The Digital and Sustainable Transformation of Electricity Systems: Understanding Information Systems Enabled Flexibility

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Cogito ergo sum.

René Descartes (1596 – 1650)

Für meine Eltern, die mir so Vieles ermöglicht haben.

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Copyright Statement

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

Abstract

To mitigate climate change, the world-wide decarbonization of electricity systems is crucial. Against this background, it is necessary to increase the share of renewable energy sources in electricity systems. The corresponding energy transition represents a fundamental transformation of electricity systems. However, an increase in renewable energy sources also poses challenges to electricity grid stability. For example, the feed-in of photovoltaic and wind power plants is intermittent due to inherent weather-dependency, and, because of physical constraints, the electricity grid has to balance supply and demand at all times. Moreover, increasing the (decentralized) feed-in of renewable energy sources might not only result in grid congestion, but could also affect electricity market structures. In this context, discussions on electricity market design attract attention that, in turn, shape electricity systems world-wide. Over the past years, research on Information Systems established the stream of Energy Informatics with the aim of providing applicable and digital solutions to the transformation of electricity systems. To cope with the ongoing transformation of electricity systems, research knows several options to increase electricity systems' flexibility that are able to account for increasing intermittency on the supply side. In this regard, increasing the flexibility on the demand side through measures of demand response is of particular interest. Therefore, both research and practice consider the important role of Information Systems in enabling and exploiting the potential of flexibility in electricity systems.

This thesis presents the most recent insights on the ongoing transformation of electricity systems relating to the integration of renewable energy sources and corresponding discussions on electricity market design, and, more specifically, on electricity pricing regimes. Subsequently, it elaborates on associated digital solutions with respect to Energy Informatics. Moreover, the thesis outlines the need for and describes different options to increase flexibility in electricity systems, and it analyzes – in more detail – the flexibility option of demand response that is applied in various sectors. Finally, the thesis considers recent research on the crucial role of Information Systems in enabling, implementing, and operating flexibility in electricity systems by bi-directional information flows, automated control, optimizations of electricity markets, and digital (market) platforms.

Overarching, seven research papers are embedded in this thesis. The thesis contextualizes the research papers’ contributions by disclosing the most recent insights to researchers and practitioners. To summarize, the thesis reflects the transformation of electricity systems world-wide and contributes to an understanding of Information Systems enabled flexibility in electricity systems.

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1 Introduction

1.1 Motivation

The ongoing climate change urgently requires immediate, purposeful, and applicable solutions. A further world-wide rise in temperature poses a threat to the entire gamut of human life, work, and society (Wheeler and Braun 2013; Cook et al. 2016). The increase in greenhouse gas emissions is one of the main causes of climate change. Consequently, various international initiatives emphasize the imperative need of action. For instance, the 2015 Paris climate agreement, ratified by 195 parties, is an important milestone in the international effort to address climate change. The ratifying parties committed themselves to a significant reduction of greenhouse gas emissions (Rogelj et al. 2016). A major goal of the Paris agreement is to keep the increase in the global average temperature below 2° C above pre-industrial levels while aiming to limit the increase to 1.5° C. Being both legally binding and a comprehensive initiative to combat climate change, Barack Obama, former president of the United States of America, reflects on this as “the best chance we have to save the one planet that we've got” (Horowitz 2016). In addition, the United Nations’ Sustainable Development Goals underline the importance of sustainable energy systems. For example, Sustainable Development Goal #7 aims, among others, at ensuring sustainable energy for all (United Nations 2021).

As the need to reduce greenhouse gas emissions and to implement sustainable energy systems prevails, the increase in non-fossil and renewable energy sources (RES) in the global energy mix is crucial (Dincer 2000). For example, the Commission of the European Union stated its aim to promote the reduction of greenhouse gas emissions of energy systems via measures toward the decarbonization of energy supply (European Union 2012; Gerbaulet et al. 2019). Against this background, the potential of RES, especially photovoltaic and wind power plants with the most fastest increasing capacities among RES (Goebel et al. 2014), must be further exploited.

In addition, with the ongoing electrification of various energy-demanding sectors, i.e., sector coupling, renewable electricity, and hence, electricity systems as part of energy systems are of particular interest to decarbonization (Brown et al. 2018). With respect to sector coupling and decarbonization through RES, electricity can substitute fossil fuels in the transportation sector, for example, in the form of e-mobility or by generating (green) synthetic fuels such as hydrogen (Emonts et al. 2019; Glenk and Reichelstein 2019). In this context, green hydrogen can also be used, among others, in the manufacturing industry to decarbonize energy-intensive production processes (Bhaskar et al. 2020). Furthermore, in the heating sector, renewable electricity can play an important role (Jonynas et al. 2020). Several countries, Norway among others, already use a large proportion of RES to provide the required energy to the heating sector (Seljom et al. 2011).

However, the increase of RES – also referred to as energy transition – manifests as an ongoing transformation of electricity systems world-wide, albeit accompanied by several challenges: It is not only challenging to promote investments in RES in order to increase their share in the energy mix, but also to deal with RES' inherent, weather-dependent intermittency (Liang 2017; Research Paper 4).[1] As a technical prerequisite, the electricity grid has to be in balance, that is, the feed-in – within a certain range of tolerance – needs to equal the consumption at all times. Hence, increasing the share of RES presents a challenge to grid operators. Moreover, as the energy transition also results in the phasing out of lignite and coal-fired power plants and even – in some countries –nuclear power plants (that provide a necessary measure of controllability and stable feed-in), the required balance of supply and demand is at stake (Halbrügge et al. 2021; Research Paper 1) as the intermittency on the supply side is expected to increase considerably. Further transforming electricity systems, the increasing share of RES also affects electricity markets in various ways structurally. On the one hand, a particular electricity market design would be able to promote investments in RES; on the other hand, RES could affect market structures and outcomes due to possible grid congestion that renew discussions about electricity market pricing regimes.

Irrespective, intermittency on the supply side requires system flexibility. This flexibility relates to the ability to balance short-term and unexpected load changes in the electricity grid (Schoepf et al. 2018). In this regard, the term "flexibility gap" from

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[1] Note: There are RES plants – for example, hydropower and biomass plants – that are not as weather-dependent as photovoltaic and wind power plants. Hence, these RES plants do not necessarily increase the variability of feed-in from RES. In Germany, for instance the installed capacity of hydropower and biomass plants is rather low, i.e., about 6 % of total capacity installed in January 2021; see, for example, www.smard.de

Papaefthymiou et al. (2018) describes the need to increase flexibility due to the transformation of electricity systems in the context of energy transition. Research identifies five options to increase flexibility within electricity systems (Research Paper 2): supply-side flexibility, storage flexibility, transmission flexibility, demand-side flexibility, and inter-sectoral flexibility. Developing, implementing, and operating applications of these flexibility options is a multi-disciplinary task. Hence, researchers from various fields, including electrical engineering, economics, politics, and Information Systems (IS) propose corresponding solution approaches to close this flexibility gap.

In light of digital transformations, IS research provides solutions to the economy and society that would enable them to thrive in fast-changing environments (Majchrzak et al. 2016; Legner et al. 2017). Against this background Gholami et al. (2016) point out the integral role of IS in the ongoing transformation of electricity systems. Within the IS research community, scholars have for years contributed to corresponding substreams such as Green IS or Energy Informatics. Literature from the IS discipline is aware of its important role in supporting a sustainable energy system (Melville 2010; Watson et al. 2010). Therefore, IS scholars recently, referred to the transformation toward a sustainable energy system "the pressing societal challenge" (Staudt et al. 2019) or "the critical digital transformation of the decade" (Watson et al. 2020). Against this background, Watson et al. (2010) – among others – call on the IS research community to contribute to a sustainable energy system.

1.2 Research Aim

IS research presents digitalization as an enabler of a sustainable energy system in order to combat climate change. Accordingly, Watson et al. (2010) propose the research stream of Energy Informatics as a subfield IS research. Furthermore, the research streams of Green IS (vom Brocke et al. 2013b), Green IT (Murugesan 2008), and IT for Green (Faucheux and Nicolaï 2011) also conduct research in the field of Energy Informatics. According to Watson et al. (2010), Energy Informatics aims at implementing of a sustainable energy system by "analyzing, designing, and implementing systems to increase the efficiency of energy demand and supply systems" (Watson et al. 2010). In addition, Goebel et al. (2014) emphasizes the important role of approaches within Energy Informatics research in balancing supply and demand in RES-based electricity systems by means of digital technologies under the research theme of so-called smart grids. Hence, this research theme elaborates on the concept of flexibility in electricity systems. Moreover, Goebel et al. (2014) also reflect on the critical role of IS in supporting the operation of electricity markets. By combining two of the most fast-growing topics of our time, namely the transformation of electricity systems toward sustainability and corresponding solution approaches with a particular focus on digitalization-enabled flexibility, this thesis positions itself in the research field of IS, more specifically in its subfield of Energy Informatics.

In this context, the aim of this thesis is, first, to provide an overview of the ongoing transformation of electricity systems with respect to the integration of RES and to related discussions on electricity market designs. Moreover, the thesis investigates IS-based solution approaches to this transformation. Second, it aims at providing an understanding of the need for and options to increase flexibility in electricity systems. In addition, it outlines insights on the flexibility option of demand response in more detail. Finally, the thesis reflects on the crucial role of IS in enabling flexibility and, hence, sustainable electricity systems.

Regarding its contribution, the thesis recognizes the inter-disciplinary nature of the IS research community (Benbasat and Zmud 2003; Agarwal and Lucas, Jr. 2005) and shows an awareness of various methodological approaches that may be categorized as behavior-oriented and design-oriented approaches (Chen and Hirschheim 2004; Hevner et al. 2004; Palvia et al. 2004; Buhl et al. 2012). While behavior-oriented research seeks to construct concepts and theories capable of explaining human behavior or the behavior of organizations, design-oriented research seeks to generate artifacts (Hevner et al. 2004). Regarding the latter, artifacts are “constructs, models, methods, and instantiations [...] to address heretofore unsolved problems” (Hevner et al. 2004) in the form of applicable solutions (Peffers et al. 2007; Gregor and Hevner 2013). Accordingly, the research is aware of the need to evaluate the created artifacts (Peffers et al. 2007; Gregor and Hevner 2013). In the context of Energy Informatics, the call of Staudt et al. (2019) for applicable solutions to the decarbonization of energy systems aligns with the aim of design-oriented research. However, constructing concepts and theories is also relevant for the Energy Informatics research stream. Because this thesis and its embedded research papers contain both design-oriented and behavior-oriented research approaches, it restrains multiple contributions. Moreover, the thesis covers both theoretical and practical perspectives on and the contributions of the role of IS to flexibility in electricity systems, thereby providing new solutions to researchers and practitioners, including all relevant stakeholders in electricity systems (ranging from policymakers and plant or grid operators to end-consumers). Finally, the thesis contributes to the successful combating of climate change by implementing sustainable electricity systems world-wide.

1.3 Structure of the Thesis and Overview of Embedded Research Papers

The following section provides an overview of the structure of this thesis and briefly describes the seven research papers that constitute its basis. Figure 1 depicts the embedding of the research papers. Overall, the thesis provides an overview of the digital and sustainable transformation of electricity systems world-wide by reflecting the need for flexibility and the corresponding role of IS in particular.

