsection II.4 analyzes the obstacles that are getting in the way of such exploitation and investment. On this basis, this subsection also suggests possible measures by means of which policymakers can reduce these obstacles or help companies navigate around them.

Section III deals with flexibility in future electricity systems. In the recent past, expenses for short-term corrective measures (e. g., in Germany for redispatch and feed-in management of RES) have increased. Hence, Subsection III.1 analyzes indicators that reveal not only the demand for adaptations of current electricity market designs but also the direction that these adaptations ought to take. Ultimately, any future market design must ensure further integration of RES. A future market design as described in Subsection III.1 must, therefore, set appropriate incentives for all flexibility options.

Subsection III.2 illustrates the possibilities to make congestion management a part of the market design. An electricity market design comprises various components, such as pricing rules, bidding languages, product design on spot markets, gate closure times for electricity trading, and the allowance for negative prices. Being perhaps the most important, pricing rules are the focus of this subsection. Essentially, there are three options for pricing rules, predicated on the geographical resolution of electricity prices. These constitute uniform, zonal, and nodal pricing, the latter also being synonymous with Locational Marginal Pricing (LMP). To provide a brief distinction of the three, it is worth noting that zonal pricing is done in such a way that each zone has a specific electricity price on electricity exchanges for each corresponding time step. Some countries have only one zone, in which case uniform pricing is used, whereas when LMP is used, each node of an electricity system has an individual electricity price. Besides the geographic granularity, the main difference between uniform/zonal pricing and LMP is that the latter takes the grid's physical constraints into account.

When shaping a future market design, scientists and policymakers must take developments in generation, transmission, storage, and consumption technologies into account. Meanwhile, IT also facilitates new and improved ways of organizing not only individual markets but the electricity system at large. Subsection III.3, therefore, examines the possibilities of IT becoming a substantial part of a future electricity system, as its notable advancements are continuing apace in both hardware and software. Smart meters, digital platforms, Distributed Ledger Technology (DLT), data analytics, and Artificial Intelligence (AI) improve the generation, storage, exchange, and processing of data. This, in turn, supports the creation of knowledge, including the knowledge to take full and efficient advantage of new flexibility potential while making the already existing options more applicable to our markets, particularly on the demand side.

Finally, Section IV concludes this thesis with a summary of all key insights (cf. Subsection IV.1) while also disclosing the corresponding limitations, outlining possible directions for further research (cf. Subsection IV.2), and acknowledging previous and related work (cf. Subsection IV.3).

Section V contains the publication bibliography. In the Appendix, Section VI provides additional information on the seven research papers included in this doctoral thesis (cf. Section VI.1). It further specifies the contributions that the author of this thesis made to each of these papers (cf. Section VI.2), and it also reproduces the (extended) abstracts of those research papers (cf. Sections VI.3 – VI.9). The supplementary material includes the full texts of all research papers (not for publication).

II Demand-Side Flexibility in Current Electricity Systems

In today's world, electricity is essential to many areas of life. What is also essential, therefore, is to guarantee a reliable and robust electricity supply. The electricity grid has various physical characteristics and is thus subject to Kirchhoff's Laws. A particular necessity, for instance, is the permanent maintenance of balance between electricity generation and supply (Short et al., 2007). This requires various flexibility options, especially in electricity systems with an increasing share of intermittent RES.

II.1 Contribution of Flexibility to Grid Stability

A stable electricity supply is an international matter, as we saw with the incident on the 8^{th} of January 2021 in the European interconnected grid of the ENTSO-E. This incident did not relate to an increasing share of RES, but it proves the vulnerability of electricity systems in general. Due to a failure triggered by an overcurrent protection in a substation in the north of Croatia, further errors cascaded through the electricity grid's infrastructure (ENTSO-E, 2021a). As a result, the Transmission System Operators (TSOs) in Europe split the European interconnected grid into two areas to prevent a further cascade reaction. The grid frequency (f) indicates the balance between electricity generation and supply. On the 8^{th} of January 2021, the grid frequency in the northwest section of the separated grid dropped to $f = 49.74\,\text{Hz}$. In the interconnected grid of the ENTSO-E, its nominal value sits at $f = 50.00\,\text{Hz}$, with downward deviations ($f < 50.00\,\text{Hz}$) reflecting an electricity supply deficit and upward deviations ($f > 50.00\,\text{Hz}$) a supply surplus (Short et al., 2007). Figure 2 illustrates the minimum and maximum grid frequency for the period from 2015 until mid-2020. The drop of the grid frequency on the 8^{th} of January 2021 would be off the scale in Figure 2, which gives some idea of the enormous extent of this incident (ENTSO-E, 2021a). In January 2021, the use of multiple flexibility options, such as conventional power plants on the supply side or interruptible loads on the demand side, helped to restore the required balance after about one hour (ENTSO-E, 2021a).

The incident on the 8^{th} of January 2021 was an exceptional situation that highlights the interdependencies in interconnected grids. Not only did we see that the system separation prevented further cascading errors, but linking several electricity systems also offers various advantages. For instance, such interconnected grids allow for international electricity trading and exchange, which increases competition and the diversification of generation and consumption patterns (Böckers et al., 2013). Furthermore, the construction of new high voltage direct current power lines, such as NordLink between Norway and Germany, demonstrates that interconnection strengthens electricity systems (Gómez et al., 2019). With regard to flexibility options, it is, therefore, crucial to take a comprehensive view of interconnected electricity systems.

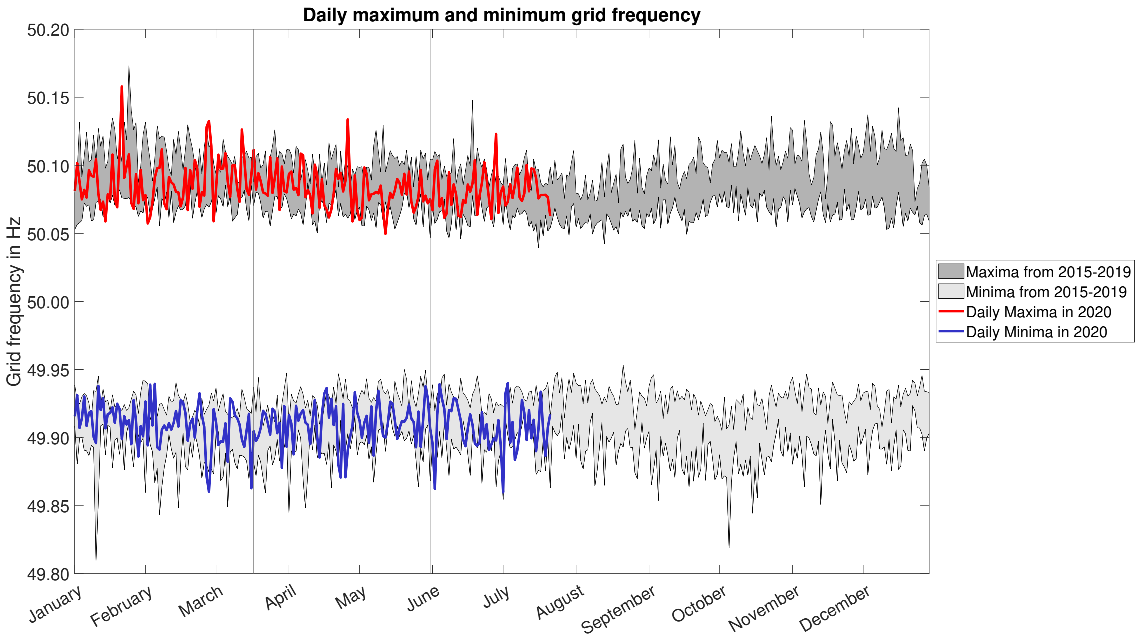

Figure 2: Daily minimum and maximum grid frequency (Research Paper 1; Réseau de Transport d'Electricité, 2020).

On the need for international collaboration, the COVID-19 pandemic represents a major challenge to countries around the world. Beginning in the spring of 2020, the COVID-19 pandemic has had an enormous impact not only on the medical sector but on our societies and economies at large. Governments imposed measures such as shielding, quarantine, social distancing, and community containment to limit the spread of COVID-19 (Wilder-Smith and Freedman, 2020). Soon, these restrictions also had a multi-faced impact on the electricity systems of many European countries (Research Paper 1). In the following, the focus will be on the first wave of this pandemic, i. e., the period from the middle of March 2020 until the end of May 2020, since its impact on the electricity systems of many countries had already dissipated by the end of July 2020 (López Prol and O, 2020). Nevertheless, more than a year after its outbreak, the struggle to contain it is not over yet.

The COVID-19 pandemic has created unprecedented and somewhat still unknown consequences for electricity systems, which makes it an interesting test case to examine how electricity systems are made more secure by four flexibility options: grid flexibility, storage flexibility, supply-side flexibility, and demand-side flexibility (Research Paper 1; Graf et al., 2021). Depending on the extent of the imposed countermeasures, the electricity consumption of some countries decreased by 15 % compared to previous years (Bompard et al., 2021). Worldwide, the COVID-19 pandemic resulted in 17 % lower daily CO_2 emissions by early April 2020, compared to 2019 (Le Quéré et al., 2020; López Prol and O, 2020). This lower electricity consumption then affected the mix of electricity generation (Research Paper 1; Werth et al., 2021). For instance, in Germany, the share of lignite and hard coal power plants dropped considerably, compared to previous years, while good weather conditions further contributed to an increasing share of RES (Research Paper 1). The result was a drop in electricity prices on electricity exchanges (Research Paper 1; Graf et al., 2021; Hauser et al., 2021). Meanwhile, in Germany, the RES share increased, yet the electricity grid remained stable (Research Paper 1; Hauser et al., 2021). The grid frequency as one indicator for grid stability is an identical quantity for an entire interconnected grid. Figure 3 illustrates the grid frequency as a heat map and allows for a comparison to previous years.

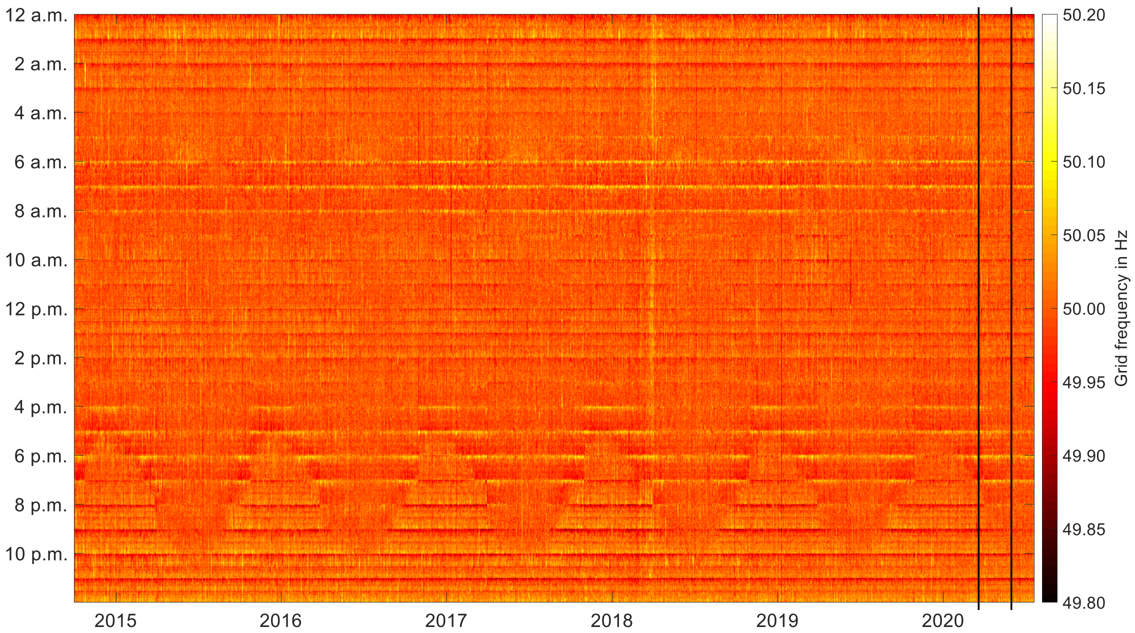

Figure 3: Grid frequency (resolution 10 s) illustrated as a heat map (Research Paper 1; Réseau de Transport d'Electricité, 2020).

