UNIVERSITÄT
BAYREUTH

Accelerating Sustainability in Electricity Systems through Digitalization:
Coping with Complexity in Times of Transition

Dissertation
zur Erlangung des Grades eines Doktors der Wirtschaftswissenschaft
der Rechts- und Wirtschaftswissenschaftlichen Fakultät
der Universität Bayreuth

vorgelegt von
Stephanie Marie Halbrügge
aus Osnabrück

Dekan:	Prof. Dr. André Meyer
Erstberichterstatter:	Prof. Dr. Gilbert Fridgen
Zweitberichterstatter:	Prof. Dr. Jens Strüker
Tag der mündlichen Prüfung:	17.10.2023

The energy of the mind is the essence of life.

Aristotle (384–322 BC)

Acknowledgments

I would like to thank all the people who supported me and made it possible for me to write this doctoral thesis. The path of my academic career so far was shaped by a supporting environment that offered me the opportunity to constantly grow and improve. I am very grateful for the support I received from different persons during this doctoral thesis.

First, I would like to thank my supervisor, Prof. Dr. Gilbert Fridgen, for his guidance. His ideas have always inspired my research. I would like to thank him for his coaching, his honest advice, his trust in me, and his dedication.

I would also like to thank Marc Körner, Jens Strüker, and Martin Weibelzahl for guiding and supporting me on this journey.

In addition, I want to thank all my friends, co-authors, and colleagues at the Branch Business & Information Systems Engineering of the Fraunhofer Institute for Applied Information Technology (FIT), the FIM Research Center for Information Management (FIM), the University of Applied Sciences Augsburg, and the University of Bayreuth.

Moreover, I would like to thank my friends and family. Thank you for your support and friendship, especially I want to thank (in alphabetical order): Jan Bochinger, Philipp Fischer, Sven Fuchs, Franziska Halbrügge, Friederike Halbrügge, Franziska Jöckel, Ise Kalker, Josef Nieberding, Stefanie Nieberding, Lisa Priebe, Kira Spieß, Tom Taborsky, and Linda Wolf.

Finally, I would like to thank my parents in particular, who have always given me strength and supported me unconditionally. You have made this path possible for me.

Copyright Statement

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

Abstract

To pursue urgently needed efforts in addressing ongoing climate change, many countries worldwide have been focusing on the decarbonization of electricity systems, which plays a crucial role in decarbonizing energy systems in general due to a large amount of carbon emissions. However, only recently have voices in research and society called for an acceleration of existing sustainability efforts. To enable such an acceleration of sustainability in electricity systems, various trends have emerged that show potential to address challenges associated with this ongoing transformation. The European Union is focusing on two trends: coupling and digitalizing electricity systems. These trends could move electricity systems toward greater sustainability and increase their efficiency. Yet, they also alter these systems and bring new dependencies, increased interconnectedness, and ultimately new emerging complexities and threats. This is particularly relevant, as electricity systems are critical to society's continued prosperity. It is therefore essential to become aware of potential threats, systemic risks, and the resulting cascading effects of evolving electricity systems and to address these threats with appropriate mitigation strategies.

This thesis presents the most recent insights from research and practice on trends within electricity systems that are evolving to become cleaner, smarter, and more efficient in relation to existing and emerging threats that affect the stability and reliability of electricity systems. In particular, this thesis addresses the potential of sector coupling and cross-border coupling in accelerating sustainability in electricity systems before analyzing the resulting dependencies and complexities within the systems. Thereafter, the thesis elaborates on the role of Green Information Systems and digital technologies in transforming electricity systems toward sustainability and discusses potential dependencies and complexities arising from the digitalization of electricity systems. Subsequently, it describes how trends such as coupling and digitalizing electricity systems might lead to emerging systemic risks and resulting cascading effects. Finally, the thesis reflects on economic and information system-based strategies for mitigating emerging threats associated with ongoing transformations.

Overall, this thesis is a cumulative work embedding six research papers. It contextualizes the research papers' contributions by revealing the most recent insights to researchers and practitioners. To summarize, the thesis reflects on trends and emerging threats within electricity systems that are transforming toward sustainability and contributes to a better understanding of the resultant complexities and the need for strategies to mitigate threats associated with ongoing transformations within electricity systems.

Table of Contents

List of Figures

I Introduction

I.1 Motivation

Ongoing climate change, accompanied by a global rise in temperature, poses a major threat to societies worldwide and requires immediate and serious action (National Centers for Environmental Information, 2023; Lee et al., 2023). For several years now, voices around the world have been urging a global commitment by all nations to pursue the mitigation of climate change, resulting in the 2015 Paris Agreement of the United Nations, which is legally binding for 196 parties worldwide. The agreement's goal is to substantially reduce global greenhouse gas emissions to limit the global rise in temperature to well below 2°C, preferably limiting the increase to 1.5°C (United Nations, 2015; Schleussner et al., 2016). To meet their commitments under the Paris Agreement, in December 2019, European Union member states set a target to achieve climate neutrality by 2050. The resulting European 'Green Deal' consists of various policy initiatives and is the strategy by which the European Union aims to achieve its 2050 target (EU Commission, 2019). Within the 'Green Deal' the European Union aims to reduce its overall greenhouse gas emissions by 80–95 % by 2050, compared to 1990 levels. As the burning of fossil fuels is the single most important cause of climate change, achieving this goal requires the European energy system to undergo a complete decarbonization that compromises neither the security of energy supply nor affordable energy prices for households and businesses (Van Nuffel et al., 2018), as also highlighted by Sustainable Development Goal # 7 within the United Nations 2030 Agenda for Sustainable Development, which is 'Ensure access to affordable, reliable, sustainable and modern energy for all' (United Nations, Department of Economic and Social Affairs - Sustainable Development, 2015).

The need for a decarbonization of the energy system has been acknowledged for years; however, only recently has there been increased awareness of the need for an acceleration of existing efforts due to the urgency of the issue (Bogdanov et al., 2019). Thus, society and research are proposing different efforts to increase the speed of decarbonization and identify the greatest lever for decarbonization. While a reduction in energy use and an increase in energy efficiency lead to reduced greenhouse gas emissions, most nations have recently focused their efforts on the promotion of non-fossil and Renewable Energy Sources (RES) (Dincer, 2000; Goebel et al., 2014). Electricity, for example, generated by wind or photovoltaic plants can also be used in a wide range of other energy sectors, such as heating or transportation (Luderer et al., 2022). In this sense, the development and promotion of alternative fuel infrastructures, are also important components of the European Commission's package of 'Fit for 55' climate law facilitating the 'Green Deal' (EU Commission, 2021). Hence, in the past few years, energy-demanding sectors, such as heating and transportation, have been electrified to accelerate decarbonization efforts. Thus, electricity systems, being part of energy systems, are of particular interest in accelerating decarbonization (Brown et al., 2018).

Within the electricity sector, several trends that support the goal of accelerating decarbonization have emerged recently. Driven by innovation, research has analyzed new technical solutions or economic concepts regarding their potential to address upcoming challenges, such as the integration of an increasing share of RES into existing electricity systems (Research Paper 6, Eriksen et al., 2017). One trend supporting the transformation of electricity systems toward sustainability is an increase in decentralization (Alstone et al., 2015). Shifting the supply structures of existing electricity systems from reliance on conventional power plants, which are based on large-scale and centralized generation, toward electricity systems that are based mostly on small-scale generation from a large number of spatially distributed generation plants (i.e., RES), results in a change of organizational structure with a loss of flexibility on the supply side. In electricity systems, it is indispensable that supply and demand need to be in balance within a given tolerance range. Consequently, intermittent electricity supply requires system flexibility, i.e., the ability to balance unexpected, short-term changes in demand on the electricity grid (Schoepf et al., 2018). In this regard, existing research identifies five options to address an increased need for flexibility due to, for example, intermittent generation by RES (Heffron et al., 2020): supply-side flexibility, storage flexibility, transmission flexibility, demand-side flexibility, and inter-sectoral flexibility. Decentralized, flexible small-scale assets offer great potential for addressing the lack of flexibility within transforming electricity systems (Schlund et al., 2017; Steber, 2018). The above-mentioned trend of electrifying and thereby coupling energy sectors, such as the transportation sector, also supports the trend for decentralized flexibility on the demand side, as it introduces new electricity-consuming units to the system.

Next to the coupling of different sectors, another trend widely promoted to integrate an increasing share of RES into existing electricity systems is cross-border coupling, which is the formation of interconnected power networks. For example, by permitting a pooling of resources to maintain balance within systems, interconnected power networks could increase the flexibility potential within power systems (Liu et al., 2020). Within an interconnected network, several regions are typically characterized by unique climatic conditions and RES potential. For example, the International European Power Network (IEPN) combines several single European power networks. The network consists of windy weather conditions in Britain, abundant hydropower potential from Norway and sunny areas on the Iberian Peninsula and Balkans, among other conditions (Bogdanov et al., 2019). Interconnected power networks thus offer the opportunity to exploit diversification in electricity generation technologies (Abdullah et al., 2014). In addition, an interconnected power network shows potential to provide flexibility within electricity systems based on a variety of different consumption patterns (Böckers et al., 2013b).

Another trend affecting electricity systems is increasing digitalization (Strüker et al., 2021). Exponential data availability and greater capacity for data analytics, such as through improved computing power, in combination with the urgent challenges arising from accelerating decarbonization in electricity systems, have led to an analysis of the potential of digital technologies worldwide in research and practice (Heymann et al., 2023; Cozzi et al., 2017). For example, digital technologies enable the real-time identification of a large number of small-scale assets that need to be integrated into electricity systems (Abdelwahed et al., 2019; Körner et al., 2023). Moreover, digital technologies may enhance the exchange of data among different components within electricity systems and thereby connect them with each other and provide the basis for monitoring them (Yohanandhan et al., 2020). Thus, the digitalization of electricity systems promises an increase in efficiency and, at the same time, a reduction in emissions (Verma et al., 2020).

While there are currently many trends within the evolution of electricity systems toward sustainability (cf. Section II), the two trends highlighted above, namely coupling and digitalizing electricity systems, are of special interest, as highlighted by the European Union's emphasising them through the agreement on the European Green Deal. Each of the above-named trends within electricity systems, namely increased coupling and digitalization, enables the acceleration of decarbonization. However, each also brings changes and consequences for electricity systems. New emerging complexities, such as by new dependencies or increasing interconnectedness, may also lead to emerging uncertainties and threats (Bompard et al., 2013; Nepal and Jamasb, 2013). Digitalizing electricity systems, for example, increases the vulnerability of the system to cyber attacks or operational faults, such as bugs within the programming of smart components (Ratnam et al., 2020). Similarly to the digitalization of electricity systems, the coupling of systems results in increased complexities and interdependencies (Research Paper 2). In May 2022, Électricité de France (EDF), the French electricity utility company, warned about a reduction in French nuclear electricity production. Nuclear electricity production needed to be reduced strongly that year as half of the reactors needed maintenance or repair services. The sudden high demand for maintenance was due to delayed maintenance services during the COVID-19 pandemic lockdowns in 2020 and 2021, in combination with required repair services to address corrosion and micro-cracks; this led to a sudden reduction in nuclear electricity production (Enerdata, 2023). Within the IEPN, France is the largest net exporter of electricity. However, the trouble with its nuclear fleet made France a net importer in the first half of 2022 (Statista, 2023). Within an interconnected power network, such national difficulties with electricity generation may become an issue for the whole grid. As electricity systems must always be in balance, grid failures in one part of an interconnected power network, for example resulting from a sudden decline in generation, can affect the entire grid due to synchronization (Körner et al., 2022; Berizzi, 2004; Ezzeldin and El-Dakhakhni, 2021).

When pursuing the urgently needed acceleration of decarbonization, electricity systems, as part of energy systems, are of particular interest and thus subject to various trends that facilitate faster decarbonization (Brown et al., 2018). Nevertheless, electricity systems are also an essential part of society and part of its critical infrastructure (Jasiūnas et al., 2021; Rocchetta, 2022; Bundesamt für Bevölkerungsschutz und Katastrophenhilfe, 2023). Increased complexity and interdependencies resulting from such a transformation of electricity systems toward sustainability may result in systemic risks, threats, and potential cascading effects within these systems (Körner et al., 2022). Thus, there is a need to become aware of the consequences of those trends in electricity systems. Finally, it is crucial to develop adequate strategies to mitigate the threats associated with the ongoing transformation.

I.2 Research Aim

As electricity systems are an essential part of human life, their reliability has been subject to research for a while now. Thus, there is a profound research stream on the resilience of electricity systems (Bajwa et al., 2019; Jesse et al., 2019; Ahmadi et al., 2021; Molyneaux et al., 2012). In this regard, many papers also elaborate on potential threats that may harm electricity systems by reviewing existing literature, classifying existing threats, and developing frameworks that structure these threats (Mishra et al., 2020; Bompard et al., 2013; Jasiūnas et al., 2021). Analyzing the risk a potential threat might pose to electricity systems must include a consideration of corresponding interdependencies between actors within the systems. Networks as integrated and connected as electricity systems are associated with systemic risks that may result in cascading effects (Körner et al., 2022). Traditionally, systemic risks have been analyzed in the field of finance (Acemoglu et al., 2015; Acharya et al., 2017; Billio et al., 2012; Haldane and May, 2011). In electricity systems, the literature analyzes mainly systemic risks from a finance- and economic-related perspective (Kerste et al., 2015; Lautier and Raynaud, 2012; Reboredo, 2015). In contrast, Berizzi (2004) as well as Ezzeldin and El-Dakhakhni (2021) analyze a certain event within an electricity system and the resulting cascading effects to identify systemic risks. While several trends are moving electricity systems toward sustainability, they also increase the complexity of electricity systems and thus the number of potential systemic risks. The digitalization of electricity systems and in this regard also Information Systems (IS) research can do both, enable sustainability and thereby increase complexity in electricity systems, as well as address resultant systemic risks and cascading effects. By analyzing current trends in transforming electricity systems toward sustainability regarding resulting potential threats and by reflecting on strategies for mitigating such threats, this thesis addresses an urgent need in literature and practice.

The aim of this thesis is, first, to provide an overview of existing threats to electricity systems. The thesis examines two existing trends in electricity systems, namely increased coupling and digitalization of electricity systems, to provide insights on the resulting complexities and interdependencies. Second, this thesis aims to provide an understanding of potential systemic risks and cascading effects that result from electricity systems' evolution to become more sustainable. Third, the thesis reflects on possible economic and IS-based strategies to mitigate the threats associated with trends in electricity systems.

The thesis contributes to research and literature by extending existing knowledge in several ways. It recognizes the impact of current trends, which enable electricity systems to move toward sustainability, on the corresponding systems. For this purpose, it describes the behavior of the German electricity system during the COVID-19 pandemic and discusses the use of different flexibility options during this period. Thereby, it improves the understanding of the relevance of electricity import and export behavior for coupled electricity systems, such as the IEPN. Furthermore, this thesis recognizes the potential of digitalizing electricity systems and respectively the use of IS designs for, e.g., improving decarbonization in the transportation sector. Regarding the mitigation of threats associated with ongoing transformations, this thesis illustrates the potential of economic strategies to achieve such mitigation that involves uncertainty and corresponding risk-attitudes in private investment decisions as well as in public decision-making. Finally, reflecting on the potential of digital technologies such as Artificial Intelligence (AI) to mitigate threats from increased complexities in electricity systems, this thesis highlights both the impact and relevance of digitalizing electricity systems. Connecting to the field of IS research, this thesis analyzes the potential of Green IS, which may be defined as investigating the use of IS to achieve environmental objectives to accelerate sustainability in electricity systems (Dedrick, 2010; Böckers et al., 2013b; Watson et al., 2008). Furthermore, by reflecting on the complexities arising from applying IS in electricity systems, this thesis links directly to recent work in the IS research stream (e.g. Veit and Thatcher, 2023) that calls for an enhanced understanding of the impact of digitalization on sustainability, especially regarding the associated costs. From a methodological point of view, this thesis refers to and builds on various academic concepts, such as expectation utility theory (Markowitz, 1959; Von Neumann and Morgenstern, 1947), Bernoulli principle for decision theory (Bernoulli, 1738; Bernoulli, 1954), and Arrow-Pratt for absolute risk aversion (Arrow, 1970), and by applying different methodologies, such as descriptive statistics, the formulation of optimization problems, academic case studies, and the development of a taxonomy.

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

The following section provides an overview of the thesis' structure and the six papers that constitute its basis. Figure 1 illustrates the corresponding embeddings of the six research papers. Overall, the thesis provides an overview of existing and emerging threats to electricity systems as they evolve to become more sustainable, and it provides strategies for mitigating these threats by reflecting on increased complexities, interdependencies, systemic risks, and potential cascading effects.

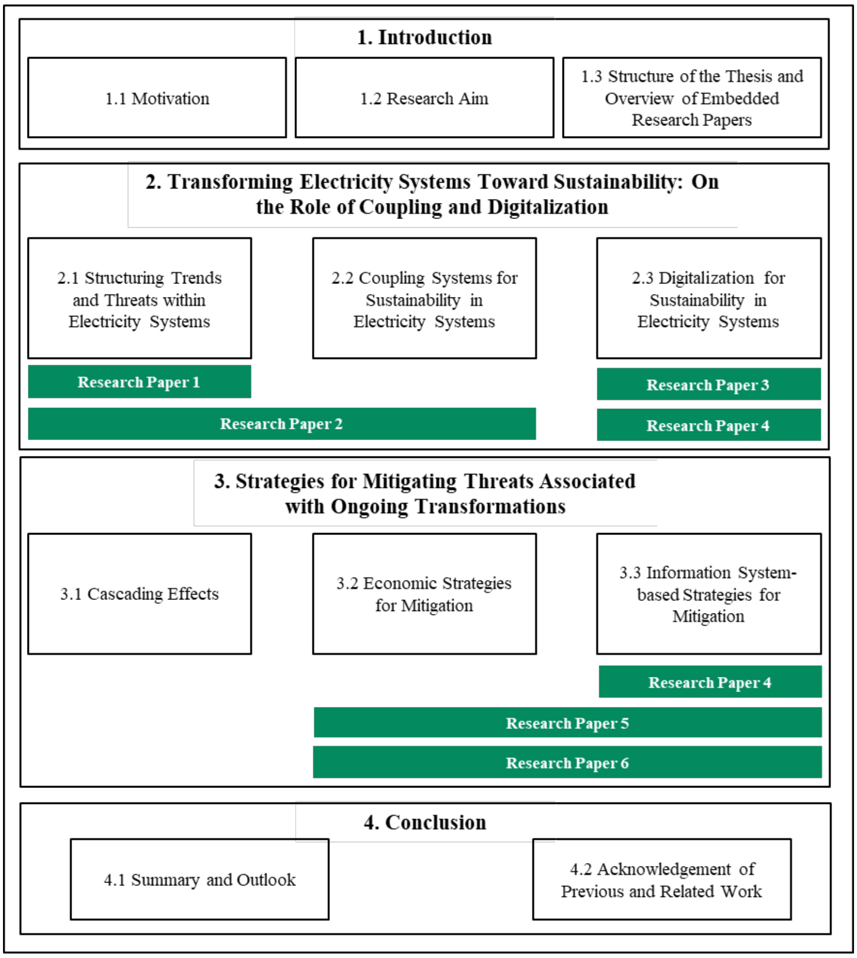


Figure 1: Structure of this doctoral thesis; Own illustration.

As this thesis is cumulative, its contribution includes insights from the six research papers embedded in it. Following the introduction (Section I), Section II elaborates on the transformation that electricity systems undergo to become more sustainable, with a focus on threats that endanger the stability and reliability of electricity systems. In more detail, Section II.1 first outlines the existing threats and provides an overview of new threats emerging from current trends within electricity systems. More specifically, two trends are emerging in multiple electricity systems worldwide (cf. Section II), and thus, this thesis focuses on an increase in the coupling and digitalization of electricity systems. Electricity systems can be coupled (Section II.2) either by coupling different sectors or by cross-border coupling. Digitalizing electricity systems (Section II.3) enables multiple challenges to be overcome and moves electricity systems toward sustainability, for example, through decarbonization in the transportation sector or transparency within a decentralized electricity system. As such trends increase complexities and interdependencies of electricity systems, Section III provides insights on mitigating the resulting threats by elaborating on systemic risks and cascading effects in coupled and digitalized electricity systems. Furthermore, Section III.2 and Section III.3 each provide economic and IS-based strategies for mitigating threats to electricity systems associated with the ongoing transformation. Finally, Section IV concludes by summarizing the insights and contributions of the thesis, presenting recommendations for future research, and acknowledging previous and related work. The references are listed in Section V and Section VI presents the appendix of the thesis. The appendix contains detailed information on all six embedded papers, providing the corresponding abstracts, respectively, extended abstracts. The supplementary material includes the full texts of all six research papers (not for publication).

