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Leveraging the Economic, Ecological, and Societal Impact of Information Systems for Electricity Systems in Transition

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Vorgelegt von

Felix Eduard André Wagon

aus Nürnberg

Dekan/in:	Prof. Dr. André Meyer
Erstberichterstatter/in:	Prof. Dr. Jens Strüker
Zweitberichterstatter/in:	Prof. Dr. Robert Keller
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The following sections partly comprise content from the research articles included in this thesis. To improve the readability of the text, I omit the standard labeling of these citations.

Abstract

The global impact of climate change puts human health and life at considerable risk. To mitigate adverse climate change effects, we must urgently take drastic actions to reduce harmful greenhouse gas emissions. Electricity systems can significantly contribute to global climate change mitigation efforts as they represent a major source of greenhouse gas emissions on a global scale. While renewable electricity generation can effectively reduce greenhouse gas emissions, transitioning electricity systems towards sustainability is fraught with challenges. Such challenges are rooted in the intermittent and decentralized nature of renewable electricity generation, which disrupts the conventional operation of electricity systems that build on electricity generation based on fossil fuels. Further, sector coupling and electrification initiatives induce additional electricity demand and change the geographical and temporal requirements for electricity transmission. Against that background, information systems emerge as a key enabler to navigate associated complexities.

This cumulative doctoral thesis takes an integrated perspective on the economic, ecological, and societal contribution of information systems in electricity system transitions towards sustainability. In doing so, this doctoral thesis provides insights into the positive impacts of information systems at the intersection of electricity supply, demand, and market coordination. First, this doctoral thesis investigates how information systems can contribute to mitigating revenue prospect risks and social acceptance risks for investments in renewable electricity generation, thereby addressing the economic and societal challenges inherent in accelerating the expansion of renewable electricity generation. Second, this doctoral thesis highlights how information systems support consumers' active participation in electricity systems and help incite demand-side flexibility. The research results of this doctoral thesis contribute to mitigating economic risks associated with consumers' active market participation. Third, this doctoral thesis provides insights into critical advancements in electricity market coordination mechanisms required to improve cost efficiency and reduce greenhouse gas emissions in electricity systems while considering social acceptance as a crucial factor. Through its comprehensive investigations on the role of information systems at the nexus of electricity supply, electricity demand, and market coordination, this doctoral thesis contributes valuable insights to address the urgent threats posed by anthropogenic climate change.

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I Introduction

I.1 Motivation

The imminent effects of climate change are global in scope and unprecedented in scale (Bellard et al., 2012; Pecl et al., 2017; United Nations, 2015b; Research Paper 2). Without drastic action today, human health and life are at considerable risk (McMichael et al., 2006; Mora et al., 2017). A wide-ranging multidisciplinary and global scientific consensus on the reality of anthropogenic climate change highlights that the threat of global warming cannot be rejected (Cook et al., 2013; Oreskes, 2004). Reducing greenhouse gas emissions produced by human activities such as burning fossil fuels, specifically the emission of carbon dioxide, other reactive gases, and aerosols, is essential to effectively curb the effects of climate change and contribute to sustainable development (Le Quéré et al., 2009). Sustainable development aims to meet the needs of the present without compromising the future generations' ability to meet their own needs while balancing social, economic, and environmental considerations (Roy et al., 2018). Despite globally aligned sustainability efforts to reduce greenhouse gas emissions and mitigate the adverse effects of climate change (United Nations, 2015a, 2023), current projections of the earth's surface temperature paint a bleak picture: Modeling by the Intergovernmental Panel on Climate Change's (IPCC) Working Group III highlights that global greenhouse gas emissions must peak at the latest before 2025 and undergo a drastic reduction of 43% relative to 2019 levels by 2030 to maintain a modest chance for limiting the earth's surface temperature to rise beyond the critical threshold of 1.5 degrees Celsius above pre-industrial levels (Shukla et al., 2022). Exceeding 1.5 degrees Celsius global warming of the earth's surface temperature may trigger dangerous climate tipping points, leading to abrupt and irreversible climate impacts with severe implications for humanity (Armstrong McKay et al., 2022; Hoegh-Guldberg et al., 2019). Today, however, global greenhouse gas emissions continue to rise unabated despite a temporary dip during the COVID-19 pandemic between 2019 and 2021 (Crippa et al., 2023). Thus, climate change demands immediate action from researchers, governments, policymakers, industry leaders, environmental organizations, and individuals alike (Shukla et al., 2022).

Electricity systems are central pillars in the global efforts against climate change, as they represent a major source of greenhouse gas emissions (International Energy Agency, 2023a). Specifically, electricity generation is expected to provide one of the most significant contributions to climate change mitigation since electrification (i.e., replacing technologies or processes that use fossil fuels with electrically-powered equivalents) increasingly gains momentum across countries and sectors (European Environment Agency, 2023; International Energy Agency, 2023d). Further, technologies for renewable electricity generation offer valuable alternatives to electricity generation based on fossil fuels (European Environment Agency, 2023; International Energy Agency, 2023d). Thus, transitioning electricity systems towards reducing greenhouse gas emissions associated with electricity generation is imperative to limit the impacts of climate change effectively (Shukla et al., 2022). Renewable electricity generation allows to effectively mitigate greenhouse gas emissions in electricity systems (International Energy Agency, 2023e). Consequently, electricity systems must structurally shift from fossil-based electricity generation (e.g., oil, natural gas, lignite, or coal) to renewable electricity generation (e.g., hydropower, wind and solar power) (Bogdanov et al., 2021). Against that background, the European Commission committed to a binding minimum target of 42.5% renewable electricity generation until 2023 and climate neutrality until 2050 (Directive 2023/2413).

Particularly, intermittent renewable electricity generation based on wind or solar power offers considerable potential for an abundant electricity supply with marginal electricity costs and greenhouse gas emissions near zero (Blazquez et al., 2018). Still, the availability of intermittent renewable electricity generation is subject to the volatility of environmental conditions and may fluctuate over time, ranging from seconds to hours or days (Helm & Mier, 2019). This intermittency severely challenges the integration of large shares of renewable electricity generation into electricity systems, as it can lead to mismatches between electricity supply and demand, grid instability, and an increased need for dispatchable backup electricity supply (Notton et al., 2018). Further, the intermittency of renewable electricity generation induces considerable risks for investments in additional renewable electricity generation capacity (Egli, 2020; Noothout et al., 2016). Investments in renewable electricity generation require significant upfront investments and are subject to the price volatility on wholesale electricity markets as well as regulatory uncertainty, among others (Egli, 2020; Noothout et al., 2016; UNDP, 2014). Since a rapid scale-up of renewable electricity generation requires large investment volumes backed by private-sector financing, the financial attractiveness of renewable electricity investments will be essential for investors to commit capital to projects with uncertain returns (Noothout et al., 2016; UNDP, 2014). To ensure the realization of renewable electricity generation investments, social acceptance is another critical factor (Drews & van den Bergh, 2016; van der Horst, 2007). Although public support for transitioning electricity systems towards sustainability is generally high, this support often tends to drop significantly once citizens are directly impacted by renewable electricity projects (van der Horst, 2007; Weber et al., 2017). For instance, concerns regarding the aesthetic and geographical implications of wind energy development frequently lead to local opposition despite broader support for expanding on-shore wind energy infrastructure (Weber et al., 2017; Wolsink, 2007). Notwithstanding significant progress in the expansion and integration of renewable electricity generation, there remains a pressing need for both significant investments in renewable electricity infrastructure and addressing local opposition against project execution. Otherwise, complying with ambitious decarbonization targets may become impossible.

To ensure the successful integration of intermittent renewable electricity generation while maintaining the affordability of electricity and grid stability – i.e., the delicate balance between demand and supply in electricity systems – flexibility on the demand side emerges as a critical factor in today's and future electricity systems (Michaelis et al., 2024). Flexibility refers to the ability of electricity systems to adjust their electricity generation, consumption, or storage in response to changes in supply or demand to maintain system reliability and efficiency (Aliyev et al., 2020). Large flexibility potentials can be found on the electricity demand side where industrial consumers with large-scale electricity consumption, as well as private consumers such as households, may contribute to the integration of intermittent renewable electricity supply (Afzalan & Jazizadeh, 2019; Buhl et al., 2021; Li et al., 2021; Michaelis et al., 2024; Moog et al., 2017). Demand-side flexibility strives to temporarily change electricity demand to follow fluctuations in electricity generation by influencing the timing and magnitude of consumer demand (Palensky & Dietrich, 2011; Strbac, 2008; Research Paper 4). As the landscape of electricity consumption undergoes fundamental changes due to cross-sectoral electrification and increasing decentralization, novel avenues for energy flexibility provision emerge (Elia Group, 2023). Specifically, new appliances are integrated into electricity systems, and the role of consumers changes as they increasingly act as prosumers – i.e., agents that both consume and produce electricity (Parag & Sovacool, 2016). On the one hand, such developments increase the overall potential for energy flexibility (Sørensen et al., 2021). On the other hand, decentralization, an increasing number of energy assets, and prosumer roles add additional layers of complexity to the management of electricity demand, requiring enhanced coordination efforts (Elia Group, 2023). Unlocking flexibility potentials and effectively managing associated complexities hinges upon robust consumer activation and participation in electricity systems (Schweiger et al., 2020). Active consumer participation in electricity systems entails empowering consumers to effectively manage and control distributed energy resources (e.g., electric vehicles or heat pumps), engage in energy flexibility measures, or collaborate with other consumers according to grid conditions and renewable electricity availability (Hyysalo et al., 2017; Schmitt et al., 2023; Schweiger et al., 2020). Today, however, much energy flexibility potential remains untapped, with limited opportunities for consumers to actively engage in electricity systems, underscoring the need for innovative approaches and solutions that enable energy flexibility and consumer-centric participation (Ibn Saif & Khadem, 2020; Michaelis et al., 2024; Sauer et al., 2022).

To effectively align electricity generation and consumption while supporting both the integration of intermittent renewable electricity and the utilization of flexibility potentials on the demand side, market coordination is critical for the successful transformation of electricity systems towards sustainability. In the context of renewable electricity generation and consumption, market coordination refers to the efficient coordination of electricity supply and demand via market-based mechanisms to ensure optimal utilization of renewable electricity sources while balancing grid stability and meeting consumer needs (Chao & Wilson, 2020; Gimpel, Hanny, et al., 2021; Liu & Zhong, 2019). Market coordination involves aligning electricity consumption patterns with renewable electricity generation patterns to enhance the utilization of renewable electricity generation and reduce reliance on fossil fuels while accounting for transmission constraints in electricity grids. In the short term, market coordination mechanisms affect the utilization of renewably generated electricity. Price signals – being one central aspect of market coordination mechanisms –

contribute to aligning consumption patterns with renewable electricity generation peaks to support the utilization of renewable electricity generation and minimize reliance on conventional, fossil fuel-based generation during demand peaks. In the long term, price signals are crucial for providing economic incentives for both renewable electricity investments and investments in active consumer participation.

With electricity systems transitioning from dispatchable electricity generation based on fossil fuels to intermittent renewable electricity generation, traditional market coordination mechanisms need to evolve. Specifically, the intermittency and decentralization of renewable electricity generation underline the urgency for enhanced market coordination that provides targeted locational signals for market participants on the supply and demand side (Bichler, Buhl, Knörr, et al., 2022; Lösch & Schneider, 2016). As the increasing intermittency and decentralization of renewable electricity generation further strain historically evolved electricity grids, market coordination plays a crucial role in successfully managing grid congestion by creating market outcomes that coordinate flexibility deployment (van Dinther et al., 2021).

Information systems offer a comprehensive toolkit to successfully master the intricate challenges accompanying the transition of electricity systems towards sustainability. Information systems generally relate to an "integrated and cooperating set of people, processes, software, and information technologies to support individual, organizational, or societal goals" (Watson et al., 2010). In the context of electricity systems, information systems are pivotal to leveraging the features of digital information and communication technology to improve energy efficiency and to integrate increasingly decentralized renewable electricity sources (Bichler, Buhl, Knörr, et al., 2022). For example, information systems can comprehensively collect real-time data from active participants in electricity systems and navigate information flows to ensure transparency and accessibility in the context of electricity markets (Abrahamsen et al., 2021; Gungor et al., 2013). This may include data on electricity generation, weather conditions, or consumer behavior. Based on that, advanced and predictive analytics capabilities can help forecast electricity generation, demand patterns, grid congestion, equipment failures, and maintenance needs, enabling proactive decision-making as well as improving electricity grid integration and utilization (vom Scheidt et al., 2020; Yu et al., 2015; Zhang et al., 2018). Further, information systems empower the integration of small-scale decentralized energy assets, such as residential photovoltaic systems, electric vehicles, and heat pumps, enabling their active contribution to renewable electricity utilization and grid stability (Dedrick et al., 2023). In this regard, information systems open new avenues for innovative business models, such as peer-to-peer electricity trading and virtual power plants, bolstering the economic viability of renewable electricity projects. Besides the integration of decentralized energy assets, information systems can provide data-driven decision support to maximize efficiency and minimize costs as well as greenhouse gas emissions associated with electricity use (Ketter et al., 2018; Sueyoshi & Tadiparthi, 2008). This may involve the implementation of algorithms for optimal dispatch of renewable resources, electricity storage management, and demand-side flexibility (Guo & Fang, 2013; Weigel et al., 2023; Yang et al., 2020). For example, through smart home energy management applications, consumers gain comprehensive insights into their energy usage, facilitating informed decision-making and real-time energy control (Berlink et al., 2015; Ozturk et al., 2013). By leveraging these features and capabilities, information systems represent a transformative opportunity to advance renewable electricity integration, foster active consumer participation, and enhance market coordination while taking economic, ecological, and societal dimensions of electricity systems into account.

I.2 Research Aim

The research aim of this doctoral thesis is threefold and takes an integrated perspective on the economic, ecological, and societal contributions of information systems at the intersections of electricity supply, electricity demand, and their market-based coordination.

First, this doctoral thesis aims to investigate how information systems can contribute to accelerating the expansion of renewable electricity generation. Scaling up renewable electricity generation and, therefore, reducing electricity generation based on fossil fuels is imperative to comply with ambitious climate change goals as put forth by the European Commission in the context of the European Green Deal (European Commission, 2019). From an investment perspective, however, current research contributions confirm that renewable electricity generation is heavily influenced by e.g., regulatory uncertainties, high upfront capital costs, technological risks, and uncertain project returns (Egli, 2020; International Energy Agency, 2023b; IRENA, 2023; Noothout et al., 2016). Therefore, this doctoral thesis aims to investigate how digital solutions may facilitate the development of novel business models and concepts that contribute to the development of renewable electricity generation capacity and increase the economic attractiveness of such investments. As the rapid expansion of renewable electricity generation is associated with severe societal implications for citizens on a local level, their support is mission-critical for the decarbonization of electricity systems (Weber et al., 2017). For example, the expansion of on-shore wind energy or electricity grid infrastructure may involve negative visual impacts, concerns regarding land use, and potential decreases in property value (Ioannidis & Koutsoyiannis, 2020; Sklenicka & Zouhar, 2018; Sunak & Madlener, 2016). Strong local opposition may be the outcome of perceived adverse effects of project initiatives that contribute to the transition of electricity systems towards sustainability (Susskind et al., 2022; van der Horst, 2007; Weber et al., 2017). To contribute to the success of renewable electricity expansion while accounting for its local implications, projects and initiatives must be grounded in the support of the local citizenry. Against that background, information systems can positively contribute to supporting citizens in learning about the implications of renewable electricity projects and support preference construction on an individual level and actively express their preferences. Thus, this doctoral thesis aims to bridge the gap between renewable electricity capacity expansion and social acceptance by citizens. In doing so, this thesis analyzes the transformative potential of information systems in empowering citizens, facilitating comprehension of implications, and shaping preferences to ensure inclusive project success on a societal level.