The period of the COVID-19 pandemic (the area between the two vertical black lines) does not exhibit any apparent deviating patterns. Therefore, the entire grid of the ENTSO-E remained stable during the first wave of the pandemic. Focusing on the German electricity system and considering how the four flexibility options contributed to a stable electricity supply during the first wave of the pandemic, it becomes evident that the grid's transmission capacities increased in relation to the decreased electricity demand (Research Paper 1). A further observation to be made with regard to grid flexibility is that Germany relied more on imported electricity from its neighboring countries during the COVID-19 pandemic, which may have also contributed to the maintenance of grid stability (Werth et al., 2021). As for the other three flexibility options, i. e., storage flexibility, supply-side flexibility, and demand-side flexibility, none of those made notably different contributions to a safe electricity supply. Therefore, the increased potential of grid flexibility, in particular, helped to prevent a power failure during the COVID-19 pandemic.

What these findings underline, then, is the importance of efforts to transform the electricity system. As soon as electricity demand returns to pre-pandemic levels – some countries reached their baseline electricity consumption back in July 2020 (López Prol and O, 2020) –, grid flexibility will once again be reduced. At that point, the other flexibility options will have to play a bigger role in maintaining a stable electricity grid. As Heffron et al. (2021) point out, there is no time to lose for policymakers to establish appropriate investment incentives and provide certainty with regard to all flexibility options.

II.2 Role of Demand-Side Flexibility in Electricity Systems

Flexibility on the demand side is a promising option to solve multiple (arising) challenges in electricity systems and can, thus play a part in closing the "flexibility gap" (Rezaee Jordehi, 2019). From a system perspective, flexible actors on the demand side can improve the balance between electricity generation and consumption, which in turn improves grid stability (Palensky and Dietrich, 2011; O'Connell et al., 2014). Furthermore, with a flexible demand side, peak loads can be reduced, which prevents the extension of the grid infrastructure and the use of peak power plants that are by and large emission-intensive, such as oil power plants (Strbac, 2008; Rezaee Jordehi, 2019). From an individual perspective, flexible actors can reduce their electricity costs or even generate revenue by becoming more flexible (Research Paper 2; Rezaee Jordehi, 2019). Compared to the other flexibility options, the demand side can provide flexibility at comparatively low marginal costs (O'Connell et al., 2014; Cardoso et al., 2020). Demand-side flexibility also faces fewer acceptance problems among consumers (Heffron et al., 2020). In the past, however, electricity demand was assumed to be inelastic, i. e., consumers were thought to purchase electricity regardless of the respective electricity price (Cargill and Meyer, 1971; Lee and Chiu, 2011). It is important, therefore, that actors on the demand side are empowered with the ability to adjust their electricity consumption according to the current share of RES or the corresponding price.

Researchers studied demand-side flexibility back in the 1970s and 1980s with the aim to increase the use of facilities and prevent peak loads (Freeman, 1974; Gellings, 1985). Gellings (1985), for example, examine the topic how to control the time and level of electricity consumption from the point of view of an energy supplier. Over time, multiple terminologies such as Demand Side Management (DSM) and Demand Response (DR) have emerged to describe adjustments on the demand side of electricity consumption (Degefa et al., 2021). Palensky and Dietrich (2011) compile a taxonomy to differentiate between these terminologies. Accordingly, all activities that have an impact on electricity consumption are known as DSM. This also includes energy efficiency measures (Palensky and Dietrich, 2011). No doubt, such measures are an important component of the energy transition. This doctoral thesis, however, focuses on short-term adjustments made on the demand side of electricity consumption. Among these short-term adjustments, DR as a subset of DSM is gaining in importance (Siano, 2014; Paterakis et al., 2017). The U.S. Department of Energy defines DR as "*changes in electric usage by end-use customers from their normal consumption patterns in response to changes in the price of electricity over time, or to incentive payments designed to induce lower electricity use at times of high wholesale market prices or when system reliability is jeopardized*" (U.S. Department of Energy, 2006). More specifically, Albadi and El-Saadany (2008) and Rezaee Jordehi (2019) divide DR into price-based and intensive-based programs. Time of Use (TOU), for instance, a price-based program in which electricity prices vary depending on the time (Albadi and El-Saadany, 2008). Load curtailment or ancillary services, on the other hand, are examples of intensive-based programs (Albadi and El-Saadany, 2008; Rezaee Jordehi, 2019). For the remainder of this doctoral thesis, the term demand-side flexibility will, therefore, denote measures of the category "DR".

Generally speaking, electricity consumption can be made more flexible if things change on the demand side of all sectors – the transportation, industrial, residential, commercial and service sectors (Umweltbundesamt, 2021). As far as transportation is concerned, the time-controlled charging of electric cars holds the potential to adjust electricity demand (Tan et al., 2016; Baumgarte et al., 2021). In the commercial and service sector, the contribution to flexibility is rather small (Cardoso et al., 2020). One reason is that the knowledge on this issue lags behind that available in other sectors (Wohlfarth et al., 2019). Another reason is that there is simply less potential for temporal flexibility here, as evidenced by the example of retail shops, which operate at fixed times (Rezaee Jordehi, 2019). However, information services such as energy-intensive data centers are requiring ever more electricity and, thus offer opportunities to make electricity consumption more flexible (Fridgen et al., 2021). For instance, data centers might shift their computing loads geographically in response to local electricity prices (Fridgen et al., 2017). In the residential sector, meanwhile, it is theoretically feasible to interrupt or reschedule the use of household appliances like dishwashers, washing machines, and dryers (Hinterstocker et al., 2017a; Rezaee Jordehi, 2019). At present, however, the potential for reductions in emissions and consumer costs is relatively low, as neither, the increase of PV-self consumption (Hinterstocker et al., 2017c) nor the proliferation of time-of-use tariffs holds a significant potential (Hinterstocker et al., 2017b). In the industrial sector, however, companies have a relatively high potential for flexibility (Rezaee Jordehi, 2019; Sauer et al., 2019; Heffron et al., 2020). For some of them, electricity costs represent a major share of their expenses (Research Paper 2), so were they to become more flexible with their energy consumption they would stand to gain by minimizing said expenses. In view of this enormous potential, the focus of the following pages lies on the demand side of the industrial sector.

Companies can monetize their flexibility as DR in a variety of ways. They can take advantage of price options for the use of DR, such as time variable electricity prices or electricity exchanges like the EEX. They can explore incentive-based options, such as ancillary services. Or they can use their flexibility to achieve the following two objectives (Research Paper 2). Objective number one: for many companies – depending on the country – a large share of their electricity expenses consists of charges, taxes, and particularly grid fees (Buhl et al., 2019). The latter might depend on the company's peak load, and greater flexibility would make it possible to reduce electricity costs by avoiding peak loads. Objective number two: companies often have their own electricity generation capacities, such as gas and steam power plants, and increased demand-side flexibility can optimize the use of their own generation capacities in order to minimize electricity purchases from the grid during periods of high electricity prices (Research Paper 2).

However, certain companies might find that increasing flexibility on the demand side is both a new and complex challenge associated with up-front capital investment and operating costs (Rezaee Jordehi, 2019; Wohlfarth et al., 2020). For companies to market such flexibility, they must have a clear structure in dealing with the prerequisites as well as with the involved stakeholders. To this end, Research Paper 2, develops a generic business model for energy-intensive companies. It draws on the framework “Business Model Canvas” by Osterwalder and Pigneur (2010) and thus uses the following nine categories: Key Partners, Key Activities, Key Resources, Value Proposition, Customer Relationships, Channels, Customer Segments, Cost Structure, and Revenue Streams. With this detailed structure, the generic business model developed in Research Paper 2 provides guidance for companies willing to explore demand-side flexibility. Since IT plays a central role in optimizing those nine categories, the following subsection focuses on IT as a facilitator of flexibility on the demand side.

II.3 Information Technology and Demand-Side Flexibility in Current Electricity Systems

As mentioned in Subsection II.2, it is necessary for actors on the demand side to gain greater power to adjust their electricity consumption. Here, IT has the potential, especially by way of Information Systems (IS), to contribute to sustainable energy systems and even shape them as various research projects in the field of “Energy Informatics” have demonstrated (Watson et al., 2010; Goebel et al., 2014; Fridgen et al., 2016b). The central purpose of Energy Informatics is to increase the efficiency of energy supply and demand systems by using IS (Watson et al., 2010). An increase in flexibility does not necessarily lead to greater individual efficiency, since a deviation from the planned load profile can result in efficiency losses, in which case a process needs more electricity for the same output because the flexible unit might leave its optimal operating point (Research Paper 4). However, since IS can make electricity systems smarter, IS-supported demand-side flexibility can contribute to the integration of RES (Goebel et al., 2014). Meanwhile, modern IS can establish automated ways to faster exchange information between different stakeholders (Watson et al., 2010). The potential for such improvements is also evident in the fact that, to this day, some companies use the telephone to communicate with customers in hopes of dispatching flexibility (Research Paper 2).

As illustrated in Subsection II.2, companies on the demand side can monetize their flexibility in various ways. Indeed, there is a whole range of markets on which companies can do so with price-based programs, i. e., by varying electricity prices according to the time of day or night (Märkle-Huß et al., 2018; Shah and Chatterjee, 2020). Likewise, there are different markets and products for incentive-based programs, i. e., ancillary services (Aryandoust and Lilliestam, 2017). Due to a certain lack of transparency, companies are still faced with some degree of complexity (Research Paper 2; Research Paper 5; Alcázar-Ortega et al., 2015), but digital platforms with IS application offer a considerable potential to create greater transparency by improving the exchange of information between various stakeholders (Hagiu and Wright, 2015; Parker et al., 2016). Furthermore, digital platforms can increase transparency by providing a common point of access for innovative services (Eisenmann et al., 2006). In other domains, there is an ever-growing impact of Multi-sided Platforms (MSPs), such as Airbnb or Uber which provide means of exchanging holiday accommodation or transportation services (Armstrong, 2006; Rochet and Tirole, 2006; Hagiu and Wright, 2015).

Meanwhile, a variety of such digital trading platforms with a high degree of flexibility have also emerged in the electricity sector. The particular focus of these digital platforms is to foster the exploitation of local flexibility, as Zhang et al. (2013) and Estermann et al. (2018) point out. Yet while these represent new opportunities for companies to exploit demand-side flexibility, a rising number of digital platforms for local flexibility can have an unintended consequence – the afore-mentioned lack of transparency. In addition, there is also a variety of service providers that can support companies in commercializing demand-side flexibility. For instance, when aggregators function as intermediaries, they can bundle the flexibility potentials of several flexible consumers and thus facilitate greater flexibility (Stede et al., 2020). However, the variety of such service providers yet again results in a lack of transparency for companies that want to market flexibility.

It is with a view to this transparency issue, that Research Paper 3 develops a digital meta-platform to support the exploitation of demand-side flexibility. It does so by linking the following three distinct sides: flexibility markets, companies as flexibility providers, and supporting services (Research Paper 3). Here, flexibility markets comprise electricity exchanges, markets for ancillary services, and also emerging digital platforms for local flexibility. The digital meta-platform functions as a broker. It mediates between these different sides and thus fits into the highly regulated electricity system, where it contributes not only to increased transparency but also to improved comparability of the opportunities available to those who wish to market flexibility or service offerings. Furthermore, this digital meta-platform also fosters so-called value co-creation, since it enables several service providers to interact with one another and thus accomplish a new or better product. For instance, a decision support system for the optimal commitment of flexibility could purchase specific price forecast data from another connected supporting service to improve its product quality. In short, this digital meta-platform can support companies in efforts to better leverage their flexibility (Research Paper 3).