II Transforming Electricity Systems Toward Sustainability: On the Role of Coupling and Digitalization

Worldwide, society and the economy rely on electricity systems. To ensure these systems' stability, research and practice must address the fact that these systems are subject to influences and threats (Research Paper 5, Research Paper 6). While some of these threats were identified a long time ago and have been extensively studied in literature, some new influences on electricity systems are arising from emerging trends resulting from, for example, ambitions to transform electricity systems toward sustainability. Several trends have been identified by research and practice: the global liberalization of electricity markets, leading to the implementation of both wholesale markets for electricity and different electricity pricing regimes and market designs (Pollitt, 2012; Weibelzahl, 2017; Bjørndal et al., 2023); the restructuring of the electricity supply side due to a scale up in RES (Chawla and Pollitt, 2013; Darby, 2020); new demand structures resulting from, for example, the electrification of other energy sectors (Darby, 2020; Gea-Bermúdez et al., 2021; Heinisch et al., 2021); and increasing energy democracy and regionalization (Moore, 2015; Van Veelen and Van Der Horst, 2018; Cantarero, 2020). At the same time, an increase in dependencies of electricity systems across the globe is resulting in the globalization of electricity systems (Yergin, 2006; Choi and Caporaso, 2002) and the increased digitalization of electricity systems, thereby unlocking the potential of digital technologies (Strüker et al., 2021). Each of these trends interfaces with and depends on others. However, two overarching trends have seemed to grow in relevance to the acceleration of decarbonization of electricity systems, as also highlighted by the European Union's emphasis on them in the agreement on the European 'Green Deal': (1) the coupling of electricity systems and (2) the digitalization of electricity systems (Bovera and Schiavo, 2022; EU Commission, 2019; Strüker et al., 2021).

Regarding the coupling of electricity systems, efforts to make electricity systems more efficient have resulted in an emerging trend of regional and interregional coupling of electricity systems (Brown et al., 2018). Aiming for more sustainability in electricity systems research and practice have also increased efforts in intersectoral coupling (Ramsebner et al., 2021). Another trend enabling the transformation of electricity systems toward sustainability is the digital transition (EU Commission, 2023a; EU Commission, 2019). Increasing the potential to achieve digitally transformed electricity systems, through the use of digital technologies, for example, may accelerate decarbonization within electricity systems. There is a great need for and potential in both (1) the coupling and (2) the digitalization of electricity systems. However, as both trends increase the number of stakeholders within electricity systems and their interconnectedness, for example, they also increase the complexity of electricity systems (Körner et al., 2022). Such an increase in complexity might lead to new threats and (systemic) risks. Consequently, it is important to analyze the possible effects of such trends on electricity systems.

Thus, Section II.1 outlines the existing and emerging threats to electricity systems. Section II.2 then elaborates on the need for and potential of coupling electricity systems, while also describing the resulting increase in complexity and emerging threats resulting from coupling electricity systems. Finally, Section II.3 describes the trend toward digitalized electricity systems. Similar to Section II.2, Section II.3 describes the potential of, need for, increasing complexity, and emerging threats of digitalized electricity systems.

II.1 Structuring Trends and Threats within Electricity Systems

Electricity systems are an essential part of modern life important to citizens, industry, and governments, and society's reliance on them continues to grow (Jasiūnas et al., 2021; Rocchetta, 2022). With this increasing reliance on electricity systems, their reliability becomes more and more important, and potential threats to their stability of electricity systems are receiving increasing attention. From mistakes in load forecasting to maintenance problems or to intentional attacks on electricity systems, various threats endanger the stability of electricity systems and might ultimately cause system blackouts. In addition, as electricity systems evolve to become cleaner, smarter, and more efficient, the types of threats endangering them are changing (Ratnam et al., 2020; Nepal and Jamasb, 2013). The present section outlines and describes existing and emerging threats to electricity systems that are currently discussed in academic literature.

The various types of threats to electricity systems differ, for example, in their source or whether there was an intention to harm the electricity system (Otuoze et al., 2018). In academic literature, classifications that cluster such threats differ slightly. Distinguishing between technical and non-technical sources of threats, the classification of Otuoze et al. (2018) differentiates between five types of threats. The authors list threats originating from the system's infrastructure, its technical operation, or its data management as threats from technical sources, and it lists threats originating from the electricity system's environment or a government's regulatory policies as threats from non-technical sources. Mishra et al. (2020) classify threats to an electricity system's resilience into natural (e.g., hurricanes, earthquakes), technological (e.g., grid outages, water damage to solar panels), and adversarial (e.g., bad actors, act of terror) hazards. Bompard et al. (2013) propose a framework to classify existing threats to electricity systems that distinguishes between accidental threats, natural threats, and malicious threats.

In 2003, the Northeast US electricity system, as well as parts of the Canadian electricity system, broke down. Cascading effects led to an outage affecting 50 million people and 61,800 MW of electric load (Burpee et al., 2006). The outage was caused by the misoperation of a Transmission System Operator (TSO) that shut down a high-voltage power line (Bompard et al., 2013). Such operational faults, such as mistakes in system planning and maintenance or wrong decision-making, have been a risk in electricity systems ever since their existence, as they appear due to accidental mistakes within the operation of a system. Another kind of accidental threat is equipment failures that may occur due to overload or aging of devices. For example, a failure of monitoring devices, which may lead to late maintenance, overvoltage, or poor heat dissipation could cause relevant components to break down.

Electricity systems have been designed to withstand average weather conditions, as well as abnormal but predictable weather. However, less frequent weather situations that are more severe than expected are happening more frequently with ongoing climate change (Panteli and Mancarella, 2015; Huang et al., 2017). During Hurricane Katrina in 2005, about 2.6 million customers in five different US states reported power outages (U.S. Government Accountability Office, 2006). Extreme weather situations, such as floods, tornadoes, hurricanes, heat, earthquakes, and avalanches, are the most common cause of electricity supply disruptions (Jasiūnas et al., 2021). Such extreme weather can harm transmission lines, power plants, and transformers and present natural threats to electricity systems that at least partly can not be controlled by humans.

Another type of natural disaster threatening electricity systems is health disasters, such as epidemics, pandemics, and famines. In 2020, the COVID-19 pandemic affected many different areas of human life, worldwide, including social relations, health, and the economy (Singh and Singh, 2020). The pandemic highlighted both the importance of a well-functioning electricity system and the need to analyze the effect that such a natural disaster might have on electricity systems (Clark-Ginsberg et al., 2020). In various countries, the first wave of the pandemic resulted in a decrease in electricity demand and an increase in the share of RES. The German share of RES, for example, rose above 55 % in the first half of 2020 in comparison to 47 % for the same period in 2019 (Fraunhofer ISE, 2019). In addition to the increased share of RES during the COVID-19 pandemic, the German electricity system also exhibited noticeable changes in electricity consumption, generation, prices, and imports and exports (Research Paper 1). However, due to sufficient flexibility within the electricity system, for example, in terms of higher grid capacity due to decreased consumption and increased electricity imports, grid stability and ancillary services did not exhibit any irregularities during this time in Germany. Although grid stability was not threatened during this time, the flexibility options that contributed to grid stability – mostly transmission flexibility and flexibility in supply – might not exist in the future (Research Paper 1). In addition, in some areas, system operators and policy makers discussed the threat of lost capacity in terms of sick employees unable to operate electricity systems. With increasing globalization, worldwide, health disasters might occur more frequently in the future (Bedford et al., 2019). Thus, it is important to analyze the impact of potential natural threats on electricity systems to secure grid stability.

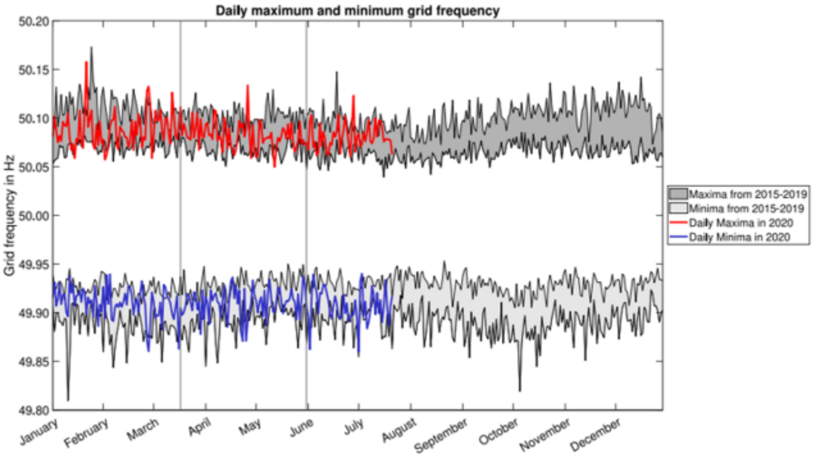


Figure 2: Daily minimum and maximum grid frequency; Source: Research Paper 1

As electricity systems are of great relevance to a functioning society, and their failure or impairment would result in lasting supply shortages, significant disruptions to public safety, or other dramatic consequences, they are defined as part of a country's critical infrastructure (Bundesamt für Bevölkerungsschutz und Katastrophenhilfe, 2023). Thus, electricity systems are at high risk of harming specific individuals, the economy, or a whole society (Bilis et al., 2013; Yamashita et al., 2008; Shuai et al., 2018). Actions that intentionally harm electricity systems can be summarized as malicious threats. Those attacks differ in their purpose, such as for political, religious, military, or economic reasons, and in their perpetrators, such as terrorists, criminals, or vandals (Bompard et al., 2013). Electricity systems can be subdivided into three layers: the physical layer, which includes all physical components of the system; the human layer, which concerns the persons having access to the system; and with the increasing digitalization of electricity systems, the cyber layer, which refers to information technology, hardware, software, data, and networks (Demiroren et al., 2001). Attacks against electricity systems may initially attack one of these layers but might ultimately affect all of them (Lai et al., 2019). Cyber-physical attacks, for example, often include a cyber attack on a protecting or monitoring device, which is then followed by a physical attack on a component within the electricity system. Thereby, such attacks are likely to cause cascading failures (see Section III.1).

While attacks on the physical components of electricity systems, such as an attack during a war to intentionally cause a blackout, have been known for a long time, other threats, such as cyber attacks, have emerged with the increasing digitalization of electricity systems. Thus, in addition to natural, accidental, and malicious physical threats to electricity systems, Bompard et al. (2013) and Jasiūnas et al. (2021) classify a fourth type of threat: emerging threats. Emerging threats result from electricity systems' evolution to become cleaner or smarter (Jasiūnas et al., 2021; Bompard et al., 2013). In smart microgrids, for example, Information and Communication Technology (ICT) can improve operational flexibility and thereby, the efficiency of decentralized energy resources (Li et al., 2017). In addition, by implementing monitoring devices, the digitalization of electricity systems may decrease the number of disruptions caused by technical failures (Jasiūnas et al., 2021). However, increased digitalization comes alongside the growing complexity of electricity systems and a greater exposure to threats. Thus, increased digitalization also results in a growing number of vulnerabilities and the emergence of new threats, such as cyber attacks by malware or hacking. Besides efforts to make electricity systems smarter through digitalization, electricity systems worldwide have also evolved to become more and more coupled. Transforming electricity systems toward sustainability by decarbonizing them is associated with integrating an increasing share of RES into existing electricity systems. Coupling energy sectors and coupling several regional electricity systems are options that hold great potential to balance intermittent generation from RES like wind or solar power. Such a coupling of systems, however, also comes with increasing complexity, an increasing number of dependencies, and ultimately new threats.

As electricity systems are subject to constant change, innovation, and efforts toward sustainability, they become more complex and are exposed to new emerging threats. Two particular developments occur in multiple electricity systems all over the world: (1) increasing coupling of sectors and (regional) electricity systems; and (2) increasing digitalization of electricity systems (Otuoze et al., 2018). Subsections II.2 and II.3 each address the need for and the potential of those two developments before analyzing how the increased complexity of electricity systems may lead to emerging threats.

II.2 Coupling Systems for Sustainability in Electricity Systems

Energy generation represents one of the greatest levers to accelerate decarbonization (Fridgen et al., 2020b). In 2022, CO_2 emissions from energy combustion and industrial processes grew to a new maximum of 36.8 Gt (International Energy Agency, 2023a). Within energy generation and use, the integration of RES represents an option to reduce CO_2 emissions that is pursued by many countries and governments worldwide, as indicated by Figure 3 (International Energy Agency, 2023b). Despite challenges in supply chains and new highs in commodity prices for raw materials driven by the COVID-19 pandemic, global annual RES capacities in 2022 reached new record levels with an increase of 6 % to almost 295 GW (International Energy Agency, 2023b). However, the integration of weather-dependent, intermittent RES into existing electricity systems results in a need for flexibility to maintain grid stability (Papaefthymiou et al., 2018).

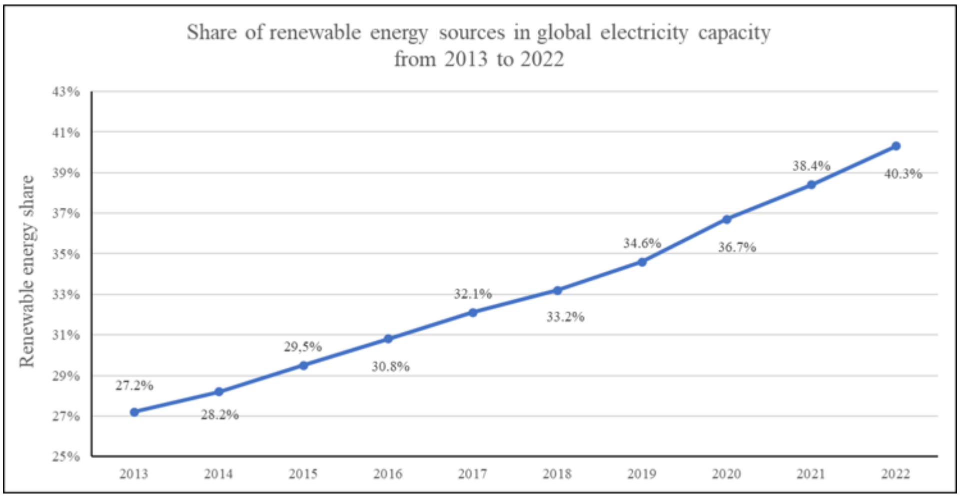


Figure 3: Share of renewable energy sources in global electricity capacity from 2013 to 2022; Own illustration, data from International Energy Agency (2023c)

There are two widely promoted options to enable the integration of RES: (1) sector coupling (i.e., coupling of different energy sectors) and (2) cross-border coupling (i.e., continent-wide transmission networks) (Brown et al., 2018). Most studies analyzing the cost-effective integration of RES within Europe find that wind generation and an expansion of the pan-European transmission network exhibit great potential to achieve such integration (Schaber et al., 2012a; Schaber et al., 2012b; Rodriguez et al., 2014; Eriksen et al., 2017; Brown et al., 2018; Darwish and Al-Dabbagh, 2020). An expansion of the IEPN may result in the exploitation of regional advantages in RES generation, as well as a better balance of weather variations passing over the continent. However, regarding the mitigating of the effects of climate change, it is not sufficient to focus only on the electricity sector. On one side, a focus on the electricity sector may lead to important greenhouse gas sources to be overlooked, for example, in the transport or heating sectors. On the other side, such a focus may also lead to the neglect of relevant sources of flexibility in other sectors that are needed to maintain grid stability. Thus, an integrated concept of (1) sector coupling and (2) cross-border coupling is needed to use synergistic and supplementary effects in integrated energy systems.

Sector Coupling

The concept of sector coupling refers to an approach that substitutes energy from sources with high emissions with RES in all end-consumption sectors (Ramsebner et al., 2021). In particular, by coupling sectors such as transport with the electricity sector, sector coupling increases storage and distribution opportunities (i.e., system flexibility) and thereby advances the use of intermittent electricity generated by RES (Trapp et al., 2022; Gea-Bermúdez et al., 2021). Thus, sector coupling can enable and even become an essential pillar of accelerating decarbonization in energy systems. In this regard, existing literature distinguishes between various scopes of the term sector coupling (Ramsebner et al., 2021; Fridgen et al., 2020b). While end-use sector coupling aims to electrify energy demand, cross-vector coupling targets the integrated use of different energy infrastructures, for example, the use of gas or heat infrastructure to cope with surplus electricity from RES (Van Nuffel et al., 2018). Providing a holistic view of sector coupling, the approach of Fridgen et al. (2020b) not only considers temporal flexibility but also spatial flexibility and states that for optimal RES integration, sector coupling should include all grids that transport energy in any form, for example, communication grids. In the case of end-use sector coupling, electric vehicles and electric heat pumps exhibit great potential for enhancing demand flexibility and ultimately fostering the integration of RES (Gea-Bermúdez et al., 2021; Maruf, 2021; Heinisch et al., 2021). However, regarding heavy-duty and long-distance traffic, such as aviation, road freight, or shipping, the electrification of demand appears to be more challenging due to considerably higher weights and longer distances than in passenger or light-duty road transport (He et al., 2021). In those cases, cross-vector coupling that enables the production of, for example, green hydrogen, unlocks an opportunity to cope with electricity surpluses from RES while reducing the need for non-renewable fossil fuels (Van Nuffel et al., 2018; Munster et al., 2020). At this point, sector coupling may also increase the profitability of RES and enable a more cost-efficient transition to a decarbonized energy system (Bernath et al., 2021; Rövekamp et al., 2021). Coupling sectors may enlarge markets for RES-based electricity (Glenk and Reichelstein, 2019), reveal new innovative business models (Trapp et al., 2022), and enable the benefits of investment in RES capacities to unfold across all coupled sectors (Munster et al., 2020).

While exhibiting great potential for the integration of RES into existing electricity systems, sector coupling is also accompanied by a number of new challenges, such as an increasing interdependence of formerly separate sectors (Li et al., 2008); a new amount and profile of electricity demand due to the electrification of transport and heating (Research Paper 3); a need for new standards, for example, to alter infrastructure to use hydrogen instead of gas (Van Nuffel et al., 2018); and uncertainty in future reinforcement needs on a distribution grid level (Munster et al., 2020). Such challenges contribute to the increased complexity of electricity systems and affect their security of supply and the underlying market structures. On the demand side, for example, new technologies such as electric vehicles represent new consumption units. Electricity demand and demand patterns resulting from such new consumption units are unknown regarding their timing, level, and location of demand (Research Paper 3). While the impact of the integration of numerous electric vehicles on the highest grid level is considered non-critical (Slednev et al., 2022), the challenges facing distribution system operators strongly depend on specific developments, such as the market shares of Electric Vehicle (EV)s, and might jeopardize the grid's stability (Venegas et al., 2021). On the supply side, coupling gas and electricity, for example, might result in economic effects on both, gas and electricity markets (Li et al., 2008). In addition, while offering more flexibility in times of surplus RES generation, new supply capacities, such as power-to-gas technologies, must also be countered into the system's balancing, which increases the complexity of the system (Qadrdan et al., 2017). In general, by introducing a number of new participating agents to the system – on the demand side as well as on the supply side – sector coupling increases the complexity of electricity systems and leads to the emergence of new threats. Moreover, the resulting need for interaction between and, thereby, the interconnectedness of those agents also result in high complexities. First, there is the exchange of energy that requires infrastructure, suitable technologies, and a definition of new standards and practices for both (Van Nuffel et al., 2018). Second, electricity systems worldwide are evolving to become more efficient and smart. An increase in the exchange of information and, especially, data is therefore indispensable when coupling systems (cf. II.3). Furthermore, the coupling of sectors also amplifies the effect of a potential conventional threat, such as a natural disaster, because due to coupling, such an event might then affect more stakeholders. In conclusion, when analyzing the potential and the effects of sector coupling for transforming electricity systems toward sustainability, it is important both to highlight this potential and to develop strategies for mitigating possible new threats.

Cross-border Coupling

Multiple studies argue that to achieve its climate goals, Europe needs a well-integrated European energy market and thus an interconnected power network that truly connects the member states' networks (Commission Expert Group And Others, 2017; EU Commission, 2020; Schlachtberger et al., 2017; Gils et al., 2017). In 2009, the European Network of Transmission System Operators for Electricity (ENTSO-E) was established to further liberalize European gas and electricity markets (ENTSOE, 2009). The corresponding interconnected European power network connects several regional European electricity systems. In particular, the network connects the transmission networks of 42 members, representing 35 different countries (ENTSOE, 2022). Worldwide, interconnected power networks couple several regional or national electricity systems. Examples beyond the European network include the Eastern Interconnection, which couples most parts of the US electricity system with most parts of the Canadian electricity system, or the Indian National Grid, which couples several transmission grids within India (Research Paper 2, Senthilkumar et al., 2020). This type of networks has gained popularity as it offers great potential to make existing electricity systems more clean, efficient, and smart. First, in most cases, coupling power networks also results in coupled electricity markets, such as the European Energy Exchange (European Energy Exchange, 2023). Such coupled markets enable the allocation of pooled generation capacities via power exchanges.

The promotion of electricity trading across wide areas thereby leads to increased competition and electricity imports and exports among the coupled markets. Such liberalization of the energy market results in lower costs and ultimately lower prices for electricity for customers within the interconnected power network (Böckers et al., 2013b). The cross-border coupling of several networks and markets thus supports the development of a more efficient electricity system. Second, interconnected power networks also offer more diverse electricity generation schemes. Especially with RES, a major factor determining the maximum capacities that can be installed is geographical conditions (Brown et al., 2018). Within Europe, different geographical conditions result in different potentials for RES, for example, high potential for hydropower in Norway and Austria and high potential for wind power in Germany, Denmark, and the Netherlands (Bogdanov et al., 2019). Such diversity can support the integration of RES into existing electricity systems (Liu et al., 2020). In addition, integrating dispatchable RES, such as hydropower, might also result in an increased security of supply. Third, the coupling of different networks also leads to different consumption patterns within the network (Böckers et al., 2013b). In the context of decarbonization, such diversity might help integrate weather-dependent, intermittent RES into existing electricity systems. For example, in times when consumption is low in one country but RES generation is high, countries with higher demand can import the surplus. Diversity in demand patterns, thus, might also result in increased security of supply as well as an increased potential to integrate RES.