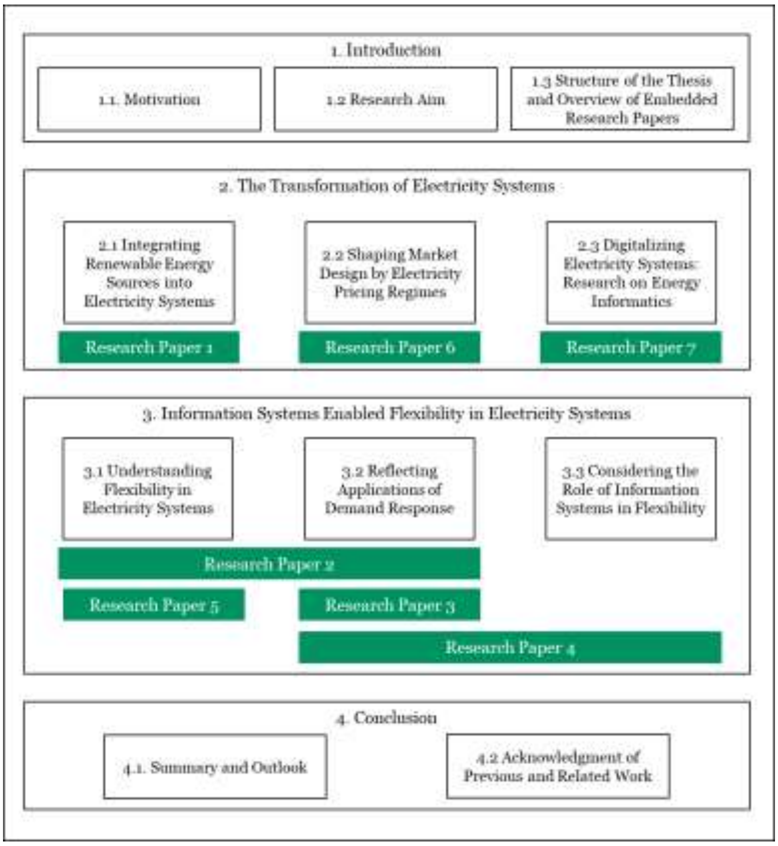

Figure 1: Structure of the Doctoral Thesis

As this thesis is cumulative, its contribution includes the insights garnered from all seven research papers embedded in the thesis. The research papers provide insights into the context of the digital and sustainable transformation of electricity systems with a focus on (IS-enabled) flexibility. Following the introduction (Section 1), Section 2 outlines the ongoing transformation of electricity systems world-wide, while also describing the benefits and challenges of two major components of this transformation in more detail. These components are the increasing share of RES in electricity systems (Section 2.1), as well as discussions on and options for electricity market design and, more specifically, electricity pricing regimes (Section 2.2). Concluding the overview of the transformation of electricity systems, Section 2.3 illustrates how research on Energy Informatics can contribute to tackling corresponding challenges in general. Subsequently, Section 3.1 discusses the essential role of flexibility in ensuring electricity grid stability in light of increasing RES, by providing an overview of different flexibility options. Section 3.2 delves deeper into a particular flexibility option, namely demand response, and concludes by reflecting on the decisive role of IS in enabling, implementing, and operating flexibility in electricity systems. Finally, Section 4 concludes by summarizing and outlining the contribution of the thesis, as well as by presenting an outlook and acknowledging previous and related work. While references are listed in Section 5, Section 6 forms the appendix of the thesis, as it contains detailed information on the embedded research papers, by providing, among others, the corresponding abstracts, respectively, extended abstracts. The supplementary material includes the full texts of all seven research papers (not for publication).

2 The Transformation of Electricity Systems

To understand the ongoing transformation of electricity systems world-wide, it is necessary to consider the most recent developments. Hence, this section describes and reflects on these economic and technological developments and corresponding issues by focusing on the integration of RES into electricity systems and on the benefits and challenges of different electricity pricing regimes as a substantial part of the market design. Thereafter, this section provides an overview of digital approaches to overcome the challenges posed by the transformation of electricity systems by outlining the research field of Energy Informatics.

Throughout the world, various developments – transforming electricity systems from traditional and unidirectional supply chains into multidirectional and multinational electricity supply networks – have changed electricity systems world-wide in the past decades (Research Paper 7): In the European Union, these developments include, among others, (1) increasing sector coupling, (2) the increasing share of decentralized RES, and (3) electricity market liberalizations. These three developments contribute to highly complex structures and processes in electricity systems. Moreover, they are interwoven as, for example, the intended decarbonization of energy systems is only expected to succeed through (1) increased sector coupling if energy supply for all sectors originates – at least for a major part – from (2) RES. Hence, Subsection 2.1 combines the description of (1) and (2) while Subsection 2.2 elaborates on electricity pricing regimes in the context of (3) electricity market liberalization. Finally, Section 2.3 provides an overview of approaches to digitalize electricity systems – in particular regarding the integration of RES into electricity systems (2) and electricity market design (3) – by considering the research stream of Energy Informatics as a sub-stream of IS research.

2.1 Integrating Renewable Energy Sources into Electricity Systems

Regarding the developments of increasing sector coupling and the increasing share of decentralized RES, it is essential to understand the importance of energy generation for the required decrease of greenhouse gas emissions (Research Paper 1). In 2018 in

Germany, for example, about 41% of energy-related greenhouse gas emissions originated from generation, that is, energy and heat generation as well as refineries and solid fuel generation (Umweltbundesamt 2020). Figure 2 – using data of the German Federal Environment Agency, i.e., Umweltbundesamt – relates the significant amount of greenhouse gas emissions originating from energy generation to other energy-consuming sectors (cf. dark blue colored bar in Figure 2). Moreover, Figure 2 also illustrates that overall emissions have already been decreasing over the past years.

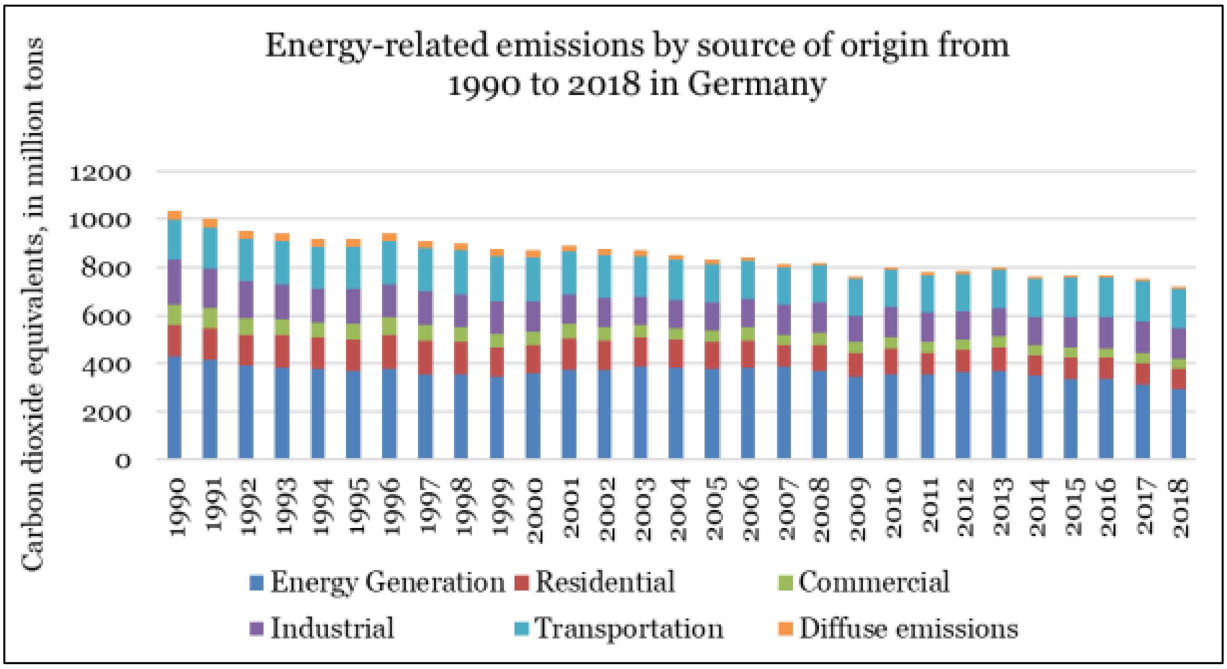

Figure 2: Energy-related Emissions by Source of Origin from 1990 to 2018 in Germany; Source: Umweltbundesamt (2020)

To decrease the high share of greenhouse gas emissions produced by energy generation, policymakers have initiated several measures over the past decades, with the aim of increasing the share of RES being one of the most prominent. Increasing the share of RES is of particular relevance as the previously mentioned advancement of sector coupling is expected to play a significant role in terms of decarbonization (Arabzadeh et al. 2020): Sector coupling aims at the electrification of all energy-consuming sectors, i.e., overall energy supply mainly originates from electricity systems (Research Paper 1). Consequently, electricity systems should to a large extent rely on RES. Therefore, a major task of policymakers and practitioners is to (further) increase the share of RES by increasing investments in RES plants. At this juncture, sector coupling may also present new opportunities to increase the profitability of RES plants (Rövekamp et al.

2021): By enlarging the market for RES-based electricity, for instance, for producing green hydrogen (Glenk and Reichelstein 2019), sector coupling may enable an increase in investments in RES plants.

Several countries introduced concomitant programs to promote investments in RES. In Germany, for example, these programs result in the prioritized feed-in of RES as well as in fixed feed-in tariffs for RES plant operators. Along with RES' low marginal costs close to zero, this also affects the so-called merit order, which determines the sequence of feed-in, i.e., order, of power plants (Sensfuß et al. 2008; Woo et al. 2016). Against this background, the share of RES in world-wide energy generation has already increased considerably (cf. Figure 3). Moreover, research and practice expect the RES share to further increase significantly in future (Lund 2007).