However, the lack of standardized communication – which also afflicts digital flexibility trading platforms – poses a major challenge for the exploitation of demand-side flexibility (Good et al., 2017; Gottschalk et al., 2018). This is particularly problematic when trying to communicate about "product" flexibility on digital platforms (Research Paper 3) or hardware, such as smart meters (ENTSO-E, 2021b). In the worst case, it can prevent companies from exploiting demand-side flexibility altogether, and when this lack of standardized communication causes a failure of interoperability it can even lead to lock-in effects. It is, then of key significance to develop and establish a data model that provides a consistent description not only of the degrees of freedom but also of the restrictions of demand-side flexibility. The "Smart Grid Mandate" reiterates this need for a consistent data modeling and description language (Mandate, 2011). Such a standardized data model for demand-side flexibility may also serve as a communication protocol in IS. It can thus contribute to increased automation when exploiting flexibility.

To date, several research projects have been dedicated to the modeling of flexibility. For instance, Degefa et al. (2021) compile a taxonomy by reviewing several publications that deal with the classification of flexibility. Another taxonomy for the description of demand-side flexibility is presented by Petersen et al. (2013). These authors cluster flexibility on the demand side in "buckets", "battery", and "bakery". However, automatic exploitation of demand-side flexibility via IS requires a comprehensive protocol that allows that captures all the characteristics of demand-side flexibility. Of particular importance is the ability to model the degrees of freedom as well as the restrictions of flexibility on the demand side. The latter represents a challenge since flexibility on the demand side might require unrestricted management of interdependencies due to such multi-faced aspects as production planning, dependencies on other production processes, and the objective to mitigate peak power load. What all of this leads to is a high level of complexity.

To mitigate this complexity, Research Paper 4 presents a generic data model that makes it possible and indeed manageable to model flexibility on the demand side. It comprises three classes that serve for the description of flexibility: flexible load, dependency, and storage. This facilitates the representation of complex flexibilities on the demand side. Figure 4 illustrates the modularity of the corresponding data model consisting of the three classes: flexible loads, dependencies, and storages.

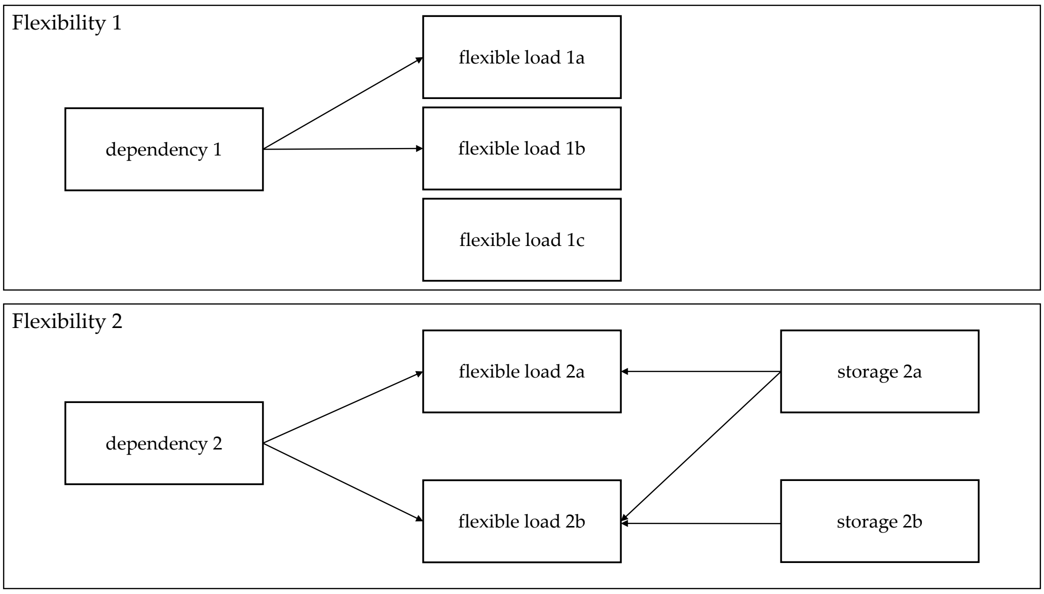

Figure 4: The generic data model according to Research Paper 4 for a modular description of flexibility.

The proposed data model contains "common" key figures to describe flexible consumers, e. g., the power states, holding duration, regeneration duration, activation/deactivation duration (Research Paper 4). Especially, with regard to flexibility on the demand side, the possibility to model dependencies play a crucial role. In production processes, adjustments made to one step of the process can require adjustments to further steps or even their removal. Companies that use this data model can depict such ramifications in the class "dependency". Thus, the proposed data model can provide a basis for standardized communication in IS, be it on digital flexibility trading platforms or in decision support systems (Research Paper 3; Seitz et al., 2019).

II.4 Obstacles to Demand-Side Flexibility

Despite the various possibilities to monetize flexibility (cf. Section II.2), and despite the many possibilities to leverage this via IT and IS (cf. Section II.3), many companies do not at present exploit their potential for demand-side flexibility or only do so partially. To illustrate this missed opportunity, the number of hours with negative prices on the day-ahead market for the market area Germany/Luxembourg may serve as indicator for a lack of flexibility, as these represent an oversupply of electricity (Research Paper 7). Figure 5 depicts the cumulative number of hours with negative prices from 2006 until mid-2020. In 2020, when the COVID-19 pandemic factored into this trend, the number of negative hours reached the previous years' maximum at the beginning of June, and it continued to rise to 298 hours by the end of 2020 (ENTSO-E, 2020).

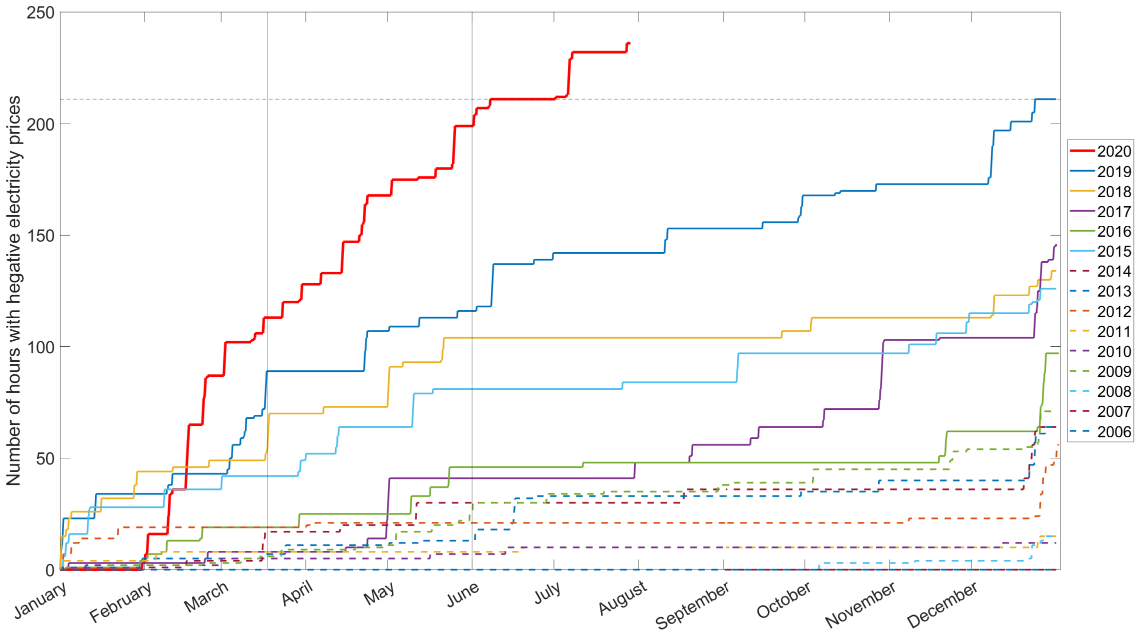

Figure 5: Cumulative number of hours with negative electricity prices on the day-ahead market (Research Paper 1; ENTSO-E, 2020).

To date, there remain several obstacles in the way of companies exploiting or investing in demand-side flexibility. for the most part, companies have focused on increasing their energy efficiency (Wohlfarth et al., 2020). Demand-side flexibility is still a rather new concept for many companies (Unterberger et al., 2018).

Given this lack of familiarity, it is important to examine the obstacles in order to devise countermeasures. In 2013, Olsthoorn et al. (2015) conducted a study with companies at work in the industrial sector to discover what was stopping them from implementing demand-side flexibility. The surveyed companies could weigh certain obstacles as to their relevance. To cluster these obstacles, Olsthoorn et al. (2015) use the categories of Cagno et al. (2013) to distinguish between technological, information, regulatory, economic, behavioral, organizational and competency obstacles. The survey by Olsthoorn et al. (2015)

reveals the major obstacles to be: disruption of operation, impact on product quality, and uncertainty about cost savings.

Research Paper 5 builds on these findings of Olsthoorn et al. (2015) with a structured literature review and a multiple case study. The objective is to identify not only how these obstacles are relevant but also how they get in the way of companies exploiting demand-side flexibility. The results of Research Paper 5 confirm those of Olsthoorn et al. (2015) Accordingly, some of the relevant obstacles are low/lacking cost savings, potential risks for production target values, and disruption of the production process. However, Research Paper 5 advances this prior understanding by revealing that there are further relevant obstacles, namely conflicts with grid fee regulations, conflicts with energy efficiency/the prioritization of energy efficiency measures, high requirements of IT systems, and high complexity levels in those IT systems. Furthermore, fixed taxes and levies distort market price signals, which can mislead companies to generate their own electricity with their own power plants even when electricity prices on electricity exchanges are negative (Research Paper 5). Another consequence is that some companies cannot make use of negative electricity prices or only do so to an extent (cf. Figure 5). Lastly, companies face uncertainty about future regulations and legislative developments, which prevents many from investing in new flexible assets (Research Paper 5).

On the strength of these insights, however, it is possible to devise certain political countermeasures. One way of removing an economic obstacle would be to introduce flexible levies and taxes that are linked to the price of electricity on electricity exchanges. This would increase price differences, which in turn would increase financial incentives for companies to adjust their electricity consumption. Another option would be for policymakers to remove the penalization of flexibility. At present, companies that increase their flexibility risk triggering a new peak load, which would result in higher grid fees. The same applies to efficiency verifications. Flexibility may have negative effects on energy efficiency, as flexible consumers might leave their optimal point of operation (Research Paper 4; Research Paper 5). An increase in flexibility might thus counteract energy efficiency measures and jeopardize the associated tax relief which would make it a financial risk for companies. One possibility to mitigate these negative effects would be the verification of the provided flexibility. This would make it possible to “remove” the effects of flexible consumption from the calculation of grid fees or energy efficiency measures. In general, companies need to find a long-term planning perspective with appropriate incentives, where the various measures required collectively for a successful energy transition do not exclude one another. Section III addresses this need by examining possibilities for a future electricity market design.

III Demand-Side Flexibility in Future Electricity Systems

As described in Section II, flexibility is essential to safeguarding electricity supply, even in current electricity systems. If we are to reach the targets of the Paris Climate Agreement, however, the share of RES in electricity systems has to increase even further (Raftery et al., 2017). With the aim being a future electricity system composed of 100 % RES, there is a clear need for a bundle of flexibility options (Deason, 2018; Heffron et al., 2021).