In 2020, the COVID-19 pandemic and the safety measures adopted by policy makers led to a decrease in electricity consumption and high shares of RES in several European countries (Prol and Sungmin, 2020; Jiang et al., 2021; Elavarasan et al., 2020). During the first half of 2020, Germany reached a maximum share of 50.5 % RES (Fraunhofer ISE, 2019). From a system perspective, such an increase in weather-dependent intermittent RES might jeopardize security of supply. However, although the electricity system was exposed to unique and unknown circumstances during the COVID-19 pandemic, no irregularities regarding the stability of the German grid in terms of grid frequency or ancillary services were observable (Research Paper 1). A reduced level of electricity consumption resulting from lockdowns and decreased production capacity in the industry may have contributed to grid flexibility. However, during this time, Germany also turned from a former net exporter of electricity to a net importer (Osorio et al., 2020; Werth et al., 2020).

Figure 4 highlights this by illustrating the commercial electricity imports and exports of the 38 bidding zones of the IEPN. The bars represent the cumulative amount of imports and exports for a given bidding zone in the years between 2015 and 2020.

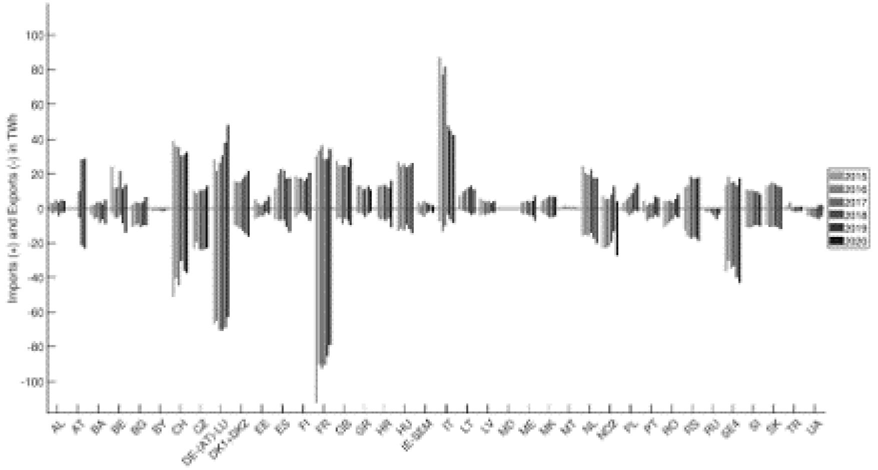


Figure 4: Cumulative commercial imports (+) and exports (-) of 38 European bidding zones for the years 2015 to 2020; Source: Research Paper 2

During the COVID-19 pandemic, flexibility on the supply side was limited when RES-generated electricity was covered by imports from other countries within the IEPN. Among other factors, those electricity imports and, thus, the flexibility of the interconnected power network enabled Germany to reach high shares of RES. However, an analysis of the leading electricity generation technologies in the countries from which Germany imported shows that Germany imported electricity primarily from countries that exhibited a lower share of RES. In particular, Germany relied on electricity imports from gas and other conventional electricity generation technologies from the Netherlands, as well as French and Swiss nuclear power plants (Research Paper 2). Thus, while interconnected power networks offer flexibility, an increase in efficiency, and the potential to become cleaner for the participating countries, to reach decarbonization, a holistic view of the network that considers dependencies is necessary.

Similar to the coupling of different sectors, the coupling of regional or national electricity systems increases the complexity of electricity systems. With every candidate joining an interconnected power network, the system's flexibility increases (Commission Expert Group And Others, 2017). However, with increasing size, the number of interconnections needed to operate a functioning grid also increases (Li et al., 2008). Those interconnections in turn lead to dependencies between the subsystems of the network and, consequently, increase the system's complexity.

Coupling several regional or national electricity systems leads to the emerging threat of increased dependencies. On the January 8, 2021, the synchronous grid of Continental Europe separated in two for one hour. Due to an overcurrent protection measure, the Croatian grid experienced an interruption of power flows in the north of the country on this day. This event cascaded through the entire electricity system, resulting in the splitting of the grid (ENTSO-E, 2021). In interconnected power networks, events happening in one part of the network can affect the whole grid. To exploit the numerous advantages and potentials of such interconnected power networks (Research Paper 2), it is important to be aware of the resulting interdependencies and effects.

In addition to causing increased dependency in terms of size and interconnections, interconnected power networks are also accompanied by complexity in terms of the different objectives of the participating countries. Security of supply is in the interest of every regional system, as is the development of a more efficient grid (Liu et al., 2020). The liberalization of electricity markets in recent decades has already led electricity systems to become more efficient. This development is favored by the entry of each additional country into the IEPN, as this increases competition among the coupled markets (Böckers et al., 2013a). However, the power system remains dependent on subsidies and political decisions to support its transformation toward a more sustainable one (Research Paper 2). As a result, regarding the path to a green and clean electricity system, the objectives of the various countries within the interconnected power network may diverge and even conflict. As described above, during the COVID-19 pandemic, Germany reached a maximum share of 50.5 % RES by relying on the IEPN. However, the electricity imported during this time by Germany stemmed from countries that exhibited a lower share of RES (Research Paper 1). This fact highlights the need for a joint coordinated, IEPN based on common objectives and policies. Within such a complex network, a strong coordination of national strategies could enable countries to jointly tackle the challenges of dealing with decarbonizing the electricity system.

II.3 Digitalization for Sustainability in Electricity Systems

Along with decarbonization and an increased coupling of systems, digitalization is one of the most relevant trends affecting every aspect of human life and, in particular, the electricity sector (Di Silvestre et al., 2018; Brown et al., 2018; Veit and Thatcher, 2023). Defining digitalization, Cozzi et al. (2017) describe it as an increasing convergence of and interaction between digital and physical components supported by a corresponding digital infrastructure and, more specifically, by the use of ICT. However, in the electricity sector, there is currently no common set of definitions of terms related to digitalization (Heymann et al., 2023). From a data-centric perspective, digitalization within the energy system aims to exploit novel data sets to optimize processes and overall efficiency (Vingerhoets et al., 2016; Küfeoglu et al., 2019). Taking a rather process-centric perspective, Cozzi et al. (2017) and Lange et al. (2020) define digitalization and digital transformation, respectively, in energy systems as applying and promoting ICT for converging physical and digital components. Heymann et al. (2023) define the digitalization of the electricity sector as the process of exploiting 'novel data sources through the application of digital technologies (i.e., ICT) across all agents in one economic sector, in order to improve safety, efficiency, and productivity' (Heymann et al., 2023). Although there are a variety of definitions of digitalization, existing research agrees on the effect of digitalization on society, the economy, and the environment worldwide and on the potential of digital technologies to improve the way single components, processes, and entire systems, such as the electricity system, work.

Societal demands of electricity systems have been changing over the last few decades (Heymann et al., 2023). Worldwide, society has raised calls to accelerate the transformation to cleaner and more efficient electricity systems. The potential of digital technologies to enable such an acceleration of the ongoing evolution toward sustainability has led to the digitalization of many electricity systems around the world (Cozzi et al., 2017). Among other factors, the digital transformation within electricity systems is driven by exponential data availability and greater capacity for data analytics, such as improved computing powers (Heymann et al., 2023). From this perspective, private or governmental investments follow the push from new upcoming technologies, for example, to create smart markets for greater efficiency (World Economic Forum, 2017). From another perspective, demands from regulations calling for a more decarbonized economy emerging from several sources result in a market pull. Thus, the potential offered by the digitalization of electricity systems may be seized by regulatory instances to drive a transformation toward sustainability in electricity systems, but it may also result in opportunities for the industry, for example, in new business models arising from it.

In research and academia, interest in the role of IS with regard to ecological sustainability has been growing since at least the mid-2000s (Chen et al., 2008). Following Mingay and Pamlin (2008) statement that Information Technology (IT) contributes about 2 % of global greenhouse gas emissions, the IS discipline's dialog on its responsibility to contribute to solving existing issues in the energy transformation began (Watson et al., 2010). The carbon footprint of ICT was estimated to be about 1.8 % – 2.8 % of global greenhouse gas emissions in 2020 (Freitag et al., 2021). Due to the effect of digitalization on greenhouse gas emissions, which is expected to grow, research on Green IT aims to mitigate and thereby minimize the negative impact of ICT on the environment by offering more energy-efficient systems (Dedrick, 2010; Chen et al., 2009; Watson et al., 2008). However, although digitalization relies strongly on energy, the IS discipline also elaborates on the great potential of information systems to enhance sustainability (Chen et al., 2008; Watson et al., 2010). In this context, IS scholars define the corresponding subfield of the IS discipline, Green IS, as an analysis of 'the use of IS to achieve environmental objectives' (Dedrick, 2010) or 'the design and implementation of IS that contributes to the implementation of sustainable business processes' (Brocke et al., 2013). Thereby, research in the field of Green IS and, consequently, IT-enabled business transformation might address the remaining 98 % of greenhouse gas emissions (Elliot, 2011). In this regard, Watson et al. (2008) find different directions for creating business opportunities with Green IS. Acknowledging both that energy consumption might increase with progressing digitalization and the enabling potential of IS in terms of a sustainable transformation of, for example, the energy system, Dedrick (2010) establishes the term 'carbon productivity', meaning economic growth with low greenhouse gas emissions (Dedrick, 2010). The author states that an increase in energy consumption must be balanced against the potential of IS to enable trends, for instance, the application of ICT for increased sustainability. Shaping the field of Green IS research also requires the involvement of non-IS scholars to realize its full potential. In the field of supply chain management, for example, Green IS can bring the trade-off between sustainability and profitability into play (Esfahbodi et al., 2023; Yang et al., 2020). Recently, academic literature, such as the work of Veit and Thatcher (2023), Pappas et al. (2023), and Andraschko et al. (2023), calls for research to further enhance the understanding of digitalization's impact on sustainability and especially its corresponding costs and its potential regarding the energy transition.

The next phase in transforming electricity systems toward sustainability and accelerating existing efforts in this respect is directly linked to the digitalization of the energy industry (Strüker et al., 2021). One goal of the digitalized electricity system is to enable decentralized units to switch independently and dynamically between self-consumption, trading, and system services (Strüker et al., 2021). This means that a digitalized electricity system provides an instantaneous determination of demand and supply at the right place and time at the lowest possible prices. Digitalizing the electricity system brings various advantages and generally improves connectivity, efficiency, transparency, accessibility, reliability, and ultimately sustainability (Cozzi et al., 2017; Heymann et al., 2023). To create a comprehensive understanding of the role digitalization plays in transforming electricity systems toward sustainability, the following explanation briefly presents approaches for applying digitalization in electricity systems by addressing two exemplary yet critical challenges: decarbonization in the transportation sector and transparency within decentralized electricity systems.

Decarbonization in the transportation sector

Decarbonizing the transportation sector remains a great challenge for policy makers worldwide (Zawieska and Pieriegud, 2018). These challenges must be set against the potential of IS and digital technologies (Faria et al., 2017). Smart transportation, or smart mobility, applies sensing, analysis, control, and communication technologies to enhance traffic management, improve the efficiency of transportation systems, and minimize environmental costs (Dedrick, 2010; Zhao et al., 2022; Cozzi et al., 2017). Currently, three fundamental transformations are changing the way people travel and transport goods and are expected to support the transport sector in moving toward decarbonization and sustainability: vehicle automation, sharing, and electrification (Dlugosch et al., 2022; Wang and Yang, 2023). As they represent two core elements for transforming the transportation sector toward decarbonization, the following elaboration focuses on the latter two transformations, namely car sharing and electrification.

Carsharing concepts provide customers with cars from a fleet when clients have mobility needs and thereby address the downsides of private car ownership, such as challenging parking conditions in urban areas and high environmental, energy, and fixed costs (Degirmenci and Breitner, 2014). Thus, the use of carsharing concepts comes with benefits such as enhanced affordability and convenience. However, unlocking the potential of carsharing concepts regarding sustainability improvements in the transportation sector is possible only if the concept is widely adopted. Currently, there are barriers that prevent society from widely adopting the concept (Litman, 2000). Understanding customers' travel behavior is relevant for carsharing operators, as it would facilitate their services and, thus, allow carsharing concepts to achieve their environmental potential. In this regard, research and practice can use digital technologies and methods to analyze and evaluate existing data sets (Baumgarte et al., 2021a). Using machine learning and explainable AI, Baumgarte et al. (2022b) analyze the data usage of a station-based carsharing service (i.e., with fixed pick-up and return point for the cars). The authors find that the most important characteristics of customers' travel behavior are time-related, for example, start or end time. From the anticipation of travel behavior to the intelligent routing or digitalization of the reservation process, digital technologies can enable carsharing concepts to overcome existing barriers and thereby unfold their environmental potential (Hildebrandt et al., 2015).

Another transformation within the transportation sector that promises to play a pivotal role in decarbonization is the electrification of transport (see also Section II.2). However, the integration of EVs also brings many challenges, such as constraints resulting from battery technologies, the need for the standardization of EVs, or challenges in charging management that create difficulties in operating profitable charging parks (Pereirinha et al., 2018). In this context, digital technologies and ICT offer the potential to address these challenges, as they enable intelligent decision-making and information dissemination between the electricity grid, charging stations, and EVs (Cao et al., 2018). One example of the application of ICT is smart charging mechanisms for charging park operators, who often struggle with the profitability of their charging parks due to volatile occupancy and high fees on peak loads that are associated with high demand charges. Smart charging mechanisms can shift charging processes by optimizing operational costs. In this sense, smart charging may enable a more profitable operation of the charging park, but it also requires the customers' flexibility to adapt their charging process. In this regard, Baumgarte et al. (2022a) develop a decision support system to analyze whether the potential costs of discounts for customers' charging flexibility may exceed the resulting savings in operating costs. The authors reveal that smart charging in this context can provide net benefits for charging park operators.

The transformation of the transportation sector also brings forth new business models.

Research Paper 3 analyzes a business model of fast charging services that rests on the value proposition of fulfilling customers' mobility needs, such as charging the vehicle, within acceptable servicing times. The advertisements of car makers, who promote the shortest technically possible charging times, combined with the charging park operator's interest to minimize demand charges, results in a gap between the vehicle driver's prior expectations and the actual performance of the charging process, called the expectation-performance gap. Research Paper 3 therefore addresses the resulting issue by analyzing how IS and more specific smart charging algorithms can reduce this expectation-performance gap.

The paper's results indicate that benefits are gained by implementing the IS, highlighting further opportunities for IS research. Similar to Research Paper 3, Baumgarte et al. (2021b) also investigate the business model of fast charging parks and, in more detail, the impact of different political support measures on the comprehensive development of fast charging infrastructures. The authors find that current support measures (in Germany) are not sufficient and that changes in demand charges inhibit the high potential to support investments in fast charging infrastructure. Furthermore, the authors call for future research and policy makers to analyze the effect of combined support measures on the expansion of fast charging infrastructure.

Transparency within decentralized electricity systems

For a purposeful and efficient decarbonization, it is essential to provide transparency on the agents participating in the electricity system. However, providing such transparency is becoming increasingly difficult as the number of participating agents within the system grows: traditionally, electricity systems have been organized in a centralized structure relying on conventional power plants (cf. Section I, Fridgen et al., 2020b). Because RES plants are typically small in scale and spatially distributed, the urgently needed integration of RES results, on the one hand, in a more decentralized generation structure (Sinsel et al., 2020). On the other hand, the increasing number of integrated RES plants also results in intermittent generation and thus an increased need for flexibility within electricity systems (Perera et al., 2019). In the case of Germany, the need for flexibility intensifies as flexible, conventional power plants phase out, which is also reflected by increasing costs for congestion management (Schlund and German, 2019). At the same time, however, numerous distributed assets, such as heat pumps or EVs, are installed within electricity systems worldwide (cf. Section II.2). In addition, industrial demand-side flexibility that stems from adjusting or shifting industrial processes holds great potential for providing flexibility (Heffron et al., 2020). This high number of distributed flexible assets might address the required bottom-up flexibility, enable an improvement in the stability of electricity systems, and ultimately enable the successful integration of RES (Schlund and German, 2019; Radecke et al., 2019).

Integrating a large number of small-scale, decentralized assets offers great potential to make electricity systems more efficient, cost-effective, and sustainable (Strüker et al., 2021). However, most of these decentralized assets are not controlled centrally and do not have access to flexibility markets. Thus, the activation, provision, and control of these small-scale flexibilities is difficult and creates a number of challenges (Schlund and German, 2019). Although from a corporate perspective, corporate carbon risk management – also demanded by several regulatory and reporting initiatives – may represent an enabler for more sustainability, carbon risk management currently represents an administrative burden to companies. Current processes lack quality, reliability, and transparency of data (Körner et al., 2023), which is why they require great efforts for collecting, processing, and providing information (Leinauer et al., 2023). An assessment of and accounting for the offered and provided flexibility, however, requires master and transaction data on the decentralized assets providing flexibility to the system (Babel et al., 2023).

In this regard, digital technologies can enable more efficient and transparent data measurement, reporting, and verification and thereby enhance the comprehensive management of (corporate) carbon emissions (Körner and Strüker, 2023). Smart meter gateways represent a communication unit within intelligent metering systems and a basis for the collection of supply and demand data for the marketing of flexibility (Bundesamt für Sicherheit in der Informationstechnik, 2023). However, as the smart meter accounts only for aggregated data on the assets behind it, a more detailed, fine-grained collection of data on an asset level is necessary. Still, in combination with the concepts that follow the self-determined identity paradigm, such digital technologies are able to make master and transition data available in a confidential and unmodified way using one identity across all areas (Babel et al., 2023). Distributed ledger technologies such as the Blockchain may also enable the urgently needed verification of data in real-time, resulting in decentralized, visible, chronological, and immutable transactions (Körner et al., 2023; IRENA, 2019). Moreover, zero-knowledge proofs offer the potential to prove the veracity of data without disclosing additional information. In this sense, Babel et al. (2023) use a non-fungible token with fractional ownership and zero-knowledge proofs to introduce a concept that addresses the need for verifiable, distinguishable data while respecting privacy requirements. In summary, end-to-end digitalization enables the verification of carbon emission data, linking carbon sources with carbon sinks. Digital machine identities fed into the digital energy register, such as proof of origin and use, may lead to the linking of carbon emission trading with carbon emission decision-making (Strüker et al., 2021).

The digitalization of electricity systems, however, is accompanied by a great increase in the systems' complexity. Combining two disciplines, each with a broad variety of stakeholders, results in a great number of actors involved in digitalizing electricity systems. Such actors include, for example, international and national policy makers, non-governmental organizations, civil representatives, electricity companies, and digital companies. The presence of a number of actors participating in operating and digitalizing electricity systems also leads to a number of somewhat conflicting objectives: (international) policy makers would like to represent their citizens; non-governmental organizations might call for improvements in environmental sustainability; electricity companies aim to maintain revenue and grid stability; and digital companies might aim to maximize profitability (Li et al., 2017; Heymann et al., 2023; Lehnhoff and Nieße, 2019). Moreover, increased interconnectedness and additional dependencies also result in a digital electricity system with increased complexity. One example of a resulting dependency is digitalization's demand for resources, especially with regard to energy demand. As stated above, in 2020, the carbon footprint of ICT was estimated to be approximately 1.8 %-2.8 % of global greenhouse gas emissions. With the increasing digitalization of electricity systems worldwide and the accompanying increasing need for data centers and ICT infrastructure, this number is expected to increase even more (Freitag et al., 2021). In this sense, research, practice, and policy makers should aim to achieve an enhanced understanding of the impact of digitalization on sustainability (Veit and Thatcher, 2023).

Finally, enhanced connectivity and a rising number of dependencies may also lead to a loss of transparency. One major threat emerging from the digitalization of electricity systems is cyber attacks. Cyber threats are malicious threats that aim to harm the functioning of information technologies, such as hardware, software, data, and communication networks, that support electricity systems. In general, cyber attacks aim to attack network availability, data integrity, or information confidentiality (Lu et al., 2010; Gunduz and Das, 2020) using malware or hacking methods. Whereas malware methods use software that is designed intentionally to cause disruption, gather information, or gain unauthorized access to a system, such as a computer, server, or networks, hacking is a process that explores methods for breaching defenses and tries to identify weaknesses in an information system or network. When working maliciously, hackers gain access to cyber systems to harm them, for example, to control electricity systems (Bompard et al., 2013; Li et al., 2017; Gunduz and Das, 2020). Remaining legacy systems, in combination with an increasing complexity of the overall system, result in the rising vulnerability of the electricity system. In this context, the characteristics of the system's vulnerabilities range from data ownership issues to network availability issues (Cozzi et al., 2017).

To summarize Section II, electricity systems, as part of critical infrastructure, are subject to both trends and threats. Coupling and digitalizing electricity systems are trends that aim to accelerate the transformation of electricity systems toward sustainability. These trends, however, also result in the systems' increased complexity and, thus, new emerging threats. After elaborating on the potential of and emerging complexities of those trends in Section II, Section III describes strategies for mitigating threats resulting from those complexities.

III Strategies for Mitigating Threats Associated with Ongoing Transformations

As described in Section II, electricity systems undergo a transformation toward sustainability driven by certain trends, such as an increasing coupling of systems or evolution to digital electricity systems. The complexities arising from those trends lead to interdependencies that imply consequences for the operation and development of electricity systems. It is important to analyze those consequences and account for them with corresponding strategies. Accordingly, Section III.1 provides an understanding of potential cascading effects from systemic risks within electricity systems. Section III.2 then elaborates on economic strategies for responding to and mitigating potential threats. Finally, Section III.3 reflects on IS-based strategies for the mitigation of threats associated with ongoing transformations.