Second, this doctoral thesis aims at enhancing active consumer participation in electricity systems through digital solutions. With growing shares of renewable electricity generation, the intermittency of electricity supply increases. In other words, electricity generation becomes increasingly weather-dependent and variable. This fundamentally challenges the operation of traditional electricity systems that rely on large shares of dispatchable electricity generation based on non-renewable electricity sources. One particularly promising approach to address the intermittency of renewable electricity supply that prior research identified and analyzed is the temporal alignment of electricity demand with the availability of renewable electricity generation, i.e., demand-side flexibility (Heffron et al., 2020; Söder et al., 2018). While enhancing the integration of renewable electricity generation, demand-side flexibility enables consumers to shift electricity consumption to periods with comparatively abundant renewable electricity generation and comparatively low electricity prices on wholesale electricity markets. Thus, demand-side flexibility comes with the opportunity to save costs and greenhouse gas emissions for consumers. This specifically applies to industrial consumers, typically accounting for large shares of electricity consumption (Buhl et al., 2021; Moog et al., 2017). Additionally, industrial consumers may use synergies to existing energy management systems to reduce investment needs in information systems required for temporal load adjustments (Lund et al., 2015). Paving the way for consumers to utilize such opportunities actively, this doctoral thesis is dedicated to extending the line of current research on demand-side flexibility by contributing novel insights on digital solutions that support the provision of demand-side flexibility. Specifically, this thesis focuses on effective approaches that allow consumers to address economic risks associated with dynamically adjusting their electricity consumption and that are grounded in the application of information systems.

Third, this doctoral thesis contributes to developing market-based coordination mechanisms that link renewable electricity generation and supply. Market coordination mechanisms represent essential building blocks for sustainable electricity systems as they are pivotal to ensure an efficient short- as well as long-term coordination of renewable electricity supply and demand by providing market participants with price signals (Weibelzahl, 2017). Different market coordination mechanisms vary in how they manage the limited transmission capacities of the electricity grid and in how pricing regimes take these scarce capacities into account (Heffron et al., 2022). With an increasing decentralization of electricity generation and a high extent of intermittency induced by renewable electricity generation, changes are needed concerning the rules governing the economic outcomes of electricity markets, as in many countries existing coordination mechanisms were designed at a time when electricity generation was concentrated on dispatchable conventional power plants, and demand was considered inelastic (Ashour Novirdoust et al., 2021). Against that background, this doctoral thesis evaluates different design options for market coordination mechanisms with respect to their effect on the incentivization of demand-side flexibility and the utilization of renewable electricity generation. Specifically, this doctoral thesis focuses on the analysis of uniform pricing and locational marginal pricing regimes for electricity markets and evaluates their economic as well as ecological qualities. In doing so, intermittent renewable electricity generation, demand-side flexibility, and critical electricity grid constraints are considered. Additionally, this doctoral thesis focuses on societal effects associated with transitions in electricity market coordination mechanisms. On a societal level, for example, moving from a uniform electricity pricing regime to a locational marginal pricing regime can imply severe effects on electricity prices or the local development of renewable electricity generation, which both represent societal effects that concern citizens individually. In this regard, the capabilities of information systems to break down complexities, providing nuanced insights into the implications at both individual and societal levels, are analyzed.

In summary, this doctoral thesis takes an integrated perspective on information systems' economic, ecological, and societal contributions to the energy transition towards sustainability. This doctoral thesis adopts a multifaceted approach that builds on the application of several research methods including reviews of current research contributions, quantitative modeling, case study analyses, empirical experiments, and surveys. Through its comprehensive investigation at the intersection of electricity supply, electricity demand, and market coordination, this thesis aims to contribute both to the academic discourse and the practical realization of a sustainable future.

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

This section provides an overview of the structure of this doctoral thesis, which encompasses seven research papers. Figure 1 illustrates that the seven research papers are embedded in three building blocks across sections II to IV of the doctoral thesis. Considering information systems as an important enabler and foundation for the transition of electricity systems, this doctoral thesis aims to take an integrated perspective to leverage information systems’ potential to positively affect economic, ecological, and societal aspects in energy transitions towards sustainability (cf. Figure 1.). This thesis contains three building blocks that contribute to facilitating the integration of renewable electricity generation into electricity systems while empowering active consumer participation as well as advancing effective market coordination of renewable electricity generation and consumption (cf. Figure 1.).

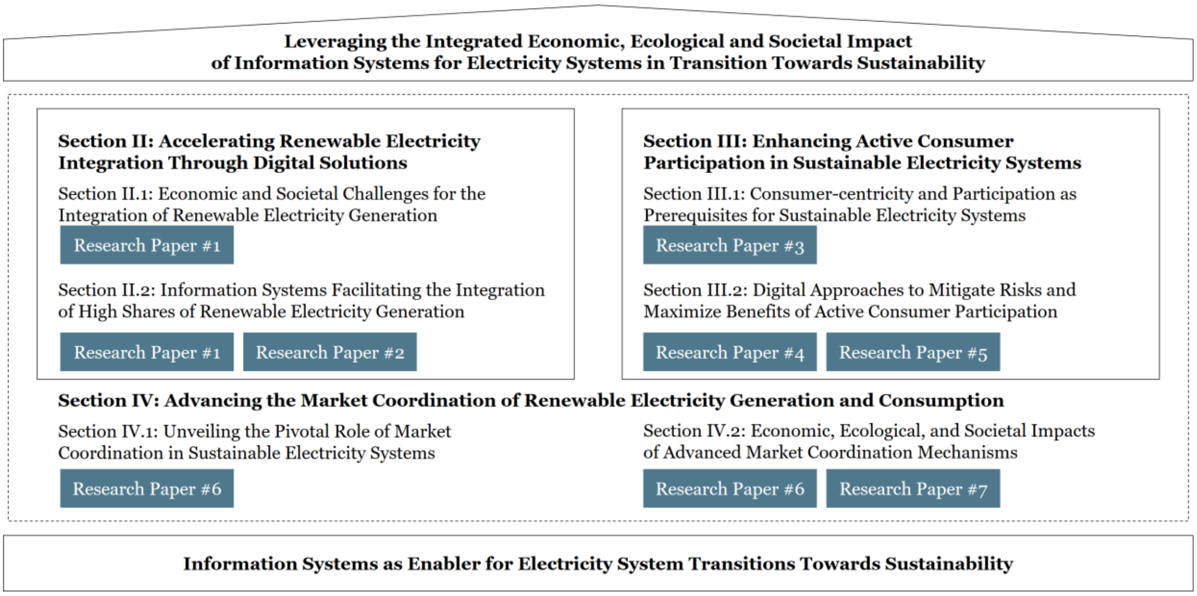

Figure 1: Conceptual outline of the doctoral thesis (own illustration).

Additionally, Table 1 provides an overview of the seven embedded research papers (Appendices in Section VII provide further information on each research paper).

Research Paper	Research Paper Title
Research Paper 1	Renewable Electricity Business Models in a Post Feed-in Tariff Era
Research Paper 2	Shaping Stable Support: Leveraging Digital Feedback Interventions to Elicit Socio-Political Acceptance of Renewable Energy
Research Paper 3	A Consumer-Satisfaction Model to Foster Consumer Participation in Digital Sustainable Energy Systems
Research Paper 4	Risk Management in Electricity Procurement Utilizing Industrial Energy Flexibility
Research Paper 5	Risk Mitigation Capability of Flexibility Performance Contracts for Demand Response in Electricity Systems
Research Paper 6	For Better or for Worse? On the Economic and Ecologic Value of Industrial Demand Side Management in Constrained Electricity Grids
Research Paper 7	Designing Electricity Markets of the Future: On the Role of Information for Social Acceptance of a Transition in the Electricity Market Design

Table 1: Overview of embedded research papers.

Following the introduction of this doctoral thesis (Section I), Section II investigates how information systems enable the integration of renewable electricity generation into electricity systems from an economic as well as societal perspective. Specifically, Section II.1 explores the multifaceted challenges investors in renewable electricity generation may encounter, explicitly focusing on volatile intermittent renewable electricity generation. Highlighting both economic issues (e.g., high upfront costs and uncertain returns) and societal issues (e.g., public opposition to renewable electricity projects), this subsection aims to provide a comprehensive understanding of challenges associated with the integration of high shares of renewable electricity generation in electricity systems. Against that background, Section II.2 investigates how information systems emerge as transformative tools, offering new means to successfully master the challenges as outlined in Section II.1 from an economic as well as societal perspective. This includes developing novel business models enabled by information systems that foster the scalable growth of renewable electricity generation and incite corresponding investments. Further, this subsection shifts the focus to the societal dimension of renewable electricity integration by recognizing the significance of social acceptance in ensuring the success of local electricity generation projects and acknowledging information systems' potential to inform citizens about the impacts of climate policies. This subsection highlights information systems' potential to empower citizens to make deliberate choices and actively participate in transformative processes. By addressing local opposition to renewable electricity integration, this subsection underscores the potential of digital tools to bridge the gap between policy objectives, private investments, and social acceptance.

Shifting the focus from renewable electricity generation to electricity consumption, Section III unravels the pivotal role of active consumer participation in renewable electricity systems. This Section highlights the potential of digital solutions in supporting consumers to actively engage in decision-making, management, and optimization of their electricity consumption. Section III.1 investigates the ever-growing need for active consumer participation in sustainable electricity systems to address the intermittency of renewable electricity consumption, complexities of decentralization, and the emergence of new market participants imposing additional needs for electricity (e.g., electric vehicles or heat pumps). Based on that, Section III.2 conducts a detailed analysis of how information systems can address economic risks associated with their electricity needs and investments in demand-side flexibility. Thereby, this subsection contributes to empowering consumers to realize both economic and ecological benefits through active participation in electricity systems.

Section IV seeks to advance the market coordination between renewable electricity generation and consumption by leveraging the capabilities of information systems from an economic, environmental, and societal perspective. Section IV.1 sets out to investigate critical advancements required in the coordination mechanisms for renewable electricity supply and demand in electricity markets. In the short term, effective market coordination is imperative for synchronizing electricity consumption with the availability of renewable electricity generation. In the long term, market coordination mechanisms are vital for driving investments in renewable electricity infrastructure and promoting active consumer participation. Clear and consistent price signals provide economic incentives for long-term investments in renewable electricity generation while encouraging consumers to engage in energy conservation and flexibility measures. Based on a deepened understanding of required advancements of coordination mechanisms in electricity markets, Section IV.2 evaluates the economic and ecological implications of specific pricing regimes coordinating renewable supply and demand in future electricity markets. The focus lies on how and under what conditions different pricing regimes can incite consumers to effectively maximize the utilization of renewable electricity generation, thereby contributing to decrease costs of electricity supply and reduce greenhouse gas emissions. Section IV.2 investigates the societal implications of transitioning the design of pricing regimes within the German electricity system.

Finally, Section V (in addition to the visual representation of Sections in Figure 1) summarizes the research results of this doctoral thesis, its contributions, its limitations, and avenues for future research. Section V concludes with an acknowledgment of previous and related work.

II Accelerating Renewable Electricity Integration Through Digital Solutions

In light of ambitious climate policy targets, the imperative to accelerate the integration of renewable electricity generation has never been more pressing. Across global initiatives, the urgency of this transition is evident. On a global level, the installed capacity of renewable electricity generation needs to triple to at least 11 TW by 2030 (COP28, 2023). However, achieving such a significant scaling up of renewable electricity generation is not without its challenges (cf. Section I).

This section addresses the economic and societal challenges inherent in investments in renewable electricity generation. Section II.1 focuses on revenue prospect risks associated with investments in renewable electricity generation. In this regard, information systems offer a transformative toolkit to mitigate investment risks, facilitate the development of novel business models, and enhance the economic attractiveness of renewable electricity projects. Section II.2 addresses the societal acceptance of renewable electricity generation investments, which stands as a pivotal factor in the success of renewable electricity projects. Against that background, information systems play a crucial role in fostering societal engagement and support by providing transparent information, empowering citizens to make informed decisions, and shaping preferences towards renewable electricity initiatives.

Through a comprehensive exploration of economic and societal challenges for the integration of renewable electricity generation and the potential of information systems to address them, this section aims to pave the way for a more sustainable and inclusive energy transition.

II.1 Economic and Societal Challenges for the Integration of Renewable Electricity Generation

Despite a massive scale-up of renewable electricity generation in the past years (International Energy Agency, 2023d), there is still a large need to keep establishing additional renewable electricity generation capacity to phase out conventional electricity generation technology based on fossil fuels and satisfy additional electricity needs due to electrification and sector coupling initiatives (International Energy Agency, 2023d, 2023e). To successfully navigate this ongoing transition, extensive investments in additional renewable electricity generation will be pivotal. On a global level, associated investment needs account for $4 trillion a year in renewable energy until 2030 to reach net-zero emissions by 2050 (International Energy Agency, 2023c). From an investor's perspective, however, significant risks are associated with investments in renewable electricity generation capacities as described in Section I. Such investment risks endanger keeping up a chance of reaching the ambitious goals for renewable electricity generation expansion.

The most significant investment risks perceived by investors include (Egli, 2020):

- **Technology Risks**. Novelty and unpredictability inherent in renewable electricity technologies pose challenges, including the risk of lower energy yield or higher maintenance costs due to factors such as faster degradation (e.g., Kayser, 2016; Lei et al., 2020; Szabó et al., 2010).
- **Resource Risks**. Inaccurate estimation of resource potential, such as wind speed or solar irradiation, can lead to diminished revenues (e.g., Bouhal et al., 2018; Neto et al., 2018; Salvo et al., 2017).
- **Curtailment Risks**. Unexpected curtailment, e.g., stemming from grid bottlenecks, presents a risk of reduced energy yield (e.g., Egli, 2020; Schermeyer et al., 2018).
- **Revenue Prospect Risks**. Uncertainty in revenue prospects due to factors such as price volatility or policy changes affecting renewable electricity support schemes can undermine the economic viability of renewable electricity projects (e.g., Kayser, 2016; Neto et al., 2018; Szabó et al., 2010).
- **Acceptance Risk**. A lack of acceptance and local opposition to the implementation of renewable electricity projects can bring the implementation of projects to a halt. Concerns surrounding visual impact, land use, and property values can fuel resistance to renewable electricity initiatives (e.g., Enzensberger et al., 2003; Szabó et al., 2010; Waissbein et al., 2013).

As renewable electricity generation technologies advance, there is potential to mitigate certain risks. Technological advancements contribute to the reduction of technology risks and related costs for renewable electricity projects (Egli, 2020; Steffen et al., 2020). Furthermore, improvements in forecasting and simulation models enhance the accuracy of resource potential estimation, minimizing uncertainties in energy yield projections in the context of resource risks (Lin et al., 2022; Müller et al., 2015). Additionally, measures such as redispatch mechanisms implemented in many countries aim to mitigate curtailment risks by providing compensation for revenue losses resulting from curtailed electricity production (Schermeyer et al., 2018). This doctoral thesis focuses on revenue prospect risks and acceptance risks as they represent significant obstacles to the expansion of renewable electricity generation.