III.1 On the Need for Adaptations in Electricity Market Design

This section deals with indicators that reveal the need for adjustments to electricity market designs in Europe. In the following pages, the term "market design" refers to the combination of design options that define the rules of electricity systems. To achieve sufficient flexibility options, it is necessary to set appropriate investment incentives, and this, in turn, makes it necessary to analyze the current market design and evolve it (Research Paper 6). The required investment incentives apply particularly to longer phases with low electricity feed-in from PV and wind power plants. With the required flexibility on the supply side, conventional power plants might then only have to run for a few hours a year to generate the required electricity. With a view to this possibility, it is worth taking a moment to offer a brief description of the goal and scope of an electricity market design. According to Cramton (2017), such design should facilitate a reliable and economic provision of electricity. It must, therefore, pursue two goals: short-run efficiency of existing resources and long-run efficiency for investments of new resources (Cramton, 2017). This market design, in particular, fits sequential markets until the actual dispatch of resources and short-term measures intended to ensure that electricity generation and consumption are always in the required balance (Cramton, 2017; Ashour Novirdoust et al., 2021). Another key question in considering a market design is how to deal with network congestion, which arises in situations where the grid's transmission capacity is insufficient to transport the traded electricity (Weibelzahl, 2017). One design option deals with this by applying different pricing rules, namely uniform, zonal, or nodal pricing (Weibelzahl, 2017). The choice of a pricing rule, however, has implications for other aspects of the market design, such as redispatch.

With a focus on European markets, the remainder of this section examines indicators that the current market design requires certain adaptations. The focus is on Europe because the market design considers electricity trading and physical grid restrictions separately in several countries (Research Paper 6). In light of an increasing share of RES, this design is leading to a growing gap between market results and the grids' physical characteristics (ENTSO-E, 2021b), which in turn leads to welfare losses (Meeus et al., 2009). Subsection III.2 discusses possibilities to depict physical characteristics and markets in an integrated way.

The liberalization of the European electricity markets began in the 1990s. It marked a shift from centralized electricity systems to a market environment that increased competition and thus efficiency (Chao and Peck, 1998). However, there is significant evidence that the European electricity markets are due structural change (Research Paper 6). Redispatch and feed-in management represent two short-term measures that correct "infeasible" market outcomes and facilitate electricity flow while taking account of the grid's physical characteristics. In redispatch, TSOs instruct ex-post to spot market trading electricity generators to adjust their planned electricity generation. Generators in an electricity deficient area increase their scheduled output and vice versa. Feed-in management allows grid operators to curtail the electricity generation of RES if they would otherwise exceed the grid's capacity (Bird et al., 2016; Schermeyer et al., 2018). In Germany, for instance, the costs for feed-in management have been rising over the past years from EUR 372.7 million in 2016 to EUR 761.2 million in 2020 (Bundesnetzagentur, 2021). In 2020, feed-in management in Germany came to a total of 6.146 TWh (Bundesnetzagentur, 2021).

This ongoing occurrence of negative prices is an indicator of wrong incentives (Research Paper 7). Figure 6 illustrates the distribution of hours with negative prices on the day-ahead market for the market area Germany/Luxembourg and for the market area Germany/Luxembourg/Austria until the end of 2018.

As Figure 6 indicates, hours with negative electricity prices have increased in the recent past, especially around midday. This phenomenon can also be an indicator that PV power plants generate a lot of electricity at midday and this is available when the level of consumption is not sufficient. Although negative prices provide an investment incentive for flexibility options and should therefore remain available in future market designs, they are a sign of inefficiencies in the market design (Research Paper 7; ENTSO-E, 2021).

Another point worth noting in this context is that an insufficient expansion of the grid infrastructure and an inadequate market design may also lead to unplanned electricity flows. This phenomenon is known as "loop flows". For instance, Poland has been affected by high amounts of unscheduled electricity flows into their grid. Wind power plants in northern Germany generated electricity, and consumers in southern Germany bought electricity but due to limited transmission capacities within Germany, the electricity followed the path of least resistance and ended up in Poland. In this scenario, the electricity traveled from Poland to the Czech Republic, onward to Austria, and ultimately to southern Germany. To limit these unintended effects and lighten the burden on their grids, Poland and the Czech Republic have already installed phase shifters at their borders that allow them to regulate the flow of electricity (Puka and Szulecki, 2014; Fraunholz et al., 2021).

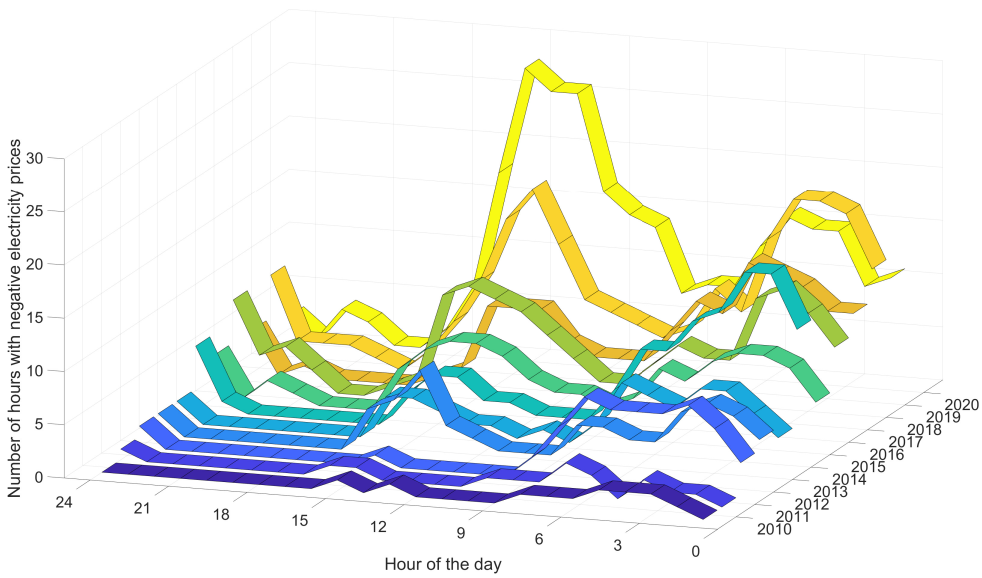

Figure 6: Distribution of negative prices for Germany/Luxembourg/(Austria) (Research Paper 7; ENTSO-E, 2020).

What these examples illustrate is the need to review the current market design and its corresponding design options in order to make adaptations that will ensure two things: the efficiency and reliability of electricity supply, both in the short and long term.

III.2 Pricing Rules for Congestion Management in Electricity Systems

Generally speaking, there are three options for an electricity market to cope with congestion management by means of pricing rules: uniform, zonal, and nodal pricing, the latter also being referred to as LMP (Weibelzahl, 2017). In nodal pricing systems, each node has an individual electricity price for each time period (Bohn et al., 1984; Hogan, 1992; Chao and Peck, 1996). Nodal prices reflect the physical restrictions of transmission capacities (Liu et al., 2009; Weibelzahl, 2017; ENTSO-E, 2021b). They represent the costs for generating an additional unit of electricity while taking into account the grid's restrictions (ENTSO-E, 2021b). As soon as the traded electricity exceeds the transmission capacities between different nodes, the prices in those different nodes change (Research Paper 7). Hence, nodal pricing allows for efficient pricing of grid congestion (Research Paper 6). Countries that use nodal pricing include Argentina, Chile, New Zealand, Russia, and some states in the USA (Sotkiewicz and Vignolo, 2006; Holmberg et al., 2015). Meanwhile, in zonal pricing systems, several nodes form a single price zone in which all of them have the same electricity price. Here, electricity trading does account for the physical restrictions within a price zone, but only those between different zones (Bjørndal et al., 2013). Countries that apply zonal pricing include Denmark, Finland, Norway, and Sweden (Fraunholz et al., 2021). As for uniform pricing systems, they merely have one zone. Where this system is used, all nodes belong to a single price zone (Weibelzahl, 2017). For instance, this is the case with Germany and Luxembourg, which together constitute one price zone. Due to the non-inclusion of grid restrictions in market-clearing, all the market designs based on zonal or uniform pricing require corrective measures, such as redispatch and feed-in management to ensure feasibility (Trepper et al., 2015).

To cope with the increasingly decentralized and intermittent electricity generation from RES, regional prices may better represent the value of electricity with regard to its location (Fraunholz et al., 2021). This also holds true for flexibility options for which the location in the electricity grid would gain in importance. Here, nodal pricing as a form of regional pricing provides investment signals as to where to invest in flexible resources (Khazaei et al., 2017; Munoz et al., 2018). Recent work, such as that conducted for Research Paper 7, also examines the impact flexible electricity consumers have on a nodal-price-based electricity system. The results indicate that flexible electricity consumers as new market participants can contribute to an increased share of RES and can further impact on electricity prices in a nodal system. What is more, flexible consumers in one node can even induce negative prices in other nodes, which, in turn, send an investment signal to other flexible resources and thus represent a possibility to increase overall welfare (Research Paper 7).

However, the transition from zonal or uniform price-based market designs to one based on nodal pricing would affect its complexity. In nodal systems, a higher number of electricity prices has to be determined. In this regard, zonal and uniform pricing systems are comparatively less complex. Furthermore, a shift from a zonal to a nodal system could require considerable altered changes to investment incentives for resources in the electricity grid. For instance, electricity-intensive industrial companies at work in areas with low electricity generation and limited grid capacity would soon face higher electricity prices. But this, in turn, would also provide new investment incentives for electricity generation resources in these areas, which would decrease the need for network expansion (Weibelzahl and Märtz, 2018b).

The long and short of this is that when policymakers shape a future market design, they need to carefully evaluate the advantages and disadvantages of the different pricing rules with special regard to the impact of (new) forces in the market, i. e., flexibility options (Research Paper 6; Research Paper 7).

III.3 Information Technology and Demand-Side Flexibility in Future Electricity Systems

The decentralization of electricity generation units associated with the energy transition is leading to a greater number of market participants, while flexibility options become ever more important in electricity systems. An increasing number of market forces also raises the risk that the required balance of electricity generation and consumption cannot be maintained (Ketter et al., 2018). Here, IT assumes an integral role. IT has the potential to enable or even enhance the interaction between an increasing number of market participants, while reducing the respective transaction costs (Research Paper 6). IT also opens up the possibility of reshaping the electricity system and market (Research Paper 6; Ashour Novirdoust et al., 2021). Therefore, locational fine-granular electricity prices, with the backing of IT, take on a crucial role in facilitating and fostering the exploitation of the required flexibility options in electricity systems (Research Paper 6).

Considering Moore's law and corresponding developments in IT, hardware and software alike are continuously making great advances (Schaller, 1997). These advances allow for the provision of computing capacities in shrinking dimensions. This expedites, among other factors, the processing speed and the transmission of data which in turn, provides the foundation for further developments. For instance, Ashour Novirdoust et al. (2021) present nine classes of IT to cluster the possibilities of promoting the generation of signals, data, information, and knowledge in electricity systems. These nine classes are: "*sensor technologies, data transmission technologies, cloud technologies and high-performance computing, database technologies, data analytics, AI, digital platforms, interfaces, and the overarching field of safety, security, and privacy*" (Ashour Novirdoust et al., 2021). While these can be applied variously in many areas of modern life, the remainder of this section examines the possible fields of application in electricity systems.

As Ibrahim et al. (2020) state, the entire electricity grid, which ranges from electricity generation via transmission and distribution all the way to utilization, would do well to take advantage of the opportunities afforded by IT/Internet of Things (IoT). Focusing on the specific application possibilities of IT in electricity systems, the following three categories – derived and adapted from Ketter et al. (2018), Ibrahim et al. (2020), and Ashour Novirdoust et al. (2021) – represent the possible applications of IT:

1. IT enables and enhances the availability of (raw) data and information to derive knowledge.
2. IT facilitates the exchange of (raw) data, information, and knowledge.
3. IT makes the automation of several participants in the electricity system possible and scalable.

The following paragraphs draw possible IT use cases from these three categories. The selection should exemplify the large scope of potential applications since it is impossible to cover them all in detail within the confines of these pages. Some of these exemplary use cases also refer to the other three flexibility options so as to broaden the view on future electricity systems and to consider interrelationships between those flexibility options.