III.1 Cascading Effects

As described in Section II, electricity systems worldwide are evolving to become cleaner, more efficient, and more robust. However, as also stated in Section II.2 and Section II.3, such trends also bring an increase in complexities and interdependencies. Moreover, digitalizing electricity systems speeds up the process of transformation toward sustainability. In this sense, the increase in complexity and interdependence results in a rise in hidden systemic risks. In contrast to risks that result in the collapse of a single component without affecting the whole system, systemic risks result in the collapse of a substantial part of the system that may ultimately lead to its breakdown (Ilin and Varga, 2015). As they are hidden by a loss of transparency to system operators, systemic risks usually reveal themselves only after they have occurred. Individual players within a system are usually not aware of the risk and its corresponding hidden effects, which is why – in the worst case – such players may contribute to increasing the risk. After the initiating failure, a systemic risk usually induces cascading effects that lead to the failure of the entire system (Körner et al., 2022). With respect to energy systems, the literature analyses systemic risks mostly from a finance- and economic-related perspective (Kerste et al., 2015; Lautier and Raynaud, 2012; Reboredo, 2015). In contrast, Berizzi (2004) as well as Ezzeldin and El-Dakhakhni (2021) take a broader perspective on systemic risks in electricity systems by analyzing a certain event and the resulting cascading effects. In addition, there is a research stream in engineering science that takes a technical perspective on the causes of blackouts (Lee et al., 2019a; Meng et al., 2017; Saleh et al., 2015; Crucitti et al., 2004; Rohden et al., 2016; Chang and Wu, 2011).

There are several causes of systemic risk in electricity systems. However, due to increased complexity and interdependencies, these causes are not usually visible before they reveal themselves through a failure and the resultant cascading effects. Analyzing past cascading effects in electricity systems, however, may identify some existing risks. From an economic perspective, complex and incomplete market designs may result in cascading effects. In December 2018, for example, incorrect forecasts for photovoltaic feed-in led to an increase in prices on the intraday market. Due to mis-designed market mechanisms, the normally expected decrease in electricity demand did not occur, and maximum balancing electricity prices appeared lower than the intraday price, which in turn allowed individual market participants to profitably use standard power reserves instead of trading on the intraday market (Preiß, S., 2019; Körner et al., 2022). To avoid a system breakdown, large German consumers were taken off the grid.

Due to the urgently needed integration of a large number of small-scale flexibility assets (cf. Section II.3), another cause of systemic risks and resulting cascading effects in transforming electricity systems may be the multi-party and fine-grained market environment (Körner et al., 2022). Ensuring system stability is increasingly challenging as the number of active and decentralized market parties grows. In addition, an increase in interconnectedness in terms of coupling systems (cf. Section II.2) leads technical causes to have a greater cascading effect on electricity systems. Coupling (national) electricity systems might also be associated with an increase in loop and transit flows (Hutcheon and Bialek, 2013). In this sense, an overloading of individual transmission lines may result in a cascading effect on the whole coupled network (Baldick and Kahn, 1997). In their research, Buldyrev et al. (2010) argue that modern coupled systems should be modeled as interdependent networks, accounting for possible cascading failures that might arise.

As mentioned, an increase in digitalization introduces new vulnerabilities to electricity systems. Differences between the internet system and electricity systems limit the application of existing cybersecurity measures and leave electricity systems vulnerable (Jasiūnas et al., 2021). One common kind of attack on electricity systems is coordinated cyber-physical, and malicious attacks. Cyber-physical attacks are likely to cause cascading failures and usually consist of two parts. First, a cyber attack on a protecting and/or monitoring device is performed without being noticed by system operators. Then, a physical attack on a component within the electricity system cannot be detected due to the failure of protecting or monitoring devices and, thus, leads to a cascading failure within the system (Lai et al., 2019). As cascading effects can cause great harm to electricity systems, and as practitioners and policy makers should respond proactively to this, the next section focuses on economic strategies for mitigation.

III.2 Economic Strategies for Mitigation

Mitigating threats associated with ongoing transformations first requires all political and economic stakeholders to be aware of the increasing complexity and resulting systemic risks of cascading failures. Thus, the inclusion of emerging threats to electricity systems must be considered not only in IS research (cf. Section III.3) but also in political decision-making and (economic) market design (Cozzi et al., 2017). One approach to mitigating systemic risks in complex networks is regulate certain topologies for networks in critical infrastructure. Schneider et al. (2011) argue that in complex networks, vulnerabilities stem from network structures that are characterized by a high degree of interconnectedness. To address the potential effects of malicious attacks, the authors propose a measure of robustness that supports improvements in robustness with reasonable economic effort. Also, to address cyber attacks, the regulation of IT architectures, such as those for information exchange, offers great potential to mitigate possible threats (cf. Section III.3). From an economic perspective, one major countermeasure to hidden risks accompanying increased complexity is the creation of adequate economic incentive structures to unlock flexibility options within electricity systems; such incentives therefore represent the focus of the following discussion.

As described above, there are several options for increasing flexibility within electricity systems (cf. Section I). However, from an economic perspective, each of these options is accompanied by uncertainties that hinder potential investments. Worldwide, network expansion that would increase transmission flexibility is under discussion; this expansion would be very cost-intensive and met with skepticism by the general public (Komendantova and Battaglini, 2016; ENTSO-E, 2023). While privately-invested, decentralized storage facilities and the resulting storage flexibilities may allow for the decoupling of supply and demand by shifting energy supply and demand between two time periods, current storage technologies are still expensive, and uncertainties regarding return on investment still hamper their market penetration (Weitemeyer et al., 2016; Wogrin and Gayme, 2014). Even with an optimal mix of storage and transmission capacities, conventional generation may still be necessary in electricity systems to guarantee flexibly adjustable production as backup to mitigate intermittent generation from RES (Stolten et al., 2013). However, gas power plants or other fast-responding technologies are still subject to commodity price uncertainties. Finally, flexible demand offers the potential to naturally follow intermittent RES generation. Such flexibility may be helpful in both the spot market, for example, for peak shaving, and in redispatch markets, where altering a consumer's consumption profile might be useful whenever the spot market outcomes result in infeasible transmission flows. However, most countries currently offer only redispatch measures on the supply side, leaving enormous potential for more efficient congestion management unlocked.

To choose the right mix of flexibility options and regulation to encourage the active integration of urgently needed flexibility options, policy makers must consider all interdependencies and arising complexities appropriately. Research Paper 6 therefore addresses the problem of choosing the right mix of flexibility options under the consideration of a decision maker's risk attitude, calling it the 'flexibility puzzle'. To solve this flexibility puzzle, the paper proposes a multi-stage Stackelberg game with different risk attitudes for decision-making under uncertainty. The proposed model accounts for public line investments by a TSO (first stage), private investments in storage and conventional backup generation facilities (second stage) based on the spot market (third stage), and correcting redispatch actions of the TSO (fourth stage). The paper formulates a four-level optimization problem, which is then reformulated to global optimality and solved with the spatial branch-and-bound method. The model is then applied to a well-known academic case study to analyze the effects of different degrees of risk aversion among public and private decision makers on long-run investments in flexibility options.. Research Paper 6 reveals the importance of uncertainties for private flexibility investment decisions and public policy making to ensure sufficient flexibility with an adequate mix of flexibility options. Thereby, the work underlines the relevance of economic strategies such as incentives for investments in flexibility options for mitigating threats associated with ongoing transformations.

Another option for unlocking flexibility – and thereby economically addressing emerging threats in electricity systems – is to enhance energy democracy by fostering the regional balancing of supply and demand and thereby pushing decentralization in energy systems. Such decentralization might relieve existing electricity systems and lower the need for large-scale expansions (cf. Section I, Bullich-Massague et al., 2018). One option for decentralization is to integrate a large number of Decentralized Energy Resources (DER)s, for example, small-scale photovoltaic plants, that meet the demand close to load centers (Quadri et al., 2018). However, from an economic perspective, there is a need for sufficient incentives for consumers to determine the installation of new renewable DERs and thereby turn into prosumers, meaning consumers who also produce and share surplus energy with grid and other users (Kitzing and Weber, 2014; Zafar et al., 2018). Again, the uncertainties and increased complexities of electricity systems pose a barrier to investments (Ländner et al., 2019) as, for example, regulatory changes and long-term electricity prices are uncertain. Such uncertainties represent severe price risks for consumers (Wickart and Madlener, 2007; Zangiabadi et al., 2011; Dietrich and Weber, 2018). So far, research considering the economics of DERs either focuses on weather conditions and the uncertain level of production (Mavromatidis et al., 2018; Akbari et al., 2014; Cardoso et al., 2013; Zhang et al., 2019) or analyzes options to hedge against electricity price uncertainties (Roques et al., 2008). Such considerations usually result in more conservative decision-making and lower investment decisions. However, such approaches lack consideration of the prosumer perspective when investing in DERs. By investing in a DER, a consumer may be able to cover a share of its electricity consumption, becoming a prosumer and interacting bidirectionally with the electricity grid. Thereby, the resulting prosumer might reduce the electricity consumed from the grid and thus should not only consider total electricity cost savings but also the effect of a reduced price risk that stems from uncertain electricity prices.

Against this background, Research Paper 5 analyzes another approach to economically mitigating emerging threats in electricity systems, namely, the effect of the risk stemming from uncertain electricity prices on individual consumers' investment decisions in DERs. The paper models a consumer, who turns into a prosumer by investing in DERs. Methodically, the approach follows the Bernoulli principle for decision theory (Bernoulli, 1738; Bernoulli, 1954), uses expectation utility theory to describe the utility function and risk preferences of the prosumer (Markowitz, 1959; Von Neumann and Morgenstern, 1947), and uses the Arrow-Pratt characterization to model the absolute risk aversion of the prosumer (Arrow, 1970). An economic investment model is formulated and analyzed, comparing the risk-neutral and risk-averse investments of a consumer. The risk-averse version thereby accounts for variance in energy cost savings due to uncertainty in electricity prices with a risk-adjusting term. The results of the paper indicate that a consideration of risk-aversion affects investment decisions in renewable DERs. In fact, for prosumers with a low share of electricity sales to the grid, an integration of risk-aversion increases the level of optimal investment. For a risk-averse 'consuming prosumer' (i.e., meaning a prosumer consuming electricity from the grid in more time periods than it sells electricity to the grid) a reduction in demand resulting from investment in DERs leads to a reduction in risk stemming from uncertain electricity price developments. Research Paper 5 describes the effect that enhances an investment in DERs by decreasing volatility in energy costs: the 'insurance effect'. In this sense, an investment in a DER might be considered an insurance premium. The paper also finds that with an increasing level of investment, a consuming prosumer turns into a producing prosumer whose production share is predominant. For such a producing prosumer, an increase in investment results in increasing volatility in revenues from DER generation. In contrast to existing literature, the results of Research Paper 5 indicate that considering uncertainties and the implicated risk-aversions of a decision maker does not always result in a lower optimal investment. In fact, policy makers should acknowledge the (insurance) effect of DERs and account for this effect when deciding on incentive structures for unlocking flexibility options in complex electricity systems.

In general, when mitigating threats associated with ongoing transformations from an economic perspective, there is a need for the implementation of a global perspective on critical and increasingly complex systems (Körner et al., 2022). Moreover, this requires the sharing of best practices by international organizations. Such a dialog might also lead to the mainstreaming of the consideration of emerging threats within energy policy making (Cozzi et al., 2017). However, technical issues such as the stability of electricity systems or integrating shares of RES cannot be overcome purely by economic considerations (Berizzi, 2004). On the one hand, sharing and managing information through ICT plays an important role in handling complex systems. On the other hand, complex decision-making, for example, when deciding on investments in flexibility options within a flexibility puzzle, implies an urgent need for IS-enabled decision support systems. Therefore, Section III.3 elaborates on the IS-based strategies for mitigating threats associated with ongoing transformations.

III.3 IS-based Strategies for Mitigation

To uncover and mitigate systemic risks in complex networks, digital technologies hold great potential as they enable a rapid and accurate assessment of the systems' conditions and enhance decision-making processes (Argyroudis et al., 2022). Many disciplines have already analyzed and identified the potential of IS-based strategies for managing systemic risks. One prominent approach is to link a physical system with a virtual equivalent, a so-called digital twin, to recognize and mitigate potential systemic risks (Grieves and Vickers, 2017). In supply chain management, such a digital twin may represent the network's status in real-time and manage potential disruptions by analyzing the supply chain surroundings (Ivanov and Dolgui, 2021; Ivanov et al., 2019).

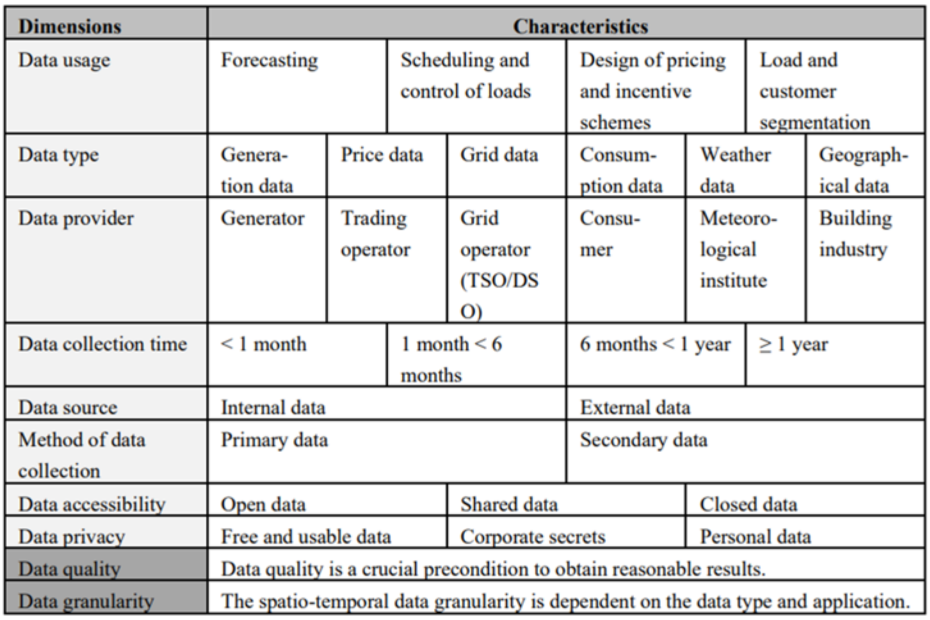
In terms of critical infrastructures, such as electricity systems, digital technologies have the potential to enhance resilience by increasing availability and data exchange, which may represent a key enabler. Several IS-based technologies and methods may enhance the uncovering of hidden risks. One example of such an application is AI. The breakthrough of AI started a few years ago, driven by the increasing availability of large amounts of data (Big Data) and of computing capacities (Abbasi et al., 2016; Duan et al., 2019). In the following discussion, and analogous to Antonopoulos et al. (2020), the term AI is used for algorithms in the areas of machine learning, nature-inspired intelligence, artificial neural networks, and multi-agent systems. Striving to not only understand but also build intelligent entities (Laughton, 1997), many industries and disciplines are paying attention to AI (Reim et al., 2020). AI also opens up opportunities for the energy industry, as its application areas range widely (Russell, 2010). In more specific terms, AI approaches may enable energy systems to become more efficient and secure by analyzing and evaluating data sets (Research Paper 4). Thus, research on potential application areas for AI in energy systems is vast. Ramos and Liu (2011) analyze the general use of AI in energy systems and markets, identifying alarm processing, diagnosis and restoration, forecasting, security assessment, planning and scheduling, and solving complex problems in energy markets as application areas for AI. Moreover, AI may play an important role in achieving climate goals with respect to increase shares of RES (Jha et al., 2017). In smart grids, the application of AI may enable stability assessment, stability control, security assessment, and fault diagnosis (Shi et al., 2020; Bose, 2017).

As it is considered to be accompanied by high complexities and interdependencies regarding decision-making processes, AI also offers great potential for supporting Demand Response (DR) processes. Additionally, the use of large-scale data, as well as the need for real-time decisions in DR, match the potential of AI algorithms (Antonopoulos et al., 2020). In fact, IS research in general analyzes the opportunities of IS for DR (Strueker and Dinther, 2012; Fridgen et al., 2016). Turning to AI for DR, Antonopoulos et al. (2020)

provide an overview of potential applications with regard to DR. The authors identify, for example, the following application areas: load and price forecasting, scheduling and control of loads, design of pricing, and incentive schemes. However, data availability, quality, accessibility, and flow are crucial to applying AI to these areas (Jöhnk et al., 2021). While general AI literature is concerned about data requirements, existing research lacks focus on data requirements for AI for DR.

Research Paper 4 consequently, addresses the gap in how input data requirements for AI approaches in the field of DR can be systematized. The paper develops a taxonomy following Nickerson et al. (2013) to structure the input data requirements of AI algorithms for demand response.

Figure 5 depicts the resulting taxonomy, which comprises eight dimensions, 30 characteristics, and two additional requirements. The taxonomy results in four application areas, in line with Antonopoulos et al. (2020), reflected by the characteristic 'data usage': forecasting, which refers to load as well as energy prices, scheduling and control of loads, design of pricing and incentive schemes, and load and customer segmentation. The taxonomy process also revealed that AI algorithms for demand response operate on a number of data types, which are selected to meet the specific goals of the AI application, such as generation data, price data, or weather data.



Dimensions	Characteristics					
Data usage	Forecasting	Scheduling and control of loads	Design of pricing and incentive schemes	Load and customer segmentation		
Data type	Generation data	Price data	Grid data	Consumption data	Weather data	Geographical data
Data provider	Generator	Trading operator	Grid operator (TSO/DSO)	Consumer	Meteorological institute	Building industry
Data collection time	< 1 month	1 month < 6 months	6 months < 1 year	≥ 1 year		
Data source	Internal data	External data				
Method of data collection	Primary data	Secondary data				
Data accessibility	Open data	Shared data	Closed data			
Data privacy	Free and usable data	Corporate secrets	Personal data			
Data quality	Data quality is a crucial precondition to obtain reasonable results.					
Data granularity	The spatio-temporal data granularity is dependent on the data type and application.					

Figure 5: Taxonomy of Input Data Requirements in the Context of AI Algorithms for DR (in dark grey further input data requirements are shown); Source: Research Paper 4

The next dimension refers to the stakeholders providing the data, meaning the data providers. Those are, to be more specific, generators, trading operators, grid operators, consumers, meteorological institutes, and the building industry. In addition, the length of the data collection period is also important for the applicability of AI algorithms for DR. The objects within this dimension range from less than one month to more than one year. The underlying data, again, differs in its source, which may be internal or external, in line with literature. Regarding the method of data collection, the paper distinguishes between primary and secondary data. Within the dimension of data accessibility, the paper finds essential differences between the objects' input data. This dimension differentiates between open data, shared data, and closed data. Finally, the dimension of data privacy formulates requirements for the use and governance of data. This dimension is divided into free and usable data, corporate secrets, and personal data.

The proposed taxonomy lays the foundation for the development of and research on AI algorithms, considering input data requirements. The results provide future research with a base for analyzing the applicability of AI algorithms for demand response and offer an opportunity for an enhanced and simpler comparison of different algorithms.

Next to AI, there are several approaches that may enable the uncovering and mitigation of hidden systemic risks to prevent cascading effects. As the providing, synchronizing, and sharing of system information represent a key enabler for addressing threats in electricity systems, research identifies an intensified exchange of system-relevant data as holding great potential (Körner et al., 2022; Lee et al., 2019b). Purposeful electricity data exchange may empower transparency in complex systems, as also noted by several initiatives within the European Union (EU Commission, 2023b; Jenssen et al., 2017; EU Commission, 2017). In this sense, reliable and focused processing, storage, and communication of system-relevant data may help to achieve such aims (Körner et al., 2022). However, relevant data is often competition-relevant or personal, bringing up privacy issues (Research Paper 4). Addressing this challenge, digital, privacy-enhancing technologies, for example, zero-knowledge-proofs or digital identities, may enhance the urgently needed provision, synchronization, and sharing of system-relevant data on a trustworthy and secure basis (cf. II.3, Körner et al., 2022). Data ecosystems that align different individual interests provide trust between participants, for example, using such technologies, ensure data sovereignty, and support data interoperability may be implemented by an appropriately designed data space (Otto et al., 2022). Data spaces provide standardized components and policies for exchanging data between individual participants and thereby enhance bilateral, authenticated data exchange (Körner et al., 2022). Due to its major advantages in enhancing sovereign data exchange, the European cloud initiative GAIA-X currently discusses the role that data spaces might take in data ecosystems (Economic Affairs and Energy, 2021).

However, addressing the threats emerging from the digitalization of electricity systems by a further digitalization might seem controversial. In its flagship report, the German Advisory Council on Global Change, however, opposes such an interpretation by clarifying that digitalization must be actively shaped to serve as a lever and support for transforming, for example, electricity systems toward sustainability. In this regard, research and practice must seize the opportunities offered by digitalization and, at the same time, contain its risks (Messner et al., 2019). In this sense, uncovering systemic risks represents an interdisciplinary problem solved by the collaboration of research, practice, and policy makers. Coupling sectors to increase the use of RES might result in an increased number of actors, such as EVs, in electricity systems (cf. Section II.2). Digital technologies may foster the integration of those actors into existing systems, but that might also lead to increased vulnerability regarding cyber attacks (cf. Section II.3). Using privacy-enhancing technologies and concepts, then, might lead to increased cyber security. Thus, the mitigation of threats associated with ongoing transformation calls for a consensus between various stakeholders, integrated approaches, and regulation supporting the use of digital technologies (Argyroudis et al., 2022).