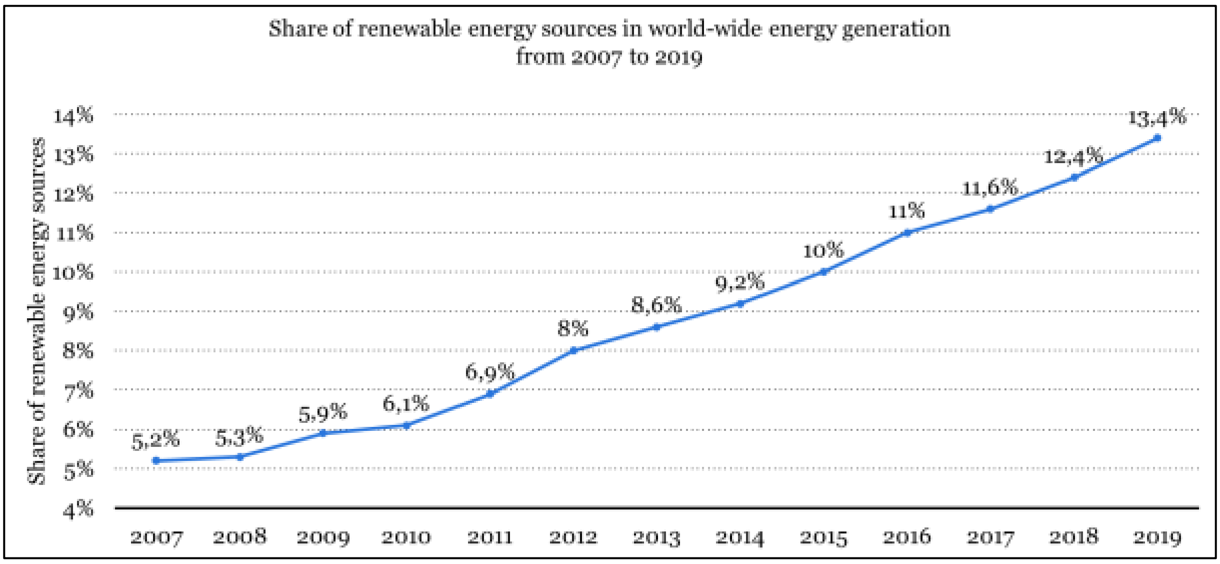

Figure 3: Share of RES in World-Wide Energy Generation from 2007 to 2019; Source: FS-UNEP (2020)

Besides increasing the share of RES, also the integration of RES into electricity systems is accompanied by high complexities (Research Paper 1): While RES' spatial distribution and the larger number of generation plants in RES-based systems[1], also RES' inherent intermittency challenges historically grown electricity systems (Halbrügge et al. 2021; Lund et al. 2015). In contrast to centralized conventional power plants, RES plants typically have a smaller capacity and are, above all, spatially distributed (Research Paper 1). Hence, electricity systems have to deal with a larger number of

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[1] Compared to electricity systems based on conventional power plants; see, for instance, Research Paper 2.

generation plants with a very decentralized feed-in, on the one hand (Perera et al. 2019). On the other hand, the feed-in of RES is to a large extent weather-dependent and therefore intermittent as it affects, among others, electricity markets (cf. Section 2.2.) and grid stability (Research Paper 1). Concerning grid stability, grid frequency indicates the balance of electricity supply and demand (Shi et al. 2018). Within the interconnected European electricity grid, the grid frequency varies around 50,0 Hz. However, grid stability only allows small deviations: failures may already arise below a frequency of 49,8 Hz (Halbrügge et al. 2021). Therefore, the intermittent feed-in of RES not only affects but challenges grid stability (Shi et al. 2018). To account for the intermittency of RES on the supply side, and hence, to ensure grid stability, research considers (new) approaches to increase the flexibility of electricity systems (cf. Section 3).

2.2 Shaping Market Design by Electricity Pricing Regimes

Apart from challenging grid stability, the increasing share of RES and its integration into electricity systems not only affect electricity markets and electricity prices but, vice versa, also the corresponding market design that can promote investments in RES (Rövekamp et al. 2021). During the past decades, the era of global liberalization provided direction to electricity systems and, in particular, to electricity markets (Pollitt 2012). In this context, the implementation of both wholesale markets for electricity and different electricity pricing regimes, i.e., different options to set the geographical granularity of electricity prices, took place (Weibelzahl 2017), following discussions about related electricity market designs (Research Paper 6). Nowadays, the integration of an increasing share of RES renews these discussions. For example, the structural shift within the merit order and RES' intermittent feed-in lead to varying and even negative prices on wholesale electricity markets (Fanone et al. 2013; Halbrügge et al. 2021). Moreover, integrating RES also requires the critical reflection of (limited) transmission capacity and corresponding grid congestion – as, for example, RES feed-in is mainly decentralized (Research Paper 6). To account for grid congestion before the market-clearing via market design, countries can apply corresponding market-based approaches, i.e., including transmission restrictions to the respective electricity pricing regime. By contrast, approaches in several European countries, such as Germany, apply a so-called redispatch to account for (possible) congestion after the market-clearing; in this regard, see, for example, Linnemann et al. (2011), Bjorndal et al. (2013), Staudt et al. (2018), and Research Paper 6. Subsequently, this section provides an overview of the role of electricity pricing regimes as a part of electricity market design in light of the ongoing transformation of electricity systems.

By implementing wholesale markets for electricity and respective pricing regimes, policymakers target an increase in efficiency – including the operational and economic aspects thereof (Conejo and Sioshansi 2018) – while simultaneously ensuring energy security and energy equity[2]. Therefore, electricity market liberalization in the European Union also broke up vertically integrated monopolies to promote (private) investments, e.g., in electricity generation projects, by means of increased competition (Pollitt 2012). Today, there exist various forms of (liberalized) electricity market designs in several countries. These forms differ, for instance, in respect of the role and power of included market parties, the specific form and setup of electricity markets, and various options for trading electricity, including electricity pricing regimes (Cramton 2003). In general, research and practice differentiate between three electricity pricing regimes: uniform pricing, zonal pricing, and nodal pricing (Gan and Bourcier 2002; Leuthold et al. 2008; Weibelzahl 2017). Figure 4 illustrates these three pricing regimes by depicting three nodes (black dots) in different (geographical) pricing zones (dashed lines).

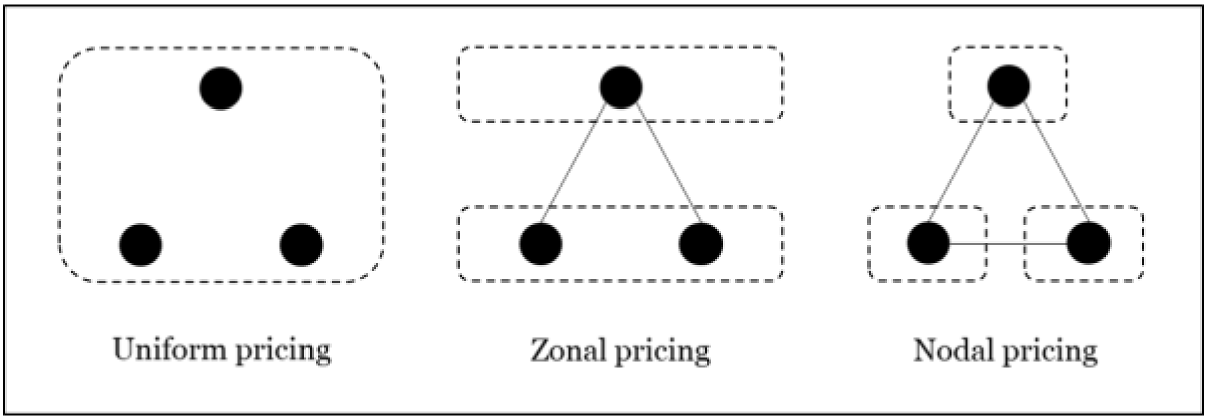

Figure 4: Schematic Illustration of Electricity Pricing Regimes; Source: Sauer et al. (2019)

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[2] Energy security, energy equity, and energy sustainability form the three horns of the energy trilemma. While sustainability was not a focus during the era of liberalization, it is currently of specific concern.

As briefly introduced above, the three pricing regimes differ in the way how they account for the limited (spatial) transmission capacities of the electricity grid – after local generation and consumption – and how they transfer these (scarce) capacities to electricity pricing (rules) and geographical granularity, that is, pricing for different regions or nodes (Linnemann et al. 2011; Weibelzahl 2017; Heffron et al. 2021b). The following discussion clarifies the distinct features of the pricing regimes, ranging from nodal through zonal to uniform pricing.

The nodal pricing regime reflects all physical and economic circumstances of an electricity system (Bohn et al. 1984). Hence, the respective market outcome, i.e., the spot-market price, accounts for electricity generation, electricity consumption, and electricity transmission capacities and restrictions (Singh et al. 1998). Thus, the nodal pricing regime ensures that electricity prices are node specific[3] and that they reflect the local, i.e., node-specific, scarcity of available electricity (Chao and Peck 1996). While this also enables corresponding price peaks on the spot market, a nodal pricing regime can ensure a market-oriented and efficient electricity system.

The zonal pricing regime pools the respective nodes of the electricity grid into several pricing zones, whereas the electricity price is the same for all nodes in a particular pricing zone (Bjørndal et al. 2003; Bjørndal and Jørnsten 2007). Here, the market outcome accounts for inter-zonal, but not for intra-zonal electricity generation, electricity consumption, as well as electricity transmission capacities and restrictions. To account for the intra-zonal restrictions, redispatch measures may be necessary, for example, conducted by a transmission system operator. Usually, redispatch occurs ex-post, i.e., after market-clearing on wholesale electricity markets, to equalize the non-considered, intra-zonal capacities and restrictions (Egerer et al. 2016). Hence, redispatch may up-regulate or down-regulate electricity generation plants or consumers to ensure the required electricity grid balance.

The uniform pricing regime only contains a single pricing zone as the electricity price is the same for all nodes linked in a respective electricity grid. Hence, this pricing regime does not consider transmission capacities and restrictions but only overall elec-

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[3] Note: This means that the price for electricity may be different at each node of the network, i.e., electricity grid.

tricity generation and electricity consumption (Kahn et al. 2001). Consequently, redispatch has to take place after market-clearing on wholesale electricity markets – similar to zonal pricing (Müsgens et al. 2014; Weibelzahl 2017).

Furthermore, the respective electricity market regimes may affect (private) investments in electricity generation plants (Heffron et al. 2021b): For example, compared to uniform pricing, nodal pricing can directly incentivize investments of operators at nodes where the electricity supply is scarce. However, when choosing an electricity pricing regime, political decisions – for example, distribution effects and concerns in the context of energy equity or market power – also play a major role. Irrespective, necessary redispatch measures under zonal- and uniform pricing regimes are cost-intensive: In Germany, almost 17 000 GWh had to be upregulated or downregulated in 2020 in the context of redispatch measures at a cost of 443 million Euros (Bundesnetzagentur 2021b). Table 1 – taken from Heffron et al. (2021b) – provides an overview of the possible benefits and challenges of the three different electricity pricing regimes.

Table 1: Selection of Benefits and Challenges of the Three Electricity Pricing Regimes; Source: Heffron et al. (2021b)

Electricity pricing regimes	Benefits	Challenges
Nodal pricing	• Efficient dispatch of generation • Local signals/incentives in long-run investments • No redispatch necessary	• High system complexity • Many small submarkets with possible low competition and market power abuse • Fluctuating local prices
Zonal pricing	• Reduced number of different prices (compared to nodal pricing) • Increased intra-zonal competition • Price stability	• Possibly, inefficient dispatch of power plants • Reduced signals for flexibility • No local signals/incentives for long-run investments • Difficult determination of zonal boundaries • Possibly, high redispatch costs and associated reallocation issues • Defining adequate remuneration for redispatch services
Uniform pricing	• High market liquidity • Low system complexity • Relatively high competition • Price stability	• Possibly, inefficient dispatch of power plants • Possibly, inefficient long-run investments

		• Possibly, high redispatch costs and associated reallocation issues

This overview indicates that all three electricity pricing regimes include benefits and challenges that have to be accounted for when analyzing a country's specific electricity generation, electricity consumption, as well as electricity transmission capacities and restrictions. To summarize, integrating an increasing share of RES into electricity systems also structurally transforms electricity markets. Electricity pricing regimes – as a substantial part of market design – offer different options to account for transmission congestion. Hence, the increasing costs of the necessary redispatch measures renewed the discussion on modifying or adjusting electricity pricing regimes, for example, in Germany that currently applies a uniform pricing regime.

2.3 Digitalizing Electricity Systems: Research on Energy Informatics

While the two previous sections illustrate challenges that accompany the transformation of electricity systems, this section provides a brief overview of current applications in pursuit of the digitalization of electricity systems. In particular, it first introduces the goals and themes of the research stream on Energy Informatics. Second, it presents exemplary approaches in the context of Energy Informatics research.