IT enables and enhances the availability of (raw) data and information, for instance by using sensors or smart meters (Ibrahim et al., 2020). Sensors make it possible to collect raw data from the electricity grid, i. e., from the distribution grid as well as from the transmission grid (Wu et al., 2012). Such raw data provide the basis upon which to develop knowledge. For example, this raw data lets one monitor the status of power lines to gain knowledge about the grid's status, which then allows one to apply the appropriate flexibility options. The resistance of a power line depends, among other things, on the temperature, since it is lower at colder temperatures. Knowing the temperature of power lines thus allows for greater grid flexibility, as it helps to better control the grid's load. Furthermore, the use of smart meters also holds great potential for demand-side flexibility (Ketter et al., 2018). By collecting raw data, it is possible to gain knowledge about the consumption behavior of households and companies (Hinterstocker et al., 2017a). This knowledge allows consumers to adjust their electricity consumption, for example to better suit time-variable electricity tariffs that reflect the respective availability of RES (Hinterstocker et al., 2017b). Smart meters are, then, an essential component of enhancing the exploitation of demand-side flexibility in future electricity systems. They offer electricity consumers the opportunity to take an active role in balancing electricity generation and consumption (Ketter et al., 2018). Furthermore, smart meters may also help grid operators to learn more about the utilization of their grid.

Of equal relevance is the fact that IT facilitates the exchange of (raw) data, information, and knowledge. Whether sensors for power lines or smart meters are concerned, it is essential to transmit data with the least possible time delay (Wu et al., 2012; Ketter et al., 2018). There is, then, an urgent need for new IT to handle the fast transfer of large amounts of data. 5G is one such option, as it plays an important role in the transmission of data between many decentralized participants (Ibrahim et al., 2020; Ashour Novirdoust et al., 2021). Other notable elements of future electricity systems are digital platforms (Research Paper 3; Ketter et al., 2018). In view of the increasing number of market forces in the electricity system, efficient interactions between stakeholders are of key significance. On the one hand, digital platforms, facilitate the exchange of raw data, information, and knowledge, which can assist in the advancement of information and knowledge (Research Paper 1; Hirth et al., 2018). On the other hand, digital platforms can improve the trading of products, which is of interest in terms of flexibility and supporting services (Research Paper 3). Furthermore, there is an emergence of DLTs like blockchain in various areas of applications (Rieger et al., 2019; Sedlmeir et al., 2020). These IT developments create new ways for stakeholders to interact in electricity systems, for instance via bilateral trading of electricity between residential prosumers (Albrecht et al., 2018; Mengelkamp et al., 2018). Digital platforms and DLTs thus make it possible to increase the level of active participation of several (new) market players in electricity systems, and this allows for greater contributions in making things more flexible.

IT also makes the automation of several participants in the electricity system possible and scalable by means of software applications. These facilitate the automation of processes and particularly of decision-making processes (Ashour Novirdoust et al., 2021). As Ibrahim et al. (2020) illustrate by focusing on the potential of machine learning as an emerging IT application and branch of AI, it is of potential benefit in the entire electricity system, everywhere from the prediction of load, price, and generation to cascading failure prediction, fault detection and diagnosis, demand-side flexibility, and detection of cyberspace attacks. On the demand side, machine learning offers various possibilities to enable and enhance flexibility applications when traditional approaches are not sufficient or reliable (Antonopoulos et al., 2020). For instance, Antonopoulos et al. (2020) illustrate that load forecasting along with scheduling and control of consumption units represent the most relevant application areas of AI to exploit demand-side flexibility. Baumgarte et al. (2021) illustrate how the use of AI fosters demand-side flexibility by optimizing the strategy to charge electric vehicles. Moreover, thinking more broadly of flexibility options, machine learning-based methods can improve the prediction of demand in the electricity system (Eseye et al., 2019). What is more, machine learning improves predictive maintenance to avoid failures, for instance of grid components (Ketter et al., 2018), and while the use of sensor data poses the risk of cyber-attacks, new IT applications like neuronal networks are capable of detecting such anomalies (Basumallik et al., 2019). What these possible applications have in common, then, is that they allow for the targeted use of flexibility options to better align electricity demand and generation in future electricity systems.

In summary, current IT developments offer various possibilities to enable and enhance the integration and indeed the exploitation of the four flexibility options, namely grid flexibility, storage flexibility, supply-side flexibility, demand-side flexibility. This might also have an impact on how the electricity system's assets and infrastructure are used. Bearing this in mind, market designers have to consider those opportunities and the respective impact of IT when shaping a future market design.

IV Conclusion

IV.1 Summary

Mitigating the climate crisis is an immense challenge for humanity. To achieve the necessary decarbonization, electricity systems worldwide must reduce the use of fossil fuels and substitute them with renewable energy sources. In 2020, the COVID-19 pandemic caused a decline in electricity consumption in many European countries, which in turn reduced emissions in the short term. For long-term decarbonization, however, the share of renewables in electricity systems must continue to increase, and it must do so in a lasting manner. Since renewables, particularly photovoltaic and wind power plants, generate electricity intermittently due to their weather dependency, they pose a special challenge to ensure the required balance between electricity generation and consumption at any given time. This requires flexibility options. Due to a decentralization of electricity generation units, ever more stakeholders are assuming an active role in electricity systems, which is why this doctoral thesis has examined demand-side flexibility and the potential of IT to enable and enhance the exploitation of such flexibility in electricity systems. The doctoral thesis has done so with a focus on the industrial sector's demand-side flexibility in current and future electricity systems.

Electricity systems are vulnerable, as illustrated by the fault cascade on the 8th of January 2021, which resulted in localized power outages in the European interconnected grid. Another recent challenge to electricity systems around the globe has been the spread of the COVID-19 pandemic. Its first wave had a notable impact in that electricity consumption decreased significantly in several European countries. This provided the opportunity to examine how electricity systems reacted to such altered circumstances and to what extent the various flexibility options could contribute to a stable electricity supply. The reduced electricity demand, in particular, led to an increased grid capacity, and this, in turn, led to increased grid flexibility, all of which ensured the stability of the affected electricity system.

Looking to the future and its resurgent electricity demand, however, all flexibility options need to play a part in balancing electricity generation and consumption. Companies in the industrial sector can make their demand-side more flexible in various ways that would also allow them to reduce their electricity costs. To achieve this, companies must meet certain requirements and ideally embrace IT as a way of implementing and maximizing their flexibility potentials. With a view to these latter benefits, this doctoral thesis has examined the potential of digital flexibility trading platforms which let companies profit as they can better market their demand-side flexibility due to increased market transparency. Moreover, such digital platforms offer the opportunity to mediate supporting services that might assist companies in fulfilling their flexibility potential. Another point worth making in this context is that IT-based communication necessitates a standardized language protocol for flexibility. The flexibility that companies can increase on their demand-side may have certain dependencies and complex interrelations which need to be identified and modeled. This doctoral thesis has, therefore, proposed a generic data model that allows companies to express their demand-side flexibility in a standardized communication protocol. This data model forms the basis upon which to enhance the automation of demand-side flexibility.

Nevertheless, several obstacles still get in the way of companies implementing or investing in demand-side flexibility. To make purposeful adjustments or reductions to these obstacles, this doctoral thesis has examined them and illustrated how they prevent companies from implementing demand-side flexibility. The main obstacles include the lack of savings, the risks to production sizes and production interruptions, the determination of grid fees, the conflicts with energy efficiency measures, and the high requirements for IT systems. Policymakers should consider these and attempt to reduce contradictions between demand-side flexibility and other regulations, such as network charges or efficiency measures. Furthermore, it is worth a thought that the flexibilization of charges and levies, depending on the availability of renewable electricity, can increase economic incentives for demand-side flexibility.

Greater volume and increased costs of corrective measures indicate that some electricity systems can only cope with a growing share of renewable energies under certain conditions. This doctoral thesis has illustrated the extent to which the separation of markets and physics leads to inefficiencies in some electricity systems. Congestion management can, however, be achieved effectively by means of pricing rules, particularly nodal pricing that takes physical grid constraints into account when determining electricity prices. This could also improve the economic incentives for flexibility options with regard to their location in the electricity grid. Moreover, IT will take a central role in promoting the integration of a growing number of participants in the decentralized electricity systems of the future. The potential of IT in this area is manifold: IT can enable the active participation of stakeholders and open up new application opportunities for each flexibility option. As far as flexible participants are concerned, new opportunities are arising for purposeful use of their flexibility potential. These developments, then, are of further importance to a future market design. The different IT applications will lead to a changed use of electricity system infrastructure, since they facilitate, for instance, a reduction of congestions on power lines. Market designers must, therefore, anticipate the changed circumstances caused by IT – in addition to the developments in generation, transmission, consumption, and storage technologies – and take full account of them when shaping a future market design.

It is my hope that this doctoral thesis has contributed to a better understanding of demand-side flexibility in current and future electricity systems. The driving motivation has been to make researchers and practitioners alike benefit from these elaborations on the prerequisites and possibilities of exploiting demand-side flexibility. Furthermore, this doctoral thesis was conducted to present how IT can help companies leverage their flexibility. Hopefully, the careful analysis of current obstacles will assist policymakers in devising effective adjustments. Finally, this doctoral thesis has discussed the possibilities of shaping a future market design, which ought to encourage a further scientific discourse on the role information technologies can play in enabling and enhancing the integration of demand-side flexibility in current and future electricity systems.

IV.2 Limitations and Outlook

Due to certain inevitable limitations, the subject matter of this doctoral thesis deserves some further exploration. Particularly the analysis of how the four flexibility options contribute to grid stability requires more work since it is based on the grid frequency as the sole indicator of grid stability. To deepen the insights this doctoral thesis has revealed in that regard, future research would do well to gather further data to extend the examinations conducted in these pages. Since some companies are still in the process of establishing IT systems adequate to the task of dealing with current electricity systems, some of the IT applications discussed in this study, such as digital flexibility trading platforms and standardized protocols for flexibility, are merely at the prototype stage. To date, then, their practicality remains somewhat unclear. One limitation of the analyzed obstacles is the fact that this analysis includes only German companies. Although some of these companies operate internationally, certain obstacles apply primarily in the German context. It is also worth noting that while this study presents some exemplary IT applications that should be of relevance in future electricity systems, these examples give an indication of potentials, rather than a comprehensive overview of all possible applications that could be brought to bear on flexibility options.

Following on from this doctoral thesis and the research papers include therein, further research ought to explore several avenues. First, it is of critical importance to develop future-proof market designs for future electricity systems that consider the multi-layered potential of information technologies to enable and enhance the four flexibility options. Further research should examine whether information technologies are fit to cope with the anticipated effects, for example, whether smart meters are effective tools to enable electricity consumers to take a more active role in balancing electricity generation and consumption. The crucial question will be how to reliably integrate IT solutions into the production control systems of various companies. Once this is achieved, companies can be more flexible in making their electricity purchases, without adversely impacting their production. To this end, it will also be necessary to reduce the obstacles that are still getting in the way of companies marketing demand-side flexibility and developing new flexibility products that better represent the technical characteristics of a company's flexibility. Furthermore, it is crucial that those who innovate the Energy Informatics discipline collaborate with leaders in related fields, such as engineers, business economists, and lawyers, so as to develop suitable IT solutions for flexibility options.

The analysis of these obstacles to demand-side flexibility has revealed the fact that the electricity sector is an interdisciplinary environment in which different fields need to develop solutions together. Ultimately, European countries have to develop those solutions and implement them in electricity systems across national borders. An integrated view of interconnected electricity systems makes it possible to diversify various flexibility options to different degrees, which will help increase economic efficiency as well as resilience.

IV.3 Acknowledgment of Previous and Related Work

In all research projects and work, I collaborated with colleagues at the Project Group Business & Information Systems Engineering of the Fraunhofer Institute for Applied Information Technology (FIT), the Research Center Finance & Information Management (FIM), the University of Augsburg, and the University of Bayreuth. Therefore, I present how my work builds on previous and related work.

The work of Fridgen et al. (2018), Schoepf et al. (2018), and Fridgen et al. (2020a) formed a viable basis for *Research Paper 2* and *Research Paper 4*. Moreover, Fridgen et al. (2016a), Fridgen et al. (2018), Thimmel et al. (2019), and Keller et al. (2020) dealt with related topics on demand-side flexibility and, thus, formed sources of ideas for *Research Paper 2*, *Research Paper 3*, *Research Paper 4*, and *Research Paper 5*. Also, Ländner et al. (2019) helped to frame the work on *Research Paper 5*. Finally, the work of Weibelzahl and Märtz (2018a), Sachs et al. (2019), Fridgen et al. (2020b), and Rövekamp et al. (2020) provided starting points for the work on *Research Paper 6* and *Research Paper 7*.