IV Conclusion

IV.1 Summary

To take the urgently needed actions to reduce global greenhouse gas emissions, which were agreed on in the Paris Agreement and addressed in legislation such as the European ‘Green Deal’, energy systems worldwide are currently undergoing complete decarbonization. The need for a decarbonization of energy systems that does not compromise security of supply or affordable energy prices for households and businesses has been acknowledged for years. However, recently, awareness of the need to accelerate existing efforts to decarbonize electricity systems, for example, by identifying the greatest lever of decarbonization, has increased. Because electricity generated by, for example, wind or photovoltaic plants can be used in a wide range of other sectors, most countries focus on promoting non-fossil and renewable energy sources and thereby decarbonizing electricity systems. Within the electricity sector, several trends supporting an acceleration in decarbonization have emerged. In the European Union, two trends in particular have been emphasized by the European ‘Green Deal’: (1) the coupling of electricity systems and (2) the digitalization of electricity systems. While enabling an acceleration of decarbonization within electricity systems, both trends, however, also come with rising dependencies and an increased interconnectedness that result in emerging complexities. These new complexities may bring forth systemic risks within electricity systems that, when they appear, may result in cascading effects. Electricity systems, though, are not only a great lever for decarbonizing energy systems; they are also critical to society and the economy. Thus, there is a need to identify the consequences of such trends in electricity systems and to develop adequate strategies to mitigate the threats resulting from the ongoing transformation.

This cumulative thesis includes six research papers that, respectively, address transforming electricity systems toward sustainability, with the role of coupling and digitalizing electricity systems in accelerating decarbonization, with increasing complexities, threats, systemic risks, and cascading effects within electricity systems stemming from transforming electricity systems, and with economic and IS-based strategies for mitigating threats associated with ongoing transformations. Hence, this thesis outlines existing threats and provides an overview of current trends within electricity systems, resulting from a transformation driven by sustainability (cf. Section II.1). Subsequently, this thesis elaborates on the potential of and arising complexity from sector coupling and cross-border coup-ling (cf. Section II.2), before introducing the research stream of Green IS and highlighting the potential of and complexities arising from digitalizing electricity systems (cf. Section II.3). As the increased complexities resulting from arising dependencies and a growing interconnectedness result in potential systemic risks, this thesis then enters into an elaboration regarding systemic risks and a potential cascading effect within electricity systems, in Section III.1. Finally, this thesis considers strategies for mitigating potential threats that result from a transformation of electricity systems and, in more specific terms, economic strategies (cf. Section III.2), and IS-based strategies (cf. Section III.3) for the mitigation of potential threats.

Overall, this thesis also displays several limitations. While it structures existing threats within electricity systems by reviewing existing literature, this thesis does not claim to provide a complete overview of all threats that currently exist. This is also highlighted by the fact that the thesis elaborates on the fact that transformations within electricity systems result in the emergence of new threats, which is an ongoing process. While the coupling and the digitalization of electricity systems represent prominent current trends in electricity systems, those two trends are accompanied by many other trends that are not the focus of this thesis but may also arise from increased complexities and new threats in electricity systems. In addition, as systemic risks are usually not transparent until they appear, another limitation of this thesis is that it cannot provide insights into all threats resulting from the increased coupling and digitalization of electricity systems. Therefore, this thesis provides a starting point for introducing exemplary economic and IS-based strategies for mitigating emerging risks. Moreover, this thesis reveals the critical role of analyzing the impact that the transformation of electricity systems has on the systems' stability and reliability, upon which future research can be based on.

The need to address the limitations of this thesis provides researchers with a broad basis for future work. With respect to identifying existing threats, future research might analyze emerging threats, such as new forms of cyber threats, that result from the constant evolution of electricity systems. Also, future research may elaborate on trends other than coupling and digitalizing electricity systems. Addressing the fact that current trends within electricity systems may also result in increased complexity and, thus, potential systemic risks, this thesis might also provide a starting point for steering discussion regarding the need for mitigation strategies in research and practice. Regarding specific strategies for mitigating threats associated with ongoing transformations, further research may contribute to the basis for economic or IS-based strategies or may even identify new disciplines that could produce new strategies for mitigating threats in evolving electricity systems.

IV.2 Acknowledgment of Previous and Related Work

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

Fridgen et al. (2020b) provided the starting point for Research Paper 2. The work of Fridgen et al. (2014a), Fridgen et al. (2014b), and Fridgen et al. (2015b) formed a viable basis for Research Paper 3 and Research Paper 5. Moreover, Research Paper 1, Research Paper 3, and Research Paper 6 relate to the work of Fridgen et al. (2016), Jäckle et al. (2019), Körner et al. (2019), and Leinauer et al. (2022), who analyze the ability of demand response to provide flexiblity in electricity system. The work of Fridgen et al. (2015a), Rieger et al. (2016), Buhl et al. (2018), and Fridgen et al. (2018) motivated Research Paper 5. Among others, Keller et al. (2019), Fridgen et al. (2020c), and Jöhnk et al. (2021) provided ideas for Research Paper 4. Finally, addressing the choice of the right mix of flexibility options, Research Paper 6 builds on the work of Grimm et al. (2016), Ländner et al. (2019), and Weibelzahl and Märtz (2020).

V References

Abbasi, A., S. Sarker, and R. H. Chiang (2016). “Big data research in information systems: Toward an inclusive research agenda”. In: *Journal of the association for information systems* 17.2, p. 3. DOI: `10.17705/1jais.00423`.

Abdelwahed, A., P. van den Berg, and T. Brandt (2019). “Enabling sustainable public transport in smart cities through real-time decision support”. In: *Proceedings of the 40th International Conference on Information Systems, ICIS 2019, Munich, Germany, December 15-18, 2019*.

Abdullah, M. A., K. M. Muttaqi, A. P. Agalgaonkar, and D. Sutanto (2014). “New approach for sharing wind generation spatial diversification in multi-area power systems using trade-off analysis”. In: *IET Generation, Transmission & Distribution* 8.8, pp. 1466–1478. DOI: `10.1049/iet-gtd.2013.0526`.

Acemoglu, D., A. Ozdaglar, and A. Tahbaz-Salehi (2015). “Systemic risk and stability in financial networks”. In: *American Economic Review* 105.2, pp. 564–608. DOI: `10.1257/aer.20130456`.

Acharya, V. V., L. H. Pedersen, T. Philippon, and M. Richardson (2017). “Measuring systemic risk”. In: *The review of financial studies* 30.1, pp. 2–47. DOI: `10.1093/rfs/hhw088`.

Ahmadi, S., Y. Saboohi, and A. Vakili (2021). “Frameworks, quantitative indicators, characters, and modeling approaches to analysis of energy system resilience: A review”. In: *Renewable and Sustainable Energy Reviews* 144, p. 110988. DOI: `10.1016/j.rser.2021.110988`.

Akbari, K., M. M. Nasiri, F. Jolai, and S. F. Ghaderi (2014). “Optimal investment and unit sizing of distributed energy systems under uncertainty: A robust optimization approach”. In: *Energy and Buildings* 85, pp. 275–286. DOI: `10.1016/j.enbuild.2014.09.009`.

Alstone, P., D. Gershenson, and D. M. Kammen (2015). “Decentralized energy systems for clean electricity access”. In: *Nature climate change* 5.4, pp. 305–314. DOI: `10.1038/nclimate2512`.

Andraschko, L., S. Sarker, D. J. Veit, et al. (2023). “On the role of smartness in helping consumers create sustainable outcomes”. In: *ECIS 2023 Research-in-Progress Papers. 38*.

Antonopoulos, I., V. Robu, B. Couraud, D. Kirli, S. Norbu, A. Kiprakis, D. Flynn, S. Elizondo-Gonzalez, and S. Wattam (2020). “Artificial intelligence and machine learning approaches to energy demand-side response: A systematic review”. In: *Renewable and Sustainable Energy Reviews* 130, p. 109899. DOI: `10.1016/j.rser.2020.109899`.

Argyroudis, S. A., S. A. Mitoulis, E. Chatzi, J. W. Baker, I. Brilakis, K. Gkoumas, M. Vousdoukas, W. Hynes, S. Carluccio, O. Keou, et al. (2022). “Digital technologies can enhance climate resilience of critical infrastructure”. In: *Climate Risk Management* 35, p. 100387. DOI: `10.1016/j.crm.2021.100387`.

Arrow, K. J. (1970). “Essays in the Theory of Risk Bearing. Amsterdam.-(1975): Gifts and exchanges”. In: *Altruism, Morality, and Economic Theory. New York*, pp. 13–28.

Babel, M., V. Gramlich, C. Guthmann, M. Schober, M.-F. Körner, and J. Strüker (2023). “Vertrauen durch digitale Identifizierung: Über den Beitrag von SSI zur Integration von dezentralen Oracles in Informationssysteme”. In: *HMD Praxis der Wirtschaftsinformatik* 60.2, pp. 478–493. DOI: `10.1365/s40702-023-00955-3`.

Bajwa, A. A., H. Mokhlis, S. Mekhilef, and M. Mubin (2019). “Enhancing power system resilience leveraging microgrids: A review”. In: *Journal of Renewable and Sustainable Energy* 11.3, p. 035503. DOI: `10.1063/1.5066264`.

Baldick, R. and E. Kahn (1997). “Contract paths, phase-shifters, and efficient electricity trade”. In: *IEEE transactions on Power Systems* 12.2, pp. 749–755. DOI: `10.1109/59.589670`.

Baumgarte, F., T. Brandt, R. Keller, F. Röhrich, and L. Schmidt (2021a). “You’ll never share alone: Analyzing carsharing user group behavior”. In: *Transportation Research Part D: Transport and Environment* 93, p. 102754. DOI: `10.1016/j.trd.2021.102754`.

Baumgarte, F., N. Eiser, M. Kaiser, K. Langer, and R. Keller (2022a). “Smart Electric Vehicle Charging considering Discounts for Customer Flexibility”. In: *AMCIS 2022 Proceedings. 9.*

Baumgarte, F., M. Kaiser, and R. Keller (2021b). “Policy support measures for widespread expansion of fast charging infrastructure for electric vehicles”. In: *Energy Policy* 156, p. 112372. DOI: `10.1016/j.enpol.2021.112372`.

Baumgarte, F., R. Keller, F. Röhrich, L. Valett, and D. Zinsbacher (2022b). “Revealing influences on carsharing users’ trip distance in small urban areas”. In: *Transportation*

Research Part D: Transport and Environment 105, p. 103252. DOI: `10.1016/j.trd.2022.103252`.

Bedford, J., J. Farrar, C. Ihekweazu, G. Kang, M. Koopmans, and J. Nkengasong (2019). “A new twenty-first century science for effective epidemic response”. In: *Nature* 575.7781, pp. 130–136. DOI: `10.1038/s41586-019-1717-y`.

Berizzi, A. (2004). “The italian 2003 blackout”. In: *IEEE Power Engineering Society General Meeting, 2004.* IEEE, pp. 1673–1679. DOI: `10.1109/PES.2004.1373159`.

Bernath, C., G. Deac, and F. Sensfuß (2021). “Impact of sector coupling on the market value of renewable energies–A model-based scenario analysis”. In: *Applied Energy* 281, p. 115985. DOI: `10.1016/j.apenergy.2020.115985`.

Bernoulli, D. (1738). “Specimen theoriae novae de mensura sortis vol. v; S. 175-192; deutsch von A”. In: *Commentarii academiae scientiarum imperialis Petropolitanae* 5, pp. 175–192.

Bernoulli, D. (1954). “Specimen theoriae novae de mensura sortis. Commentari Academiae Scientiarum Imperialis Petropolitanae. Versão traduzida: Expositions of a new theory on the measurement of risk”. In: *Econometrica* 1738, pp. 2–10.

Bilis, E. I., W. Kröger, and C. Nan (2013). “Performance of electric power systems under physical malicious attacks”. In: *IEEE Systems Journal* 7.4, pp. 854–865. DOI: `10.1109/JSYST.2012.2223512`.

Billio, M., M. Getmansky, A. W. Lo, and L. Pelizzon (2012). “Econometric measures of connectedness and systemic risk in the finance and insurance sectors”. In: *Journal of financial economics* 104.3, pp. 535–559. DOI: `10.1016/j.jfineco.2011.12.010`.

Bjørndal, E., M. H. Bjørndal, S. Coniglio, M.-F. Körner, C. Leinauer, and M. Weibelzahl (2023). “Energy storage operation and electricity market design: On the market power of monopolistic storage operators”. In: *European Journal of Operational Research* 307.2, pp. 887–909. DOI: `10.1016/j.ejor.2022.09.012`.

Böckers, V., J. Haucap, and U. Heimeshoff (2013a). *Benefits of an integrated European electricity market.* 109. DICE Discussion Paper. ISBN: 9783863041083.

Böckers, V., J. Haucap, and U. Heimeshoff (2013b). *Cost of Non-Europe in the Single Market for Energy: Annex IV: Benefits of an Integrated European Electricity Market: the Role of Competition.* Publications Office of the European Union. DOI: `10.2861/19914`.

Bogdanov, D., J. Farfan, K. Sadovskaia, A. Aghahosseini, M. Child, A. Gulagi, A. S. Oyewo, L. de Souza Noel Simas Barbosa, and C. Breyer (2019). “Radical transformation pathway towards sustainable electricity via evolutionary steps”. In: *Nature communications* 10.1, p. 1077. DOI: `10.1038/s41467-019-08855-1`.

Bompard, E., T. Huang, Y. Wu, and M. Cremenescu (2013). “Classification and trend analysis of threats origins to the security of power systems”. In: *International Journal of Electrical Power & Energy Systems* 50, pp. 50–64. DOI: `10.1016/j.ijepes.2013.02.008`.

Bose, B. K. (2017). “Artificial intelligence techniques in smart grid and renewable energy systems—Some example applications”. In: *Proceedings of the IEEE* 105 (11), pp. 2262–2273. DOI: `10.1109/JPROC.2017.2756596`.

Bovera, F. and L. L. Schiavo (2022). “From energy communities to sector coupling: a taxonomy for regulatory experimentation in the age of the European Green Deal”. In: *Energy Policy* 171, p. 113299. DOI: `10.1016/j.enpol.2022.113299`.

Brocke, J. vom, R. T. Watson, C. Dwyer, S. Elliot, and N. Melville (2013). “Green information systems: Directives for the IS discipline”. In: *Communications of the association for information systems* 33.1, p. 30. DOI: `10.17705/1CAIS.03330`.

Brown, T., D. Schlachtberger, A. Kies, S. Schramm, and M. Greiner (2018). “Synergies of sector coupling and transmission reinforcement in a cost-optimised, highly renewable European energy system”. In: *Energy* 160, pp. 720–739. DOI: `10.1016/j.energy.2018.06.222`.

Buhl, H. U., T. Gaugler, and P. Mette (2018). “The" insurance effect": how to increase the investment amount in green buildings-a model-based approach to reduce the energy efficiency gap”. In: *Environmental Engineering & Management Journal (EEMJ)* 17.7.

Buldyrev, S. V., R. Parshani, G. Paul, H. E. Stanley, and S. Havlin (2010). “Catastrophic cascade of failures in interdependent networks”. In: *Nature* 464.7291, pp. 1025–1028. DOI: `10.1038/nature08932`.

Bullich-Massague, E., F. Díaz-González, M. Aragüés-Peñalba, F. Girbau-Llistuella, P. Olivella-Rosell, and A. Sumper (2018). “Microgrid clustering architectures”. In: *Applied energy* 212, pp. 340–361. DOI: `10.1016/j.apenergy.2017.12.048`.

Bundesamt für Bevölkerungsschutz und Katastrophenhilfe (2023). *Kritische Infrastrukturen. Was sind Kritische Infrastrukturen und warum sind sie so wichtig?*

Bundesamt für Sicherheit in der Informationstechnik (2023). *Smart Meter Gateway. The beating heart of an intelligent metering system.*

Burpee, D, H Dabaghi, L Jackson, F Kwamena, J Richter, T Rusnov, K Friedman, L Mansueti, and D Meyer (2006). *U.S. - Canada Power System Outage Task Force: final report on the implementation of task force recommendations*.

Cantarero, M. M. V. (2020). "Of renewable energy, energy democracy, and sustainable development: A roadmap to accelerate the energy transition in developing countries". In: *Energy Research & Social Science* 70, p. 101716. DOI: `10.1016/j.erss.2020.101716`.

Cao, Y., N. Ahmad, O. Kaiwartya, G. Puturs, and M. Khalid (2018). "Intelligent transportation systems enabled ICT framework for electric vehicle charging in smart city". In: *Handbook of Smart Cities: Software Services and Cyber Infrastructure*, pp. 311–330. DOI: `10.1007/978-3-319-97271-8_12`.

Cardoso, G., M. Stadler, A. Siddiqui, C. Marnay, N. DeForest, A. Barbosa-Póvoa, and P. Ferrão (2013). "Microgrid reliability modeling and battery scheduling using stochastic linear programming". In: *Electric power systems research* 103, pp. 61–69. DOI: `10.1016/j.epsr.2013.05.005`.

Chang, L. and Z. Wu (2011). "Performance and reliability of electrical power grids under cascading failures". In: *International Journal of Electrical Power & Energy Systems* 33.8, pp. 1410–1419. DOI: `10.1016/j.ijepes.2011.06.021`.

Chawla, M. and M. G. Pollitt (2013). "Global trends in electricity transmission system operation: where does the future lie?" In: *The Electricity Journal* 26.5, pp. 65–71. DOI: `10.1016/j.tej.2013.05.004`.

Chen, A. J., R. T. Watson, M.-C. Boudreau, and E. Karahanna (2009). "Organizational adoption of green IS & IT: An institutional perspective". In: *ICIS 2009 Proceedings. 142.*

Chen, A. J., M.-C. Boudreau, and R. T. Watson (2008). "Information systems and ecological sustainability". In: *Journal of systems and Information technology* 10.3, pp. 186–201. DOI: `10.1108/13287260810916907`.

Choi, Y. and J. Caporaso (2002). "Comparative regional integration". In: *Handbook of international relations*, pp. 480–499. DOI: `10.4135/9781848608290.n25`.

Clark-Ginsberg, A., I. A. Rueda, J. Monken, J. Liu, and H. Chen (2020). "Maintaining critical infrastructure resilience to natural hazards during the COVID-19 pandemic: hurricane preparations by US energy companies". In: *Journal of infrastructure preservation and resilience* 1, pp. 1–6. DOI: `10.1186/s43065-020-00010-1`.

Commission Expert Group And Others (2017). *Towards a sustainable and integrated Europe-Report of the Commission Expert Group on electricity interconnection targets*. URL: `https://energy.ec.europa.eu/system/files/2017-11/report_of_the_commission_expert_group_on_electricity_interconnection_targets_0.pdf`. checked on 18/05/2023.

Coniglio, S., S. Halbrügge, A. Märtz, and M. Weibelzahl (2023). "The Flexibility Puzzle in Liberalized Electricity Markets: Understanding Flexibility Investments under Different Risk Attitudes". In: *Working Paper*.

Cozzi, L., D. Turk, T. Abergel, J. Bartos, E. Bellevrat, S. Bennett, T. Berly, S. Bouckaert, J. Dulac, C. F. Alvarez, et al. (2017). *Digitalization and Energy*. OECD. ISBN: 978-9264286276.

Crucitti, P., V. Latora, and M. Marchiori (2004). "Model for cascading failures in complex networks". In: *Physical Review E* 69.4, p. 045104. DOI: `10.1103/PhysRevE.69.045104`.

Darby, S. J. (2020). "Energy, human activity, and knowledge: Addressing smart city challenges". In: *Energy and Behaviour*. Elsevier, pp. 237–260. DOI: `10.1016/B978-0-12-818567-4.00010-7`.

Darwish, A. S. and R. Al-Dabbagh (2020). "Wind energy state of the art: present and future technology advancements". In: *Renewable Energy and Environmental Sustainability* 5, p. 7. DOI: `10.1051/rees/2020003`.

Dedrick, J. (2010). "Green IS: Concepts and issues for information systems research". In: *Communications of the Association for Information Systems* 27.1, p. 11. DOI: `10.17705/1CAIS.02711`.

Degirmenci, K. and M. Breitner (2014). "Carsharing: A literature review and a perspective for information systems research". In: *MKWI 2014-Multikonferenz Wirtschaftsinformatik*, pp. 962–979.

Demiroren, A, H. Zeynelgil, and N. Sengor (2001). "The application of ANN technique to load-frequency control for three-area power system". In: *2001 IEEE Porto Power Tech Proceedings (Cat. No. 01EX502)*. Vol. 2. IEEE, 5–pp. DOI: `10.1109/PTC.2001.964793`.

Di Silvestre, M. L., S. Favuzza, E. R. Sanseverino, and G. Zizzo (2018). "How Decarbonization, Digitalization and Decentralization are changing key power infrastructures". In: *Renewable and Sustainable Energy Reviews* 93, pp. 483–498. DOI: `10.1016/j.rser.2018.05.068`.

Dietrich, A. and C. Weber (2018). “What drives profitability of grid-connected residential PV storage systems? A closer look with focus on Germany”. In: *Energy Economics* 74, pp. 399–416. DOI: `10.1016/j.eneco.2018.06.014`.

Dincer, I. (2000). “Renewable energy and sustainable development: a crucial review”. In: *Renewable and sustainable energy reviews* 4.2, pp. 157–175. DOI: `10.1016/S1364-0321(99)00011-8`.

Dlugosch, O., T. Brandt, and D. Neumann (2022). “Combining analytics and simulation methods to assess the impact of shared, autonomous electric vehicles on sustainable urban mobility”. In: *Information & Management* 59.5, p. 103285. DOI: `10.1016/j.im.2020.103285`.