Revenue Prospect Risks (cf. Research Paper 1)

Uncertain revenue prospects pose significant challenges to the profitability and attractiveness of investments in renewable electricity generation projects. Two primary factors contribute to this uncertainty:

First, wholesale electricity markets and associated price fluctuations are pivotal determinants of revenue potential for renewable electricity generation projects. With growing shares of intermittent renewable electricity generation, volatility in electricity prices tends to increase (Kyritsis et al., 2017; Wozabal et al., 2016). An increased electricity price volatility stems from the high correlation among renewable electricity generation, e.g., leading to periods of surplus supply and low prices. More specifically, renewable electricity supply is characterized by lower short-term operating costs compared to conventional electricity supply generated from fossil fuels or nuclear power. In wholesale electricity markets operating on the merit order principle, generators are dispatched based on operating costs, with the lowest-cost generators dispatched first to meet electricity demand. Consequently, renewable electricity supply is prioritized for dispatch when available. During periods of high renewable electricity supply, this leads to (comparatively) lower electricity prices compared to times with limited renewable electricity supply. A constant supply curve and the absence of electrical storage capacities or flexibility potentials on the demand side are underlying assumptions in this regard. However, as renewable electricity supply tends to be highly correlated within a single market bidding zone, these market dynamics result in decreased revenue potentials for renewable electricity generation (Blazquez et al., 2018; Research Paper 1). Figures 2 and 3 illustrate said market dynamics in a stylized example[1] and two different scenarios. Consequently, the revenue prospects of renewable electricity generation projects may diminish as the share of renewable electricity generation in the overall electricity mix increases, making it challenging to achieve high levels of renewable electricity integration based on wholesale electricity market price developments (Blazquez et al., 2018). Additionally, the illustrated market dynamics lead to an increased price volatility that reflects the temporal availability of renewable electricity supply (Blazquez et al., 2018).

[1] Underlying assumptions include: linear decreasing electricity demand function; (constant) positive operating costs for renewable and conventional electricity supply; short-term operating costs close to zero for renewable electricity supply.

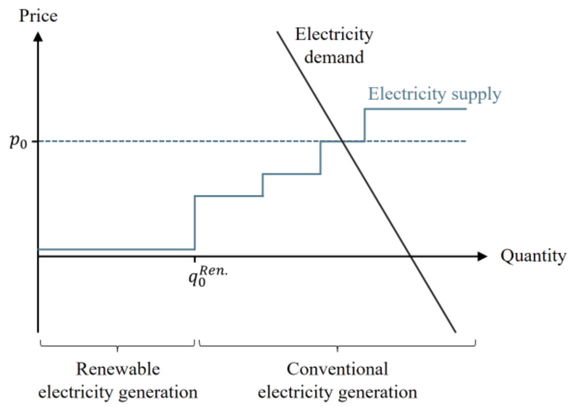

Figure 2: Wholesale electricity market scenario with low intermittent renewable electricity supply (own illustration adapted from Research Paper 1).

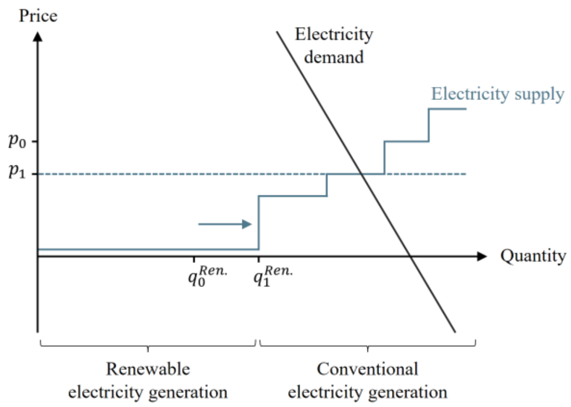

Figure 3: Wholesale electricity market scenario with high intermittent renewable electricity supply (own illustration adapted from Research Paper 1).

Second, policy support mechanisms profoundly influence the revenue prospects of renewable electricity generation projects. Various policy regimes, such as fixed feed-in tariffs as observed in Germany, provide crucial support by guaranteeing specific revenues or prices per unit of electricity generated. Such policy support mechanisms aim to address investment risks associated with uncertain revenue prospects. However, the abrupt alteration or termination of such policies can severely impact the economic viability of renewable electricity projects. Additionally, as support mechanisms may expire over time, renewable electricity projects face the challenge of sustaining operations without public support (Research Paper 1).

This highlights the critical challenges facing investments in renewable electricity generation projects, emphasizing uncertain revenue prospects as a crucial obstacle.

Public Acceptance Risks (cf. Research Paper 2)

The acceptance of renewable electricity generation projects presents another significant risk for investors. For the successful implementation of renewable electricity generation projects, both socio-political acceptance and community acceptance are crucial. Otherwise, public opposition expressed by protests, petitions, referendum votes, or legal action can delay or prevent the realization of renewable electricity projects. Socio-political acceptance refers to social acceptance on the broadest, most general level and includes acceptance of general climate policies and the adoption of specific renewable electricity technologies (Wüstenhagen et al., 2007). By contrast, community acceptance relates to the acceptance of siting decisions and renewable electricity projects by local stakeholders, e.g., residents or regional authorities (Wüstenhagen et al., 2007). Generally, socio-political acceptance of renewable electricity technologies and policies is high in many countries (McGrath & Bernauer, 2017). However, community acceptance is less given for renewable electricity projects. More precisely, local opposition and legal challenges keep hindering the execution of renewable electricity projects, potentially disrupting investment returns (McGrath & Bernauer, 2017; Weber et al., 2017; Wüstenhagen et al., 2007).

In the past, both scholars and practitioners widely suggested the commonly known NIMBY (Not in my backyard) phenomenon as one potential cause for lacking community acceptance (Bell et al., 2005; Dear, 1992; van der Horst, 2007). In the context of renewable electricity generation, a conventional perspective on the NIMBY phenomenon suggests that people are generally in favor of renewable electricity but are opposed to the construction of renewable electricity facilities in their own area (Wolsink, 2000). However, the use of the NIMBY phenomenon to explain local opposition is seen as an overly simplistic explanation, with selfish reasons as the cause behind local opposition (O'Hare, 1977; Wolsink, 2007). Instead, converging research results in this field suggest that critical factors such as the visual evaluation of the impact of renewable electricity projects on the landscape (e.g., in the context of wind energy) or feelings about equity and fairness represent the most dominant factors in explaining local opposition, rather than selfishness and NIMBY-motives (Bergquist et al., 2021; Drews & van den Bergh, 2016; Wolsink, 2007).

One way to contribute to the community acceptance of renewable electricity projects and reaching both socio-political acceptance as well as community acceptance for climate policies is by actively engaging with communities and providing opportunities for public participation in decision-making processes (Perlaviciute, 2022). Once citizens feel excluded from decision-making, local opposition to climate policies becomes more likely (Carattini et al., 2019; Gross, 2007; Perlaviciute, 2022). Increasing transparency about the outcomes of renewable electricity projects and fostering involvement of the public in the planning, development, and implementation processes can, therefore, mitigate local opposition and facilitate the successful implementation of climate policies (Bidwell, 2016; Devine-Wright, 2005; Perlaviciute, 2022; Wolsink, 2007). This, in turn, may contribute to successfully addressing acceptance risks for investments in renewable electricity projects while ensuring public support and engaging with citizens, which is critical when it comes to the implementation of renewable electricity projects.

II.2 Information Systems Facilitating the Integration of High Shares of Renewable Electricity Generation

In the following, this doctoral thesis will focus on the capabilities of information systems to address investment risks associated with revenue prospects as well as public acceptance of renewable electricity generation (cf. Section II.1).

Information Systems to Enhance the Economic Viability of Renewable Electricity Investments (cf. Research Paper 1)

Information systems provide a valuable contribution to mitigating revenue prospect risks in renewable electricity generation investments. On the one hand, information systems provide new means to support the economic viability of traditional business models for renewable electricity generation, which typically relate to marketing electricity on wholesale electricity markets. On the other hand, information systems pave the way for the development and successful implementation of entirely new business models for renewable electricity generation. Such information systems enabled business models are essential for navigating energy transitions towards sustainability. Apart from wholesale electricity markets, novel business models for renewable electricity involve strategies such as marketing renewable electricity through physical power purchase agreements (PPAs), leveraging self-consumption of renewable electricity, exploring sector coupling opportunities (power-to-X), or engaging in energy sharing initiatives within communities (cf. Research Paper 1).

The capabilities of information systems are crucial for the profitable operation of intermittent renewable electricity sources due to their ability to collect, process, and exchange data. By leveraging information systems' capabilities, renewable electricity projects can enhance operational efficiency, reduce downtime, and leverage revenue potentials, significantly contributing to the economic viability of renewable electricity projects.

The most relevant capabilities of information systems in this regard include:

- **Data Analytics and Forecasting**. By collecting and analyzing vast datasets on renewable electricity generation, weather patterns, electricity demand, and grid conditions, information systems enable optimized operations for renewable electricity projects. Advanced analytics facilitate tasks like scheduling maintenance during periods of low demand based on real-time weather forecasts, thereby enhancing efficiency and cost-effectiveness (e.g., Debnath & Mourshed, 2018; Zhang et al., 2018; Zhu et al., 2022).
- **Risk Management**. Incorporating data-driven forecasts into business strategies aids in managing revenue uncertainties and optimizing financial performance. For instance, in the context of PPAs, information systems facilitate risk assessment, contract evaluation, and hedging strategies (e.g., Gabrielli et al., 2022; Mijatovic et al., 2022).
- **Optimization and Control**. Real-time optimization and control capabilities empower businesses to capitalize on price fluctuations and maximize revenue opportunities (e.g., Hannan et al., 2020; Jarrah et al., 2015).
- **Data Exchange and Integration**. Seamless data exchange facilitated by information systems enhances transparency and trust among market participants, enabling effective decision-making. In the context of PPAs or energy communities, these systems facilitate the exchange of production, consumption, and financial data between sellers and buyers of electricity (e.g., Ghiassi-Farrokhfal et al., 2021).
- **Market Access and Trading**. Information systems provide access to electricity markets and trading platforms, allowing to sell excess generation and participate in various markets simultaneously. This may be particularly valuable for renewable electricity business models operating in sector coupling applications (e.g., Ketter et al., 2018).
- **Performance Monitoring and Maintenance**. Continuous monitoring of renewable electricity assets enables proactive identification of performance inefficiencies and maintenance needs. Real-time monitoring of key performance indicators optimizes asset performance, extends equipment lifespan, and minimizes downtime, thereby enhancing project viability (e.g., Hashemnia et al., 2021; Tian et al., 2011).

These capabilities underscore the critical role of information systems in bolstering the economic viability of renewable electricity generation business models through data-driven decision-making, operational optimization, risk management, market participation, and asset performance enhancement.

As they have the potential to support the economic viability of renewable electricity investments, information systems can play a pivotal role in reducing the dependence of renewable electricity projects on public subsidies. Typically, public support schemes for the operation of renewable electricity projects end after an ex-ante known period. This leaves investors uncertain about their economically viable business operation after support schemes ended (Research Paper 1). Information systems' ability to support the inherent economic viability of renewable electricity generation supports a continued operation, even after the expiration of public support schemes, such as feed-in tariffs or tax incentives. Ultimately, this benefits consumers as costs for public support schemes decrease. This shift towards market-driven sustainability not only fosters innovation and technological advancements in the field of renewable electricity but also creates a more resilient and adaptive electricity infrastructure capable of meeting the evolving needs of society.

In conclusion, information systems play an important role in mitigating investment risks associated with uncertain revenue prospects in renewable electricity generation. By enabling the development of economically viable business models and reducing dependence on public support schemes, information systems positively contribute to accelerating transitions towards sustainable electricity generation.

Information Systems to Enhance Public Understanding of Climate Policies and Address Public Acceptance Risks (cf. Research Paper 2)

Beyond investment risks related to revenue prospects, information systems have the potential to address acceptance risks in the context of renewable electricity investments. Resolving the Grand Challenges, such as providing affordable and sustainable electricity, requires collective understanding and participation (Dincer & Acar, 2017; United Nations, 2015b). In other words, climate policies such as energy transitions towards sustainability can only be resolved as we all understand what it takes to be part of the solution. Climate policy outcomes that affect citizens directly or indirectly, however, often appear vague, highly complex, or unfamiliar to citizens. As our cognitive resources for processing information and anticipating consequences are limited, citizens often struggle to anticipate the individual implications of climate policy outcomes. This becomes particularly problematic in contexts where climate policy success hinges on citizens' support. Germany's transition to a low-carbon electricity system, with pledges to phase out coal and nuclear energy, provides a relevant example in this regard. While there is generally high public support for renewable energies, plans for expanding wind energy capacity have faced strong opposition at the local level (Groh & Möllendorff, 2020; Liebe & Dobers, 2019). Public support tends to drop when aesthetic and geographical implications of wind energy development become apparent (Groh & Möllendorff, 2020; Ioannidis & Koutsoyiannis, 2020). Close engagement with citizens in the context of climate policies is crucial to prevent such developments and counteract community acceptance risks for renewable electricity investments. This involves taking citizens' preferences into account early in planning processes to counteract local opposition effectively.

Against that background, information systems offer novel avenues to engage with citizens and communities, providing opportunities for public participation in renewable electricity projects and the implementation of climate policies. Specifically, information systems allow to illustrate and comprehensively present the implications of climate policies to citizens (i.e., users of such information systems). By creating informative environments and even immersive experiences, information systems can redirect citizens' focus to policy implications that may have been overlooked previously due to their complexity or citizens' unfamiliarity with the context at hand. This can encourage citizens to reflect on climate policy outcomes and facilitate learning about potential consequences.

Allowing citizens to understand climate policy outcomes on an individual level supports citizens' preference construction on climate policy. This contributes to citizens expressing deliberate political decisions that reflect their individual preferences and are more likely aligned with their values and beliefs (e.g., in a referendum, petition, or vote). Further, information systems can support citizens in actively expressing their preferences and contributing to decision-making processes on a communal, regional, or national level. By employing information systems, investors and local planners can gauge the local sentiment of relevant stakeholders (such as citizens) and address concerns effectively. This fosters transparency regarding citizens' preferences and contributes to engaging with citizens in realizing climate policies.

One specific example that highlights the potential of information systems to support citizens' preferences construction regarding renewable electricity development and provides novel insights in this regard refers to an online experiment on the acceptance of (onshore) wind energy in Germany (cf. Research Paper 2). In the online experiment, 430 German citizens actively engaged with an information system that visualized to what extent and where additional wind turbines would have to be built to enable the phase-out of coal-fired electricity generation in Germany. Citizens were requested to submit their preference on the proportion of coal-fired electricity generation that they would substitute with renewable wind energy within the next five years – assuming they had freedom of choice[2]. The information system visualized four maps of varying scales on a municipality, county, state, and country (i.e., Germany) level, each specifically tailored to citizens' current residence. Each of these four maps illustrated the required number and location of wind turbines, with citizens able to switch between maps. While white turbines represented existing turbines, blue turbines indicated the new turbines necessary to compensate for a selected proportion of coal-fired electricity generation. Figure 4 illustrates the graphical user interface of the information system.

[2] Please note that participants received a detailed introduction to all functionalities before interacting with the information system. At any point during the online experiment, participants could retrieve additional information explaining the assumptions behind the decision at hand and the information presented in the online experiment.