At least since the mid-2000s, IS scholars became aware of the important role of IS in sustainable energy systems with an increasing RES share as well as of the IS discipline's responsibility to develop respective solution approaches (Buhl and Jetter 2009; Watson et al. 2010). In this context, IS scholars describe the "need for a new discipline, Energy Informatics" (Watson et al. 2012) as "a new scientific field" (vom Brocke et al. 2013a). While Energy Informatics research deals with "information and information flows in energy systems" (vom Brocke et al. 2013a), Watson et al. (2010) summarize the idea of Energy Informatics to the following formula by considering the possibility that information, meaning IS, can contribute to the reduction of energy consumption, and subsequently, of greenhouse gas emissions:

$$Energy + Information < Energy$$

Zhang et al. (2018) note that Energy Informatics reflects digital technologies to provide solutions for challenges in the context of electricity systems. Recent streams of Energy Informatics involve not only the IS community but also different disciplines, since corresponding approaches range across “the perspectives of electrical engineering, energy economics, and information technology” (Staudt et al. 2019). To shape the research stream of Energy Informatics, Goebel et al. (2014) introduced a comprehensive framework to illustrate the scope of Energy Informatics (cf. Figure 5).

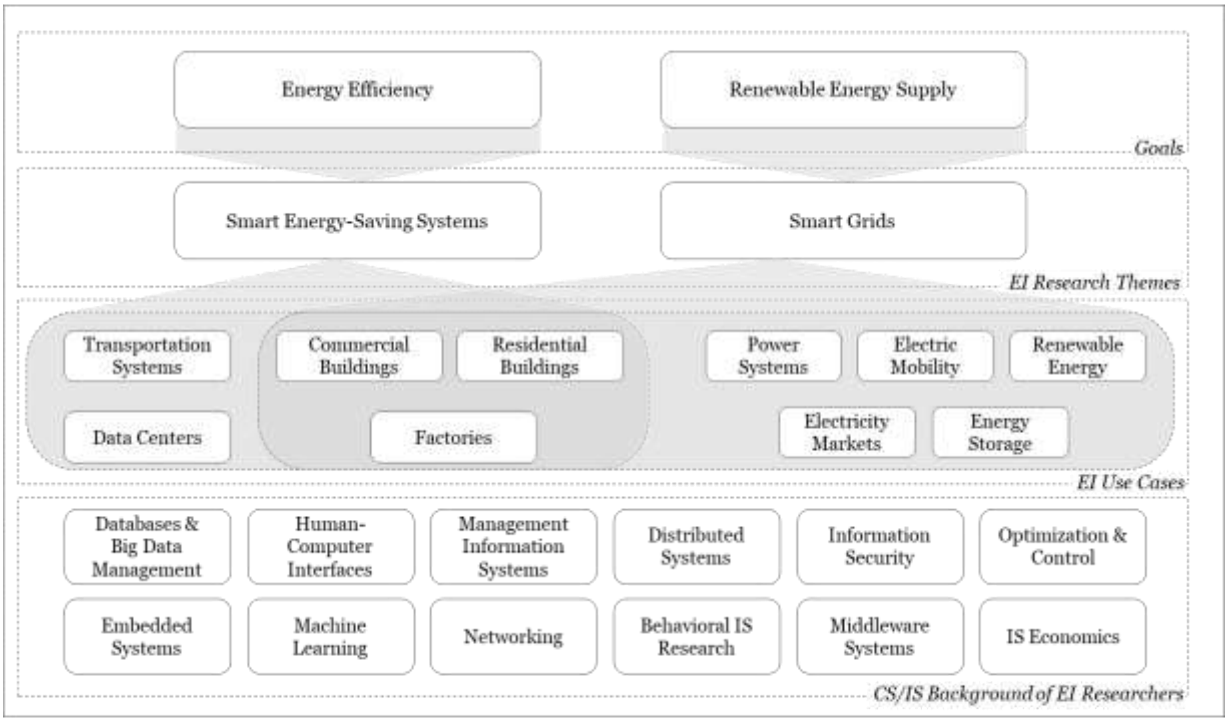

Figure 5: Scope of Energy Informatics Research; Source: Goebel et al. (2014)

In line with Goebel et al. (2014), respectively Figure 5, Energy Informatics research distinguishes between smart energy-saving systems and smart grids. First, smart energy-saving systems aim at increasing the efficiency of energy demand by reducing it effectively and efficiently, for example, in the transportation sector as well as in the context of IT applications, such as data centers (cf. EI Use Cases in Figure 5). In this regard, academic literature on reducing the energy demand of information technology (IT) and data centers – a demand which is expected to increase over the next years (Jones 2018) – is sometimes also linked to the research stream on Green IT (Murugesan 2008). This is also in line with Elliot (2011), who suggests that Energy Informatics research can contribute to a decrease in the ecological (negative) impact of humans. Second, the research theme of smart grids aims at digital solutions to cope with the challenge of integrating an increasing share of RES into the electricity system (Goebel et al. 2014).

Research Paper 4 illustrates that both research themes drawn from Goebel et al. (2014) do not necessarily are not mutually exclusive: Whereas the analyzed artifact – an integrated energy system consisting of an RES-plant and a temporally flexible data center application – may decrease the greenhouse gas emissions of the data center (refers to smart energy-saving systems), it can also provide required flexibility to electricity systems (refers to smart grids); see also Section 3.3.

To provide a deepened understanding of the multifariousness of Energy Informatics research, the following exposition briefly presents exemplary approaches of Energy Informatics that aim at providing IS-enabled solutions for the identified challenges of electricity systems. In particular, the illustrative examples outline approaches regarding the optimization of electricity markets and microgrids before focusing on the potential of blockchain technology and self-sovereign identities for future electricity systems with a high penetration of RES. Finally, the following provides an outlook on flexibility in electricity systems, being the focus of Section 3.

In general, digital solutions can support the integration of RES into electricity systems, for instance, through control and real-time monitoring, market and asset optimization, specific decision support systems, various kinds of platforms, or data exchange across various (electricity) market players (Watson et al. 2010; Vargas and Samper 2012; Watson et al. 2012; Jørgensen et al. 2015; Nielsen et al. 2017; Antonopoulos et al. 2020; Research Paper 7).

Regarding electricity markets, Ketter et al. (2018) note that IS can provide insights into (the optimization of) respective market mechanisms dealing with electricity market design. For instance, Weibelzahl and Märtz (2020) analyze the optimization of investments in the transmission grid and storages in a zonal electricity market.[4] In this case, Energy Informatics supports the provision to solutions for highly complex optimization problems in terms of the required computational power. Moreover, Bichler et al. (2010) recommend research to develop applicable approaches to enable real-time decision making in electricity markets. To ensure this, Energy Informatics research also reflects the potential of artificial intelligence that may support the automation of real-

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[4] For a description of zonal electricity markets, see Section 2.2.

time decision making (Antonopoulos et al. 2020). Furthermore, Bichler et al. (2020) propose alternative IS-enabled auction formats on electricity markets to account, among others, for physical transmission grid restrictions.

Energy Informatics also researches so-called microgrids that are sometimes also linked to energy communities (European Union 2018; Ketter et al. 2018; Gui and MacGill 2018; Sachs et al. 2019). Typically, microgrids pool several (local) energy consumers or prosumers[5] who are able to trade energy within their community resulting in a microgrid pool. Microgrids can operate in an islanded mode or can be coupled with external (micro-) grids, while they do not require RES-typical, spatial energy transportation that usually accompanies the high costs of transmission lines and energy loss during transportation (Research Paper 1). The implementation and operation of microgrids require the use of advanced IS (Mengelkamp et al. 2018). To enable control and transactions within microgrids, several approaches consider blockchain technology (Goranovic et al. 2017). The Brooklyn Microgrid features among the most prominent examples (Mengelkamp et al. 2018). In this context, Goranovic et al. (2017) provide an overview of current blockchain applications in microgrids.

Research on Energy Informatics also considers the use of blockchains for other applications (Wu and Tran 2018; Andoni et al. 2019). For example, literature outlines the role of blockchain technology – along with self-sovereign identities – in increasing data exchange among the various electricity market players (Research Paper 7). While their number increased due to electricity market liberalization, it is necessary to promote cooperation and to ensure the improved monitoring of electricity systems, including the control of systemic risks (Research Paper 7). Energy Informatics reflects these technologies, also to enable a real-time electricity sector (Wang et al. 2015; Shi et al. 2017): To bring the real-time electricity sector to a working stage, policymakers and system operators need to bridge the existing digital gap. For example, the short-term balancing of electricity supply and demand will require the integration of millions of decentralized, small-scale consumption and generation plants as active market participants, into electricity systems (Strüker et al. 2021). In a real-time electricity sector, decentralized consumption plants must be able to switch self-sovereignly and dynamically between self-consumption, thereby providing system services and active participation in

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[5] Prosumers are consumers that are also able to generate (“produce”) energy; see, for example, Zafar et al.2018.

electricity market trading, among others – this is sometimes also referred to as the next step after the so-called redispatch 2.0 (BMWi 2021). In this case, blockchain technology and self-sovereign identities can contribute to the building of an appropriate and digital infrastructure (Research Paper 7).

Finally, Energy Informatics research also contributes significantly to enable the required flexibility in electricity systems (Strüker and van Dinther 2012; Fridgen et al. 2016; Ketter et al. 2018); see also Section 3.3. As further outlined in Section 3.2, demand response is a subset of flexibility on the demand side and refers to short-term adjustments in energy demand due to market price signals (Palensky and Dietrich 2011). Literature applies IS-enabled demand response in various areas, for example, in industrial systems (Huang et al. 2019; Körner et al. 2019), in the residential sector (O'Neill et al. 2010; Haider et al. 2016), and in the transportation sector, i.e., e-mobility (Holly et al. 2020; Baumgarte et al. 2021). In all cases, digital solution approaches allow consumers to flexibly adjust their demand to ensure electricity grid stability. As Section 3 deals with flexibility in electricity systems, this thesis contributes to the Energy Informatics research theme of smart grids in the sense of Goebel et al. (2014).

To summarize, the increasing share of RES – that also needs to be reflected in the context of sector coupling – the integration of RES into electricity systems and the corresponding discussions on market design transform and challenge electricity systems world-wide. However, as illustrated in this section, various digital solution approaches can provide support attempts to deal with these challenges. One of the main challenges to solve is RES’ inherent intermittency. Therefore, Section 3 elaborates on the necessity of increasing flexibility in electricity systems.

3 Information Systems Enabled Flexibility in Electricity Systems

As described above, electricity systems need to integrate an increasing share of RES to support the world-wide combat of climate change. Against this background, the following sections elaborate on flexibility in electricity systems that, according to research, is expected to play a key role in future. Accordingly, Section 3.1 provides an understanding of (the need for) flexibility and presents several flexibility options that are currently discussed in academic literature. Section 3.2 analyzes one of these flexibility options in more detail, namely demand response. Finally, Section 3.3 reflects on the critical role of IS in enabling and implementing flexibility.