Duan, Y., J. S. Edwards, and Y. K. Dwivedi (2019). “Artificial intelligence for decision making in the era of Big Data–evolution, challenges and research agenda”. In: *International journal of information management* 48, pp. 63–71. DOI: `10.1016/j.ijinfomgt.2019.01.021`.

Economic Affairs, G. F. M. for and Energy (2021). *GAIA-X: a federated data infrastrcture for Europe*.

Elavarasan, R. M., G. Shafiullah, K. Raju, V. Mudgal, M. T. Arif, T. Jamal, S. Subramanian, V. S. Balaguru, K. Reddy, and U. Subramaniam (2020). “COVID-19: Impact analysis and recommendations for power sector operation”. In: *Applied energy* 279, p. 115739. DOI: `10.1016/j.apenergy.2020.115739`.

Elliot, S. (2011). “Transdisciplinary perspectives on environmental sustainability: a resource base and framework for IT-enabled business transformation”. In: *Mis quarterly*, pp. 197–236. DOI: `10.2307/23043495`.

Enerdata (2023). *EDF’s power generation in France reached a record low in 2022*. URL: `https://www.enerdata.net/publications/daily-energy-news`. checked on 08/07/2023.

ENTSO-E (2021). *System separation in the Continental Europe Synchronous Area on 8 January 2021 – 2nd update*. URL: `https://www.entsoe.eu/news/2021/01/26/system-separation-in-the-continental-europe-synchronous-area-on-8-january-2021-2nd-update/`. checked on 25/07/2021.

ENTSO-E (2023). *High-Level Report TYNDP 2022*. URL: `https://eepublicdownloads.blob.core.windows.net/public-cdn-container/tyndp-documents/TYNDP2022/public/high-level-report.pdf`. checked on 20/06/2023.

ENTSOE (2009). *Annual Report 2009*. URL: `https://eepublicdownloads.entsoe.eu/clean-documents/pre2015/publications/entsoe/Annual_Report/100610_ENTSO-E_Annual_Report_2009.pdf`. checked on 18/05/2023.

ENTSOE (2022). *ENTSO-E – Market report 2022*. URL: `https://ee-public-nc-downloads.azureedge.net/strapi-test-assets/strapi-assets/2022_ENTSO_E_Market_report_Web_836ec0a601.pdf`. checked on 18/05/2023.

Eriksen, E. H., L. J. Schwenk-Nebbe, B. Tranberg, T. Brown, and M. Greiner (2017). "Optimal heterogeneity in a simplified highly renewable European electricity system". In: *Energy* 133, pp. 913–928. DOI: `10.1016/j.energy.2017.05.170`.

Esfahbodi, A., Y. Zhang, Y. Liu, and D. Geng (2023). "The fallacy of profitable green supply chains: The role of green information systems (GIS) in attenuating the sustainability trade-offs". In: *International Journal of Production Economics* 255, p. 108703. DOI: `10.1016/j.ijpe.2022.108703`.

EU Commission (2017). *A European Strategy for data*. URL: `https://digital-strategy.ec.europa.eu/en/policies/strategy-data`. checked on 09/07/2023.

EU Commission (2019). *Communication from the Commission to the European Parliament, the European Council, the Council, the European Economic and Social Committee and the Committee of the Regions - The European Green Deal*. URL: `https://eur-lex.europa.eu/legal-content/EN/TXT/?qid=1588580774040&uri=CELEX%3A52019DC0640`. checked on 08/07/2023.

EU Commission (2020). *Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions - Powering a climate-neutral economy: An EU Strategy for Energy System Integration*. URL: `https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52020DC0299`. checked on 11/05/2023.

EU Commission (2021). *Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions - 'Fit for 55': delivering the EU's 2030 Climate Target on the way to climate neutrality*. URL: `https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52021DC0550`. checked on 06/07/2023.

EU Commission (2023a). *Green digital sector: Europe's digital transition goes hand in hand with the European Green Deal.* URL: `https://digital-strategy.ec.europa.eu/en/policies/green-digital`. checked on 08/07/2023.

EU Commission (2023b). *New European Interoperability Framework: Promoting seamless services and data flows for European public administrations.* URL: `https://ec.europa.eu/isa2/sites/default/files/eif_brochure_final.pdf`. checked on 09/07/2023.

European Energy Exchange (2023). *Current market conditions.* URL: `https://www.eex.com/en/markets/current-market-conditions`. checked on 18/05/2023.

Ezzeldin, M. and W. E. El-Dakhakhni (2021). "Robustness of Ontario power network under systemic risks". In: *Sustainable and resilient infrastructure* 6.3-4, pp. 252–271. DOI: `10.1080/23789689.2019.1666340`.

Faria, R., L. Brito, K. Baras, and J. Silva (2017). "Smart mobility: A survey". In: *2017 International conference on internet of things for the global community (IoTGC)*. IEEE, pp. 1–8. DOI: `10.1109/IoTGC.2017.80089720`.

Fraunhofer ISE (2019). *Net public electricity generation in Germany in 2019.* URL: `https://www.energy-charts.de/energy_pie.htm?year=2019`. checked on 18/07/2020.

Freitag, C., M. Berners-Lee, K. Widdicks, B. Knowles, G. S. Blair, and A. Friday (2021). "The real climate and transformative impact of ICT: A critique of estimates, trends, and regulations". In: *Patterns* 2.9, p. 100340. DOI: `10.1016/j.patter.2021.100340`.

Fridgen, G., A. Gründler, and M. Rusic (2015a). "Energy Cooperatives as an Application of Microgrids: Multi-Criteria Investment Decision Support". In: *ICIS 2015 Proceedings*.

Fridgen, G., L. Häfner, C. König, and T. Sachs (2014a). "Toward Real Options Analysis of IS-Enabled Flexibility in Electricity Demand". In: *ICIS 2014 Proceedings*.

Fridgen, G., L. Häfner, C. König, and T. Sachs (2015b). "The value of IS-enabled flexibility in electricity demand-a real options approach". In: *Proceedings of the 12th International Conference on Wirtschaftsinformatik (WI), Osnabrück, Germany, March 2015*.

Fridgen, G., L. Häfner, C. König, and T. Sachs (2016). "Providing utility to utilities: the value of information systems enabled flexibility in electricity consumption". In:

Journal of the Association for Information Systems 17.8, p. 1. DOI: `10.17705/1jais.00434`.

Fridgen, G., S. Halbrügge, M.-F. Körner, A. Michaelis, and M. Weibelzahl (2022). "Artificial intelligence in energy demand response: a taxonomy of input data requirements". In: *Wirtschaftsinformatik 2022 Proceedings. 4.*

Fridgen, G., S. Halbrügge, C. Olenberger, and M. Weibelzahl (2020a). "The insurance effect of renewable distributed energy resources against uncertain electricity price developments". In: *Energy Economics* 91, p. 104887. DOI: `10.1016/j.eneco.2020.104887`.

Fridgen, G., M. Kahlen, W. Ketter, A. Rieger, and M. Thimmel (2018). "One rate does not fit all: An empirical analysis of electricity tariffs for residential microgrids". In: *Applied energy* 210, pp. 800–814. DOI: `10.1016/j.apenergy.2017.08.138`.

Fridgen, G., R. Keller, M.-F. Körner, and M. Schöpf (2020b). "A holistic view on sector coupling". In: *Energy Policy* 147, p. 111913. DOI: `10.1016/j.enpol.2020.111913`.

Fridgen, G., P. Mette, and M. Thimmel (2014b). "The Value of Information Exchange in Electric Vehicle Charging". In: *ICIS 2014 Proceedings*.

Fridgen, G., A. Michaelis, M. Rinck, M. Schöpf, and M. Weibelzahl (2020c). "The search for the perfect match: Aligning power-trading products to the energy transition". In: *Energy Policy* 144, p. 111523. DOI: `10.1016/j.enpol.2020.111523`.

Gea-Bermúdez, J., I. G. Jensen, M. Münster, M. Koivisto, J. G. Kirkerud, Y.-k. Chen, and H. Ravn (2021). "The role of sector coupling in the green transition: A least-cost energy system development in Northern-central Europe towards 2050". In: *Applied Energy* 289, p. 116685. DOI: `10.1016/j.apenergy.2021.116685`.

Gils, H. C., Y. Scholz, T. Pregger, D. L. de Tena, and D. Heide (2017). "Integrated modelling of variable renewable energy-based power supply in Europe". In: *Energy* 123, pp. 173–188. DOI: `10.1016/j.energy.2017.01.115`.

Glenk, G. and S. Reichelstein (2019). "Economics of converting renewable power to hydrogen". In: *Nature Energy* 4.3, pp. 216–222. DOI: `10.1038/s41560-019-0326-1`.

Goebel, C., H.-A. Jacobsen, V. Del Razo, C. Doblander, J. Rivera, J. Ilg, C. Flath, H. Schmeck, C. Weinhardt, D. Pathmaperuma, et al. (2014). "Energy informatics: current and future research directions". In: *Wirtschaftsinformatik* 56, pp. 31–39. DOI: `10.1007/s11576-013-0396-9`.

Grieves, M. and J. Vickers (2017). “Digital twin: Mitigating unpredictable, undesirable emergent behavior in complex systems”. In: *Transdisciplinary perspectives on complex systems: New findings and approaches*, pp. 85–113. DOI: 10.1007/978-3-319-38756-7_4.

Grimm, V., A. Martin, M. Weibelzahl, and G. Zöttl (2016). “On the long run effects of market splitting: Why more price zones might decrease welfare”. In: *Energy Policy* 94, pp. 453–467. DOI: 10.1016/j.enpol.2015.11.010.

Gunduz, M. Z. and R. Das (2020). “Cyber-security on smart grid: Threats and potential solutions”. In: *Computer networks* 169, p. 107094. DOI: 10.1016/j.comnet.2019.107094.

Halbrügge, S., H. U. Buhl, G. Fridgen, P. Schott, M. Weibelzahl, and J. Weissflog (2022). “How Germany achieved a record share of renewables during the COVID-19 pandemic while relying on the European interconnected power network”. In: *Energy* 246, p. 123303. DOI: 10.1016/j.energy.2022.123303.

Halbrügge, S., P. Schott, M. Weibelzahl, H. U. Buhl, G. Fridgen, and M. Schöpf (2021). “How did the German and other European electricity systems react to the COVID-19 pandemic?” In: *Applied Energy* 285, p. 116370. DOI: 10.1016/j.apenergy.2020.116370.

Halbrügge, S., L. Wederhake, and L. Wolf (2020). “Reducing the expectation-performance gap in EV fast charging by managing service performance”. In: pp. 47–61. DOI: 10.1007/978-3-030-38724-2_4.

Haldane, A. G. and R. M. May (2011). “Systemic risk in banking ecosystems”. In: *Nature* 469.7330, pp. 351–355. DOI: 10.1038/nature09659.

He, G., D. S. Mallapragada, A. Bose, C. F. Heuberger-Austin, and E. Gençer (2021). “Sector coupling via hydrogen to lower the cost of energy system decarbonization”. In: *Energy & Environmental Science* 14.9, pp. 4635–4646. DOI: 10.1039/d1ee00627d.

Heffron, R., M.-F. Körner, J. Wagner, M. Weibelzahl, and G. Fridgen (2020). “Industrial demand-side flexibility: A key element of a just energy transition and industrial development”. In: *Applied Energy* 269, p. 115026. DOI: 10.1016/j.apenergy.2020.115026.

Heinisch, V., L. Göransson, R. Erlandsson, H. Hodel, F. Johnsson, and M. Odenberger (2021). “Smart electric vehicle charging strategies for sectoral coupling in a city energy system”. In: *Applied Energy* 288, p. 116640. DOI: `10.1016/j.apenergy.2021.116640`.

Heymann, F., T. Milojevic, A. Covatariu, and P. Verma (2023). “Digitalization in decarbonizing electricity systems–Phenomena, regional aspects, stakeholders, use cases, challenges and policy options”. In: *Energy* 262, p. 125521. DOI: `10.1016/j.energy.2022.125521`.

Hildebrandt, B., A. Hanelt, E. Piccinini, L. Kolbe, and T. Nierobisch (2015). “The value of is in business model innovation for sustainable mobility services-the case of carsharing”. In: *Wirtschaftsinformatik Proceedings 2015. 68.*

Huang, T, R Pi, E Bompard, F Profumo, P Cuccia, G Fulli, and M Masera (2017). “Analysis and visualization of natural threats against the security of electricity transmission system”. In: *The Scientific Bulletin of Electrical Engineering Faculty*. DOI: `10.1515/sbeef-2016-0019`.

Hutcheon, N. and J. W. Bialek (2013). “Updated and validated power flow model of the main continental European transmission network”. In: *2013 IEEE Grenoble Conference*. IEEE, pp. 1–5. DOI: `10.1109/PTC.2013.6652178`.

Ilin, T. and L. Varga (2015). “The uncertainty of systemic risk”. In: *Risk management* 17, pp. 240–275. DOI: `10.1057/rm.2015.15`.

International Energy Agency (2023a). *CO2 Emissions in 2022*. URL: `https://www.iea.org/reports/co2-emissions-in-2022`. checked on 10/05/2023.

International Energy Agency (2023b). *Renewable Energy Market Update*. URL: `https://www.irena.org/Publications/2023/Jul/Renewable-energy-statistics-2023`. checked on 10/07/2023.

International Energy Agency (2023c). *Renewable energy statistics 2023*. URL: `https://www.iea.org/reports/co2-emissions-in-2022`. checked on 10/05/2023.

IRENA (2019). *Innovation Landscape for a Renewable-Powered Future*. URL: `https://www.irena.org/publications/2019/Feb/Innovation-landscape-for-a-renewable-powered-future`. checked on 25/07/2023.

Ivanov, D. and A. Dolgui (2021). “A digital supply chain twin for managing the disruption risks and resilience in the era of Industry 4.0”. In: *Production Planning & Control* 32.9, pp. 775–788. DOI: `10.1080/09537287.2020.1768450`.

Ivanov, D., A. Dolgui, and B. Sokolov (2019). “The impact of digital technology and Industry 4.0 on the ripple effect and supply chain risk analytics”. In: *International* *journal of production research* 57.3, pp. 829–846. DOI: `10.1080/00207543.2018.1488086`.

Jäckle, F., M. Schöpf, J. Töppel, and F. Wagon (2019). "Risk mitigation capability of flexibility performance contracts for demand response in electricity systems". In: *Potentials of energy informatics to incentivize flexibility in the energy system in a short-and long-term perspective*, p. 59.

Jasiūnas, J., P. D. Lund, and J. Mikkola (2021). "Energy system resilience–A review". In: *Renewable and Sustainable Energy Reviews* 150, p. 111476. DOI: `10.1016/j.rser.2021.111476`.

Jenssen, Å, T Borsche, and J Wolst (2017). "Data exchange in electric power systems: European state of play and perspectives". In: *THEMA Consulting: Oslo, Norway*.

Jesse, B.-J., H. U. Heinrichs, and W. Kuckshinrichs (2019). "Adapting the theory of resilience to energy systems: a review and outlook". In: *Energy, Sustainability and Society* 9.1, pp. 1–19. DOI: `10.1186/s13705-019-0210-7`.

Jha, S. K., J. Bilalovic, A. Jha, N. Patel, and H. Zhang (2017). "Renewable energy: Present research and future scope of Artificial Intelligence". In: *Renewable and Sustainable Energy Reviews* 77, pp. 297–317. DOI: `10.1016/j.rser.2017.04.018`.

Jiang, P., Y. Van Fan, and J. J. Klemeš (2021). "Impacts of COVID-19 on energy demand and consumption: Challenges, lessons and emerging opportunities". In: *Applied energy* 285, p. 116441. DOI: `10.1016/j.apenergy.2021.116441`.

Jöhnk, J., M. Weißert, and K. Wyrtki (2021). "Ready or not, AI comes—an interview study of organizational AI readiness factors". In: *Business & Information Systems Engineering* 63, pp. 5–20. DOI: `10.1007/s12599-020-00676-7`.

Keller, R., A. Stohr, G. Fridgen, J. Lockl, and A. Rieger (2019). "Affordance-experimentation-actualization theory in artificial intelligence research: a predictive maintenance story". In: *ICIS 2019 Proceedings*.

Kerste, M., M. Gerritsen, J. Weda, and B. Tieben (2015). "Systemic risk in the energy sector—Is there need for financial regulation?" In: *Energy policy* 78, pp. 22–30. DOI: `10.1016/j.enpol.2014.12.018`.

Kitzing, L. and C. Weber (2014). "Support mechanisms for renewables: How risk exposure influences investment incentives". In: *EWL Working Paper No. 03/2014*. DOI: `10.2139/ssrn.2505976`.

Komendantova, N. and A. Battaglini (2016). "Beyond Decide-Announce-Defend (DAD) and Not-in-My-Backyard (NIMBY) models? Addressing the social and public acceptance of electric transmission lines in Germany”. In: *Energy research & social science* 22, pp. 224–231. DOI: `10.1016/j.erss.2016.10.001`.

Körner, M.-F., D. Bauer, R. Keller, M. Rösch, A. Schlereth, P. Simon, T. Bauernhansl, G. Fridgen, and G. Reinhart (2019). “Extending the automation pyramid for industrial demand response”. In: *Procedia CIRP* 81, pp. 998–1003. DOI: `10.1016/j.procir.2019.03.241`.

Körner, M.-F., A. Michaelis, S. Spazierer, and J. Strüker (2023). “Accelerating sustainability in companies: A taxonomy of information systems for corporate carbon risk management”. In: *ECIS 2023 Research Paper* 248.

Körner, M.-F., J. Sedlmeir, M. Weibelzahl, G. Fridgen, M. Heine, and C. Neumann (2022). “Systemic risks in electricity systems: A perspective on the potential of digital technologies”. In: *Energy Policy* 164, p. 112901. DOI: `10.1016/j.enpol.2022.112901`.

Körner, M.-F. and J. Strüker (2023). “Digital Data Ecosystems for the Verification of Corporate Carbon Emission Reporting”. In: *Bayreuth Digital Science Conference , 10.02.2023 , Bayreuth.*

Küfeoglu, S., G. Liu, K. Anaya, and M. Pollitt (2019). “Digitalisation and new business models in energy sector”. In: *Energy Policy Research Group, University of Cambridge*.

Lai, K., M. Illindala, and K. Subramaniam (2019). “A tri-level optimization model to mitigate coordinated attacks on electric power systems in a cyber-physical environment”. In: *Applied energy* 235, pp. 204–218. DOI: `10.1016/j.apenergy.2018.10.077`.

Ländner, E.-M., A. Märtz, M. Schöpf, and M. Weibelzahl (2019). “From energy legislation to investment determination: Shaping future electricity markets with different flexibility options”. In: *Energy Policy* 129, pp. 1100–1110. DOI: `10.1016/j.enpol.2019.02.012`.

Lange, S., J. Pohl, and T. Santarius (2020). “Digitalization and energy consumption. Does ICT reduce energy demand?” In: *Ecological economics* 176, p. 106760. DOI: `10.1016/j.ecolecon.2020.106760`.

Laughton, M. (1997). “Artificial intelligence techniques in power systems”. In: *IEE Colloquium on Artificial Intelligence Techniques in Power Systems*. IET, pp. 1–1. DOI: `10.1049/ic:19971179`.

Lautier, D. and F. Raynaud (2012). “Systemic risk in energy derivative markets: a graph-theory analysis”. In: *The Energy Journal* 33.3. DOI: `10.5547/01956574.33.3.8`.

Lee, H., G.-S. Byeon, J.-H. Jeon, A. Hussain, H.-M. Kim, A. O. Rousis, and G. Strbac (2019a). “An energy management system with optimum reserve power procurement function for microgrid resilience improvement”. In: *IEEE Access* 7, pp. 42577–42585. DOI: `10.1109/ACCESS.2019.2907120`.

Lee, H., K Calvin, D Dasgupta, G Krinner, A Mukherji, P Thorne, C. Trisos, J Romero, P Aldunce, K Barrett, et al. (2023). “AR6 Synthesis Report: Climate Change 2023”. In: *Summary for Policymakers*. URL: `https://www.ipcc.ch/report/sixth-assessment-report-cycle/`. checked on 25/07/2023.

Lee, J. T., J. Freitas, I. L. Ferrall, D. M. Kammen, E. Brewer, and D. S. Callaway (2019b). “Review and perspectives on data sharing and privacy in expanding electricity access”. In: *Proceedings of the IEEE* 107.9, pp. 1803–1819. DOI: `10.1109/JPROC.2019.2919306`.

Lehnhoff, S. and A. Nieße (2019). “Event-driven Reorganization of Distributed Business Processes in Electrical Energy Systems”. In: *SysRisk@ Wirtschaftsinformatik*, pp. 38–40.

Leinauer, C., M.-F. Körner, and J. Strüker (2023). *Toward net 0: Digital CO2 proofs for the sustainable transformation of the European economy*. Tech. rep. University of Bayreuth, Chair of Information Systems Management. DOI: `10.15495/EPub_UBT_00006827`.

Leinauer, C., P. Schott, G. Fridgen, R. Keller, P. Ollig, and M. Weibelzahl (2022). “Obstacles to demand response: Why industrial companies do not adapt their power consumption to volatile power generation”. In: *Energy Policy* 165, p. 112876. DOI: `10.1016/j.enpol.2022.112876`.

Li, T., M. Eremia, and M. Shahidehpour (2008). “Interdependency of natural gas network and power system security”. In: *IEEE Transactions on Power Systems* 23.4, pp. 1817–1824. DOI: `10.1109/TPWRS.2008.2004739`.