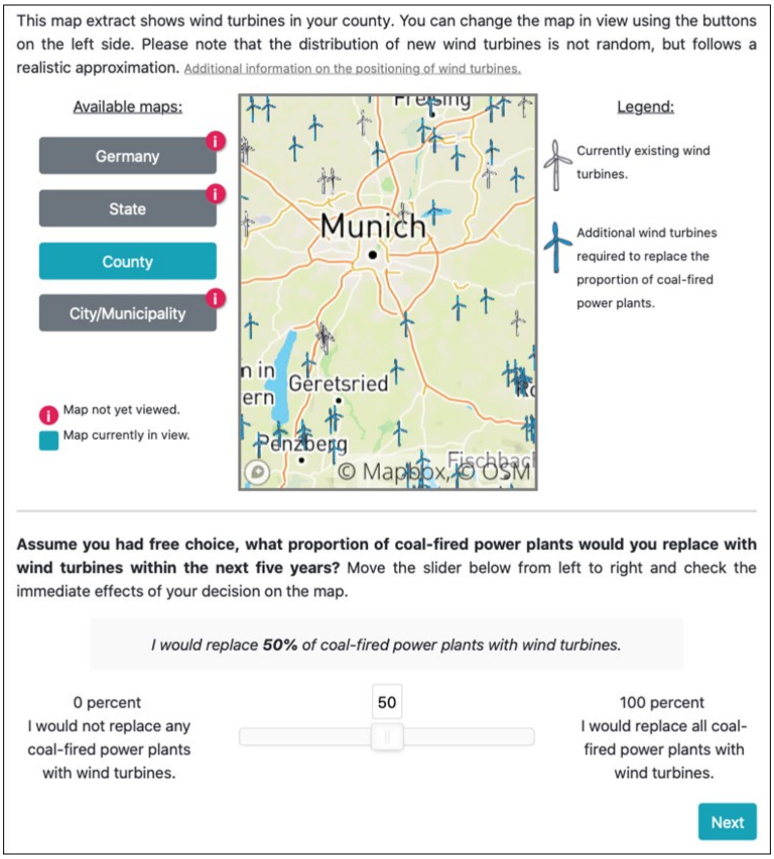

Figure 4: Information system presented in the online experiment for an exemplary Munich postal code (Research Paper 2).

In the online experiment, the information system prompted citizens with immediate feedback on the real-world ramifications of their preferences regarding the envisaged phase-out of coal-fired electricity generation in the form of visual information. Citizens could employ the information system to track the respective consequences on the maps visually. This approach provided citizens with valuable information to make informed decisions regarding wind energy, which would otherwise be challenging to anticipate, enhancing their engagement and understanding of renewable electricity projects.

The results of the online experiment highlight that after processing the implications of a coal phase-out, citizens' support of renewable wind energy is lower than initially claimed. In other words, citizens overstated their support of renewable wind energy – which suggests that they did not fully account for the visual implications associated with the expansion of wind energy. However, this may lead to more stable support for renewable wind expansion. Further, citizens who meaningfully engage with the information system are more likely to revise their initial preference on the proportion of coal-fired electricity generation that they would substitute with renewable wind energy. This highlights the capability of information systems to trigger the introspection needed to learn about the consequences of wind energy expansion among citizens.

Overall, information systems, as proposed in Research Paper 2, can serve policymakers and the greater public alike in promoting a paradigm of inclusive democracy and argument-based reasoning as the joint foundation of societal change. As policy changes entail profound implications regarding all aspects of citizens' lives, information systems can significantly contribute to unlocking citizens' political engagement as well as to prevent and address community acceptance issues. This, in turn, paves the way for renewable electricity projects that are deeply grounded in citizens' sustained support.

III Enhancing Active Consumer Participation in Sustainable Electricity Systems

Along with the increasing integration of renewable electricity generation, the operational paradigms of electricity systems are subject to fundamental change (Research Paper 3). High shares of renewable electricity generation are associated with a high number of decentralized energy assets instead of a small number of large fossil generators (Research Paper 3). As described in Section I, the intermittent nature of renewable electricity generation requires a high degree of temporal flexibility to maintain the delicate balance between demand and supply in electricity systems. One particularly promising approach to maintaining this balance is flexibility on the demand side, with consumers playing a key role in contributing their inherent flexibility potential to adjust their electricity consumption patterns (Kubli et al., 2018; Research Paper 3). On the demand side, industrial consumers as well as private consumers can provide large flexibility potentials and contribute to the integration of intermittent renewable electricity supply (Afzalan & Jazizadeh, 2019; Buhl et al., 2021; Li et al., 2021; Moog et al., 2017). To leverage decentralized flexibility potentials on the demand side, consumers need to take on an increasingly active role in electricity systems. By adapting electricity consumption behaviors in response to market and grid dynamics, consumers can actively engage in electricity markets. This proactive involvement not only bolsters grid stability but also yields significant benefits for consumers themselves, including cost and greenhouse gas emission reductions.

This section highlights the imperative of active consumer participation in sustainable electricity systems (cf. Section III.1) as well as the central role of information systems in mitigating economic risks associated with consumers' active market participation in terms of providing demand-side flexibility to electricity systems (cf. Section III.2). Information systems emerge as indispensable tools in empowering consumers to take an active stance in electricity systems. By leveraging the capabilities of information systems, consumers can navigate the economic challenges associated with demand-side flexibility, thereby curbing costs and contributing decisively to decarbonizing society. Thus, this section provides novel insights on approaches enabled by information systems that contribute to moving consumers to action in sustainable electricity systems.

III.1 Consumer-centricity and Participation as Prerequisites for Sustainable Electricity Systems

The increasing shares of renewable electricity generation accentuates reliance on external factors like weather conditions for electricity supply. Likewise, adopting electric assets such as heat pumps and electric vehicles surges, diminishing greenhouse gas emissions in heating and mobility sectors but amplifying overall electricity consumption. Those developments in electricity markets increasingly result in periods where electricity demand exceeds the availability of electricity supply and vice versa (German Federal Network Agency, 2024; Kockel et al., 2022; Schill, 2014). Figure 5 illustrates such discrepancies (i.e., residual loads) between electricity supply and demand for an exemplary three-day period and the German/Luxembourg bidding zone (German Federal Network Agency, 2024).

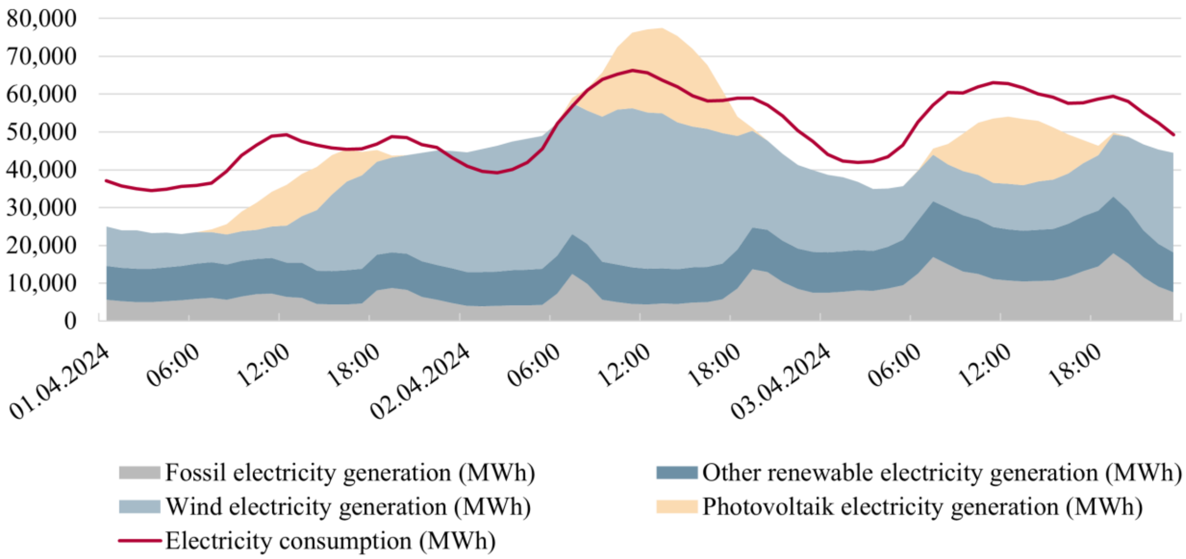

Figure 5: Realized electricity generation and consumption for an exemplary period of three days (01.04.2024 to 03.04.2024) and the German/Luxembourg bidding zone (German Federal Network Agency, 2024).

Utilizing the availability of intermittent electricity supply offers the most sustainable and cost-efficient way to fulfill consumers' electricity needs. Therefore, aligning consumers' electricity consumption with the availability of intermittent renewable electricity holds promise to effectively reduce electricity costs (Förster et al., 2024). However, temporarily aligning electricity consumption with the availability of intermittent renewable electricity generation is challenging, requiring changes in consumption behavior or investment in additional appliances (e.g., electrical storage systems or smart energy management systems). Effectively inciting consumers to harness their flexibility potential and encouraging them to play an active role in electricity systems requires novel approaches and solutions that facilitate consumer participation. This includes granting market access and creating incentives for consumers' active participation, e.g., through targeted price signals reflecting renewable electricity availability and grid conditions (Michaelis et al., 2024). This, in turn, can prompt consumers to adjust their electricity consumption, such as by modifying electric vehicle charging schedules.

Ensuring participation and safe integration of consumers in electricity systems requires advanced coordination between consumers, grid operators, and utilities (Schmitt et al., 2023). Otherwise, consumers' direly needed potential to contribute to grid stability and renewable electricity utilization will remain untapped (Schmitt et al., 2023). Consumers must incorporate new technologies and approaches into daily routines to meet these requirements (Schweiger et al., 2020; Verbong et al., 2013). Specifically, information systems enable consumers to monitor and control electricity usage based on internal and external signals and data, contributing to cost reduction and increased agency (Research Paper 3). Further, information systems and their characteristics, such as fast distribution of information, connectivity, or autonomy, substantially enable consumers' roles to shift from merely a passive role towards an active role, e.g., by generating and trading electricity or by dynamically aligning their electricity consumption with the availability of (renewable) electricity supply (Schweiger et al., 2020; Research Paper 3). For example, digital software solutions for home-management applications allow private electricity consumers to adapt their consumption (e.g., electric vehicle charging) to the availability of renewable electricity generation and to corresponding price signals (Saba et al., 2022; Research Paper 3). Such software solutions enable consumers to decrease electricity costs and increase agency as they provide the means for consumers to monitor and actively control their electricity consumption (Research Paper 3).

The impact of information systems and digital solutions such as smart meters on electricity consumption and flexibility depends heavily on social characteristics such as individual preferences, social relations, or daily routines in a household or organization (Hargreaves et al., 2010; Schweiger et al., 2020). Results of an extensive online survey with 401 private and 40 industrial consumers in Germany reveal that consumers are aware that electricity consumption has gained novel and important features due to the new possibilities of information systems and the ongoing transition towards sustainability (Research Paper 3). As a consequence of this high awareness, consumers' perception of electricity as a commodity has changed, and their willingness to play an active role in electricity systems is high (Research Paper 3). For example, both private and industrial consumers perceive increasing their energy autarky and profit potentials associated with generating electricity or marketing flexibility potentials as exciting opportunities to play an active role in electricity systems and gain economic as well as ecologic benefits (Research Paper 3).

While there are promising opportunities to enhance consumer participation and increase flexibility within electricity systems, sustained efforts are necessary to mitigate the economic risks linked with demand-side flexibility. This involves not only promoting active provision of flexibility but also investing in enabling technologies (Michaelis et al., 2024). Addressing these economic risks is vital for encouraging consumer engagement and unlocking the full potential of demand-side flexibility within sustainable electricity systems.

III.2 Digital Approaches to Mitigate Risks and Maximize Benefits of Active Consumer Participation

A central strategy that allows consumers to play an active role in electricity systems and leverage their energy flexibility potentials is by aligning electricity consumption with variable prices on wholesale electricity markets (Bichler, Buhl, Bühner, et al., 2022; Mays, 2021). Scheduling and adjusting electricity consumption according to time-varying electricity prices incites the utilization of consumers' energy flexibility potentials and, consequently, empowers consumers to reduce electricity costs (Mays, 2021). From an ecological perspective, this strategy contributes to reducing greenhouse gas emissions associated with electricity consumption. Typically, electricity prices are lower in periods with abundant renewable electricity generation and vice versa (cf. Figures 2 and 3), creating an opportune window for consumers to capitalize on cost savings while effectively contributing to decarbonization. In this regard, industrial consumers play a crucial role in unleashing the potential of energy flexibility on the demand side (Buhl et al., 2021). On the one hand, industrial consumers typically account for a significant share of total electricity consumption due to their scale of operations and associated electricity needs (Buhl et al., 2021; Moog et al., 2017). On the other hand, industrial processes often allow for substantial flexibility in electricity usage (Moog et al., 2017). Industrial processes often can be scheduled or modified to align with market signals such as wholesale electricity market prices (Bichler, Buhl, Bühner, et al., 2022). From an economic perspective, synchronizing electricity consumption with the availability of electricity generation according to market price signals allows consumers to realize cost savings by effectively utilizing price differentials.

While adjusting electricity consumption to variable prices on wholesale electricity markets offers both economic and ecological benefits, it also introduces potential consumer risks (Dong et al., 2022; Kyritsis et al., 2017; Wozabal et al., 2016). Historically, consumers have relied on fixed-price electricity contracts with utilities to mitigate price risks associated with electricity consumption (Schlereth et al., 2018). By contrast, variable electricity prices reflect the temporal dynamics between supply and demand in wholesale electricity markets and are subject to substantial price volatility and the risk involved (Freier & Loessl, 2022; Schlereth et al., 2018). Even though consumers can capitalize on lower electricity prices during abundant renewable electricity generation periods, they are increasingly exposed to the volatility of wholesale electricity market prices. In the short term, wholesale electricity market prices can fluctuate unpredictably due to factors such as unforeseen weather conditions or demand peaks (Bichler, Buhl, Knörr, et al., 2022). In the mid to long term, regulatory changes or exogeneous shocks can severely affect wholesale electricity market prices (Ciarreta et al., 2020; Sæther & Neumann, 2024). For example, the market developments during the 2021 to 2022 energy crisis on European wholesale electricity markets highlight that unforeseen electricity price developments can endanger the economic viability of entire sectors and economies (Kuik et al., 2022; Smith et al., 2024). Therefore, consumers seeking to leverage the opportunities presented by volatile electricity prices and energy flexibility potentials are in need of effective strategies to manage electricity price risks. By doing so, consumers can ensure the realization of both economic and ecological benefits even in dynamic market environments.

Against that background, information systems have an important role to play in empowering consumers to effectively secure the benefits and manage the risks of engaging in energy flexibility strategies. By providing the foundation to collect, process, and transport data in real-time, information systems enable consumers to make informed decisions about when to adjust their electricity consumption to maximize electricity cost as well as emission savings while minimizing exposure to electricity price volatility (Research Paper 5). Specifically, an advanced information system infrastructure enables the implementation of smart devices and autonomous controllers, which facilitate bidirectional information and communication streams (Ghorbanian et al., 2019; Siano, 2014; Research Paper 5). Thus, information systems represent the transmission medium for signals and information, e.g., between grid operators, utilities, aggregators, and consumers (Fridgen et al., 2016; Research Paper 5). This, in turn, builds the foundation to apply optimization algorithms that support decisions on when and how to adapt electricity consumption and initiate and control adaptions in business processes accordingly while taking associated economic risks into account (Fridgen et al., 2016). Therefore, information systems empower consumers to actively manage their electricity usage in response to changing market conditions and to secure the economic and ecological benefits associated with their active participation in electricity systems.

The first of the two following paragraphs highlights how a comprehensive risk management approach enabled by information systems can support consumers to effectively mitigate electricity price risks in their electricity procurement portfolio. The second of the following paragraphs introduces novel risk management instruments that provide consumers with the means to address the economic risks associated with investments in their capability to utilize energy flexibility potentials.