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VI Appendix

VI.1 Research Papers Relevant to this Doctoral Thesis

Research Paper 1: How did the German and other European electricity systems react to the COVID-19 pandemic?

Halbrügge, S.; Schott, P.; Weibelzahl, M.; Buhl, H. U.; Fridgen, G.; Schöpf, M. (2021). "How did the German and other European electricity systems react to the COVID-19 pandemic?". In: *Applied Energy*. DOI: 10.1016/j.apenergy.2020.116370.
(VHB-Jourqual 3 Category: n.a., SNIP 2019: 2.865, SJR 2019: 3.607, CiteScore 2019: 16.4 / 99 % percentile)

Research Paper 2: Strukturierte Analyse von Nachfrageflexibilität im Stromsystemund Ableitung eines generischen Geschäftsmodells für (stromintensive) Unternehmen

Haupt, L.; Körner, M.-F.; Schöpf, M.; Schott, P.; Fridgen, G. (2020). "Strukturierte Analyse von Nachfrageflexibilität im Stromsystem und Ableitung eines generischen Geschäftsmodells für (stromintensive) Unternehmen". In: *Zeitschrift für Energiewirtschaft*. DOI: 10.1007/s12398-020-00279-5.
(VHB-Jourqual 3 Category: C, SNIP 2019: n.a., SJR 2019: n.a., CiteScore 2019: n.a. % percentile)

Research Paper 3: A Platform of Platforms and Services: Bringing Flexible Electricity Demand to the Markets

Schott, P.; Fridgen, G.; Keller, R. (2020). "A Platform of Platforms and Services: Bringing Flexible Electricity Demand to the Markets". *Submitted*.

Research Paper 4: A Generic Data Model for Describing Flexibility in Power Markets

Schott, P.; Sedlmeir, J.; Strobel, N.; Weber, T.; Fridgen, G.; Abele, E. (2019). "A Generic Data Model for Describing Flexibility in Power Markets". In: *energies*. DOI: 10.3390/en12101893.
(VHB-Jourqual 3 Category: n.a., SNIP 2019: 1.154, SJR 2019: 0.635, CiteScore 2019: 3.8 / 81 % percentile)

Research Paper 5: Obstacles to Demand Response: Why Industrial Companies Do Not Adapt Their Power Consumption to Volatile Power Generation

Keller, R.; Leinauer, C.; Ollig, P.; Schott, P.; Weibelzahl, M.; Fridgen, G. (2020). "Obstacles to Demand Response: Why Industrial Companies Do Not Adapt Their Power Consumption to Volatile Power Generation". *Submitted.*

Research Paper 6: Electricity Market Design in the Energy Transition: A Guide to the Literature

Bichler, M.; Buhl, H. U.; Knörr, J.; Maldonado, F.; Schott, P.; Waldherr, S.; Weibelzahl, M. (2020). "Electricity Market Design in the Energy Transition: A Guide to the Literature". Submitted to (1st major revision): *Schmalenbach Journal of Business Research.*[1] (BuR: VHB-Jourqual 3 Category: B, SNIP 2019: 1.337, SJR 2019: 0.629, CiteScore 2019: 2.7 / 72 % percentile; SBR: VHB-Jourqual 3 Category: B, SNIP 2019: n.a., SJR 2019: n.a., CiteScore 2019: n.a. % percentile; ZfbF: VHB-Jourqual 3 Category: B, SNIP 2019: 0.395, SJR 2019: 0.129, CiteScore 2019: 0.3 / 20 % percentile)

Research Paper 7: Negative Electricity Prices as a Signal for Lacking Flexibility? On the Effects of Demand Flexibility on Electricity Prices

Halbrügge, S.; Heeß, P.; Schott, P.; Weibelzahl, M. (2020). "Negative Electricity Prices as a Signal for Lacking Flexibility? On the Effects of Demand Flexibility on Electricity Prices". *Submitted.*

[1] Schmalenbach Journal of Business Research (SBUR) replaces Business Research (BuR), Schmalenbach Business Review (SBR), and builds on Schmalenbachs Zeitschrift für betriebswirtschaftliche Forschung (ZfbF). Therefore, the metrics comprise these three previous journals.

Over the course of the dissertation, I also co-authored the following book chapters and research papers. These papers are not part of this doctoral thesis.

Hinterstocker, M.; Schott, P.; von Roon, S. (2017). "Disaggregation of household load profiles". In: *Internationale Energiewirtschaftstagung, Vienna.*

Hinterstocker, M.; Schott, P.; von Roon, S. (2017). "Increasing residential self-consumption of PV energy by DSM". In: *Internationale Energiewirtschaftstagung, Vienna.*

Hinterstocker, M.; Schott, P.; von Roon, S. (2017). "Evaluation of the effects of time-of-use pricing for private households based on measured load data". In: *2017 14th International Conference on the European Energy Market (EEM)* (pp. 1-6). IEEE.

Schott, P.; Ahrens, R.; Bauer, D.; Hering, F.; Keller, R.; Pullmann, J.; Schel, D.; Schimmelpfennig, J.; Simon, P.; Weber, T.; Abele, E.; Bauernhansl, T.; Fridgen, G.; Jarke, M.; Reinhart, G. (2018). "Flexible IT platform for synchronizing energy demands with volatile markets". In: *it-Information Technology*, 60(3), 155-164.

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VI.2 Individual Contribution to the Included Research Papers

This doctoral thesis is cumulative and comprises seven research papers. All of them were written in collaboration with multiple co-authors. In this section, I will describe my individual contribution to each of the seven papers.

The first research paper (Halbrügge et al., 2021) is titled "*How did the German and other European electricity systems react to the COVID-19 pandemic?*" (cf. Subsection VI.3). It was written by a team of six. Along with one other co-author, I was responsible for the preparation of the real-world data, the analysis of that data, and the visualization of the evaluations. Three authors, including myself, shared primary responsibility for the writing of the text. The other three co-authors supported us in the conceptualization of the research project and provided feedback. As a team, we agreed that two of the co-authors and I should assume the roles of lead authors of the research paper. The other three co-authors made equal contributions as subordinate authors.

The second research paper (Haupt et al., 2020) is titled "*Strukturierte Analyse von Nachfrageflexibilität im Stromsystem und Ableitung eines generischen Geschäftsmodells für (stromintensive) Unternehmen*" (cf. Subsection VI.4). This paper was written in a team of five. In collaboration with three co-authors, I conceptualized this paper. With the same three co-authors, I also conducted the expert workshops that constitute a major part of this project. Based on those expert workshops and a literature review, one co-author and I derived a generic business model. The other two co-authors conducted the qualitative validation of this model. One co-author with experience in this area guided the research process and provided us with valuable feedback. As a team, we agreed that three of the co-authors and I should act as lead authors of the research paper. The other member of the team contributed to the writing as a subordinate author.

The third research paper (Schott et al., 2020) is titled "*A Platform of Platforms and Services: Bringing Flexible Electricity Demand to the Markets*" (cf. Subsection VI.5). This study was conducted in a team of three. Since I am the lead author of this paper, I organized the majority of its conception. I was closely involved in the research process of the action design and participated in each design stage. Ultimately, I was responsible for consolidating the content and writing it up in the form of a research paper. Even though much of it was my own work, the paper benefited from the continuous participation of all co-authors. With mutual consent, we agreed that I should act as lead author, while one team member contributed as subordinate and the other team member as sub-subordinate author.

The fourth research paper (Schott et al., 2019) is titled "*A Generic Data Model for Describing Flexibility in Power Markets*" (cf. Subsection VI.6). It was written by a team of six. In collaboration with one co-author, I designed the general structure of the paper and directed its preparation. Our main contribution focused on the data model classes "flexible loads" and "dependencies", while two other co-authors worked on the class "storages". Furthermore, one co-author and I were responsible for the data model class "flexibility measure" and the validation of the data model. In addition, I also created the visualizations. Together, we determined that one of the co-authors and I made significant contributions as the two lead authors of the research paper. The remaining team members contributed as subordinate and sub-subordinate authors.

The fifth research paper (Leinauer et al., 2020) is titled "*Obstacles to Demand Response: Why Industrial Companies Do Not Adapt Their Power Consumption to Volatile Power Generation*" (cf. Subsection VI.7). This paper was written in a team of six. By then, I had acquired rather extensive experience as a researcher, so I guided the research process with one other lead author. The second lead author focused on the structured literature review. Together, we conducted multiple case studies, including the expert interviews and the corresponding evaluation. In further collaboration with this co-author, I worked on the formulation of the paper. The other co-authors supported the project as subordinates, and given their various areas of research experience, they contributed from different perspectives. By mutual consent, we agreed that one of the co-authors and I made significant contributions as the two lead authors of the research paper. The other four co-authors assumed the roles of subordinate authors.

The sixth research paper (Bichler et al., 2020) is titled "*Electricity Market Design in the Energy Transition: A Guide to the Literature*" (cf. Subsection VI.8). It was written by a team of seven. All authors developed the idea and structure for this paper by way of collaboration. Two co-authors and I focused on three topics, number one being the indicators for an adjustment of the market design, number two being the technological developments in electricity generation, flexible demand, storage, and information technology, and number three being the different options for pricing rules. The other co-authors were primarily responsible for developing the content on bidding languages. Together, we agreed that we all contributed to this research paper in equal parts.

The seventh research paper (Halbrügge et al., 2020) is titled "*Negative Electricity Prices* *as a Signal for Lacking Flexibility? On the Effects of Demand Flexibility on Electricity Prices*" (cf. Subsection VI.9). This paper was written in a team of four. I assumed the role of the experienced researcher, and with the support of the other co-authors, I developed the idea and structure of the paper. One co-author took the lead in modeling the case study. My particular contribution consisted in the evaluation and visualization of the results. Furthermore, I made contributions to the interpretation of the findings. The writing of the paper was done as a joint project. All co-authors agreed that we made equal contributions to this research paper.

VI.3 Research Paper 1: How did the German and other European electricity systems react to the COVID-19 pandemic?

Authors:
Stephanie Halbrügge; Paul Schott; Martin Weibelzahl; Hans Ulrich Buhl; Gilbert Fridgen; Michael Schöpf

Published in:
Applied Energy (2021)

Abstract:
The first wave of the COVID-19 pandemic led to decreases in electricity demand and a rising share of Renewable Energy Sources in various countries. In Germany, the average proportion of net electricity generation via Renewable Energy Sources rose above 55 % in the first half of 2020, as compared to 47 % for the same period in 2019. Given these altered circumstances, in this paper we analyze how the German and other European electricity systems behaved during the COVID-19 pandemic. We use data visualization and descriptive statistics to evaluate common figures for electricity systems and markets, comparing developments during the COVID-19 pandemic with those of previous years. Our evaluation reveals noticeable changes in electricity consumption, generation, prices, and imports/exports. However, concerning grid stability and ancillary services, we do not observe any irregularities. Discussing the role of various flexibility options during the COVID-19 pandemic, a relatively higher grid capacity resulting from a decreased electricity consumption, in particular, may have contributed to grid stability.