3.1 Understanding Flexibility in Electricity Systems

Several physical circumstances apply to electricity systems, for example, those encapsulated by Kirchhoff's Laws. Among others, these circumstances require the electricity grid to be in balance, i.e., electricity supply has to equal electricity demand at any time – within a certain range of tolerance (cf. Section 2.1). As outlined in the previous sections, the increasing share of feed-in from RES increasingly tackles this balance, i.e., grid stability. To ensure grid stability, operators have to intervene on an increasing basis: German grid operators had to curtail almost 6500 GWh of RES feed-in in 2019 whereas, in 2009, the required curtailment of RES feed-in only totaled 74 GWh (Bundesnetzagentur 2021a). This example illustrates the increasing imbalance within the electricity system and thus enormous demand for RES curtailment. Curtailment is necessary when grid stability is compromised by transmission constraints.

In the past, electricity supply originated from a few controllable and conventional power plants, including coal-fired or nuclear power plants (Research Paper 2). Hence, electricity supply could be aligned to fit the respective (inelastic) electricity demand patterns by ramping the various power plants up or down (Research Paper 5). This inelasticity means that electricity demand does not react to price changes in accordance with (short-term) changes in electricity supply (Cargill and Meyer 1971). However, the ongoing transformation of electricity systems described in Section 2 changes the structure of the electricity supply side. In light of the phase-out of conventional power plants as well as the increasing feed-in from RES, it will be increasingly difficult to provide the necessary flexibility of the supply-side in its current form (Heydarian-Forushani et al. 2017; Research Paper 5).

Accordingly, Degefa et al. (2021) comprehensively define flexibility as “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.” Research distinguishes between spatial and temporal flexibility (Research Paper 5): Whereas spatial flexibility denotes the transport of electricity from areas where it is generated to areas where it is consumed[1], temporal flexibility not only refers to short-term adjustments due to increased or decreased supply or demand but also – in respect of RES – to relevant seasonal patterns (Palensky and Dietrich 2011; Mulder 2014; Fridgen et al. 2017). As previously indicated, Papaefthymiou et al. (2018) describe the critical need to increase the flexibility of electricity systems as the flexibility gap. In line with Research Paper 2, there are five different options to close the flexibility gap: (1) (new) supply-side flexibility, (2) storage flexibility, (3) transmission, i.e., grid, flexibility, (4) demand-side flexibility, and (5) inter-sectoral flexibility. The aim of all flexibility options is to close – or at least to reduce – the flexibility gap in order to ensure the stability of the electricity grid. The following overview briefly describe the five flexibility options.

First, supply-side flexibility refers to the adjustment of electricity feed-in, i.e., supply, from electricity generating plants to align with electricity demand. Excluding, for example, coal-fired or nuclear power plants, there are only a few conventional power plants that can provide a certain amount of flexibility. For instance, gas-fired power plants can provide short-term flexibility on the supply-side due to their respective ramping up or down characteristics; see, for instance, the considerations of Glensk and Madlener (2019). It can be argued that the curtailment of RES depicts the possibility of adjusting the electricity supply. However, this cost-intensive possibility can only be used to decrease the electricity supply.

Second, storage flexibility provides temporal flexibility as it allows the balancing of temporal inequalities between electricity supply and electricity demand (Després et al.

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[1] See, for example, the discussions about planned DC transmission lines from Northern to Southern Germany.

2017; Weibelzahl and Märtz 2018). In this sense, for example, electrical batteries are able to demand and store electricity at times when it is abundant and feed-in electricity back to the grid, i.e., supply, in times when electricity is scarce (Peker et al. 2018).

Third, transmission flexibility is able to provide spatial flexibility (Lannoye et al. 2015). In particular, RES plants feed-in their electricity in a decentralized manner and sometimes also off-shore – as is the case in respect of certain wind power plants. In this regard, the transmission grid is able to transport the electricity to locations where electricity demand is located. Hence, transmission flexibility allows the inter-regional transport of electricity. However, increases in transmission flexibility, by building new transmission lines, is often confronted with public protests from the public; see, for instance, the ongoing discussions about the planned Suedlink transmission line in Germany (Neukirch 2020).

Fourth, demand-side flexibility enables electricity consumers to be flexible. This flexibility option – involving short-term adaptions often referred to as demand response as a subset of demand-side flexibility – is able to provide both temporal flexibility by rescheduling electricity consumption and spatial flexibility by distributing demand spatially among redundant consumers (Strbac 2008; O'Connell et al. 2014; Fridgen et al. 2017). Section 3.2 provides a deep dive into this flexibility option.

Finally, inter-sectoral flexibility entails the concept of sector coupling. It is based on connecting and electrifying various energy-consuming sectors (Research Paper 1). Here, power-to-X technologies enable this flexibility option (Buttler and Spliethoff 2018). However, in some countries, current regulation may inhibit comprehensive inter-sectoral flexibility, including various grids that transport energy from real-world implementation, so far (Fridgen and Körner 2020).

Besides the potential of increased flexibility in electricity systems, the literature also discusses corresponding obstacles that may be manifold; see, for example, Olsthoorn et al. (2015), who survey flexibility barriers in the manufacturing industry. Corresponding, an increasingly high number of hours with negative electricity prices most likely indicate the need to implement additional flexibility in electricity markets to reduce the effect or to overcome these obstacles (Halbrügge et al. 2021).[2]

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[2] Halbrügge et al. (2021) note that, in 2019, there were 211 hours with negative (day-ahead) prices in the market area of Germany and Luxembourg.

Apart from obstacles, the literature also elaborates on the possible consequences of flexibility in electricity markets. For instance, some research considers the impact of flexible electricity demand on electricity markets (Gutierrez et al. 2003; Bompard et al. 2007). Accordingly, Bompard et al. (2009) analyze the impact of demand-side flexibility on market power in competitive electricity markets, including strategic bidding behavior. This research specifically elaborates on the role of electricity storage with reference to market power concerning short-run electricity prices and system costs (Research Paper 6). More recently, several studies find that the introduction of electricity storages may affect electricity prices in competitive markets (Weibelzahl and Märtz 2018; Djeumou Fomeni et al. 2019; Grübel et al. 2020). These analyses are likely to directly affect ongoing discussions about electricity market design and electricity pricing regimes (cf. Section 2.2).

Nevertheless, research and practice clearly underline the need to increase flexibility in electricity systems. Hence, it is important to remember that the five flexibility options are not mutually exclusive: This means that the successful integration of RES into electricity systems does not require a single option but rather (a combination of) all available options. Also, it is important to note that there is no universal research use of the five-fold classification of flexibility options. For instance, one may argue that inter-sectoral flexibility is located at the interface of demand-side flexibility as well as storage flexibility.[3] However, the concept of sector coupling will play an important role in respect of the future decarbonization of energy systems. Thus, and in line with the research of Lund et al. (2015) on power-to-X technologies, Halbrügge et al. (2021), Research Paper 2, and Research Paper 5, this thesis regards inter-sectoral flexibility as a separate flexibility option. The next section focuses in more detail on demand response, whereas Section 3.3 covers the critical role of IS in enabling flexibility in electricity systems.

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[3] This would be line with, for instance, Ländner et al. 2019, who only reflect four different flexibility options.

3.2 Reflecting Applications of Demand Response

Regarding flexibility options, Research Paper 2 argues that demand response may pose fewer challenges to (social) acceptance. Moreover, Cardoso et al. (2020) consider demand response to be a cost-effective flexibility option. In this context, academic literature highlights demand response as a promising flexibility option and a key building block of future electricity systems world-wide (Albadi and El-Saadany 2007; O'Connell et al. 2014). To indicate applications of demand response, this section first locates the concept of demand response among the measures of demand-side flexibility and, second, outlines varying types of demand response programs before finally describing the adaptation of demand response in different sectors.

Research assigns demand response as a subset of demand-side flexibility to the measures of demand-side management (Strbac 2008; Palensky and Dietrich 2011). The term demand-side management encompasses all “modifications in the demand side energy consumption pattern to foster better efficiency and operations in electrical energy systems” (Behrangrad 2015). The measures of demand-side management include energy efficiency, time of use pricing, demand response, and balancing power (Palensky and Dietrich 2011). Among others, these four forms of demand-side management differ in respect of their temporal dimensions. While measures concerning energy efficiency account for decreasing consumption, and therefore, greenhouse gas emissions in the long run, adaptions in the sense of demand response can ensure a balance between electricity generation and consumption in the short run (Palensky and Dietrich 2011; Feuerriegel and Neumann 2014; O'Connell et al. 2014; Buhl et al. 2019).

Demand response depicts the adaption of electricity consumption to align with the current electricity supply, i.e., contributing to the balance between electricity generation and consumption (Siano 2014; Paterakis et al. 2017; Jordehi 2019). Against this background, Albadi and El-Saadany (2007) describe demand response as “all intentional modifications to consumption patterns of electricity of end-use customers that are intended to alter the timing, level of instantaneous demand, or the total electricity consumption.” Moreover, demand response enables electricity consumers to benefit from lower electricity prices since electricity markets reflect grid imbalances – also in the short-run (Paulus and Borggrefe 2011; Feuerriegel and Neumann 2014).

Both literature and practice note different forms of demand response. To structure these forms, Albadi and El-Saadany (2007) and Nikzad and Mozafari (2014) distinguish between demand response programs based on incentives and demand response programs based on prices. Incentive-based demand response programs include, for example, ancillary services markets or capacity markets. Incentive-based programs reward their participants with financial benefits according to their amount of demand increase or decrease, respectively (Imani et al. 2018). Price-based demand response programs, by contrast, entail dynamic price rates, i.e., electricity tariffs that dynamically adapt the electricity supply, including, for example, real-time pricing or time-of-use pricing (Haider et al. 2016; Monfared et al. 2019). In general, demand response programs typically encourage electricity consumers to adapt their consumption through market signals.

Regarding the different consumers, various electricity-demanding sectors may adapt demand response programs, with the inclusion of the residential, the transportation, the commercial and service, as well as the industrial sector (Torriti et al. 2010; Boßmann and Eser 2016; Kiliccote et al. 2016; Li and Pye 2018). The following overview outlines corresponding applications in these sectors.

In the residential sector, several household applications qualify for demand response programs. Residential electricity consumers may shift, for example, space and water heating, as well as dish washer and dryer activities according to market signals (Kiliccote et al. 2016; Li and Pye 2018). However, for instance, O'Neill et al. (2010) also mention that implementing an appropriate infrastructure for residential demand response, i.e., home energy management systems and advanced metering infrastructure, among others, can hinder the broad implementation of demand response in this sector. Against this background, Hinterstocker et al. (2017) find that time-of-use pricing does not currently have sufficient potential for the residential sector.

Within the transportation sector, research analyzes the potential of electric vehicles for demand response programs in particular (Kahlen et al. 2014; Baumgarte et al. 2021) – also referred to as the concept of smart charging (van der Kam and van Sark 2015). In this context, electric vehicles, or more specifically their batteries, offer the potential for demand response when there is a negative difference between the required time to recharge the battery and the parking time of the electric vehicle (Fridgen et al. 2014). However, the potential of electric vehicles for demand response programs is, among others, dependent on the enabling of mechanisms that control the scheduling of charging cycles.

With respect to the commercial and service sector, literature on demand response has not yet given sufficient attention to this sector – also because of the existence of several barriers (Cardoso et al. 2020). For example, Wohlfarth et al. (2019) highlight market barriers to inhibit demand response in the (classical) commercial sector. According to Grein and Pehnt (2011), refrigeration systems are among the most promising applications for demand response in the commercial sector. Nevertheless, recent academic research and practice do analyze the potential of demand response applications in the field of information services, i.e., data centers, in more detail (Fridgen et al. 2017; Bahrami et al. 2019; Research Paper 4).