Information Systems for Risk Management in Electricity Procurement (cf. Research Paper 4)

Information systems can form the backbone of dynamic risk management approaches that allow consumers to develop and manage effective hedging strategies against unanticipated electricity price developments. Such risk management approaches may consider consumers' energy flexibility potentials and combine electricity procurement from wholesale markets with the strategic use of risk management instruments, such as electricity derivatives (Deng & Oren, 2006; Research Paper 4). Specifically, the identification, assessment, management, and monitoring of risks associated with dynamic electricity price developments necessitate the targeted integration of various risk instruments into an electricity procurement portfolio (Diederichs, 2023; Research Paper 4). As outlined at the beginning of Section II.2, without the utilization of such risk instruments, consumers would be heavily reliant on market developments, which could severely impact electricity costs (Research Paper 4). Constructing and adjusting an electricity procurement portfolio effectively is particularly critical for industrial consumers with extensive electricity needs. However, the strategic integration of risk management instruments is also essential for residential consumers to capitalize on price fluctuations while mitigating risks associated with wholesale electricity price dynamics. For both industrial and residential consumers, the coordination and integration of different risk management instruments into a cohesive electricity procurement portfolio is complex and depends on numerous internal and external factors, such as risk perception and electricity needs.

In this regard, information systems play a crucial role by providing real-time data, predictive analytics, and decision support. They enable consumers to monitor market conditions, assess risk exposures, and optimize their portfolio of risk instruments effectively. By gathering and analyzing data from wholesale electricity markets, information systems empower consumers to make informed decisions and proactively respond to market dynamics. This is particularly relevant for the effective implementation of risk management strategies. Further, advanced analytics and risk modeling tools integrated into information systems allow consumers to evaluate the impact of different risk scenarios on their operations and financial performance. Furthermore, information systems facilitate the complex integration and coordination of various risk instruments, such as electricity derivatives, into a comprehensive risk management strategy.

A comprehensive analysis and evaluation of the effectiveness of electricity procurement portfolios considering energy flexibility potentials reveals how such approaches can effectively reduce costs while accounting for electricity price risks (cf. Research Paper 4). The quantitative case study evaluation based on electricity market data from the German/Luxembourg bidding zone as presented in Research Paper 4 demonstrate that the utilization of consumers' energy flexibility can significantly contribute to reducing expected electricity costs. Thus, aligning electricity consumption with time-variable electricity prices allows consumers to benefit from price fluctuations and effectively reduce electricity costs. Additionally, the design of a portfolio of various risk instruments is shown to be crucial for hedging against unforeseen electricity price developments. Particularly through the use of electricity derivatives, such as options and futures, the risk of cost developments threatening competitiveness due to sharply rising electricity prices can be effectively mitigated. Further, the results underscore the importance of tailoring the specific design of such a portfolio of different risk instruments to consumers' preferences and needs, considering factors such as existing energy flexibility potentials or risk aversion. Finally, the results highlight how a comprehensive risk management approach in the context of electricity procurement enabled by information systems can help consumers profit from electricity price fluctuations by leveraging their flexibility potentials while at the same time accounting for price risks by hedging unforeseen electricity price developments.

Information Systems for Risk Mitigation in the Context of Individual Energy Flexibility Investments (cf. Research Paper 5)

Information systems not only aid consumers in constructing and managing electricity price risks within targeted electricity procurement portfolios but also facilitate the development of innovative risk management instruments tailored to individual investments in energy flexibility. The profitability of energy flexibility investments hinges on electricity price volatility. High electricity price volatility allows for optimizing electricity consumption through flexibility measures, resulting in electricity cost reductions compared to non-flexible approaches. Limited electricity price volatility may reduce potential cost savings, jeopardizing the profitability of energy flexibility investments and consumers' active market participation. Additionally, the coordination between flexible adjustments of consumers' electricity consumption and electricity price volatility is essential: Short-term flexibility benefits from short-term electricity price fluctuations, and vice versa. Specifically, consumers capable of shifting loads within a short time frame (e.g., less than two hours) can benefit from short-term price volatility. Conversely, consumers capable of load shifting over several days or weeks can only profit from price volatilities spanning a similar time frame. Thus, unforeseen developments in electricity price volatility on wholesale electricity markets create uncertainties regarding the electricity cost savings that can be achieved by energy flexibility investments (Bichler, Buhl, Bühner, et al., 2022). Quantifying and managing economic risks in energy flexibility marketing is thus pivotal for investment decision-making (Bichler, Buhl, Bühner, et al., 2022). Therefore, consumers require effective instruments to mitigate economic risks and foster a reliable environment for investments in energy flexibility (Bichler, Buhl, Bühner, et al., 2022).

One promising avenue for consumers to mitigate economic risks associated with energy flexibility investments is through flexibility performance contracts offered by flexibility aggregators. A flexibility performance contract defines the allocation of financial benefits that follow from utilizing energy flexibility potentials between the consumer (acting as flexibility provider) and the flexibility aggregator. Flexibility aggregators support consumers in utilizing their flexibility (Ikäheimo et al., 2010). Besides technical installation and system maintenance, flexibility aggregators provide expertise in assessing and exploiting economic benefits as well as in fulfilling necessary requirements, e.g., prequalification, for energy flexibility investments (Ikäheimo et al., 2010). In a flexibility performance contract, consumers transfer the right to market energy flexibility to aggregators in exchange for financial compensation, typically comprising fixed and variable incentives. Therefore, flexibility performance contracts enable consumers to transfer economic risks associated with investments in energy flexibility to issuers of flexibility performance contracts.

A formal analysis of flexibility performance contract designs and a case study-based evaluation demonstrate the risk mitigation capability of such contracts for consumers (cf. Research Paper 5). Figure 6 illustrates the present value distribution associated with electricity cost savings resulting from the utilization of the energy flexibility of an exemplary industrial process (considering 10,000 different electricity price scenarios over a period of five years). Despite having a positive average present value of € 10,544 of electricity cost savings, the present value distribution ranges from € -27,282 € to € 48,734 with a standard deviation of € 11,619, depending on the electricity price development. By contrast, Figure 7 highlights the present value distribution associated with electricity cost savings from the utilization of the energy flexibility of the same industrial process while applying an exemplary configuration of a flexibility performance contract (considering 10,000 different electricity price scenarios over a period of 5 years). While the average present value of electricity cost savings remains consistent with the non-contract scenario (€ 10,544), a notably lower standard deviation of € 3,950 yields a value range for the net present value of electricity cost savings from € 5,195 to € 27,379. These results underline that the flexibility performance contracts considered are well-suited risk transfer instruments for consumers that provide flexibility potentials by aligning electricity consumption with electricity price signals (Research Paper 5). Therefore, flexibility performance contracts have the potential to enhance the attractiveness of investments in energy flexibility for risk-averse consumers (Research Paper 5).

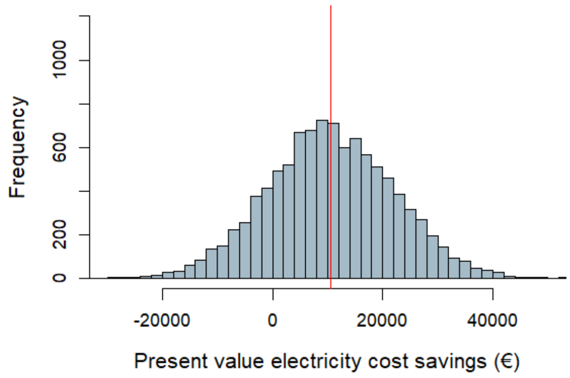

Figure 6 : Present value distribution electricity cost savings without flexibility performance contract (Research Paper 5).

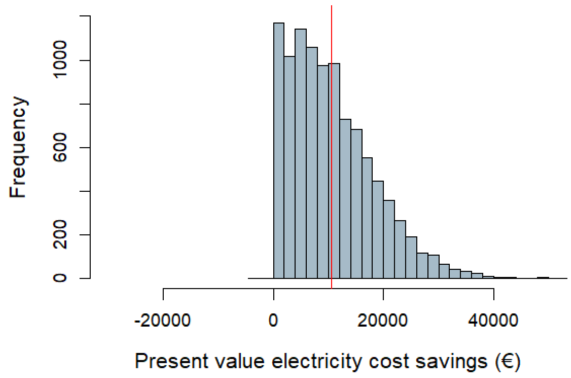

Figure 7: Present value distribution electricity cost savings with flexibility performance contract (Research Paper 5).

In summary, information systems facilitate both managing effective hedging strategies against unforeseen electricity price developments and risk transfer for individual investments in energy flexibility. By providing real-time data, predictive analytics, and decision support, information systems enable consumers to make informed decisions about when to adjust their electricity consumption, optimizing both cost and greenhouse gas emission savings while minimizing exposure to price risks.

IV Advancing the Market Coordination of Renewable Electricity Generation and Consumption

Efforts to increase renewable electricity generation and stimulate active consumer participation on the demand side are integral to supporting the decarbonization of electricity systems. However, achieving this goal effectively hinges on the establishment of targeted incentives within electricity markets to balance renewable electricity supply and demand in the short term while encouraging investment in renewable electricity and energy flexibility technologies in the mid-to-long term. In most countries that initiated ambitious decarbonization strategies for their electricity systems, corresponding market coordination mechanisms come from an era dominated by dispatchable conventional power plants based on fossil fuels and inflexible demand. With the transition towards intermittent renewable electricity generation, there is a pressing need to reevaluate and advance these market coordination mechanisms to meet the evolving needs of sustainable electricity systems, which also includes millions of active consumers.

Against that background, Section IV.1 underscores the pivotal role of electricity market coordination mechanisms in steering the transition towards sustainability. Being a key determinant of market coordination mechanisms, this section highlights the qualities of different pricing regimes and their effect on navigating critical challenges for electricity systems in transition, such as congestion management. Section IV.2 highlights how locational marginal price signals on electricity markets can contribute to cost efficiency and reduce greenhouse gas emissions associated with electricity generation. Additionally, the influence of carbon pricing schemes on the effectiveness of pricing regimes in unlocking the economic and ecological potential of demand-side flexibility within increasingly renewable electricity systems is highlighted. Based on the results of exemplary case study evaluations and empirical insights from the citizenry, Section IV.2 investigates how significant changes in market coordination mechanisms can impact both citizens individually and society at large. In this regard, a thorough evaluation of the social acceptance of two exemplary pricing regimes provides novel insights into the critical role of information systems as tools for informing citizens and gauging public support for advancements in electricity market coordination.

Overall, this section provides comprehensive insights into the critical advancements necessary in designing and developing market coordination mechanisms for renewable electricity supply and demand, highlighting how advanced market coordination mechanisms can generate economic and ecological value while considering the societal perspective of such advancements.

IV.1 Unveiling the Pivotal Role of Market Coordination in Sustainable Electricity Systems

The shift towards sustainable electricity systems brings forth profound challenges in effectively coordinating electricity supply and demand. Vital for encouraging renewable electricity generation and demand-side energy flexibility, coordination mechanisms in electricity systems are pivotal for taking, among others, the physical constraints imposed by the electricity grid infrastructure into account. Against that background, several aspects challenge traditional coordination mechanisms in electricity systems:

First, renewable electricity generation based on wind and solar power is inherently intermittent and variable, meaning electricity generation fluctuates based on weather conditions (Dubus et al., 2022; Research Paper 7). Second, renewable electricity generation is associated with wide-ranging geographical distribution and decentralization, as wind and solar electricity generation are bound to regions with favorable natural conditions. However, renewable electricity assets may be far from major consumption centers, which affects requirements for electricity transmission (Ashour Novirdoust et al., 2021; Research Paper 7). Third, cross-sectoral decarbonization efforts lead to increased electrification and new consumer groups entering the electricity system (e.g., electric vehicles and heat pumps), which induces novel demand, changes demand patterns, and drives geographical and temporal requirements for electricity transmission. Finally, existing grid infrastructures may not be adequately equipped to handle the increased volume and intermittency of renewable electricity generation as well as the additional electricity demand associated with new consumer groups. Limited transmission capacity of historically developed transmission lines and substations may lead to grid congestion, particularly during periods of high renewable electricity generation. Grid congestion refers to situations in which physical transmission constraints, including limited transmission line capacities, restrict the scheduling of electricity supply and demand (Weibelzahl, 2017). While expanding the electricity grid infrastructure to accommodate higher renewable energy penetration levels is one essential way to address grid congestion, such measures often require time and significant investment.

Besides grid expansion, developing market coordination mechanisms that adapt to the changing needs of increasingly renewable electricity systems is a key lever to manage grid congestion and ensure the security and affordability of renewable electricity supply. As described in Section I.1, market coordination refers to the coordination of electricity supply and demand via market-based mechanisms (Chao & Wilson, 2020; Gimpel et al., 2021; Liu & Zhong, 2019). Standard economic theory suggests that market-based coordination mechanisms generally promise to be more efficient in allocating and utilizing economic resources than hierarchical approaches based on central planning and directives put forth by public authorities (Arentsen & Künneke, 1996; Moroney & Lovell, 1997; Schumpeter & Keynes, 1936). Market-based coordination mechanisms allow market participants to compete against each other to achieve individual economic goals based on their individual price setting (Arentsen & Künneke, 1996). In the context of electricity systems, market-based coordination mechanisms aim to ensure optimal utilization of renewable electricity sources while balancing grid stability and meeting consumer needs (Chao & Wilson, 2020; Gimpel et al., 2021; Liu & Zhong, 2019).

In line with such standard economic theory, one particularly important aspect in the context of market coordination mechanisms is the design of pricing regimes that apply to electricity markets. For the scope of this doctoral thesis, a pricing regime is defined as the rules that determine the economic outcomes of wholesale electricity markets, and in particular the resulting prices and quantities. Pricing regimes substantially affect market participants and, therefore, are critical determinants of market outcomes with respect to economic efficiency (Bichler, Buhl, Knörr, et al., 2022; Grimm et al., 2016; Weibelzahl, 2017). Further, pricing regimes affect congestion management and determine short-term network and market operations as well as long-term transmission, generation, and flexibility investments (Weibelzahl, 2017). Specifically, the most established pricing regimes in electricity markets are locational marginal pricing (also referred to as nodal pricing), zonal pricing, and uniform pricing (Weibelzahl, 2017).

Locational marginal pricing accounts for the capacity of transmission lines that connect the different nodes of an electricity grid in the price formation (Bichler, Buhl, Knörr, et al., 2022; Research Paper 7). This results in individual electricity prices for each node (Research Paper 7). Such node-specific electricity prices reflect the locational and temporal scarcity of electricity and provide valuable information to local electricity generators and consumers, aiding in, e.g., the determination of optimal siting decisions (Bichler, Buhl, Knörr, et al., 2022; Research Paper 7). Assuming perfect competition, locational marginal pricing has been identified as the most efficient, market-based coordination mechanism for welfare maximization in congestion management (Grimm et al., 2016; Weibelzahl, 2017; Weibelzahl & Märtz, 2018; Research Paper 6). In this regard, (theoretical) arguments that favor the implementation of locational marginal pricing regimes include welfare maximization and locational investment signals in the form of locational prices (Ashour Novirdoust et al., 2021). In contrast, a possibly high number of local prices and perceived complex coordination of submarkets are possibly seen as challenges of locational marginal pricing regimes (Ding & Fuller, 2005; Ramachandran & Senthil, 2010; Weibelzahl, 2017; Research Paper 6).

Partitioning network nodes into price zones that share a common electricity price is referred to as zonal pricing (Weibelzahl, 2017). In a uniform pricing regime, all nodes belong to a single price zone, and only a single system price is calculated (Weibelzahl, 2017). Zonal and uniform pricing regimes relax parts of the physical transmission constraints within a price zone and consider relevant transmission constraints only between price zones (Ländner et al., 2019; Research Paper 6). As a direct consequence, in zonal and uniform pricing regimes, ex-post adjustments of market outcomes are required, which is commonly referred to as redispatch (Weibelzahl, 2017). Ultimately, these pricing regimes are typically associated with welfare losses, increased system costs, and other forms of inefficiency (Bertsch, 2015; Bjorndal & Jornsten, 2001; Harvey & Hogan, 2000).