Li, Z., M. Shahidehpour, and F. Aminifar (2017). “Cybersecurity in distributed power systems”. In: *Proceedings of the IEEE* 105.7, pp. 1367–1388. DOI: `10.1109/JPROC.2017.2687865`.

Litman, T. (2000). “Evaluating carsharing benefits”. In: *Transportation Research Record* 1702.1, pp. 31–35. DOI: `10.3141/1702-04`.

Liu, S., Z. Yang, Q. Xia, W. Lin, L. Shi, and D. Zeng (2020). “Power trading region considering long-term contract for interconnected power networks”. In: *Applied Energy* 261, p. 114411. DOI: `10.1016/j.apenergy.2019.114411`.

Lu, Z., X. Lu, W. Wang, and C. Wang (2010). “Review and evaluation of security threats on the communication networks in the smart grid”. In: *2010-Milcom 2010 Military Communications Conference*. IEEE, pp. 1830–1835. DOI: `10.1109/MILCOM.2010.5679551`.

Luderer, G., S. Madeddu, L. Merfort, F. Ueckerdt, M. Pehl, R. Pietzcker, M. Rottoli, F. Schreyer, N. Bauer, L. Baumstark, et al. (2022). “Impact of declining renewable energy costs on electrification in low-emission scenarios”. In: *Nature Energy* 7.1, pp. 32–42. DOI: `10.1038/s41560-021-00937-z`.

Markowitz, H. M. (1959). “Portfolio Selection, 1959”. In: *Journal of Finance* 7, p. 7791.

Maruf, M. N. I. (2021). “Open model-based analysis of a 100% renewable and sector-coupled energy system–The case of Germany in 2050”. In: *Applied Energy* 288, p. 116618. DOI: `10.1016/j.apenergy.2021.116618`.

Mavromatidis, G., K. Orehounig, and J. Carmeliet (2018). “A review of uncertainty characterisation approaches for the optimal design of distributed energy systems”. In: *Renewable and Sustainable Energy Reviews* 88, pp. 258–277. DOI: `10.1016/j.rser.2018.02.021`.

Meng, L., Q. Shafiee, G. F. Trecate, H. Karimi, D. Fulwani, X. Lu, and J. M. Guerrero (2017). “Review on control of DC microgrids and multiple microgrid clusters”. In: *IEEE journal of emerging and selected topics in power electronics* 5.3, pp. 928–948. DOI: `10.1109/JESTPE.2017.2690219`.

Messner, D., S. Schlacke, M. Fromhold-Eisebith, U. Grote, E. Matthies, K. Pittel, H. J. Schellnhuber, I. Schieferdecker, U. Schneidewind, K. Augenstein, et al. (2019). *Unsere gemeinsame digitale Zukunft*. WBGU. ISBN: 978-3-946830-02-3.

Mingay, S. and D. Pamlin (2008). “Assessment of global low-carbon and environmental leadership in the ICT sector, by Gartner and WWF”. In: *Gartner & WWF*.

Mishra, S., K. Anderson, B. Miller, K. Boyer, and A. Warren (2020). “Microgrid resilience: A holistic approach for assessing threats, identifying vulnerabilities, and designing corresponding mitigation strategies”. In: *Applied Energy* 264, p. 114726. DOI: `10.1016/j.apenergy.2020.114726`.

Molyneaux, L., L. Wagner, C. Froome, and J. Foster (2012). “Resilience and electricity systems: A comparative analysis”. In: *Energy Policy* 47, pp. 188–201. DOI: `10.1016/j.enpol.2012.04.057`.

Moore, S. (2015). *Visions for sustainable energy transformations: Integrating power and politics in the Mediterranean region*. PhD dissertation. University of Michigan. ISBN 9781321720785.

Munster, M., D. Moller Sneum, R. Bramstoft, F. Buhler, B. Elmegaard, S. Giannelos, G. Strbac, M. Berger, D.-C. Radu, D. Elsaesser, et al. (2020). “Sector coupling: concepts, state-of-the-art and perspectives”. In: *European Technology & Innovation Platforms - Smart Networks for Energy Transition*. URL: `{https://www.etip-snet.eu/sector-coupling-concepts-state-art-perspectives/}`. checked on 25/07/203.

National Centers for Environmental Information (2023). *Monthly Global Climate Report for January 2023*. URL: `https://www.ncei.noaa.gov/access/monitoring/monthly-report/global/202301/supplemental/page-1.`. checked on 22/06/2023.

Nepal, R. and T. Jamasb (2013). “Security of European electricity systems: Conceptualizing the assessment criteria and core indicators”. In: *International Journal of critical infrastructure protection* 6.3-4, pp. 182–196. DOI: `10.1016/j.ijcip.2013.07.001`.

Nickerson, R. C., U. Varshney, and J. Muntermann (2013). “A method for taxonomy development and its application in information systems”. In: *European Journal of Information Systems* 22.3, pp. 336–359. DOI: `10.1057/ejis.2012.26`.

Osorio, S., R. C. Pietzcker, M. Pahle, and O. Edenhofer (2020). “How to deal with the risks of phasing out coal in Germany”. In: *Energy Economics* 87, p. 104730. DOI: `10.1016/j.eneco.2020.104730`.

Otto, B., M. ten Hompel, and S. Wrobel (2022). *Designing Data Spaces: The Ecosystem Approach to Competitive Advantage*. Springer Nature. DOI: `10.1007/978-3-030-93975-5`.

Otuoze, A. O., M. W. Mustafa, and R. M. Larik (2018). “Smart grids security challenges: Classification by sources of threats”. In: *Journal of Electrical Systems and Information Technology* 5.3, pp. 468–483. DOI: `10.1016/j.jesit.2018.01.001`.

Panteli, M. and P. Mancarella (2015). “Modeling and evaluating the resilience of critical electrical power infrastructure to extreme weather events”. In: *IEEE Systems Journal* 11.3, pp. 1733–1742. DOI: `10.1109/JSYST.2015.2389272`.

Papaefthymiou, G., E. Haesen, and T. Sach (2018). “Power System Flexibility Tracker: Indicators to track flexibility progress towards high-RES systems”. In: *Renewable Energy* 127, pp. 1026–1035. DOI: `10.1016/j.renene.2018.04.094`.

Pappas, I. O., P. Mikalef, Y. K. Dwivedi, L. Jaccheri, and J. Krogstie (2023). “Responsible Digital Transformation for a Sustainable Society”. In: *Information Systems Frontiers*, pp. 1–9. DOI: `10.1007/s10796-023-10406-5`.

Pereirinha, P. G., M. González, I. Carrilero, D. Anseán, J. Alonso, and J. C. Viera (2018). “Main trends and challenges in road transportation electrification”. In: *Transportation research procedia* 33, pp. 235–242. DOI: `10.1016/j.trpro.2018.10.096`.

Perera, A., V. M. Nik, P. Wickramasinghe, and J.-L. Scartezzini (2019). “Redefining energy system flexibility for distributed energy system design”. In: *Applied Energy* 253, p. 113572. DOI: `10.1016/j.apenergy.2019.113572`.

Pollitt, M. G. (2012). “The role of policy in energy transitions: Lessons from the energy liberalisation era”. In: *Energy policy* 50, pp. 128–137. DOI: `10.1016/j.enpol.2012.03.004`.

Preiß, S. (2019). *Steigender Anteil Erneuerbarer führt zu erhöhtem Flexibilitätsbedarf im Stromnetz*. URL: `https://www.contextcrew.de/steigender-anteil-erneuerbarer-fuehrt-zu-erhoehtem-flexibilitaetsbedarf-im-stromnetz/`. checked on 08/07/2023.

Prol, J. L. and O Sungmin (2020). “Impact of COVID-19 measures on short-term electricity consumption in the most affected EU countries and USA states”. In: *Iscience* 23.10, p. 101639. DOI: `10.1016/j.isci.2020.101639`.

Qadrdan, M., H. Ameli, G. Strbac, and N. Jenkins (2017). “Efficacy of options to address balancing challenges: Integrated gas and electricity perspectives”. In: *Applied energy* 190, pp. 181–190. DOI: `10.1016/j.apenergy.2016.11.119`.

Quadri, I. A., S Bhowmick, and D Joshi (2018). “A comprehensive technique for optimal allocation of distributed energy resources in radial distribution systems”. In: *Applied energy* 211, pp. 1245–1260. DOI: `10.1016/j.apenergy.2017.11.108`.

Radecke, J., J. Hefele, and L. Hirth (2019). “Markets for local flexibility in distribution networks”. In: *Working Paper, ZBW – Leibniz Information Centre for Economics, Kiel, Hamburg*.

Ramos, C. and C.-C. Liu (2011). “AI in power systems and energy markets”. In: *IEEE Intelligent Systems* 26.2, pp. 5–8. DOI: `10.1109/MIS.2011.26`.

Ramsebner, J., R. Haas, A. Ajanovic, and M. Wietschel (2021). “The sector coupling concept: A critical review”. In: *Wiley interdisciplinary reviews: energy and environment* 10.4, p. 396. DOI: `10.1002/wene.396`.

Ratnam, E. L., K. G. Baldwin, P. Mancarella, M. Howden, and L. Seebeck (2020). “Electricity system resilience in a world of increased climate change and cybersecurity risk”. In: *The Electricity Journal* 33.9, p. 106833. DOI: `10.1016/j.tej.2020.106833`.

Reboredo, J. C. (2015). “Is there dependence and systemic risk between oil and renewable energy stock prices?” In: *Energy Economics* 48, pp. 32–45. DOI: `10.1016/j.eneco.2014.12.009`.

Reim, W., J. Åström, and O. Eriksson (2020). “Implementation of artificial intelligence (AI): a roadmap for business model innovation”. In: *AI* 1.2, p. 11. DOI: `10.3390/ai1020011`.

Rieger, A., R. Thummert, G. Fridgen, M. Kahlen, and W. Ketter (2016). “Estimating the benefits of cooperation in a residential microgrid:A data-driven approach”. In: *Applied Energy* 180, pp. 130–141. DOI: `10.1016/j.apenergy.2016.07.105`.

Rocchetta, R. (2022). “Enhancing the resilience of critical infrastructures: Statistical analysis of power grid spectral clustering and post-contingency vulnerability metrics”. In: *Renewable and Sustainable Energy Reviews* 159, p. 112185. DOI: `10.1016/j.rser.2022.112185`.

Rodriguez, R. A., S. Becker, G. B. Andresen, D. Heide, and M. Greiner (2014). “Transmission needs across a fully renewable European power system”. In: *Renewable Energy* 63, pp. 467–476. DOI: `10.1016/j.renene.2013.10.005`.

Rohden, M., D. Jung, S. Tamrakar, and S. Kettemann (2016). “Cascading failures in ac electricity grids”. In: *Physical Review E* 94.3, p. 032209. DOI: `10.1103/PhysRevE.94.032209`.

Roques, F. A., D. M. Newbery, and W. J. Nuttall (2008). “Fuel mix diversification incentives in liberalized electricity markets: A Mean–Variance Portfolio theory approach”. In: *Energy Economics* 30.4, pp. 1831–1849. DOI: `10.1016/j.eneco.2007.11.008`.

Rövekamp, P., M. Schöpf, F. Wagon, M. Weibelzahl, and G. Fridgen (2021). “Renewable electricity business models in a post feed-in tariff era”. In: *Energy* 216, p. 119228. DOI: `10.1016/j.energy.2020.119228`.

Russell, S. J. (2010). *Artificial intelligence a modern approach*. Pearson Education, Inc.

Saleh, M. S., A. Althaibani, Y. Esa, Y. Mhandi, and A. A. Mohamed (2015). “Impact of clustering microgrids on their stability and resilience during blackouts”. In: *2015 International Conference on Smart Grid and Clean Energy Technologies (ICSGCE)*. IEEE, pp. 195–200. DOI: `10.1109/ICSGCE.2015.7454295`.

Schaber, K., F. Steinke, and T. Hamacher (2012a). “Transmission grid extensions for the integration of variable renewable energies in Europe: Who benefits where?” In: *Energy Policy* 43, pp. 123–135. DOI: `10.1016/j.enpol.2011.12.040`.

Schaber, K., F. Steinke, P. Mühlich, and T. Hamacher (2012b). “Parametric study of variable renewable energy integration in Europe: Advantages and costs of transmission grid extensions”. In: *Energy policy* 42, pp. 498–508. DOI: `10.1016/j.enpol.2011.12.016`.

Schlachtberger, D. P., T. Brown, S. Schramm, and M. Greiner (2017). “The benefits of cooperation in a highly renewable European electricity network”. In: *Energy* 134, pp. 469–481. DOI: `10.1016/j.energy.2017.06.004`.

Schleussner, C.-F., J. Rogelj, M. Schaeffer, T. Lissner, R. Licker, E. M. Fischer, R. Knutti, A. Levermann, K. Frieler, and W. Hare (2016). “Science and policy characteristics of the Paris Agreement temperature goal”. In: *Nature Climate Change* 6.9, pp. 827–835. DOI: `10.1038/nclimate3096`.

Schlund, J. and R. German (2019). “A distributed ledger based platform for community-driven flexibility provision”. In: *Energy Informatics* 2, pp. 1–20. DOI: `10.1186/s42162-019-0068-0`.

Schlund, J., D. Steber, P. Bazan, and R. German (2017). “Increasing the efficiency of a virtual battery storage providing frequency containment reserve power by applying a clustering algorithm”. In: *2017 IEEE Innovative Smart Grid Technologies-Asia (ISGT-Asia)*. IEEE, pp. 1–8. DOI: `10.1109/ISGT-Asia.2017.8378430`.

Schneider, C. M., A. A. Moreira, J. S. Andrade Jr, S. Havlin, and H. J. Herrmann (2011). “Mitigation of malicious attacks on networks”. In: *Proceedings of the National Academy of Sciences* 108.10, pp. 3838–3841. DOI: `10.1073/pnas.1009440108`.

Schoepf, M., M. Weibelzahl, and L. Nowka (2018). "The impact of substituting production technologies on the economic demand response potential in industrial processes". In: *energies* 11.9, p. 2217. DOI: `10.3390/en11092217`.

Senthilkumar, V., K. Reddy, and U. Subramaniam (2020). "COVID-19: Impact analysis and recommendations for power and energy sector operation". In: *Applied Energy* 279.115739, p. 44. DOI: `10.1016/j.apenergy.2020.115739`.

Shi, Z., W. Yao, Z. Li, L. Zeng, Y. Zhao, R. Zhang, Y. Tang, and J. Wen (2020). "Artificial intelligence techniques for stability analysis and control in smart grids: Methodologies, applications, challenges and future directions". In: *Applied Energy* 278, p. 115733. DOI: `0.1016/j.apenergy.2020.115733`.

Shuai, M., W. Chengzhi, Y. Shiwen, G. Hao, Y. Jufang, and H. Hui (2018). "Review on economic loss assessment of power outages". In: *Procedia computer science* 130, pp. 1158–1163. DOI: `10.1016/j.procs.2018.04.151`.

Singh, J. and J. Singh (2020). "COVID-19 and its impact on society". In: *Electronic Research Journal of Social Sciences and Humanities* 2.

Sinsel, S. R., R. L. Riemke, and V. H. Hoffmann (2020). "Challenges and solution technologies for the integration of variable renewable energy sources—a review". In: *renewable energy* 145, pp. 2271–2285. DOI: `10.1016/j.renene.2019.06.147`.

Slednev, V., P. Jochem, and W. Fichtner (2022). "Impacts of electric vehicles on the European high and extra high voltage power grid". In: *Journal of Industrial Ecology* 26.3, pp. 824–837. DOI: `10.1111/jiec.13216`.

Statista (2023). *Electricity trade from France in Europe 2022, by country*. URL: `https://www.statista.com/statistics/1279015/france-electricity-trade-in-europe-by-country/`. checked on 08/07/2023.

Steber, D.-B. (2018). "Integration of decentralized battery energy storage systems into the german electrical power system". PhD thesis. Friedrich-Alexander-Universität Erlangen-Nürnberg (FAU).

Stolten, D., B. Emonts, T. Grube, and M. Weber (2013). "Hydrogen as an enabler for renewable energies". In: *Transition to renewable energy systems*, pp. 195–216. DOI: `10.1002/9783527673872.ch12`.

Strueker, J. and C. Dinther (2012). "Demand response in smart grids: research opportunities for the IS discipline". In: *AMCIS 2012 Proceedings. 7.*

Strüker, J., M. Weibelzahl, M.-F. Körner, A. Kießling, A. Franke-Sluijk, and M. Hermann (2021). "Dekarbonisierung durch Digitalisierung: Thesen zur Transformation der Energiewirtschaft". In: *Bayreuther Arbeitspapiere zur Wirtschaftsinformatik ; 67*. DOI: `10.15495/EPub_UBT_00005596`.

Trapp, C. T., D. K. Kanbach, and S. Kraus (2022). "Sector coupling and business models towards sustainability: The case of the hydrogen vehicle industry". In: *Sustainable Technology and Entrepreneurship* 1.2, p. 100014. DOI: `10.1016/j.stae.2022.100014`.

United Nations (2015). *Report of the Conference of the Parties on its twenty-first session, held in Paris from 30 November to 13 December 2015*. URL: `https://unfccc.int/resource/docs/2015/cop21/eng/10.pdf`. checked on 22/06/2023.

United Nations, Department of Economic and Social Affairs - Sustainable Development (2015). *Transforming our world: the 2030 Agenda for Sustainable Development*. General Assembly. URL: `https://sdgs.un.org/2030agenda`. checked on 25/07/2030.

U.S. Government Accountability Office (2006). *Hurricanes Katrina and Rita Disaster Relief: Improper and Potentially Fraudulent Individual Assistance Payments Estimated to Be Between $600 Million and $1.4 Billion*. URL: `https://www.gao.gov/products/gao-06-844t`. checked on 08/07/2023.

Van Nuffel, L., J. G. Dedecca, T. Smit, and K. Rademaekers (2018). *Sector coupling: how can it be enhanced in the EU to foster grid stability and decarbonise?* URL: `https://www.europarl.europa.eu/RegData/etudes/STUD/2018/626091/IPOL_STU(2018)626091_EN.pdf`. checked on 25/07/2023.

Van Veelen, B. and D. Van Der Horst (2018). "What is energy democracy? Connecting social science energy research and political theory". In: *Energy Research & Social Science* 46, pp. 19–28. DOI: `/10.1016/j.erss.2018.06.010`.

Veit, D. J. and J. B. Thatcher (2023). "Digitalization as a problem or solution? Charting the path for research on sustainable information systems". In: *Journal of Business Economics*, pp. 1–23. DOI: `10.1007/s11573-023-01143-x`.

Venegas, F. G., M. Petit, and Y. Perez (2021). "Active integration of electric vehicles into distribution grids: Barriers and frameworks for flexibility services". In: *Renewable and Sustainable Energy Reviews* 145, p. 111060. DOI: `10.1016/j.rser.2021.111060`.

Verma, P., R. Savickas, S. Buettner, J Strüker, O. Kjeldsen, and X. Wang (2020). "Digitalization: enabling the new phase of energy efficiency". In: *Group of Experts on Energy Efficiency, GEEE-7*, pp. 2020–12.

Vingerhoets, P., M. Chebbo, N. D. Hatziargyriou, G. Kariniotakis, R. Donnelly, S. de Boeck, A.-C. Schneider, A. Johansson, S. Dotto, P. Hickey, et al. (2016). "The Digital Energy System 4.0 2016". PhD thesis. European technology platform for the electricity networks of the future.

Von Neumann, J. and O. Morgenstern (1947). "Theory of games and economic behavior, 2nd rev". In: *Princeton university press*.

Wang, J. and H. Yang (2023). "Low carbon future of vehicle sharing, automation, and electrification: A review of modeling mobility behavior and demand". In: *Renewable and Sustainable Energy Reviews* 177, p. 113212. DOI: `0.1016/j.rser.2023.113212`.

Watson, R. T., M.-C. Boudreau, A. Chen, and M. Huber (2008). "Green IS: Building sustainable business practices". In: *Information systems*, pp. 1–17.

Watson, R. T., M.-C. Boudreau, and A. J. Chen (2010). "Information systems and environmentally sustainable development: energy informatics and new directions for the IS community". In: *MIS quarterly*, pp. 23–38. DOI: `10.2307/20721413`.

Weibelzahl, M. (2017). "Nodal, zonal, or uniform electricity pricing: how to deal with network congestion". In: *Frontiers in Energy* 11, pp. 210–232. DOI: `10.1007/s11708-017-0460-z`.

Weibelzahl, M. and A. Märtz (2020). "Optimal storage and transmission investments in a bilevel electricity market model". In: *Annals of Operations Research* 287, pp. 911–940. DOI: `10.1007/s10479-018-2815-1`.

Weitemeyer, S., D. Kleinhans, L. Wienholt, T. Vogt, and C. Agert (2016). "A European perspective: potential of grid and storage for balancing renewable power systems". In: *Energy Technology* 4.1, pp. 114–122. DOI: `10.1002/ente.201500255`.

Werth, A., P. Gravino, and G. Prevedello (2020). "Impact analysis of COVID-19 responses on energy grid dynamics in Europe". In: *Applied energy* 281, p. 116045. DOI: `10.1016/j.apenergy.2020.116045`.

Wickart, M. and R. Madlener (2007). "Optimal technology choice and investment timing: A stochastic model of industrial cogeneration vs. heat-only production". In: *Energy Economics* 29.4, pp. 934–952. DOI: `10.1016/j.eneco.2006.12.003`.