Finally, the industrial sector entails a high potential for demand response programs (Sauer et al. 2019; Roth et al. 2020; Research Paper 2; Research Paper 3). Nevertheless, literature states that the industrial sector has thus not been the focus of demand response research (Shoreh et al. 2016; Huang et al. 2019). Companies within the industrial sector may be able to optimize their production costs, in particular their energy purchasing costs, to a significant extent through demand response programs (Research Paper 3). This optimization may also include expenses for grid charges as they are linked to respective peak loads of companies in some countries (Buhl et al. 2019). Given its high potential, demand response in the industrial sector may face, however, also barriers (Olsthoorn et al. 2015; Cardoso et al. 2020). While the implementation of demand response programs requires standards and modeling, industrial applications are very diverse - compared to, for example, applications in the residential sector (Bauer et al. 2017; Schott et al. 2019). Thus, Huang et al. (2019) argue that the variety in the industrial sector leads to impeding complexity issues for enabling demand response. Moreover, in light of barriers to industrial demand response, Shoreh et al. (2016) mention the role of sophisticated production processes that often hamper a (short-term) adjustment of production rates.

Against this background, research clearly states that advanced metering infrastructures and digital control mechanisms are key prerequisites for exploiting the potential of demand response (Shoreh et al. 2016; Huang et al. 2019; Körner et al. 2019). Hence, the following Section 3.3 elaborates on the role of IS and digital solutions in enabling flexibility.

3.3 Considering the Role of Information Systems in Flexibility

As mentioned in Section 2.3, Energy Informatics research identifies flexibility in electricity systems as a major field to which it can contribute. Hence, IS scholars publish a variety of literature dealing with IS-enabled flexibility in journals and conference proceedings, see, for example, Strüker and van Dinther (2012), Feuerriegel and Neumann (2014), Kahlen et al. (2014), Eisel et al. (2015), Fridgen et al. (2016), or Watson et al. (2020). For instance, Strüker and van Dinther (2012) provide an overview of the role of IS in flexibility on the demand side, while Fridgen et al. (2016) quantify IS-enabled flexibility through an analysis of the transportation sector, in particular, regarding electric vehicles. This section considers the role of IS in flexibility. In particular, it outlines IS' role in the context of bi-directional information flows and the automated control of plants and devices. Moreover, it considers IS for the optimization of electricity markets as well as for digital (market) platforms. Finally, this section elaborates on IS applications themselves to provide flexibility.

Research widely recognizes the relevance of IS in balancing electricity grids (Strüker and van Dinther 2012; Gholami et al. 2016; Ketter et al. 2018). To enable flexibility, there is a need for digital metering infrastructures, smart devices, as well as specific processors that enable bi-directional information flows and the automated control of electricity generating plants as well as electricity demanding devices (Siano 2014; Jäckle et al. 2019). Therefore, since IS provide information and signals that support decision making on the (real-time) exploitation of flexibility, it constitutes an infrastructural and technical cornerstone of flexibility in electricity systems. In addition, IS support the activation and monitoring of corresponding processes. Accordingly, for example, the microgrid framework of Sachs et al. (2019) highlights the importance of IS for flexibility as the respective layer "Information & Communication Infrastructure" plays a key role in enabling application systems and governance "to manage [...] energy technology efficiently."

To (further) exploit flexibility on the demand side, it is necessary to enable automated control of electricity consumers, not only on the (aggregate) household or manufacturing plant level, but foremost on the level of specific devices, in the broader sense of the Internet of Things (Körner et al. 2019; Watson et al. 2020). In this way, IS enable bi-directional information flows, including automated control and electricity flows (Watson et al. 2010).

Moreover, the variety of electricity market players relies on the sharing and processing of information to ensure operating flexibility (Sachs et al. 2019). Therefore, IS present new opportunities and decreased transaction costs to flexibility (Watson et al. 2010; Watson et al. 2013) – especially considering that, for example, some companies within the German electricity system still rely on analog communication via telephone or telefax (Research Paper 3). In addition, the exploitation of flexibility requires a real-time electricity market with corresponding prices that enable and incentivize suppliers and consumers to flexibly adapt their generation and demand, respectively (Watson et al. 2020). As outlined in Section 2.3, IS also support the optimization of market mechanisms, for example, with respect to auction formats.

Considering the exploitation of flexibility, the existing lack of transparency and the current occurrence of complexity can prevent companies from participating in the respective programs (Research Paper 3). In this regard, digital platforms may provide an appropriate solution approach, for example, through aggregators who pool and market the flexibility of several consumers (Ottesen et al. 2018; Stede et al. 2020). Against this background, research also discusses the concept of virtual power plants that combines several (RES) generation plants, storages, and consumers “to create a single operating profile” (Ruiz et al. 2009). Moreover, digital (local) platforms can enable the balancing of supply and demand within energy communities (Schlund et al. 2017; Correa-Florez et al. 2020). Here, also distributed-ledger technologies like blockchain gain attention recently (Schlund and German 2019): Blockchain allows the utilization of the benefits of pooling flexible consumers without being exposed to the potential challenges of (central) aggregators (Schlund and German 2019). In this context, Andoni et al. (2019) provide an overview of blockchain applications in energy systems, including, for example, billing, trading, or grid management, i.e., on the enabling of flexibility. More recently, the three (electricity) transmission system operators TenneT, Swissgrid, and Terna implemented the blockchain-based Equigy platform as European Crowd Balancing platform (Equigy 2020). The Equigy platform aims at enabling small-scale consumers to exploit their flexibility. Despite pioneering these solutions approaches, research already considers the next level or the next step after the so-called redispatch 2.0 (cf. Section 2.3): In addition to the benefits of blockchain, privacy-enhancing technologies such as zero knowledge proofs, and secure multiparty computation, self-sovereign identities may enable small-scale consumers to dynamically switch between self-consumption, providing system services, and active participation in electricity market trading (Strüker et al. 2021). Ultimately, this enables the exploitation of a significant amount of (new) flexibility potential.[4]

Besides the identified IS approaches that contribute to a sustainable energy system by enabling necessary flexibility measures, research critically reflects on IS applications' increasing share of electricity demand of IS applications, for instance, data centers, that emerge along with increasing digitalization (Jones 2018). Hence, it is essential to consider approaches that are able to flexibilize energy-intensive IS applications. Furthermore, IS-enabled approaches can support the exploitation of flexibility as is the case with an IS-enabled, integrated energy system consisting of an RES plant and a data center (Research Paper 4). Figure 6 illustrates the integrated energy system developed in Research Paper 4.

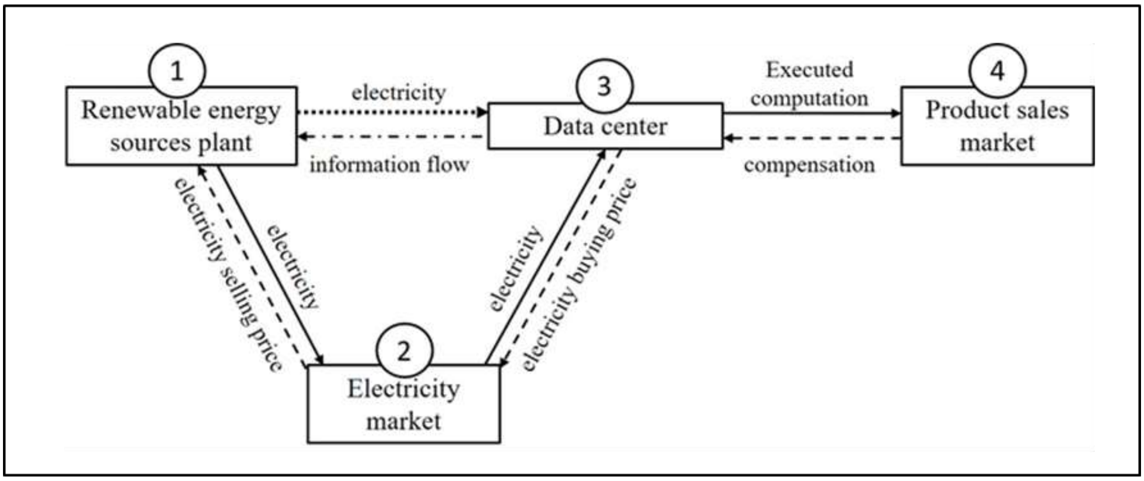

Figure 6: Integrated Energy System Consisting of an RES-Plant and a Temporally Flexible Data Center Application; Source: Research Paper 4

The concept of the integrated energy system consists of (1) an RES plant that is able to either sell its generated electricity on (2) the electricity market or to consume its generated electricity within the integrated energy system by (3) an on-site data center. Computation executed in the data center can be sold on (4) the respective markets.

While Goebel et al. (2014) differentiate between the role of IS in energy systems along two research themes, namely smart energy-saving systems and smart grids (cf. Section 2.3), the implications of the integrated energy system illustrate that these research

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[4] Against the background of decentralized technologies like blockchain and self-sovereign identities, one may argue that there is no further need for a (centralized) platform to exploit this flexibility potential.

themes do not necessarily have to be mutually exclusive: First, the integrated energy system can contribute to the research theme of smart energy-saving systems, i.e., the decarbonization of data centers, as it enables data centers to directly use renewable electricity, thereby contributing to decarbonization. Second, the integrated energy system is able to provide flexibility (cf. Energy Informatics research theme of smart grids) as the data center can consume (external) electricity bought via electricity markets at times of high loads in the electricity grid; and vice-versa, at times of low loads, the RES-plant can feed its generated electricity into the electricity grid, assuming that the data center operation is temporally flexible. Thus, IS-enabled energy-saving approaches should also reflect on how they can contribute to increase the exploitation of flexibility. Moreover, Energy Informatics research must also consider approaches that are capable of flexibilizing energy-intensive IS applications.

To summarize, IS can contribute to the enabling of flexibility in various ways. This entails, among others, an automated control of electricity-consuming devices, IS-enabled real-time markets, digital platforms, as well as flexible IS applications. Therefore, IS-enabled approaches constitute a key enabler of flexibility in electricity systems. However, research and practice confirm that economic and regulatory conditions must support flexibility measures in order to enable their exploitation (Olsthoorn et al. 2015). Here, for example, grid charges and other taxes that currently distort electricity prices for end-consumers in Germany may present several obstacles to the exploitation of flexibility on the supply and the demand side. Nevertheless, research in the context of IS, and in particular, in the context of Energy Informatics, significantly contributes to sustainable electricity systems relying on an increasing share of RES, and thus, finally, to the urgently required decarbonization of energy systems world-wide.

4 Conclusion

4.1 Summary and Outlook

Tackling ongoing climate change requires immediate action and applicable solutions. In this context, the decarbonization of energy systems world-wide is crucial. One way to contribute to the decarbonization of energy systems is to transform electricity systems by increasing the share of renewable energy sources. However, (further) increasing the share of renewable energy sources tackles electricity grid stability as, for example, the feed-in of photovoltaic and wind power plants is weather-dependent and thus intermittent and challenging to control. Moreover, an increasing share of renewable energy sources also transforms electricity markets, and hence, renews discussions on respective electricity market designs and electricity pricing regimes. Among others, to contribute to overcome the challenges with respect to the transformation of electricity systems, the Information Systems community formed a new research stream, namely Energy Informatics. To cope with the ongoing transformation of electricity systems, research knows several options that are able to account for increasing intermittency on the supply side, in order to increase flexibility in electricity systems: Research considers five flexibility options, namely, new supply-side flexibility, storage flexibility, transmission flexibility, demand-side flexibility, and inter-sectoral flexibility. Accordingly, flexibility on the demand side through measures of demand response is of particular interest. Against this background, academic scholars and practitioners consider the crucial role of Information Systems in enabling and exploiting flexibility in electricity systems.