Despite academic literature providing evidence supporting the implementation of locational marginal pricing regimes for market coordination in sustainable electricity systems, empirical evidence reveals a wide variance in electricity pricing mechanisms implemented globally (Eicke & Schittekatte, 2022). For instance, while the United States have embraced a nodal pricing system (Eicke & Schittekatte, 2022; Holmberg & Lazarczyk, 2015), European nations rely on forms of zonal pricing regimes (Eicke & Schittekatte, 2022). Notably, in Germany, ongoing deliberations center around the potential advantages of bidding zone splitting (i.e., introducing multiple price zones for Germany) as a strategy to alleviate welfare losses due to redispatch measures and associated cost increases for electricity consumers (Fraunholz et al., 2021; Knörr et al., 2024). As outlined at the beginning of this section, electricity systems in the transition towards sustainability challenge traditional market coordination mechanisms and require forward-moving action to advance associated pricing regimes. Pricing regimes that disregard transmission constraints and the locational value of electricity, such as uniform or zonal pricing, may fail to provide important incentives for market participants and may consequently lead to an escalation in overall costs for electricity supply. It should, therefore, be carefully assessed whether existing market coordination mechanisms are fully adequate to facilitate the integration of renewable electricity generation, demand-side flexibility, and accounting for congestion management. In doing so, however, it is imperative to recognize that potential adaptations in market coordination mechanisms exert a direct impact on various stakeholders invested in electricity systems, as they may engender variations in electricity price levels across different regions. Therefore, policymakers must rigorously evaluate such adaptations to ensure the continued refinement and enhancement of market coordination mechanisms serve the interests of key stakeholders in electricity systems.

IV.2 Economic, Ecological, and Societal Impacts of Advanced Market Coordination Mechanisms

This section evaluates the impact of advancing market coordination mechanisms and electricity pricing regimes on the economic, ecological, and societal dimensions of electricity systems transitioning towards sustainability. As highlighted in Sections II.1 and III.1, electricity prices severely impact investments in renewable electricity generation capacity as well as investments in demand-side flexibility and the adoption of corresponding flexibility potentials.

In this regard, information systems play a critical role in the successful operationalization of advanced market coordination mechanisms and pricing regimes, in particular, that constitute the formation of electricity price signals and allow for effective market coordination. Information systems are a backbone of secure data exchange between market participants and authorities (Ibrahim et al., 2020). Thereby, information systems enhance market transparency by providing market participants with timely and accurate price signals (Di Silvestre et al., 2018; Ma et al., 2024).

Such price signals may reflect relevant market conditions such as the temporal availability of renewable electricity generation and physical restrictions in electricity systems such as grid congestion. Further, information systems enable market participants to make informed decisions in response to price signals and optimize their electricity consumption or generation patterns accordingly (vom Scheidt et al., 2020). Therefore, the integration of effective market coordination mechanisms and pricing regimes with information systems – facilitating responsive actions of market participants based on price signals – goes hand in hand and emerges as a critical imperative for the design of future electricity systems. The analyses presented in Research Papers 6 and 7 offer novel perspectives on the design of market coordination mechanisms, shedding light on their effectiveness in navigating the complexities of transitioning electricity systems towards sustainability.

In particular, Research Paper 6 analyzes to what extent locational marginal pricing can serve as a market coordination mechanism to unlock the economic and ecological value of demand-side flexibility to electricity systems. Therefore, this work sheds light on how demand-side flexibility may affect costs and greenhouse gas emissions in a transmission capacity-constrained electricity grid and a locational marginal pricing regime (Research Paper 6). Accordingly, Research Paper 6 presents a quantitative short-term market model that accounts for demand-side flexibility (with a focus on industrial consumers) as well as conventional electricity supply based on fossil fuels and renewable electricity supply within a transmission capacity-constrained electricity grid (Research Paper 6). A case study analysis that builds on the standard six-node network proposed by Chao and Peck (1998) and data from the German electricity system (BDEW, 2020; ED Netze GmbH, 2021; German Federal Network Agency, 2024) evaluates the developed model.

The results of the case study evaluation indicate that demand-side flexibility leads to total system cost reductions of around 6% and greenhouse gas emission reductions of around 2% for the analyzed network parametrization (Research Paper 6). However, the extent to which demand-side flexibility can contribute economic and ecological value to electricity systems is heavily influenced by its location in the electricity grid, relevant transmission constraints, and the (local) merit order of electricity supply (Research Paper 6). Therefore, an effective market coordination mechanism should ensure that highly needed flexibility potentials are untapped at locations in a transmission capacity-constrained electricity grid, where they contribute the most economic and ecologic value (Research Paper 6). In this regard, location-specific electricity price signals are a means to reflect the need for flexibility and incentivize demand-side flexibility investments and operationalization (Research Paper 6). The results of Research Paper 6 suggest that a locational marginal pricing regime may effectively fulfill these requirements.

Beyond the need for locational price signals to incentivize demand-side flexibility, Research Paper 6 illustrates that in transmission capacity-constrained electricity grids, the operationalization of demand-side flexibility depends on the local merit order of electricity supply (Research Paper 6). Demand-side flexibility may lead to reduced costs but higher greenhouse gas emissions if the technology-specific greenhouse gas emissions of the generation technologies represented in the merit order of electricity supply do not reflect the technology-specific marginal generation costs (Research Paper 6). In that case, demand-side flexibility may lead to increased utilization of electricity generation technologies with comparably lower marginal costs but comparably higher greenhouse gas emission factors (Research Paper 6). Thus, demand-side flexibility could even increase greenhouse gas emissions in electricity systems (Research Paper 6). Therefore, energy policy should align the marginal costs of electricity supply with the respective technology-specific carbon emissions for all electricity generators participating in the merit order, e.g., through carbon pricing approaches (Research Paper 6). Otherwise, key pillars of the energy transition, such as demand-side flexibility, electrical storage, or power-to-gas applications, receive incentives that may adversely affect the overall costs and greenhouse gas emissions in electricity systems (Research Paper 6).

On the one hand, these results highlight that demand-side flexibility has a high potential to support electricity systems in transition by reducing costs and emissions associated with electricity generation (Research Paper 6). On the other hand, the case study results represent an urgent call to action for policymakers to advance current regulation to ensure that demand-side flexibility can unfold maximum positive impact regarding its economic and ecologic value contribution (Research Paper 6).

Building on those results and based on empirical insights from Germany, Research Paper 7 examines the social acceptance of transitioning the design of market coordination mechanisms within the German electricity system (Research Paper 7). Specifically, Research Paper 7 evaluates the economic and ecological impacts of transitioning from a uniform pricing regime to a locational marginal pricing regime in Germany and analyzes citizens' acceptance of such a transition through an online experiment (Research Paper 7).

In the first step, a quantitative market model, considering investments in electricity generation capacity, was developed and parameterized using data on electricity prices, demand, generation, and transmission capacities in Germany (e.g., German Federal Network Agency, 2022, 2024; Joint Allocation Office, 2023; Research Paper 7). A subsequent model analysis yielded insights into electricity prices and the expansion of renewable electricity generation under both a uniform pricing regime and a locational marginal pricing regime (Research Paper 7). The analysis revealed that a locational marginal pricing regime consistently leads to reduced electricity costs for consumers (i.e., citizens), albeit with some experiencing higher and others lower electricity prices compared to each other (Research Paper 7). Similarly, capacity investments in generation technologies varied considerably between the two pricing regimes given the made assumptions (Research Paper 7).

Based on these findings, a between-subjects online experiment was designed to investigate the social acceptance of transitioning from a uniform to a locational marginal pricing regime (Research Paper 7). In doing so, the results of the model analysis were integrated into the online experiment (Research Paper 7). Further, the design of the online experiment builds on the Theory of Planned Behavior to analyze the social acceptance of German citizens regarding the transition from uniform to locational marginal pricing (Ajzen, 1991, 2002; Research Paper 7). Social acceptance, crucial for the successful implementation of policy measures significantly affecting citizens, is considered necessary to establish societal consent (van Meegeren, 2001; Research Paper 7). In the energy research domain, social acceptance is recognized as a critical factor influencing the effective implementation of new developments and policy measures, particularly regarding renewable electricity generation and other energy-related technologies (Fournis & Fortin, 2017; Huijts et al., 2012; Kortsch et al., 2015; Panori et al., 2022; Research Paper 7). Hereby, the Theory of Planned Bahavior has been extensively employed to investigate social acceptance regarding renewable electricity generation (e.g., Liobikienė et al., 2021; Shakeel & Rahman, 2018), nuclear power (e.g., Alzahrani et al., 2023; Belmonte et al., 2023), or electric vehicles (e.g., Wang et al., 2016). By integrating the theoretical foundations of social acceptance research and the findings from the market model analysis, an information system was developed to provide German citizens with targeted insights into the economic and ecological impacts of market coordination mechanisms (Research Paper 7). The information system equipped German citizens with valuable information about the economic and ecological implications of transitioning from a uniform pricing to a locational marginal pricing regime in Germany (Research Paper 7). Subsequently, this information system played a central role in the online experiment, where German citizens actively engaged with the provided information (Research Paper 7).

Overall, 2,400 German citizens participated in the online experiment (Research Paper 7). Subsequent findings suggest that German citizens generally accept a transition towards a locational marginal pricing system and do not express outright opposition to such a transition (Research Paper 7). This insight is crucial for German policymakers considering advancements in market coordination, as locational marginal pricing entails significant changes, including variations in electricity prices across different locations (Research Paper 7). Additionally, the study reveals that citizens' attitudes exert the highest and statistically significant influence on social acceptance (Research Paper 7). To foster a positive attitude towards the transition in the design of market coordination mechanisms, perceived benefits and costs derived from the impacts associated with different market coordination mechanisms are paramount (Research Paper 7). It is essential to ensure that perceived benefits outweigh perceived costs to achieve a high level of social acceptance (Research Paper 7). In this regard, multi-channel outreach – comprising public forums, educational campaigns, and stakeholder engagement initiatives – aimed at transparently addressing concerns and highlighting the potential economic and ecological benefits of transitioning to a locational marginal pricing regime, are key building blocks to ensuring sustained support and informed consent from the citizenry.

The research results presented in this section highlight the importance of market coordination mechanisms in shaping the economic, ecological, and societal dimensions of electricity systems. Consequently, they underscore the imperative for policymakers to leverage market coordination mechanisms for driving sustainable transitions within electricity systems. While German citizens generally seem to be open to changes in market coordination mechanisms and may accept corresponding implications on electricity prices and renewable electricity generation expansion, considering citizens' attitudes is pivotal to avert public opposition. Here, information systems can substantially contribute to gauging public support and informing citizens regarding the implications of changes in electricity market coordination mechanisms. Therefore, these insights serve as a crucial call to action, urging policymakers and researchers to develop resilient market coordination mechanisms grounded in societal acceptance, paving the way for a successful transition of electricity systems towards sustainability.

V Conclusion

V.1 Summary and Contribution

This doctoral thesis sets out to take an integrated perspective on information systems' economic, ecological, and societal contributions to the successful transition of electricity systems towards sustainability. The seven research papers presented in this doctoral thesis focus on the application of information systems at the intersections of electricity supply, electricity demand, and their market-based coordination. The seven research papers apply various research methods including literature reviews, quantitative modeling, case study analyses, empirical experiments, and surveys to provide a rigorous examination and comprehensive understanding of information systems' contribution in sustainable electricity systems.

To accelerate the expansion of renewable electricity generation capacity, this doctoral thesis first investigates how information systems can positively contribute to mitigating revenue prospects and public acceptance risks for investments in renewable electricity generation (cf. Section II). Despite substantial growth, there remains a significant need to establish additional renewable electricity generation capacity, particularly considering efforts to phase out fossil fuel-based technologies and to meet the increasing electricity demand from electrification and sector coupling initiatives. Thus, extensive investments in additional renewable electricity generation capacity are required to effectively reduce greenhouse gas emissions while ensuring the affordability of electricity supply. This doctoral thesis highlights the significant challenges posed by uncertain revenue prospects for investments in renewable electricity projects. Research results reveal how information systems can contribute to mitigating these risks, facilitating the design of novel business models, and enhancing the profitability of renewable electricity projects. This, in turn, contributes valuable insights for investors and can help accelerate the future integration of renewable electricity generation. Further, this doctoral thesis emphasizes the crucial role of information systems from a societal perspective. Information systems can facilitate public participation and mitigate public acceptance risks associated with renewable electricity projects. Information systems enable citizens to understand climate policy outcomes on an individual level and support citizens' preference construction. This contributes to citizens expressing deliberate political decisions and to inclusive decision-making processes on renewable electricity projects. By providing insights into citizens' sentiments and preferences, information systems empower investors to align project designs with community needs, fostering transparency and enhancing citizens' engagement in climate policy implementation.

Further, this doctoral thesis focuses on the role of information systems in promoting consumers' active participation and inciting the provision of demand-side flexibility (cf. Section III). As the integration of renewable electricity generation expands, encouraging consumers to engage in electricity systems actively becomes imperative for grid stability, among other things. Thus, active consumers are at the heart of energy transitions towards sustainability (Michaelis et al., 2024). Consumers' active participation in electricity systems not only contributes to the integration of renewable electricity generation and to grid stability but also yields significant benefits for consumers themselves, including cost reductions and greenhouse gas emission mitigation. A central strategy that allows consumers to play an active role in electricity systems and leverage their energy flexibility potentials is by aligning electricity consumption with variable prices on wholesale electricity markets (Bichler, Buhl, Bühner, et al., 2022; Mays, 2021). The results of this doctoral thesis underscore the pivotal role of information systems in empowering consumers to manage both the benefits and risks associated with energy flexibility strategies. This doctoral thesis provides novel insights into how information systems facilitate dynamic risk management by integrating consumers' flexibility potentials with data on wholesale market dynamics to develop effective hedging strategies against unforeseen electricity price developments. Moreover, this doctoral thesis highlights the opportunities for innovative risk management instruments tailored to individual investments in energy flexibility. Such instruments incentivize risk-averse consumers to participate actively in electricity markets by mitigating economic risks. By empowering consumers to optimize cost and emission savings while minimizing exposure to electricity price risks, information systems leveraging consumers' flexibility potential play a key role in advancing energy transitions towards sustainability.

Finally, this doctoral thesis provides comprehensive insights into the critical advancements necessary for designing and developing electricity market coordination mechanisms (cf. Section IV). Specifically, presented research results reveal how advancing electricity pricing regimes can contribute to navigating critical challenges for electricity systems in transition towards sustainability, such as grid congestion. As standard economic theory posits, the design of pricing regimes that apply to electricity markets substantially affects market participants and, therefore, is a critical determinant of overall market outcomes with respect to economic efficiency (Arentsen & Künneke, 1996; Bichler, Buhl, Knörr, et al., 2022; Grimm et al., 2016; Weibelzahl, 2017). This doctoral thesis reveals how locational marginal price signals can contribute to congestion management which can improve cost efficiency and reduce greenhouse gas emissions associated with electricity generation. Additionally, the influence of carbon pricing schemes on the effectiveness of pricing regimes in unlocking the economic and ecological potential of demand-side flexibility within increasingly renewable electricity systems is highlighted. Based on empirical insights, this doctoral thesis investigates the social acceptance of two exemplary market coordination mechanisms in Germany. Corresponding results provide novel insights regarding the social acceptance of significant changes in market coordination mechanisms, which can impact both citizens individually and society at large. Further, this doctoral thesis sheds light on the promising role of information systems as crucial tools for informing citizens and gauging public support for advancements in market coordination mechanisms. Finally, by examining the economic, ecological, and societal impacts of advanced market coordination mechanisms enabled by information systems, research results offer actionable insights for policymakers on designing market coordination mechanisms that optimize resource allocation and mitigate greenhouse gas emissions.