Keywords:
Electricity System, COVID-19 Pandemic, Renewable Energy Sources, Flexibility, Grid Stability

VI.4 Research Paper 2: Strukturierte Analyse von Nachfrageflexibilität im Stromsystem und Ableitung eines generischen Geschäftsmodells für (stromintensive) Unternehmen

Authors:

Leon Haupt; Marc-Fabian Körner; Michael Schöpf; Paul Schott; Gilbert Fridgen

Published in:

Zeitschrift für Energiewirtschaft (2020)

Zusammenfassung:

Im Zuge des Ausbaus erneuerbarer Energien bedarf es im Stromsystem entsprechender Flexibilität, um das Gleichgewicht von Stromerzeugung und -verbrauch jederzeit aufrechterhalten zu können. Gleichzeitig nimmt der Industriesektor aufgrund der stromintensiven Prozesse und dem daraus resultierenden hohen Strombedarf eine zentrale Rolle für eine erfolgreiche Energiewende ein. Industrielle Nachfrageflexibilität kann im Vergleich zu anderen Flexibilitätsoptionen eine kostengünstige Alternative darstellen. Unternehmen können wiederum durch die Bereitstellung von Flexibilität die eigenen Strombeschaffungskosten reduzieren. Aufgrund eines komplexen Entscheidungsumfelds sowie mangelnder Planungssicherheit nutzen aktuell nur wenige Unternehmen das vorhandene Potenzial. Zum Erreichen der Ziele der Energiewende muss das genutzte Potenzial noch deutlich gehoben werden, d. h. die Unternehmen müssen die Stromnachfrage zukünftig stärker an das vorhandene Stromangebot anpassen. Der vorliegende Artikel soll Unternehmen bei diesem Transformationsprozess unterstützen, indem Dimensionen und Ausprägungen eines generischen Geschäftsmodells für Nachfrageflexibilität aufgezeigt werden. Durch eine Literaturstudie und anschließende Expertenworkshops wird ein generisches Geschäftsmodell für Unternehmen abgeleitet, welches Transparenz hinsichtlich der notwendigen Aktivitäten und Ressourcen für die Befähigung sowie der Umsetzung von Nachfrageflexibilität schafft. Die Ergebnisse wurden mithilfe des etablierten Business Model Canvas erarbeitet. Dadurch werden Unternehmen, die sich bislang noch nicht mit Nachfrageflexibilität auseinandersetzen, bei der Einführung unterstützt, und somit Einstiegsbarrieren reduziert. Die vorgestellten Ergebnisse tragen dadurch zu einer Steigerung des Nachfrageflexibilitätspotenzials der Industrie bei.

Schlüsselwörter:

Demand Side Management, Nachfrageflexibilität, Demand Side Integration, Industrie, Geschäftsmodell, Strommarkt

Abstract:

The expansion of renewable energy requires appropriate flexibility in the electricity system in order to maintain the balance between electricity generation and consumption at all times. The industrial sector plays a central role for a successful energy transition due to the power-intensive processes and the resulting high electricity demand. Industrial demand response may be a cost-effective alternative to other flexibility options. At the same time, companies can reduce electricity procurement costs by providing demand response. Nevertheless, due to a complex decision-making environment and a lack of planning security, only a few companies are currently exploiting the existing potential. To reach the goals of the energy transition, the potential used must still be raised significantly, i. e., companies must align their demand for electricity more closely to the existing supply of electricity. This article supports companies in this transformation process by illustrating dimensions and characteristics of a business model for demand response. Through a literature study and subsequent expert workshops, a generic business model for companies is derived that provides transparency regarding the necessary activities and resources for enabling and implementing demand response. The results were developed using the established Business Model Canvas. This supports companies that have not yet started to use demand response in their business model development and thus reduces barriers to entry. The results presented contribute to an increase in the demand response potential of the industry.

Keywords:

Demand Side Management, Demand Response, Demand Side Integration, Industry, Business Model, Electricity Market

VI.5 Research Paper 3: A Platform of Platforms and Services: Bringing Flexible Electricity Demand to the Markets

Authors:
Paul Schott; Robert Keller; Gilbert Fridgen

Extended Abstract[2]**:**
In the course of the energy transition, the share of intermittent renewable energies in electricity systems is continuously increasing. The required balance between electricity generation and consumption is, therefore, ever more reliant on the contribution of various flexibility options. One such option with considerable potential is demand-side flexibility, i. e., the deliberate adjustment of electricity consumption (Palensky and Dietrich, 2011). A promising area in which to leverage this potential is in the industrial sector with its large share of electricity consumption (Heffron et al., 2020). Companies can do so by pursuing various strategies to monetize demand-side flexibility. As Alam et al. (2017) point out, there is a whole range of electricity markets, and thus flexibility markets, with different intentions. Furthermore, there are many other emerging markets that enable local trading of flexibility, and there are also various service providers, such as aggregators, that can support companies in implementing and exploiting demand-side flexibility. However, an increasing number of flexibility markets and service providers result in a lack of transparency for companies that want to market demand-side flexibility. This lack of transparency, in turn, prevents companies from exploring existing flexibility options and investing in new ones.

In this context, multi-sided platforms (MSPs) offer the opportunity to improve transparency (Hagiu and Wright, 2015), since they facilitate the exchange of data and information between different user groups. Developing an MSP would, therefore, appear to be key to unlocking the demand-side flexibility of companies in the industrial sector. With this in mind, we pose the research question as to how an MSP can facilitate the exploitation of flexibility in different electricity markets. To answer this question, we apply an Action Design Research (ADR) approach and develop an MSP in the context of a German research project (Sein et al., 2011; Mullarkey and Hevner, 2019). In the iterative cycles of *Diagnosis, Design*, and *Implementation*, we evaluate the developed MSP artifact with practitioners and potential end-users of the MSP. Based on the evaluation in each cycle,

[2] At the time of writing, this research paper is under review for publication in a scientific journal. Therefore, an extended abstract is provided here.

we make interventions and corresponding adjustments to the MSP design.

In the *Diagnosis* cycle, we – the authors are also part of the ADR team – establish relevant requirements for an MSP that should foster the exploitation of companies' demand-side flexibility. In order to improve transparency, the MSP needs to facilitate a standardized interaction between three distinct sides: flexibility markets, flexibility providers (i. e., companies), and supporting services (e. g., aggregators or price forecasts). Our results reveal that there is a need for an overarching digital flexibility trading platform that also bundles emerging isolated markets, i. e., digital platforms for trading local flexibility. Therefore, we adjusted the requirement and determined that the MSP should function as a digital meta-platform. This also includes the adjustment that the digital meta-platform should not take an active role. Instead, it should function as a mediator between the three distinct sides. This adjustment allows the digital meta-platform to fit into the highly regulated environment of electricity systems.

In the *Design* cycle, we develop a component diagram to specify the architecture of the digital flexibility trading meta-platform. Our evaluation with potential end-users led to adjustments in the definition of the interfaces of supporting services. The digital meta-platform should also facilitate value co-creation between the services. In other words, a supporting service that optimizes the commitment of a company's flexibility potential can access certain data, such as price forecast data, for a relevant flexibility market from another service. Acting as flexibility providers, companies may thus combine different supporting services via the digital meta-platform. Moreover, our discussions emphasize the need for a standardized language for demand-side flexibility, i. e. a communication protocol. This is an important component because it contributes to interoperability between the three connected sides of the digital meta-platform. As such, the digital meta-platform can avoid lock-in effects between companies and supporting services.

In the *Implementation* cycle, we produce a prototype of the digital meta-platform. A fictitious refrigerated warehouse with three CPU fans serves as an example of a company that can offer flexibility by adjusting the number and speed of the three CPU fans. We implement the digital meta-platform as a web service. The company can access the digital meta-platform via a web interface and can market its flexibility on an exemplary flexibility market. The prototype reveals a further need to adopt the communication protocol for demand-side flexibility. Aside from the opportunity to model the possibilities of flexible electricity consumption, there is also a need to model concrete deviations, i. e., flexibility measures, to make the required adaptations. Therefore, we extend the data model with the possibility to model flexibility measures.

Based on the findings of the three respective ADR cycles – *Diagnosis, Design*, and *Implementation* –, we determine generalized design principles for digital platforms that are also applicable in other domains. We will conduct the fourth stage, the *Evolution* cycle, at a later point. In domains where sites have multiple entities, for instance, in the electricity sector, a digital meta-platform is a suitable approach to increase transparency. Accordingly, the digital meta-platform functions as a mediator, which offers the further advantage of integrating the platform in highly regulated domains. Here, a standardized communication protocol is crucial as it allows a digital meta-platform to ensure interoperability while preventing lock-in effects.

Keywords:
Multi-Sided Platform, Action Design Research, Power Markets, Power Flexibility

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VI.6 Research Paper 4: A Generic Data Model for Describing Flexibility in Power Markets

Authors:

Paul Schott; Johannes Sedlmeir; Nina Strobel; Thomas Weber; Gilbert Fridgen; Eberhard Abele

Published in:

energies (2019)

Abstract:

In this article, we present a new descriptive model for industrial flexibility with respect to power consumption. The advancing digitization in the energy sector opens up new possibilities for utilizing and automatizing the marketing of flexibility potentials and therefore facilitates a more advanced energy management. This requires a standardized description and modeling of power-related flexibility. The data model in this work has been developed in close collaboration with several partners from different industries in the context of a major German research project. A suitable set of key figures allows for also describing complex production processes that exhibit interdependencies and storage-like properties. The data model can be applied to other areas as well, e. g., power plants, plug-in electric vehicles, or power-related flexibility of households.

Keywords:

Demand Side Management, Demand Response, Generic Flexibility Data Model, Flexibility Modeling, Power System, Industrial Processes, Digitalization

VI.7 Research Paper 5: Obstacles to Demand Response: Why Industrial Companies Do Not Adapt Their Power Consumption to Volatile Power Generation

Authors:
Christina Leinauer; Paul Schott; Gilbert Fridgen; Robert Keller; Philipp Ollig; Martin Weibelzahl

Extended Abstract[3]:
Companies in the industrial sector have a considerable potential to adjust their electricity consumption, i. e., demand response, for a dual benefit: to compensate for intermittent electricity generation from renewable energies and to reduce their electricity costs (Paterakis et al., 2017). Nevertheless, many companies do not use their (full) potential for demand-side flexibility or do not invest in new flexibility options, even though the possibilities to monetize demand-side flexibility and demand response have notably increased in recent years (Alcázar-Ortega et al., 2015; Paterakis et al., 2017). To address this issue, Olsthoorn et al. (2015) conducted a survey and questioned companies on the weighting of different obstacles that get in the way of them improving their demand response. After Cagno et al. (2013) devised categories for obstacles to energy efficiency measures, Olsthoorn et al. (2015) cluster obstacles to demand response in the same categories: economic, regulatory, technological, organizational, behavioral, informational, and competence. The analysis of Olsthoorn et al. (2015) reveals that, from a company's point of view, the most relevant obstacles are "disruption of operations", the "impact on product quality", and the "uncertainty about cost savings". Based on this work by Olsthoorn et al. (2015), we can advance the knowledge about how these obstacles come to be, how they interrelate, and how they get in the way of companies exploiting their potential for demand response.

This paper, then, addresses the question of how the obstacles – grouped according to the aforementioned categories – restrict companies from exploiting their demand response potential. We conduct a structured literature review, following the approach of Webster and Watson (2002), and with the work of Yin (2017) in mind we perform a multiple case study with energy experts from German companies in the industrial sector. The structured literature review covers 80 papers on the obstacles that companies encounter when trying

[3] At the time of writing, this research paper is under review for publication in a scientific journal. Therefore, an extended abstract is provided here.

to improve their demand response. The multiple case study comprises 16 interviews with energy experts from German companies. For the interviews, we apply a semi-structured protocol. The combination of the structured literature review and the multiple case study allows us to merge and compare current insights from literature and practice.