This cumulative thesis includes seven research papers that, respectively, deal with the ongoing transformation of electricity systems regarding the integration of renewable energy sources, with the ongoing challenges induced by electricity market design, with the important role of flexibility, as well as with the crucial role of Information Systems in the required decarbonization of electricity systems. Hence, this thesis highlights how the integration of renewable energy sources transforms current electricity systems through their intermittency and decentralized feed-in (cf. Section 2.1). Subsequently, it elaborates on the role of market design in light of electricity systems that rely on renewable energy sources and discusses different options for electricity pricing regimes in accordance with their benefits and challenges (cf. Section 2.2). Hereafter, this thesis briefly introduces the research stream of Energy Informatics that aims to apply information systems to solve existing and emerging challenges in light of transforming electricity systems (cf. Section 2.3). Being aware of the crucial contribution of flexibility to future electricity systems, this thesis provides an overview of the five flexibility options in Section 3.1. Moreover, it enters into a more detailed analysis of one of these options, namely, demand response that provides flexibility on the demand-side (cf. Section 3.2). Finally, this thesis considers the important role in information systems for exploiting flexibility in electricity systems (cf. Section 3.3).

Overall, this thesis displays several limitations. While it, for example, elaborates on exemplary approaches in the field of information systems enabled flexibility, it does not claim to provide a complete overview of all approaches that are currently discussed. Moreover, this thesis mainly indicates the benefits of the ongoing transformation in electricity systems and, in particular, of increasing flexibility. However, increasing renewable energy sources, modifying electricity pricing regimes, or exploiting flexibility are accompanied by various challenges. For instance, the modification of electricity pricing regimes is a deeply policy-driven process in which many perspectives must be balanced. Therefore, this thesis aims at contributing to a better understanding of the need to increase flexibility in electricity systems. In particular, it provides researchers and practitioners with insights into current Information Systems enabled developments in the field of demand response. Moreover, this thesis reveals the critical role of Information Systems in coping with the challenges posed by the transformation of electricity systems.

Regarding the limitations of the thesis, the embedded research papers provide a broad basis for further research. With respect to electricity market design, for instance, future research may analyze the effect of increasing flexibility on market power particularly in light of sector coupling that research reflects to affect various markets. Moreover, research may also elaborate in detail on business models in the context of flexibility that encourage companies to exploit and market their flexibility potential. In addition, future literature may deal with the impact of decentralized identity management, for example, in the form of self-sovereign identities, on the exploitation of flexibility. Finally, this thesis notes that research and practice may reflect the interplay of different flexibility options since only the combination of all available flexibility options will be able to ensure the expedient decarbonization of electricity systems.

4.2 Acknowledgment of Previous and Related Work

On all research projects and papers, I worked with colleagues at the University of Bayreuth, the University of Augsburg, the Project Group Business and Information Systems Engineering of the Fraunhofer Institute for Applied Information Technology (FIT), and the Research Center Finance and Information Management (FIM). Therefore, I indicate how my work builds on previous and related work conducted within these organizations.

Research Paper 1 and Research Paper 4 relate to the work of Fridgen et al. (2017) and Thimmel et al. (2019), who consider data centers for spatial flexibility. Moreover, Sedlmeir et al. (2020) motivated Research Paper 4, in particular. Among others, for example, Fridgen et al. (2014), Buhl et al. (2019), Körner et al. (2019), and Schott et al. (2019) provided ideas for Research Paper 2 and Research Paper 3. The insights garnered from Halbrügge et al. (2021), Haupt et al. (2020b), and Ländner et al. (2019) on flexibility in general influenced the work on Research Paper 5. Dealing with market design, Research Paper 6 builds on Weibelzahl (2017), Weibelzahl and Märtz (2018), and Weibelzahl and Märtz (2020). Finally, Fridgen et al. (2015) and Fridgen et al. (2019) provided starting points for Research Paper 7.

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6 Appendix

6.1 Research Papers Relevant to This Thesis[1] [2]

Research Paper 1

Fridgen, Gilbert; Keller, Robert; Körner, Marc-Fabian; Schöpf, Michael (2020):

A Holistic View on Sector Coupling.

In: *Energy Policy*.
DOI: 10.1016/j.enpol.2020.111913.

VHB Jourqual 3: Category B, CiteScore 2020: 10.2, SJR 2020: 2.093, SNIP 2020: 1.941 / 95th percentile

Research Paper 2

Heffron, Raphael; Körner, Marc-Fabian; Wagner, Jonathan; Weibelzahl, Martin; Fridgen, Gilbert (2020):

Industrial demand-side flexibility: A key element of a just energy transition and industrial development.

In: *Applied Energy*.
DOI: 10.1016/j.apenergy.2020.115026.

VHB Jourqual 3: n.a., CiteScore 2020: 17.6, SJR 2020: 3.035, SNIP 2020: 2.696 / 99th percentile

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[1] Papers 1–7 can be found in the supplement. Kindly note that the text formatting and the reference style may differ from published papers, to allow for a consistent layout. There is a separate reference section, as well as a separate numbering of figures, tables, and footnotes for each paper.

[2] Continued on the next pages.

Research Paper 3

Haupt, Leon; Körner, Marc-Fabian; Schöpf, Michael; Schott, Paul; Fridgen, Gilbert (2020a):

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, CiteScore 2020: n.a., SJR 2020: n.a., SNIP 2020: n.a. / n.a. percentile

Research Paper 4

Fridgen, Gilbert; Körner, Marc-Fabian; Walters, Steffen; Weibelzahl, Martin (2021):

Not All Doom and Gloom: How Energy-Intensive and Temporally Flexible Data Center Applications May Actually Promote Renewable Energy Sources.

In: *Business & Information Systems Engineering*.
DOI: 10.1007/s12599-021-00686-z.

VHB Jourqual 3: Category B, CiteScore 2020: 10.3, SJR 2020: 1.022, SNIP 2020: 2.992 / 93rd percentile

Research Paper 5

Heffron, Raphael; Körner, Marc-Fabian; Schöpf, Michael; Wagner, Jonathan; Weibelzahl, Martin (2021a):

The role of flexibility in the light of the COVID-19 pandemic and beyond: Contributing to a sustainable and resilient energy future in Europe.

In: *Renewable and Sustainable Energy Reviews*.
DOI: 10.1016/j.rser.2021.110743.

VHB Jourqual 3: Category n.a., CiteScore 2020: 30.5, SJR 2020: 3.522, SNIP 2020: 4.684 / 97th percentile

Research Paper 6

Bjørndal, Endre; Bjørndal, Mette; Coniglio, Stefano; Körner, Marc-Fabian; Leinauer, Christina; Weibelzahl, Martin (2021):

Energy Storage Operation and Electricity Market Design: On the Market Power of Monopolistic Storage Operators.

submitted

Research Paper 7

Körner, Marc-Fabian; Sedlmeir, Johannes; Weibelzahl, Martin; Fridgen, Gilbert; Heine, Moreen; Neumann, Christoph (2021):

Systemic Risks in Electricity Systems: A Perspective on the Potential of Digital Technologies.

submitted

During my PhD, I also contributed to a number of other publications, which are listed below. These publications are not part of the dissertation.

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6.2 Declaration of Co-authorship and Individual Contribution

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.

Research Paper 1 was written by four co-authors. All authors contributed equally to this paper. Together will all authors, I developed the model for a holistic sector coupling. In particular, I contributed to the research paper by conducting the literature review and by elaborating on the contribution of our work. Moreover, I organized the research project. By this, I also wrote the major share of the text in the article.

The work for Research Paper 2 was done by five co-authors. Together with three co-authors, I set-up the idea for this paper. With these three co-authors, I also analyzed existing literature on the paper's topic. Moreover, I also contributed to develop the monitoring approach presented in the paper. One co-author with experience in this area guided the research process and provided us with valuable feedback. The other three co-authors and I acted as lead authors of the research paper. The fifth member of the team contributed to the writing as a subordinate author.

Regarding Research Paper 3, I conceptualized the paper in collaboration with three co-authors. With the same three co-authors, I also realized the workshops with various experts that were a major part of this project. Moreover, I contributed to the consequent literature review, and the qualitative validation of the initial results generated. The other co-author with experience in this area guided the research process and provided us with valuable feedback. Hence, he contributed as sub-ordinate author, whereas the other three co-authors and I acted as lead authors.

Three co-authors and I conducted the work of Research Paper 4. All authors contributed equally to this paper. In particular, I elaborated on the (theoretical) framing and the methodology of the paper. Moreover, one co-author and I developed the use-case applied within the evaluation of the developed model. With this co-author, I also wrote the major share of the text in the article. Moreover, I organized the research project, and presented an earlier version at a scientific conference.

Research Paper 5 was written by five co-authors. All authors contributed equally to this paper. Together with two co-authors, I conducted the literature review on the paper's topic. The other two co-authors provided the initial idea to write this paper and guided us with valuable feedback throughout the paper process. In particular, I contributed to the reflections on (the need for) flexibility. Moreover, together with two co-authors, I worked out the policy implications of the paper.

Six co-authors worked on Research Paper 6. While all authors contributed equally to this paper, together with one co-author I was responsible for the framing of the paper, in particular. Moreover, I provided feedback for the model development and the evaluation cases. With reference to the text of the paper, I closely assist in writing it. The other four co-authors contributed with valuable feedback and expertise in the context of electricity market modeling.

For the work of Research Paper 7 I assigned as lead-author to the paper. The other authors contributed as sub-ordinate authors. In particular, I set up the research idea and wrote a major part of the paper. Moreover, I organized the paper project. While one co-author contributed, in particular, to the section on current risk and crisis management, another co-author provided insights from a practitioner-perspective. The other two co-authors guided the paper process, one with a focus on electricity systems, and one with a focus on digital technologies.

6.3 Research Paper 1 — A Holistic View on Sector Coupling.

Authors: Fridgen, Gilbert; Keller, Robert; Körner, Marc-Fabian; Schöpf, Michael

Published in: *Energy Policy (2020)*

Abstract: Sector coupling (SC) describes the concept of a purposeful connection and interaction of energy sectors to increase the flexibility of supply, demand, and storing. While SC is linked to research on smart energy system and locates itself in the research stream of 100% renewable energy systems, it currently focusses on counteracting challenges of temporal energy balancing induced by the intermittent feed-in of renewable energy sources. As regarding the coupling of grids, SC currently remains within classical energy grids. It does not exploit the coupled sectors' potential to its full extent and, hence, lacks a holistic view. To include this view, we call on the use of all grids from coupled sectors for spatial energy transportation, resulting in an infrastructural system. By using the different loss structures of coupled grids, we illustrate how a holistic view on SC minimizes transportation losses. We argue that SC should include all grids that transport whichever type of energy (e.g., even transportation or communication grids). Ultimately, we derive and discuss implications relevant for policy makers and research: We illustrate why regulation and market design should be aligned in a way that the resulting incentives within and across the different sectors support climate change goals.