V.2 Limitations and Future Research

While this doctoral thesis sheds light on critical aspects of the role of information systems in the transition to sustainable electricity systems, it is not without limitations. Addressing these limitations offers a multitude of starting points for future research. Each research paper that forms part of this doctoral thesis contains detailed information about the limitations of the work conducted therein. This section summarizes the overarching limitations of this doctoral thesis and discusses avenues for future research in this regard.

First, this doctoral thesis addresses the economic and societal challenges inherent in investments in renewable electricity generation, with a specific focus on the role of information systems in mitigating revenue prospect risks and public acceptance risks from an investment perspective. While the scope of this thesis is comprehensive within its chosen focus, future research could investigate complementary approaches to mitigate further investment risks perceived by investors, such as technology or resource-related investment risks. Exploring such aspects could contribute to further incentivizing investments in renewable electricity generation capacity and, therefore, contribute to the increasing decarbonization of electricity supply. In pursuit of addressing revenue prospect risks linked to investments in renewable electricity generation, this doctoral thesis offers new insights into how information systems can enhance the economic viability of business models for renewable electricity generation. Future research could expand on comprehensive analyses of information systems' value-added, e.g., by conducting extensive case studies, empirical analyses of renewable electricity projects that leverage information systems or insights from stakeholders involved in renewable electricity projects (e.g., public and private investors, project developers, local planners, and policymakers). In this regard, employing modeling approaches may be beneficial in quantifying the economic benefits of information systems. Finally, while this thesis offers first but highly relevant insights into how information systems can address acceptance risks in renewable electricity projects, there is vast potential for further exploration. Future research could for instance empirically refine design specifications of information systems to enhance citizen engagement and acceptance in renewable electricity projects and other contexts related to energy transitions towards sustainability.

Second, this doctoral thesis investigates how information systems can support consumers in taking an increasingly active role in electricity systems and leveraging decentralized flexibility potentials on the demand side. While the research presented in this doctoral thesis acknowledges the influence of social variables and individual preferences on consumer participation in electricity systems, the empirical investigations conducted in this regard contribute to an overarching rather than a detailed understanding of consumers' preferences in this regard. Thus, the results presented in this doctoral thesis warrant further investigation to dive deeper into the socio-economic and behavioral determinants that shape consumer preferences and decision-making. Comprehensively understanding these factors can inform the design of targeted and effective information system-based interventions supporting consumer participation. Further, a thorough understanding of consumer preferences can inform future policies that effectively facilitate participation in electricity systems and incite required investments. Further, this doctoral thesis provides novel insights into how information systems can contribute to developing and executing effective strategies to navigate the economic challenges posed by volatile wholesale electricity prices and allow consumers to align electricity consumption with renewable electricity generation availability for economic and ecological benefits. Future research may extend this line of research by exploring the integration of machine learning algorithms and predictive analytics to enhance the proposed portfolio management approaches. Further, incorporating insights from adjacent research disciplines, such as behavioral economics, may be valuable to decode and model consumer decision-making processes and preferences in the context of demand-side flexibility provision. Ultimately, future research may extend the presented work on the conceptualization and evaluation of flexibility performance contracts for demand-side flexibility investments across diverse consumer segments and industries to identify sector-specific challenges and opportunities as well as to evaluate the scalability of contract designs.

Third, this doctoral thesis underscores the pivotal role of electricity market coordination mechanisms in improving cost efficiency and reducing greenhouse gas emissions in electricity systems while effectively managing electricity grid congestion. The proposed market models in this doctoral thesis represent meaningful abstractions of real-world electricity markets that, e.g., allow to analyze the economic and ecological impact of demand-side flexibility from a system perspective. However, the proposed models rely on a series of assumptions. Although proposed market models build on standards widely used in the academic literature and are well-suited to illustrate interdependencies in electricity markets, I encourage future research to develop and assess market models that more accurately reflect real-world electricity system characteristics and, therefore, allow to infer comprehensive implications regarding the design of market coordination mechanisms on electricity markets. Moreover, future research could expand upon the analyses presented regarding the impact of the merit order of electricity supply on the economic and ecological benefits of demand-side flexibility in electricity systems. Exploring novel approaches to ensure that demand-side flexibility consistently reduces costs and greenhouse gas emissions in electricity systems is essential. One particularly promising avenue for investigation is enhancing the temporal and regional resolution of greenhouse gas emissions associated with electricity consumption. In line with the leading work conducted by Körner and Strüker (2023), digital technologies and information systems have the potential to enable consumers to use and process verifiable carbon emission data and facilitate cost- and carbon-adaptive electricity consumption. This entails providing consumers with real-time access to verifiable data on the carbon footprint of electricity generation. By empowering consumers to manage both electricity costs and associated greenhouse gas emissions actively, such approaches warrant further investigation in future research projects.

Successfully navigating energy transitions towards sustainability demands transdisciplinary research approaches that inform fellow researchers, industry leaders, policymakers, environmental organizations, and the citizenry alike. While this doctoral thesis is not without limitations, it serves as a catalyst for future research endeavors contributing to leverage information systems' economic, ecological, and societal impact on electricity systems in transition towards sustainability.

V.3 Acknowledgement of Previous and Related Work

In all the research papers and projects that I have conducted and presented in this doctoral thesis, I collaborated with esteemed colleagues at the Fraunhofer Institute for Applied Information Technology, the FIM Research Center for Information Management, the University of Bayreuth, the University of Augsburg, and the Augsburg University of Applied Sciences. This section outlines how prior and related research conducted at these organizations has contributed to my work.

The work of Graf et al. (2020) on supporting citizens in the context of politically relevant decisions through novel approaches enabled by information systems provided the foundation for the experimental design developed and applied in Research Paper 2. Further, the research contributions of Töppel and Tränkler (2019) constitute the conceptual foundation for the research approach and the design of flexibility performance contracts, as presented in Research Paper 5. Finally, the research contributions by Weibelzahl (2017), Weibelzahl and Märtz (2018), Ländner et al. (2019), and Gimpel et al. (2021) provided valuable insights and starting points in the research field concerned with market coordination mechanisms and the importance of pricing regimes for congestion management in electricity systems. This informed and supported the research conducted in Research Paper 6 and Research Paper 7.

Please note that I have used different writing assistance programs (i.e., DeepL, Grammarly, and ChatGPT) for text editing and grammatical proof-checking. However, I have carefully reviewed all suggestions of the writing assistance programs and take full responsibility for the content presented in this thesis.

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VII Appendix

VII.1 Research Papers Relevant to this Doctoral Thesis

Research Paper 1: Renewable Electricity Business Models in a Post Feed-in Tariff Era

Rövekamp, P., Schöpf, M., Wagon, F., Weibelzahl, M., & Fridgen, G. (2021). Renewable Electricity Business Models in a Post Feed-in Tariff Era. *Energy*, 216, 119228. https://doi.org/10.1016/j.energy.2020.119228

(VHB-Ranking 2024 Category: B)

Research Paper 2: Shaping Stable Support: Leveraging Digital Feedback Interventions to Elicit Socio-Political Acceptance of Renewable Energy

Wagon, F., Tiefenbeck, V., & Fridgen, G. (2024). Shaping Stable Support: Leveraging Digital Feedback Interventions to Elicit Socio-Political Acceptance of Renewable Energy. *Submitted.*

Research Paper 3: A Consumer-Satisfaction Model to Foster Consumer Participation in Digital Sustainable Energy Systems

Heinrich, T., Wagon, F., & Weibelzahl, M. (2024). A Consumer-Satisfaction Model to Foster Consumer Participation in Digital Sustainable Energy Systems. *Submitted.*

Research Paper 4: Risk Management in Electricity Procurement Utilizing Industrial Energy Flexibility

Weigel, M., Förster, R., & Wagon, F. (2023). Diversification of economic risks in marketing industrial energy flexibility in the context of Demand Response. *Zeitschrift Für Energiewirtschaft*, 47(4), 26–45. https://doi.org/10.1007/s12398-023-0936-y

(VHB-Ranking 2024 Category: C)

Research Paper 5: Risk Mitigation Capability of Flexibility Performance Contracts for Demand Response in Electricity Systems

Jäckle, F., Schöpf, M., Töppel, J., & Wagon, F. (2019). Risk Mitigation Capability of Flexibility Performance Contracts for Demand Response in Electricity Systems. *Proceedings of the 27th European Conference on Information Systems (ECIS)*. https://aisel.aisnet.org/ecis2019_rp/175

(VHB-Ranking 2024 Category: A, subsection conference proceedings)

Research Paper 6: For Better or for Worse? On the Economic and Ecologic Value of Industrial Demand Side Management in Constrained Electricity Grids

Rövekamp, P., Schöpf, M., Wagon, F., & Weibelzahl, M. (2023). For Better or for Worse? On the Economic and Ecologic Value of Industrial Demand Side Management in Constrained Electricity Grids. *Energy Policy*, 183, 113781. https://doi.org/10.1016/j.enpol.2023.113781

(VHB-Ranking 2024 Category: B)

Research Paper 7: Designing Electricity Markets of the Future: On the Role of Information for Social Acceptance of a Transition in the Electricity Market Design

Eble, D., Wagon, F., & Weibelzahl, M. (2024). Designing Electricity Markets of the Future: On the Role of Information for Social Acceptance of a Transition in the Electricity Market Design. *Submitted.*

Over the course of my doctoral candidacy, I also co-authored the following research papers and book chapters. This work is not part of this doctoral thesis:

- Bachmann A., Bank L., Bark C., Bauer D., Blöchl B., Brugger M., Buhl H. U., Dietz B., Donnelly J., Friedl T., Halbrügge S., Hauck H., Heil J., Hieronymus A., Hinck T., Ilieva-König S., Johnzén C., Koch C., Köberlein J., Köse E., Lochner S., Lindner M., Mayer T., Mitsos A., Roth S., Sauer A., Scheil C., Schilp J., Schimmelpfennig J., Schulz J., Schulze J., Sossenheimer J., Strobel N., Tristan A., Vernim S., Wagner J., Wagon F., Weibelzahl M., Weigold M., Weissflog J., Wenninger S., Wöhl M., Zacharias J., & Zäh M. F. (2021). Energieflexibel in die Zukunft – Wie Fabriken zum Gelingen zur Energiewende beitragen können. https://doi.org/10.24406/FIT-N-638765.
- Buhl, H. U., Gabrek, N., Gerdes, J.-N., Kaymakci, C., Rauland, K., Richter, F., Sauer, A., Schneider, C., Schott, P., Seifermann, S., Tristan, A., Wagner, J., Wagon, F., Weibelzahl, M., Weissflog, J., & Zachmann, B. (2021). Industrial flexibility options and their applications in a future energy system. Whitepaper. https://doi.org/10.24406/fit-n-639062.

- Bichler, M., Buhl, H. U., Bühner, V., Cam, E., Ebinger, K., Ganz, K., Hanny, L., Harper, R., Hofmann, N., Kern, T., Knörr, J., Lange, K., Neuhoff, K., Ober, S., Ott, M., Reichmuth, M., Richstein, J., Richter, F., Schmidt, A., Schöpf, M., Schott, P., Sitzmann, A., Stöter, M., Wagon, F., Weibelzahl, M., Weißflog, J., Wuntke, M., & Zilke, P. (2022). Gestaltung des aktuellen und zukünftigen Markt- und Stromsystems. In A. Sauer, H. U. Buhl, A. Mitsos, & M. Weigold (Eds.), Energieflexibilität In Der Deutschen Industrie: Band 2: Markt- und Stromsystem, Managementsysteme und Technologien energieflexibler Fabriken.
- Held, A., Bekk, A., Fahl, U., Müller, T., Pahle, M., Buhl, H. U., Hanny, L., Rockstuhl, S., Wagon, F., Weibelzahl, M., Niessen, S. Fechner, S., Mohringer, N., Frank, D., Schmid, E., Powalla, O., & Pflug V. (2022). Regulatorische Handlungsoptionen für ein klimaneutrales Energiesystem. *Position Paper*.
- Wagon, F., Tiefenbeck, V., Fridgen, G. (2023). Supporting Citizens with Digital Behavioral Interventions in Political Decisions – Evidence from the Sustainability Context. *Submitted*.
- Merkl, L.-M., Koch, T., Wagon, F., & Germelmann, C. C. (2023). Digital Help for those Who are Already Covered? An Experimental Study on the Effects of Digital Nudging to Promote Sustainable Consumer Behavior. *Submitted*.
- Weigel, M., Förster, R., & Wagon, F. (2023). Risikomanagement in der Strombeschaffung unter Nutzung industrieller Energieflexibilität. Zeitschrift Für Energiewirtschaft, 47(4), 26–45. https://doi.org/10.1007/s12398-023-0936-y.
- Göritz, S., Schneider, M., Wagon, F., & Weibelzahl, M. (2024). On the Design of Operating Models for Company Charging Parks: How Industry Can Unleash The Power of Electric Mobility Through Sector Coupling. *Submitted*.
- Meuser, B., Valett, L., Wagon, F., & Weibelzahl, M. (2024). Navigating Digital Transformation towards Sustainability: A Maturity Model for Industrial Decarbonization. *Americas Conference on Information Systems 2024 Proceedings*. https://aisel.aisnet.org/amcis2024/sig_green/sig_green/10.

VII.2 Individual Contributions to Research Papers

Seven research papers constitute the foundation for this cumulative doctoral thesis. All seven research papers were collaboratively developed in teams among multiple co-authors. This section describes my individual contribution to each research paper.

Research Paper 1 is titled *Renewable Electricity Business Models in a Post Feed-in Tariff Era*. This research paper was conducted in a team of five co-authors. All co-authors contributed equally to this paper. In close collaboration with one of the other co-authors, I substantially contributed to positioning our research in the context of related research streams and to designing, executing, and analyzing an extensive literature review that constitutes the foundation for the research results presented in this paper. In further collaboration with this co-author, I worked on the formulation of the paper. The remaining three co-authors provided valuable guidance and feedback on the study's conceptualization, validation, and supervision.

Research Paper 2 is titled *Shaping Stable Support: Leveraging Digital Feedback Interventions to Elicit Socio-Political Acceptance of Renewable Energy*. This research paper was conducted in a team of three co-authors. As a team, we agreed that I should assume the lead author role of the research paper. The other two co-authors made equal contributions as subordinate authors. Subsequently, I elaborated on the design of an online experiment that builds the research paper's empirical foundation. Further, I collected data and conducted subsequent analyses. Finally, I was responsible for writing the initial draft of the research paper and refining the research paper based on the feedback of my co-authors, who provided me with valuable academic guidance on the conceptualization, conducted analyses, and in the writing process.

Research Paper 3, titled *A Consumer-Satisfaction Model to Foster Consumer Participation in Digital Sustainable Energy Systems*, was co-authored by a team of three, with all authors contributing equally to the research paper. The responsibility for the initial idea of the paper, including its research approach, was shared among the three co-authors. In collaboration with one of the co-authors, I worked on designing and evaluating a comprehensive literature review and contributed to conceptualizing subsequent results. This co-author worked on the initial draft of the research paper while I substantially revised and further developed the research paper. The third co-author supervised the research process and provided valuable feedback for conceptualizing and refining the research paper.