In total, we find 63 obstacles by combining the results of the structured literature review and the case study. Out of these, 16 obstacles stem from the literature review alone, whereas 5 obstacles stem exclusively from the interviews. The remaining 42 obstacles appear in both the literature review and the interviews. Our results confirm the findings of Olsthoorn et al. (2015) and advance the knowledge of how obstacles get in the way of companies developing better responses to their demand profiles. Based on how many interviewees mentioned a specific obstacle, some categories or specific obstacles would appear to be of particular importance from the companies' point of view. Accordingly, economic, regulatory, and technological obstacles are particularly difficult to overcome. In comparison, organizational, behavioral, informational and competence obstacles seem to be less troublesome. Indeed, the two most frequently mentioned obstacles relate to economic: "(Power) cost savings through demand response are low" and "Lack of revenues through demand response" are obstacles that highlight the lack of cost savings. The "potential risk on production target values" and "greater economic appeal of alternative measures to optimize power costs" are also prevailing economic obstacles. Furthermore, the greater economic appeal of alternative measures refers to regulatory obstacles as well, since companies state a "prioritization of energy efficiency measures" and report "conflicts with energy measures". Demand response might, then, have a negative impact not only on targets for energy efficiency but also on grid fees, as the interviewees mention "conflicts with grid fee regulations" as an important obstacle. The technical barriers – "technical risk of disruption of production process", "technical infeasibility to reduce peak load", and "high requirements of IT/high effort and complexity within IT systems" – round out the list of most mentioned obstacles. Moreover, companies note an "uncertainty about future regulations and legislative developments" which impedes the long-term planning of demand response.

With this paper, we contribute to better identification of the current obstacles, their underlying causes, and their interdependencies, which ought to help policymakers to devise dedicated measures to reduce these obstacles. In order to increase the economic incentives for companies to respond to the share of RES, policymakers could readjust taxes and levies for electricity. One conceivable strategy would be to couple those taxes to the electricity price, i. e., to dynamize them so as to increase the price spreads and, thus, the financial incentives for demand response. In addition, it is advisable to erase possible negative effects of demand response measures, i. e., peak loads or efficiency losses, when determining grid fees or the proof of efficiency. Further long-term measures to promote demand response in the industrial sector include the funding of developments for improved communication standards and IT systems. In summary, reducing the obstacles to demand response would increase the flexibility potential in the electricity system. This, in turn, would allow for further integration of intermittent renewable energy sources in electricity systems. Ultimately, companies would have improved opportunities to reduce their electricity costs and, thus, increase their competitiveness.

Keywords:
Demand Flexibility, Demand Side Management, Demand Response, Industrial Sector, Obstacles for Demand Flexibility, Case Study Research

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VI.8 Research Paper 6: Electricity Market Design in the Energy Transition: A Guide to the Literature

Authors:
Martin Bichler; Hans Ulrich Buhl; Johannes Knörr; Felipe Maldonado; Paul Schott; Stefan Waldherr; Martin Weibelzahl

Extended Abstract[4]:
An electricity market design is the combination of various design options that constitute the rules of electricity markets. The aim of a market design is the reliable and economic supply of electricity. Particular consideration has to be given to the two facts that electricity as a commodity is difficult to store and that electricity grids have certain physical characteristics (Cramton, 2017; Khazaei et al., 2017). A market design needs to address both short-term welfare-maximizing dispatch and appropriate incentives for efficient long-term investments to facilitate the ongoing integration of renewable energy sources (Cramton, 2017; Gallego, 2018). In Europe, electricity market designs first emerged when electricity systems had a relatively low share of intermittent renewable energy sources. The growing share of those intermittent renewables now poses a challenge to existing market designs, as indicated by the increasing use of short-term corrective measures to safeguard the electricity supply. In Germany, for instance, the amount and cost for feed-in management, i. e., the controlled shutdown of renewable energy sources to avoid the violation of grid restrictions, has increased considerably over the last few years.

The development of a sustainable market design covers various research areas and poses challenges for several disciplines within business research, such as operations research, production and operations management, marketing finance, and business and information systems engineering. This paper outlines these challenges and demonstrates the need for interdisciplinary collaboration among those disciplines and beyond so as to coordinate efforts with economists and engineers. With this in mind, we analyze technological developments of electricity generation, demand, storage, and information technologies. We also examine bidding languages from the perspective of flexibility providers and pricing rules given these technological developments. In order to understand the challenges and opportunities, we consider the electricity market in the United States of America (USA) and that in Germany as part of the coupled European market. These two examples of

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market designs differ in several key features which makes them ideal for a comparison of different design options.

Some states in the USA apply nodal pricing as a pricing rule. This results in locational marginal prices in each node of the electricity system within a certain time period, whereas nodal prices also reflect grid congestion and losses (Bohn et al., 1984; Hogan, 1992; Chao and Peck, 1996). In the US markets, there is a central clearing authority for system and market operation that determines the dispatch of the relevant resources, while taking into account the system constraints as well as the participants' costs and preferences (Cramton, 2017; Gallego, 2018). In contrast, Germany applies a type of zonal pricing, more specifically, uniform pricing, which means that the common price zone of Germany and Luxembourg has a single electricity price. The corresponding electricity price does not, however, reflect the grid's restrictions. Moreover, in Germany, the system operation is uncoupled from the market operation, which makes it necessary for transmission system operators to be in charge of ensuring grid stability (Cramton, 2017). Furthermore, on the day-ahead market, the bids cover hourly products and block bids for longer periods which does not allow for welfare maximization (Meeus et al., 2009).

Considering the technological changes in electricity generation wind and solar power plants represent essential generation technologies. Both technologies exhibit marginal costs close to zero. However, due to their weather dependency, wind and solar power plants generate electricity intermittently which creates the so-called "flexibility gap" (Papaefthymiou et al., 2018). Technological developments on the demand side and in the storage of electricity hold the promising potential to close this flexibility gap. In particular, electrochemical storages, such as battery solutions, and flexibility on the demand side of the industrial sector may contribute to the important balance between electricity generation and consumption (Schmidt et al., 2019; Heffron et al., 2020). Given that electricity systems are becoming more decentralized and the number of active market participants is growing, developments in information technology also offer opportunities to improve the options of a future market design. Information technologies can (1) improve the availability of data to derive knowledge, (2) facilitate the exchange of information, for instance, via digital platforms or decentralized databases (Sedlmeir et al., 2020), and (3) increase the automation of the electricity system (Ketter et al., 2018). Due to these opportunities, information technologies can enable and indeed enhance both the integration and the interaction of market players in electricity systems, be it that of existing or new players.

Despite these technological advances, bidding languages remain an important design option for any market design. Bidding languages for electricity products should reflect the underlying circumstances, such as types of costs, or the technical characteristics of electricity generators, flexible consumers, and storages (Goebel et al., 2014; Tejada-Arango et al., 2019). For instance, the fixed block bids constrain the charging and discharging phases of storage facilities, which results in welfare losses, yet electricity prices must increasingly reflect the physical realities of the electricity grid (Cramton, 2017). In this context, pricing rules play an important role. Smaller pricing zones that no longer represent an entire country or nodal pricing, represent possibilities for locational prices, which would also set new investment incentives in an electricity system, depending on whether there is a generation surplus or deficit at a given node (Khazaei et al., 2017).

To summarize, two topics are worthy of particular attention when considering a future market design. First, it is necessary to integrate new market forces, such as flexible consumers and storages, in the electricity system so as to close the emerging “flexibility gap”. The use of information technologies as well as the development of new bidding languages can facilitate such integration. Second, the transition to more geographically fine-grained prices or even nodal prices seems mandatory to better reflect the locational value of electricity. In both respects, the afore-mentioned research disciplines within business research need to collaborate on future market designs and manage the transition to sustainable and reliable electricity systems with an interdisciplinary approach.

Keywords:
Electricity Market Design, Energy Transition, Renewable Energy Sources, Technological Changes, Spot Markets, Literature Review

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VI.9 Research Paper 7: Negative Electricity Prices as a Signal for Lacking Flexibility? On the Effects of Demand Flexibility on Electricity Prices

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Extended Abstract[5]:
In recent years, the number of hours with negative electricity prices has increased in wholesale markets (Bajwa and Cavicchi, 2017). In 2019, for instance, on the day-ahead market for the market area Germany/Luxembourg, there were 211 hours with negative electricity prices. Negative prices imply that electricity generators have to pay for producing electricity. The consensus among researchers is that negative electricity prices elate to a lack of flexibility on the supply side as well as a comparatively inelastic electricity demand (Ketterer, 2014; Härtel and Korpas, 2020). Therefore, this paper examines how electricity prices may be influenced by flexible market players on the demand side, i. e., by consumers who can shift their load between different time periods.

We examine the circumstances that lead to negative prices. Considering the merit order, i. e., the ascending sorting of electricity generation capacities based on their marginal costs, one could assume that negative electricity prices cannot actually occur. However, among others, Fanone et al. (2013), De Vos (2015), and Bajwa and Cavicchi (2017) examine the occurrence of negative prices in different markets. In general, there are two main reasons for negative electricity prices: support mechanisms for renewable energy sources and inflexible conventional power plants. With regard to the former, the prioritized infeed and corresponding support payments foster the occurrence of negative electricity prices. Renewable energy operators receive remuneration and as long as this is higher than negative electricity prices, these operators are willing to produce electricity (De Vos, 2015; Bajwa and Cavicchi, 2017). With regard to inflexible conventional power plants, depending on the type of power plant, they have costly and time-intensive ramp-up and ramp-down phases. There are, then, several technical limits that restrict the ability for short-term adjustment of electricity generation by those conventional power plants (De Vos, 2015). Furthermore, conventional power plants that provide ancillary services – and receive remuneration for these services – must be in operation and, thus generate a certain

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level of electricity (De Vos, 2015; Bajwa and Cavicchi, 2017).

Within the scope of this research project, we examine the extent to which new market players in the electricity system can affect electricity prices, particularly, with regard to negative electricity prices. To this end, we implement an energy-only market model for the day-ahead market and consider two time periods. We apply the established six node network according to Chao and Peck (1996) while considering limited transmission capacities as well as Kirchhoff's laws to represent the grid's physical restrictions. The nodes have conventional generators, renewable energy sources, and electricity consumers. In the first period, renewable energy sources can generate electricity. In the second period, there is only the possibility to generate electricity with conventional power plants. In this paper, we assume marginal costs for renewable energy sources to be zero. To determine the effect of flexible electricity consumers, we first consider the reference case, i. e., the model with inflexible consumers that maintain a certain electricity consumption in the two considered time periods. Subsequently, we examine the model with flexible consumers. More specifically, we consider flexibility on the demand side as load shifting. Thus, electricity consumers can shift – for given costs – a share of their originally planned consumption from one period to another, and they can do so without loss of efficiency, i. e., with no additional electricity consumption due to this load shifting. We set the focus of our evaluation on the nodal prices, the share of renewable energy sources, and the total system costs.

The reference case with inflexible consumers does not exhibit any negative prices. Assuming that electricity consumers can be flexible, negative electricity prices occur at two nodes, which would appear to be a contradiction, since negative prices are commonly attributed to a lack of flexibility. However, the prices at the nodes reflect the marginal cost of an additional unit of electricity. Therefore, the negative prices at the two nodes represent an incentive to reduce the total system costs by consuming additional electricity at these nodes. Increasing the consumption at these nodes, while taking into account Kirchhoff's laws, makes it possible to alter the use of the generation units in the entire electricity system. The additional consumption at a node with a negative electricity price allows other flexible consumers to shift their electricity while complying with the grid's restrictions. In such a scenario, conventional power plants produce less electricity while renewable energy sources produce more. As the corresponding savings in electricity generation exceed the cost of load shifting, flexibility on the demand side can reduce overall system costs. This load shifting also contributes to an increase in the share of renewable energy sources in total electricity generation.

Accordingly, our research indicates that new market players can influence price structures in electricity systems. As our case study illustrates, flexible consumers can induce negative electricity prices. Although, negative prices have long been associated with a lack of flexibility in electricity systems, our results demonstrate that negative prices can be an incentive for the targeted use of flexibility on the demand side. On the one hand, flexibility on the demand side can reduce system costs. On the other hand, it can contribute to an increased share of renewable energy sources in electricity systems. Our work in this area may serve as a starting point for a detailed examination of how new market players impact electricity systems. To this end, it is important to extend our first analysis of negative electricity prices in electricity systems so as to provide policymakers with sufficient information on the extent to which negative prices should be part of a future market design, if indeed they should be.

Keywords:
Electricity Pricing, Renewable Energy Sources, Demand Flexibility, Nodal Pricing, Market Design, Case Study

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