6.4 Research Paper 2 — Industrial demand-side flexibility: A key element of a just energy transition and industrial development.

Authors: Heffron, Raphael; Körner, Marc-Fabian; Wagner, Jonathan; Weibelzahl, Martin; Fridgen, Gilbert

Published in: *Applied Energy (2020)*

Abstract: In many countries, industry is one of the largest consumers of electricity. Given the special importance of electricity for industry, a reliable electricity supply is a basic prerequisite for further industrial development and associated economic growth. As countries worldwide transition to a low-carbon economy (in particular, by the development of renewable energy sources), the increasing fluctuation in renewable energy production requires new flexibility options within the electricity system in order to guarantee security of supply. It is advanced in this paper that such a flexibility transition with an active participation of industry in general has unique potential: It will not only promote green industrial development, but also become an engine for inclusive industrial development and growth as well as delivering a just transition to a low-carbon economy. Given the high potential of industrial demand-side flexibility, a first monitoring approach for such a flexibility transition is illustrated, which bases on a flexibility index. Our flexibility index allows for an indication of mis-developments and supports an appropriate implementation of countermeasures together with relevant stakeholders. Hence, it holds various insights for both policy-makers and practice with respect to how industrial demand-side flexibility can ensure advances towards an inclusive, just, and sustainable industrial development.

6.5 Research Paper 3 — Strukturierte Analyse von Nachfrageflexibilität im Stromsystem und Ableitung eines generischen Geschäftsmodells für (stromintensive) Unternehmen.

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

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.

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.

6.6 Research Paper 4 — Not All Doom and Gloom: How Energy-Intensive and Temporally Flexible Data Center Applications May Actually Promote Renewable Energy Sources.

Authors: Fridgen, Gilbert; Körner, Marc-Fabian; Walters, Steffen; Weibelzahl, Martin

Published in: *Business & Information Systems Engineering* (2021)

Abstract: To achieve a sustainable energy system, a further increase in electricity generation from renewable energy sources (RES) is imperative. However, the development and implementation of RES entail various challenges, e.g., dealing with grid stability issues due to RES' intermittency. Correspondingly, increasingly volatile and even negative electricity prices question the economic viability of RES-plants. To address these challenges, this paper analyzes how the integration of an RES-plant and a computationally intensive, energy-consuming data center (DC) can promote investments in RES-plants. An optimization model is developed that calculates the net present value (NPV) of an integrated energy system (IES) comprising an RES-plant and a DC, where the DC may directly consume electricity from the RES-plant. To gain applicable knowledge, this paper evaluates the developed model by means of two use-cases with real-world data, namely AWS computing instances for training Machine Learning algorithms and Bitcoin mining as relevant DC applications. The results illustrate that for both cases the NPV of the IES compared to a stand-alone RES-plant increases, which may lead to a promotion of RES-plants. The evaluation also finds that the IES may be able to provide significant energy flexibility that can be used to stabilize the electricity grid. Finally, the IES may also help to reduce the carbon-footprint of new energy-intensive DC applications by directly consuming electricity from RES-plants.

6.7 Research Paper 5 — The role of flexibility in the light of the COVID-19 pandemic and beyond: Contributing to a sustainable and resilient energy future in Europe.

Authors: Heffron, Raphael; Körner, Marc-Fabian; Schöpf, Michael; Wagner, Jonathan; Weibelzahl, Martin

Published in: *Renewable and Sustainable Energy Reviews* (2021)

Abstract: The energy sector provides fuel for much of everyday life, particularly economically and socially. Fighting against the COVID-19 pandemic, a well-functioning and resilient energy sector is vital for maintaining the operation of critical infrastructures, including, most importantly, the health sector, and timely economic recovery. Notwithstanding its importance in everyday life and crises, the energy sector itself is currently in a complex and far-reaching transformation to combat climate change whilst supporting the transition to a low-carbon economy and society, mainly through the development of variable renewable energy sources (RES) such as wind and solar photovoltaics. This paper highlights the need for energy resilience as countries face the triple challenge of the COVID-19 health crisis, the consequent economic crisis, and the climate crisis. Focusing on Europe, it is advanced here that with the ability to balance fluctuating electricity generation and demand, flexibility allows the energy sector to utilise low-carbon RES reliably, ensuring a more resilient and sustainable energy future. This paper derives five urgent policy recommendations for Europe that address possible impacts of COVID-19 on the economic and societal prerequisites for flexibility in energy systems.

6.8 Research Paper 6 — Energy Storage Operation and Electricity Market Design: On the Market Power of Monopolistic Storage Operators.

Authors: Bjørndal, Endre; Bjørndal, Mette; Coniglio, Stefano; Körner, Marc-Fabian; Leinauer, Christina; Weibelzahl, Martin

Under Review

Extended Abstract[1]

The rapid growth of the share of energy generated via renewable sources highly challenges grid stability (Ludig et al., 2011). The supply by renewable sources can only be controlled to a limited extent as, while they can be curtailed, upwards adjustments of supply are limited to the respective source of electricity generation such as solar energy or wind. Hence, flexibility is key to balance the electricity supply and demand. As a relatively new player in the energy market, the Energy Storage System (ESS) is capable of providing such flexibility, acting as both a consumer and producer. Hence, ESSs allow for avoiding the electricity mismatch with a high variety of applications for securing grid stability (Lund et al., 2015). While the Directive (EU) 2019/944 of the European Union requires ESSs to be operated by an independent market player, ESSs are already becoming an important player in different electricity markets. As hence, the capacity of ESSs operating in the electricity grid increases, it is important to closely examine the influence of the ESSs' participation on the electricity spot market and real-time balancing market. To prevent effects that are potentially harmful for the electricity grid and disadvantageous for other market participants, the regulators must constantly scrutinize the market design and the respective behavior of the market participants (Gencer et al., 2020).

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[1] At the time of this thesis' publication, this research paper is under review for publication in a scientific journal. Therefore, an extended abstract covering the paper's content is provided.

Crucially, it is difficult for, e.g., market-monitoring authorities, to compare the bid cost functions to the true opportunity costs of an ESS. Motivated by this, in this paper we elaborate on the potential of an ESS to exercise market power in a liberalized electricity market. As the capacity of storage facilities operated in the electricity grid increases, comparatively large facilities may emerge and exercise market power by influencing market prices: The question arises if the behavior of a monopolistic storage operator may also have negative impacts on grid stability, and subsequently may increase costs for redispatch. Hence, it is relevant to analyze the behavior of the storage operator and the potential of an inefficient market outcome that reduces the surplus for the other market participants and consequently also decreases the overall social welfare. In particular, we analyze how a monopolistic ESS operator may influence short-run market outcomes, e.g., prices and system costs, depending on different market designs including a nodal, a zonal, and a uniform pricing system (Bjørndal et al., 2013, Weibelzahl, 2017). For this purpose, we propose a four-stage Stackelberg game where the monopolistic ESS operator first decides on its day-ahead market bids (level 1), followed by day-ahead market clearing (level 2), after which the ESS submits bids to the real-time balancing market (level 3), which is then cleared (level 4); see Dempe et al. (2015), Coniglio et al. (2020), or Weibelzahl & Märtz (2020). In addition, the model is able to represent several market designs. Next, we translate the problem of computing an equilibrium in our four-stage Stackelberg model into a four-level hierarchical optimization problem. Accordingly, we illustrate how to reformulate such an optimization problem into a single-level one. In particular, we illustrate how to combine the two levels where the strategic ESS operator submits bids to either of the two electricity markets into a single upper-level problem, and how to replace these two lower-level problems by their Karush–Kuhn–Tucker conditions, whose complementary conditions are then linearized. By means of different case studies, we conclude that the monopolistic storage operator can exercise market power by strategically bidding prices and quantities on a day-ahead market and the subsequent real-time balancing market. Comparing the different market designs, we illustrate that, in case of a monopolistic storage operator, the nodal market design can lead to the smallest increase in system costs as all the transmission lines are accounted for in the day-ahead market. With zonal and uniform market designs, we observe that the storage operator may strategically bid to violate omitted transmission constraints or withhold dispatch capacity. These options allow the storage operator for increased revenues by operating on two spatially different electricity markets.

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6.9 Research Paper 7 — Systemic Risks in Electricity Systems: A Perspective on the Potential of Digital Technologies.

Authors: Körner, Marc-Fabian; Sedlmeir, Johannes; Weibelzahl, Martin; Fridgen, Gilbert; Heine, Moreen; Neumann, Christoph

Under Review

Extended Abstract[1]

In the last decades, several developments have transformed electricity systems in Europe towards liberalized and decentralized systems that are coupled inter-sectorally and inter-regionally. With respect to the European Union (EU), this shift results in particular from (1) electricity market liberalizations, (2) transformations towards decentralized systems based on renewable energy sources, (3) increased sector coupling, and (4) inter-regional coupling of national electricity systems, which yields highly complex and interdependent system structures (Berizzi, 2004; Chu and Majumdar, 2012; Fridgen et al., 2020; Jamasb and Pollitt, 2005). These developments have yielded various benefits, such as increased efficiency. However, we argue that they have also caused new interdependencies with an increase of (hidden) systemic risks, e.g., local failures may spread faster and more extensively throughout the system (Acemoglu et al., 2015). In this paper, we illustrate how systemic risks may arise in European electricity systems. Moreover, we structure current risks and corresponding crisis management in electricity systems and elaborate on its main challenges before, during, and after a potential blackout (Khan et al., 2008). We also discuss the decisive role of digitalization that, on the one hand, speeds up the developments transforming electricity systems, but on the other

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[1] At the time of this thesis' publication, this research paper is under review for publication in a scientific journal. Therefore, an extended abstract covering the paper's content is provided.

hand may also provide solutions to tackle systemic risks. We argue that, especially in a strongly interconnected world, policymakers must implement a global perspective on these critical and increasingly complex systems, requiring adequate cooperation with respect to data. In particular, we call for further collaboration and coordination with respect to relevant data collection, provision, and exchange to be able to construct a global picture of the current state of the system (Fridgen et al., 2019). The current participation of respective stakeholders in committees, such as ENTSO-E, is without any doubt a highly valuable first step, but such efforts need to be intensified and expanded if systemic risks are to be adequately addressed. Using an exemplary case from Germany, we illustrate how an intensified data exchange may help to address systemic risks. As we also argue, while the simplest solution to obtain the required comprehensive information would be a centralized IT system, such a system might be challenging to implement due to economic and political reasons, such as the threat of the new platform being a systemic risk on its own, leading to a data monopoly, or the exchange of sensitive information about a critical infrastructure with other countries. Digital technologies that offer possibilities of an exchange of data and even the reliable enforcement of business logic through smart contracts in decentralized architectures (such as self-sovereign identities and blockchain, combined with privacy-enhancing technologies such as zero knowledge proofs and multi party computation) may help to increase trust and collaboration among the involved market parties, and additionally contribute to security to ensure a more integrated management and control of systemic risks (Zare-Garizy et al., 2018; Zhang et al., 2019). Ultimately, we argue that combining these decentralized technologies with privacy-enhancing computing in order to prove or aggregate necessary information (involving multiple stakeholders) might be a promising direction for the electricity system and requires further research at the interface of decentralized identity management, distributed ledger technologies, privacy-enhancing technologies and systemic risk mitigation in electricity systems.

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