Wogrin, S. and D. F. Gayme (2014). "Optimizing storage siting, sizing, and technology portfolios in transmission-constrained networks". In: *IEEE Transactions on Power Systems* 30.6, pp. 3304–3313. DOI: `10.1109/TPWRS.2014.2379931`.

World Economic Forum (2017). *Digital Transformation of Industries*. URL: `https://www.weforum.org/reports/digital-transformation-of-industries/`. checked on 08/07/2023.

Yamashita, K., S.-K. Joo, J. Li, P. Zhang, and C.-C. Liu (2008). “Analysis, control, and economic impact assessment of major blackout events”. In: *European Transactions on Electrical Power* 18.8, pp. 854–871. DOI: `10.1002/etep.304`.

Yang, Z., J. Sun, Y. Zhang, and Y. Wang (2020). “Synergy between green supply chain management and green information systems on corporate sustainability: An informal alignment perspective”. In: *Environment, Development and Sustainability* 22, pp. 1165–1186. DOI: `10.1007/s10668-018-0241-9`.

Yergin, D. (2006). “Ensuring energy security”. In: *Foreign affairs*, pp. 69–82. DOI: `10.2307/20031912`.

Yohanandhan, R. V., R. M. Elavarasan, P. Manoharan, and L. Mihet-Popa (2020). “Cyber-physical power system (CPPS): A review on modeling, simulation, and analysis with cyber security applications”. In: *IEEE Access* 8, pp. 151019–151064. DOI: `10.1109/ACCESS.2020.3016826`.

Zafar, R., A. Mahmood, S. Razzaq, W. Ali, U. Naeem, and K. Shehzad (2018). “Prosumer based energy management and sharing in smart grid”. In: *Renewable and Sustainable Energy Reviews* 82, pp. 1675–1684. DOI: `10.1016/j.rser.2017.07.018`.

Zangiabadi, M., R. Feuillet, H. Lesani, N. Hadj-Said, and J. T. Kvaløy (2011). “Assessing the performance and benefits of customer distributed generation developers under uncertainties”. In: *Energy* 36.3, pp. 1703–1712. DOI: `10.1016/j.energy.2010.12.058`.

Zawieska, J. and J. Pieriegud (2018). “Smart city as a tool for sustainable mobility and transport decarbonisation”. In: *Transport policy* 63, pp. 39–50. DOI: `10.1016/j.tranpol.2017.11.004`.

Zhang, M., Q. Wang, D. Zhou, and H. Ding (2019). “Evaluating uncertain investment decisions in low-carbon transition toward renewable energy”. In: *Applied Energy* 240, pp. 1049–1060. DOI: `10.1016/j.apenergy.2019.01.205`.

Zhao, C., K. Wang, X. Dong, and K. Dong (2022). “Is smart transportation associated with reduced carbon emissions? The case of China”. In: *Energy Economics* 105, p. 105715. DOI: `10.1016/j.eneco.2021.105715`.

VI Appendix

VI.1 Research Papers Relevant to this Doctoral Thesis

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

Halbrügge, S.; Schott, P.; Weibelzahl, M.; Buhl, H. U.; Fridgen, G.; Schöpf, M. (2021). "How did the German and other European electricity systems react to the COVID-19 pandemic?". In: *Applied Energy*. DOI: 10.1016/j.apenergy.2020.116370.

(VHB-Jourqual 3 Category: n.a., SNIP 2022: 2.758, SJR 2022: 2.907, CiteScore 2022: 21.1 / 99 % percentile)

Research Paper 2: How Germany achieved a record share of renewables during the COVID-19 pandemic while relying on the European interconnected power network

Halbrügge, S.; Buhl, H.U.; Fridgen, G.; Schott, P.; Weibelzahl, M.; Weissflog, J. (2022). "How Germany achieved a record share of renewables during the COVID-19 pandemic while relying on the European interconnected power network". In: *Energy*. DOI: 10.1016/j.energy.2022.123303.

(VHB-Jourqual 3 Category: n.a., SNIP 2022: 2.132, SJR 2022: 1.989, CiteScore 2022: 14.9 / 98 % percentile)

Research Paper 3: Reducing the Expectation-Performance Gap in EV Fast Charging by Managing Service Performance

Halbrügge, s.; Wederhake, L.; Wolf, L. (2020). "Reducing the Expectation-Performance Gap in EV Fast Charging by Managing Service Performance". *Lecture Notes in Business Information Processing*. DOI: $10.1007/978-3-030-38724-2_4$.

(VHB-Jourqual 3 Category: C, SNIP 2022: n.a., SJR 2022: n.a., CiteScore 2022: n.a. % percentile)

Research Paper 4: Artificial Intelligence in Energy Demand Response: A Taxonomy of Input Data Requirements

Fridgen, G.; Halbrügge, S.; Körner, M.-F.; Michaelis, A.; Weibelzahl, M. (2022). "Artificial Intelligence in Energy Demand Response: A Taxonomy of Input Data Requirements" In: *Wirtschaftsinformatik 2022 Proceedings*. DOI: 10.3390/en12101893.

(VHB-Jourqual 3 Category: C, SNIP 2022: n.a., SJR 2022: n.a., CiteScore 2022: n.a. % percentile)

Research Paper 5: The insurance effect of renewable distributed energy resources

Fridgen, G.; Halbrügge, S.; Olenberger, C.; Weibelzahl, M. (2020). “The insurance effect of renewable distributed energy resources”. *Energy Economics*. DOI: 10.1016/j.eneco.2020.104887.

(VHB-Jourqual 3 Category: B, SNIP 2022: 2.622, SJR 2022: 3.039, CiteScore 2022: 14.7 / 98 % percentile)

Research Paper 6: The Flexibility Puzzle in Liberalized Electricity Markets: Understanding Flexibility Investments under Different Risk Attitude

Coniglio, S.; Halbrügge, S.; Märtz, A.; Weibelzahl, M. (2023). “The Flexibility Puzzle in Liberalized Electricity Markets: Understanding Flexibility Investments under Different Risk Attitudes”. *Submitted*.

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

- Heffron, R.; Halbrügge, S.; Körner, M.-F.; Obeng-Darko, N. A.; Sumarno, T.; Wagner, J.; Weibelzahl, M. (2021). Justice in Solar Energy Development. In: Solar Energy. DOI: 10.1016/j.solener.2021.01.072
- Halbrügge, S.; Schöpf, M.; Schott, P.; Carda, S. (2019). Papierindustrie. In: Sauer, A.; Abele, E.; Buhl, H. U. (Hrsg.), In: Energieflexibilität in der deutschen Industrie: Ergebnisse aus dem Kopernikus-Projekt – Synchronisierte und energieadaptive Produktionstechnik zur flexiblen Ausrichtung von Industrieprozessen auf eine fluktuierende Energieversorgung (SynErgie) (S. 595-608). Stuttgart, Deutschland: Fraunhofer Verlag.
- Müller, T.; Bötsch, M.; Halbrügge, S.; Leinauer, C.; Schöpf, M.; Schott, P.; Sedlmeir, J. (2019). Graphitherstellung. In: Sauer, A.; Abele, E.; Buhl, H. U. (Hrsg.), In: Energieflexibilität in der deutschen Industrie: Ergebnisse aus dem Kopernikus-Projekt – Synchronisierte und energieadaptive Produktionstechnik zur flexiblen Ausrichtung von Industrieprozessen auf eine fluktuierende Energieversorgung (SynErgie) (S. 505-521). Stuttgart, Deutschland: Fraunhofer Verlag.
- Roth, S.; Schott, P.; Ebinger, K.; Halbrügge, S.; Kleinertz, B.; Köberlein, J.; Püschel, D.; Buhl, H. U.; Ober, S.; Reinhart, G.; von Roon, S. (2020). The challenges and opportunities of energy-flexible factories: a holistic case study of the model region Augsburg in Germany. In: Sustainability, 12(1), 360.
- Halbrügge, S.; Heeß, P.; Schott, P.; Weibelzahl, M. (2023). Negative electricity prices as a signal for lacking flexibility? On the effects of demand flexibility on electricity prices. In: International Journal of Energy Sector Management. Vol. ahead-of-print No. ahead-of-print. DOI: 10.1108/IJESM-12-2021-0005
- Bollenbach, J.; Halbrügge, S.; Wederhake, L.; Weibelzahl, M.; Wolf, L. (2023) Fast charging at large charging parks: Addressing customer satisfaction by expectation-performance gaps. *Submitted.*

VI.2 Individual Contribution to the Included Research Papers

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

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

For the work of the second research paper (Halbrügge et al., 2022) with the title *How Germany achieved a record share of renewables during the COVID-19 pandemic while relying on the European interconnected power network* (cf. Subsection VI.4) I assigned as lead-author to the paper. The other five 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 two co-authors contributed, in particular, the preparation of the real-world data, the analysis of those data, and the visualization of the evaluations, the other two co-authors provided feedback especially regarding the conceptualization of the research project and guided the paper process.

The third research paper (Halbrügge et al., 2020) is titled *Reducing the Expectation-Performance Gap in EV Fast Charging by Managing Service Performance* (cf. Subsection VI.5). This paper was written by three co-authors, all authors contributed equally to this paper. In this paper, I developed the research methodology and conceptualized the research project. Together with one other co-author, I organized the research project, and presented the paper at a scientific conference. The third author conducted the formal analysis and set up the software. All co-authors contributed to the validation of the information system and the writing of the paper.

Five co-authors worked on the fourth research paper (Fridgen et al., 2022) with the title *Artificial Intelligence in Energy Demand Response: A Taxonomy of Input Data Requirements* (cf. Subsection VI.6). While all authors contributed equally to this paper, together with two co-authors I was responsible for the framing of the paper, in particular. Moreover, I provided feedback for the literature review, the framework development and the evaluation of the framework. With reference to the text of the paper, I closely assisted in writing it. The other two co-authors contributed with valuable feedback and expertise in the context of demand response.

The fifth research paper (Fridgen et al., 2020a) is titled *The insurance effect of renewable distributed energy resources* (cf. Subsection VI.7) and was written by four co-authors. All authors contributed equally to this paper. Together with all the other authors, I developed the economic model reflecting the results of the paper. In particular, I contributed to the research paper by conducting the literature review, developing the model that analyzed the insurance effect, and by elaborating on the contribution of our work. Moreover, I organized the research project. Furthermore, I also wrote the major share of the text in the article.

Regarding the sixth research paper (Coniglio et al., 2023) with the title *The Flexibility Puzzle in Liberalized Electricity Markets: Understanding Flexibility Investments under Different Risk Attitudes* (cf. Subsection VI.8), I conceptualized the paper in collaboration with three co-authors. All authors contributed equally to this paper and developed the structure for this paper, conducted the literature review and evaluation. Together with two other co-authors, I conducted a case study. These two co-authors and I also evaluated and discussed this case study. One other co-author and I carried out the data collection. The other two co-authors contributed to the mathematical formulation of the problem and provided feedback and guidance.

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

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

Published in:
Applied Energy (2021)

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

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

VI.4 Research Paper 2: How Germany achieved a record share of renewables during the COVID-19 pandemic while relying on the European interconnected power network

Authors:

Stephanie Halbrügge; Hans Ulrich Buhl; Gilbert Fridgen; Paul Schott; Martin Weibelzahl; Jan Weissflog

Published in:

Energy (2022)

Abstract:

In 2020, Germany reached a maximum share of 50.5 % intermittent renewables in electricity generation. Such a high share results in an increasing need for flexibility measures such as international transmission flexibility, i.e., electricity imports and exports. In fact, during the COVID-19 pandemic, Germany changed from a former electricity net exporter to a net importer. This paper, therefore, analyzes what we can learn from the resulting development of German electricity imports as a flexibility measure from a market, environmental, and network perspective. We analyze data on electricity imports/exports, generation, prices, and interconnection capacities of 38 bidding zones, respectively 11 countries within the ENTSO-E. In particular, we formulate three hypotheses to partition our overarching research question. Our results reveal that from a market perspective, Germany's increased need for transmission flexibility did not generally result in increased prices for German electricity imports. Also, from an environmental perspective, Germany increasingly relied on electricity imports from countries that exhibited a lower share of renewables. Finally, during the COVID-19 pandemic some of Germany's interconnection capacities to its neighboring countries exhibited a higher utilization. In view of our results, German policymakers may reflect on decarbonization policies considering a holistic European perspective.

Keywords:

European electricity system, COVID-19 pandemic, Electricity imports, Electricity exports

VI.5 Research Paper 3: Reducing the Expectation-Performance Gap in EV Fast Charging by Managing Service Performance

Authors:

Stephanie Halbrügge; Lars Wederhake; Linda Wolf

Published in:

Lecture Notes in Business Information Processing (2020)

Abstract:

Electric mobility is considered pivotal to decarbonising transport. The operation of fast charging services has become a mobility business model. Its value proposition rests on the promise that fast chargers re-empower drivers to fulfil their mobility needs within acceptable servicing times. This is in particular important when levels for tolerance are low like on long-distance journeys. That value proposition might set inflated customer expectations. Due to economic considerations and operational restrictions, charging park operators might not live up to these expectations. This leads to an expectation-performance gap, which has received little scientific attention, to date. This paper presents an information system (IS) design, which aims at reducing that gap by managing performance. Our findings indicate significant benefits by the IS and highlights further opportunities for the IS discipline. Also, this article invites researchers from service science to discover opportunities for better expectation management and further reduction of the identified gap.

Keywords:

Electric Mobility, Fast charging, Customer Expectation, Service Performance, Information System

VI.6 Research Paper 4: Artificial Intelligence in Energy Demand Response: A Taxonomy of Input Data Requirements

Authors:

Gilbert Fridgen; Stephanie Halbrügge; Marc-Fabian Körner; Anne Michaelis; Martin Weibelzahl

Published in:

Wirtschaftsinformatik 2022 Proceedings (2022)

Abstract:

The ongoing energy transition increases the share of renewable energy sources. To combat inherent intermittency of RES, increasing system flexibility forms a major opportunity. One way to provide flexibility is demand response (DR). Research already reflects several approaches of artificial intelligence (AI) for DR. However, these approaches often lack considerations concerning their applicability, i.e., necessary input data. To help putting these algorithms into practice, the objective of this paper is to analyze, how input data requirements of AI approaches in the field of DR can be systematized from a practice-oriented information systems perspective. Therefore, we develop a taxonomy consisting of eight dimensions encompassing 30 characteristics. Our taxonomy contributes to research by illustrating how future AI approaches in the field of DR should represent their input data requirements. For practitioners, our developed taxonomy adds value as a structuring tool, e.g., to verify applicability with respect to input data requirements.

Keywords:

Energy Informatics, Green IS, Demand Response, Artificial Intelligence, Input Data Requirements

VI.7 Research Paper 5: The insurance effect of renewable distributed energy resources

Authors:

Gilbert Fridgen; Stephanie Halbrügge; Christian Olenberger; Martin Weibelzahl

Published in:

Energy Economics (2020)

Abstract:

To combat climate change, many countries all around the world currently foster the development of renewable energy sources (RES). However, in contrast to traditional energy systems that relied on few central power plants, RES are typically highly decentral and spread all over a country. Against this backdrop, the promotion of a decentralization of the energy system by fostering a regional balance of energy demand and supply with a corresponding increase in energy democracy is seen as a promising approach. However, energy democracy driven by an increasing involvement of consumers requires adequate investments of consumers in their own local RES in order to become active players, usually called prosumers. Risk associated with uncertain long-term electricity price developments is generally seen as a barrier to investments. In contrast, we describe that an investment in distributed energy resources (DERs) may actually serve as a consumer's insurance against price risk. Our results set out that the consideration of risk-aversion may actually positively shift an investment decision in renewable DERs. This is due to the prosumer becoming more self-sufficient and less dependent on uncertain price developments. To analyze such an insurance effect, we create a formal decision model considering the prosumer's risk-aversion and derive the prosumer's optimal investment in renewable DERs. However, our results also indicate that under some circumstances the insurance effect disappears: When a prosumer turns into a predominant producer, the prosumer is again exposed to risk in terms of uncertain revenues. Ultimately, our work highlights the importance of a consideration of the insurance effect when assessing an investment in renewable DERs.

Keywords:

Renewable energy sources, Distributed energy, resources, Insurance effect, Investment decision

VI.8 Research Paper 6: The Flexibility Puzzle in Liberalized Electricity Markets: Understanding Flexibility Investments under Different Risk Attitudes

Authors:

Stefano Coniglio; Stephanie Halbrügge; Alexandra Märtz; Martin Weibelzahl

Under Review

Extended Abstract[1]:

Modern electricity systems are changing rapidly. In the past, the load-following operation of conventional power plants was a key characteristic of electricity systems and a main ingredient for system stability (Fridgen et al., 2020). However, the ongoing decarbonization of energy systems that led to a steady growth of the share of renewable energy sources (International Energy Agency, 2023) also results in highly variable energy generation that ultimately leads to a loss in electricity-production flexibility (Schoepf et al., 2018). To compensate for such a flexibility loss and ensure a successful low-carbon transformation with a secure electricity supply, electricity systems must invest in and exploit alternative flexibility options. There are different options to increase the degree of flexibility in modern electricity systems. They typically belong to four categories: (i) transmission flexibility, (ii) storage flexibility, (iii) generation flexibility, and (iv) demand flexibility (Papaefthymiou et al., 2018). From an economic perspective, though, each of these options is accompanied by uncertainties that hinder their potential. In this regard, network expansion projects that increase transmission capacities and, thus, transmission flexibility, are very cost-intensive and met with skepticism by the general public (Komendantova and Battaglini, 2016). Privately-invested, decentralized storage facilities may result in increased storage flexibility, however, are also accompanied by uncertainties regarding return on investment (Weitemeyer et al., 2016; Wogrin and Gayme, 2014). Conventional generation units, providing the flexibility needed to guarantee flexibly adjustable production for backup, bring up uncertainties regarding commodity prices (Stolten et al., 2013). Finally, increasing demand flexibility offers the opportunity to naturally follow intermittent RES generation, however, most countries currently face challenges regarding an integration of small-scale flexible assets (Schlund and German, 2019). Policy makers must

---

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

take complex interdependencies between different flexibility options into account and solve the corresponding optimization problem in order to find and nudge a future-proof flexibility mix. Motivated by this, in this paper, we address the so-called flexibility puzzle by proposing a multi-stage Stackelberg game in which different players with different risk attitudes make decisions under uncertainty. As a main feature, flexibility investments are made in a highly uncertain environment, where uncertainties may stem from, e.g., unknown CO_2 prices. In this paper, the first stage accounts for public line investments made by a transmission system operator (TSO) in anticipation of private investments in storage and conventional backup generation facilities. These private investments take place in the second stage based on expected spot-market profits, which are determined within a zonal spot market in the third stage. Finally, the fourth stage accounts for redispatch actions of a TSO in the case that contracted spot market quantities cannot be transmitted through the electricity network. We translate our proposed multi-stage Stackelberg game into a four-level (equilibrium-finding) optimization problem and, from it, derive an equivalent single-level reformulation, which we then solve to global optimality with a state-of-the-art spatial branch-and-bound solver. By means of a well-adopted academic case study, we use our model to analyze the effects of different degrees of risk aversion of public and private decision-makers on long-run investments in the flexibility options we considered. Our work highlights the importance of taking uncertainties into account for private flexibility investment decisions and public policy making to ensure sufficient flexibility with an adequate mix of different flexibility options.

Keywords:
Risks, Electricity Pricing, Electricity Storage, Renewable Energy, Long-Run Investments, Multi-level Optimization, Stackelberg Game

References

Fridgen, G., R. Keller, M.-F. Körner, and M. Schöpf (2020). “A holistic view on sector coupling”. In: *Energy Policy* 147, p. 111913. DOI: `10.1016/j.enpol.2020.111913`.

International Energy Agency (2023). *CO2 Emissions in 2022*. URL: `https://www.iea.org/reports/co2-emissions-in-2022`. checked on 10/05/2023.

Komendantova, N. and A. Battaglini (2016). “Beyond Decide-Announce-Defend (DAD) and Not-in-My-Backyard (NIMBY) models? Addressing the social and public acceptance of electric transmission lines in Germany". In: *Energy research & social science* 22, pp. 224–231. DOI: `10.1016/j.erss.2016.10.001`.

Papaefthymiou, G., E. Haesen, and T. Sach (2018). "Power System Flexibility Tracker: Indicators to track flexibility progress towards high-RES systems". In: *Renewable Energy* 127, pp. 1026–1035. DOI: `10.1016/j.renene.2018.04.094`.

Schlund, J. and R. German (2019). "A distributed ledger based platform for community-driven flexibility provision". In: *Energy Informatics* 2, pp. 1–20. DOI: `10.1186/s42162-019-0068-0`.

Schoepf, M., M. Weibelzahl, and L. Nowka (2018). "The impact of substituting production technologies on the economic demand response potential in industrial processes". In: *energies* 11.9, p. 2217. DOI: `10.3390/en11092217`.

Stolten, D., B. Emonts, T. Grube, and M. Weber (2013). "Hydrogen as an enabler for renewable energies". In: *Transition to renewable energy systems*, pp. 195–216. DOI: `10.1002/9783527673872.ch12`.

Weitemeyer, S., D. Kleinhans, L. Wienholt, T. Vogt, and C. Agert (2016). "A European perspective: potential of grid and storage for balancing renewable power systems". In: *Energy Technology* 4.1, pp. 114–122. DOI: `10.1002/ente.201500255`.

Wogrin, S. and D. F. Gayme (2014). "Optimizing storage siting, sizing, and technology portfolios in transmission-constrained networks". In: *IEEE Transactions on Power Systems* 30.6, pp. 3304–3313. DOI: `10.1109/TPWRS.2014.2379931`.