Research Paper 4 is titled *Risk Management in Electricity Procurement Utilizing Industrial Energy Flexibility*. This research paper was conducted by a team of three co-authors who contributed equal parts to the research paper. In my role as co-author, I significantly contributed to the initial idea and to the conceptualization of the paper. Further, I investigated the results from the quantitative analyses conducted in the research paper and inferred implications for key stakeholders concerned with the research objectives. The initial and revised manuscript was written jointly by all co-authors

Research Paper 5 is titled *Risk Mitigation Capability of Flexibility Performance Contracts for Demand Response in Electricity Systems*. A team of four co-authors developed this research paper. In close collaboration with one of the co-authors, I worked on establishing a conceptual model for flexibility performance contracts and the quantitative simulations and evaluations associated with the presented case study. The remaining co-authors provided guidance on the theoretical foundations of the research paper and contributed to the design of the research approach. The initial and revised manuscript was written jointly by all co-authors

Research Paper 6 is titled *For Better or for Worse? On the Economic and Ecologic Value of Industrial Demand Side Management in Constrained Electricity Grids* and was developed by four co-authors. I substantially contributed to the conceptualization of the research paper, positioning our work in the context of prior research contributions and to extensive analyses resulting from the quantitative market model and its evaluation. Further, I played a central role in the writing and editing of the manuscript, ensuring its clarity and coherence. All co-authors, including myself, shared the writing responsibilities for revising the research paper. We agreed that we all contributed to this research paper in equal parts.

Research Paper 7 is titled *Designing Electricity Markets of the Future: On the Role of Information for Social Acceptance of a Transition in the Electricity Market Design*. The three co-authors contributed equal parts to the research paper and developed the idea and structure for this research paper in close collaboration. While two co-authors primarily worked on developing and parametrizing the quantitative market model, I contributed to developing the overarching research approach, the conceptualization, and execution of the conducted online experiment with German citizens. Further, I substantially contributed to writing and refining the research paper.

VII.3 Research Paper 1: Renewable Electricity Business Models in a Post Feed-in Tariff Era

Authors:

Patrick Rövekamp; Michael Schöpf; Felix Wagon; Martin Weibelzahl

Published in:

Energy (2021)

Abstract:

To expand intermittent renewable electricity sources (RESs), worldwide energy policy makers have introduced fixed feed-in tariffs (FITs). However, FITs typically expire after a limited time period. Due to the intermittent electricity supply of RES, market distortions, and insufficient flexibility options, exclusive participation in wholesale electricity markets might not be a viable business model for RES that no longer receive a FIT. Thus, it remains unclear which RES business models (RBMs) ensure a viable operation of RES in the post FIT era. To close this research gap, we present a typology encompassing five RBM archetypes: wholesale electricity market (1), physical power purchase agreements (2), nonphysical power purchase agreements (3), self-consumption (4), and on-site power-2-X (5). The typology includes three additional service layers, which may enhance the profitability of RBM archetypes by opening up additional revenue streams: infrastructure services (1), electricity storage services (2), and ancillary services (3). We highlight the need for new approaches to quantify the viability of RBM archetypes and service layers under different regulatory, technological, and market conditions. To prevent the imminent decommissioning of existing RESs, policy makers must shape the next era of the energy transition, weighting the implications of market-based and intervention-based energy policy approaches.

Keywords:

Energy Transition; Renewable Electricity Sources; Business Model Canvas; Business Model Typology; Feed-In Tariffs; Energy Policy

VII.4 Research Paper 2: Shaping Stable Support: Leveraging Digital Feedback Interventions to Elicit Socio-Political Acceptance of Renewable Energy

Authors:

Felix Wagon; Gilbert Fridgen; Verena Tiefenbeck

Extended Abstract[3]:

The impact of climate change is global in scope and unprecedented in scale (United Nations, 2015). Without drastic action today, preserving our planet's ability to sustain human life is at considerable risk (Gasparrini et al., 2017; Pecl et al., 2017; Voosen, 2019). Although most people agree with the scientific consensus on environmental problems (Fairbrother, 2016; Oreskes, 2004), the transition towards sustainability has proven to be an uphill battle. One reason for this is that public support tends to drop as soon as climate policies affect people individually (Drews & van den Bergh, 2016; McGrath & Bernauer, 2017; Weber et al., 2017). For example, Germany has been among the first countries to transition to a low-carbon energy system and aspires to be the first major economy to phase out coal and nuclear energy. The expansion of Germany's wind energy capacity is a central pledge in the election manifestos of the country's leading political parties and has been a contentious issue in several electoral campaigns. Recent surveys suggest a generally high public support for renewable energies (Local Energy Consulting, 2020). Nevertheless, plans for the expansion of Germany's wind energy capacity have faced strong opposition at a local level (Arifi & Winkel, 2021; Kamlage et al., 2020; Weber et al., 2017) as public support tends to drop as soon as aesthetic and geographic implications of wind energy development become apparent (Weber et al., 2017).

Such political engagement among the citizenry – be it through an election, a referendum, a petition, an opinion survey, a protest, or involvement in political parties and organizations – is a substantial driver of policy change in democratic countries (Drews & van den Bergh, 2016; Huttunen et al., 2022; Jaradat et al., 2024). Consequently, citizens' preferences on climate policies are a potent determinant of public conduct and decision-making. Climate policy outcomes typically appear to be

[3] This Research paper is under review for publication in a scientific peer-reviewed journal at the time of submission of this doctoral thesis. Therefore, an extended abstract is provided.

vague, highly complex, or unfamiliar to individuals. As our cognitive resources to anticipate the consequences of climate policy outcomes are limited, citizens frequently form sub-optimal and irrational preferences. This notion of bounded rationality can become particularly problematic where the success of policy measures hinges on the individual support of citizens.

Such political engagement among the citizenry – be it through an election, a referendum, a petition, an opinion survey, a protest, or involvement in political parties and organizations – is a substantial driver of policy change in democratic countries (Drews & van den Bergh, 2016; Huttunen et al., 2022; Jaradat et al., 2024). Consequently, citizens' preferences on climate policies are a potent determinant of public conduct and decision-making. Climate policy outcomes typically appear to be vague, highly complex, or unfamiliar to individuals. As our cognitive resources to anticipate the consequences of climate policy outcomes are limited, citizens frequently form sub-optimal and irrational preferences. This notion of bounded rationality can become particularly problematic where the success of policy measures hinges on the individual support of citizens.

Feedback interventions are regarded as powerful instruments to counteract these effects and support individuals to act and decide in line with their preferences, but so far have hardly been applied in political decision contexts (Tiefenbeck et al., 2018; Tiefenbeck et al., 2019). Taking feedback interventions to the digital realm creates further opportunities in broader social contexts and allows to visualize information, personalize contents, and even create immersive experiences that help to effectively shift citizens' attention to climate policy implications that may have remained disregarded before. First but highly relevant recent studies propose digital information visualization techniques and digital feedback as a decision aid to encourage citizens to learn about facts and to allow for reliable preference construction (Aubert & Lienert, 2019; Aubert et al., 2023; Aubert et al., 2022; Laurila-Pant et al., 2019). Extending this research line, we aim to prompt citizens with information that immediately visualizes decision implications and creates a personalized digital feedback intervention.

Against that background, this study develops a digital feedback intervention to support citizens in their preference construction that government stakeholders can use as "sensors" for climate policy support. Specifically, we conducted an online experiment with German citizens (N= 430), asking them what percentage of the current coal-fired electricity generation they would replace with renewable wind energy, assuming they had freedom of choice. Respondents then see the ramifications of their choice as they receive visualized information on the number and location of wind turbines required to replace their preferred proportion of coal-fired electricity generation.

The study reveals three key findings: First, while citizens' support of renewable wind energy that results from digital feedback is lower than initially claimed, the change may lead to more stable support for renewable wind expansion. Second, citizens who meaningfully engage with the digital feedback intervention are more likely to revise their initial preference for wind energy. Third, and surprisingly, citizens' ecological attitude and place attachment had no significant effect on the extent to which they revised their initial preference. Our study highlights the effectiveness of digital feedback interventions in helping citizens explore the consequences of policy change and learn about alternatives. Thus, our study contributes to a deepened understanding of the context in which digital feedback interventions can provide insights into citizens' preferences and inform decision-making on climate policies. Our study serves policymakers and the greater public in these practical ways while promoting inclusive democracy and argument-based reasoning as the joint foundation of societal change.

Keywords:

Digital Feedback Intervention; Citizen Engagement; Online Experiment; Wind Energy; Renewable Energy Acceptance

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VII.5 Research Paper 3: A Consumer-Satisfaction Model to Foster Consumer Participation in Digital Sustainable Energy Systems

Authors:

Theresa Heinrich; Felix Wagon; Martin Weibelzahl

Extended Abstract[4]:

The impacts of climate change require drastic action today. Otherwise, ecosystems and human life are at risk (Gasparrini et al., 2017; Pecl et al., 2017; Voosen, 2019). We urgently need to scale up the adoption of renewable energies to comply with our ambitious climate goals, reduce energy costs, and decrease dependencies on fossil fuels. Against this background, it will be imperative for consumers to participate in and actively contribute to the energy transition (Schweiger et al., 2020). For example, consumers may actively participate in digital sustainable electricity systems by engaging in renewable electricity generation on their own premises (e.g., photovoltaic systems).

Consumer participation is a prerequisite for successfully managing the energy transition towards sustainability (Schweiger et al., 2020). Emerging digital technologies and information systems are key enablers for a more sustainable, affordable, and resilient energy supply and provide new means for consumer participation in sustainable energy systems (Arjmand et al., 2023; Watson et al., 2010; Zhu et al., 2022). For example, information systems allow real-time, autonomous, secure, and local peer-to-peer electricity trading between decentralized renewable electricity generators and consumers (Sousa et al., 2019) or to control grid utilization intelligently on the basis of interactive communication, control, and monitoring of different energy assets (Guerrero et al., 2020). With digital technologies becoming more prevalent for consumers (e.g., in smart homes or smart factories), an array of opportunities exist to take an active role in the energy system. However, those opportunities for consumers typically affect the characteristics of consumed or sold energy, which we refer to as energy features (e.g., electricity price, sustainability of electricity supply, or regionality of electricity generation). To achieve a rapid and consumer-driven energy transition, it is essential to consider consumer preferences for

[4] This Research paper under review for publication in a scientific peer-reviewed journal at the time of submission of this doctoral thesis. Therefore, an extended abstract is provided.

energy features and resulting consumer satisfaction (Lee & Reiner, 2023). Consumer preferences represent crucial determinants of whether consumers will actively participate in digital sustainable energy systems. Therefore, consumer satisfaction regarding energy features is pivotal. To that end, our study aims to link the features of energy supply and generation induced by novel technology-enabled opportunities for consumer participation with consumer preferences. In doing so, we deliberately focus on private and industrial consumers. Private consumers (i.e., households) and industrial consumers represent two particularly relevant consumer segments, as they typically account for large shares of energy consumption, e.g., more than half of total energy consumption in Europe (International Energy Agency, 2022). Thus, private and industrial consumers feature high potential to contribute to achieving our ambitious climate targets.

Numerous studies have explored digital business models for consumer participation to actively co-create digital sustainable energy systems (Elliot, 2011; Kahlen et al., 2018). So far, however, few studies have focused on the associated effects on consumer satisfaction, representing an important determinant of consumers' willingness to seize such opportunities (Hajiabadi et al., 2019; Shin & Managi, 2017). This study sets out to bridge this gap between technology-enabled opportunities for consumer participation and consumer satisfaction. In particular, we infer novel energy features and examine the importance that private and industrial consumers attach to those features. Further, we investigate how energy features affect consumer satisfaction. In doing so, the Kano Model builds the theoretical foundation of our study. The Kano Model is widely applied in both Marketing and Information Systems Research and is usually employed to understand and categorize consumer needs regarding features of products or services in the digital realm (Gimpel et al., 2018; Gimpel et al., 2021; Kano et al., 1984).

Against this background, we conduct an online survey to elicit private and industrial consumers' preferences. We collected data from 401 private and 40 industrial consumers. Our study yields three key findings: First, consumers consistently perceive energy features as important. Second, for private and industrial consumers, energy price and excludability from energy consumption are performance features – they increase consumer satisfaction when fulfilled but decrease satisfaction if not. Third, energy autarky and profit potentials are excitement features for private and industrial consumers – they increase consumer satisfaction when fulfilled, but do not cause dissatisfaction. Additionally, having greater agency regarding the energy transition and contributing to reduced energy system costs are excitement features for industrial consumers.

These insights, we believe, bring us one important step closer to gaining a deeper understanding of how to incite consumers to positively contribute to the energy transition, e.g., by installing a photovoltaic system and selling excess electricity or installing an electrical storage system to increase utilization of renewable energies. As digital technologies are an enabler for active consumer participation in energy systems, this study highlights the relevance of sustainable digital energy systems research in advancing the energy transition and contributing to a more sustainable digital future.

Keywords:

Consumer-Centric Market Design; Sustainable Energy Systems; Consumer Preferences; Consumer Satisfaction; Kano Model

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VII.6 Research Paper 4: Risk Management in Electricity Procurement Utilizing Industrial Energy Flexibility

Authors:

Maren Weigel; Robert Förster; Felix Wagon

Published in:

Zeitschrift für Energiewirtschaft (2023)

Abstract:

Due to the Russian invasion of Ukraine, electricity prices on the German and European markets for industrial consumers increased dramatically in 2022 compared to the previous years. For a number of years, an ever increasingly volatile electricity price could be observed due to advancing feed-in of weather-dependent electricity generated from renewable energies. Both developments pose a severe challenge to the (international) competitiveness of energy-intensive companies, in some cases threatening their economic viability, and underline the need for a holistic approach to managing electricity procurement risks. In this context, the use of energy flexibility for short-term adjustment to price fluctuations and the use of electricity derivatives for medium- to long-term hedging against rising price levels are two particularly relevant instruments for risk management. This paper sets out to investigate the risk mitigation capability of those risk management instruments. For this purpose, a multi-stage optimization model for minimizing electricity procurement costs and associated risks is developed and evaluated, which takes electricity price forecasts, industrial energy flexibility and electricity derivatives into account. The developed holistic risk management approach can be used by industrial companies to develop effective hedging strategies depending on industrial energy flexibility potentials and thus lead to significant risk reductions and cost savings in electricity procurement.

Keywords:

Risk Management, Portfolio Optimization, Energy Flexibility, Industrial Decarbonization

Zusammenfassung:

Aufgrund des russischen Angriffskrieges auf die Ukraine stiegen im Jahr 2022 die Preise auf deutschen und europäischen Strommärkten für Industrieunternehmen im

Vergleich zum Vorjahresniveau drastisch an. Gleichzeitig kann seit vielen Jahren eine steigende Volatilität der Strompreise vor dem Hintergrund der zunehmenden Einspeisung des witterungsabhängig erzeugten Stroms aus erneuerbaren Energien beobachtet werden. Beide Entwicklungen stellen eine teils existenzgefährdende Herausforderung für den Erhalt der internationalen Wettbewerbsfähigkeit energieintensiver Unternehmen dar und unterstreichen die Notwendigkeit eines ganzheitlichen Ansatzes zum Risikomanagement bei der Strombeschaffung. Zwei besonders relevante Instrumente zur Risikosteuerung sind der Einsatz von Energieflexibilität zur kurzfristigen Anpassung an Preisschwankungen sowie die Nutzung von Stromderivaten zur mittel- bis langfristigen Absicherung gegenüber steigenden Preisniveaus und zukünftig volatilen Spotmärkten. In diesem Beitrag werden die Potenziale dieser Risikoinstrumente eingehend untersucht und ganzheitlich betrachtet. In diesem Zusammenhang wird ein mehrstufiges Optimierungsmodell zur Minimierung von Strombeschaffungskosten und damit einhergehenden Risiken entwickelt und evaluiert, welches Strompreisprognosen, industrielle Energieflexibilität sowie Stromderivate berücksichtigt. Der entwickelte ganzheitliche Ansatz zum Risikomanagement kann von Industrieunternehmen im Rahmen ihres Risikomanagementsystems eingesetzt werden, um wirksame Absicherungsstrategien in Abhängigkeit industrieller Energieflexibilitätspotenziale zu entwickeln und somit zu bedeutsamen Risikoreduzierungen und Kosteneinsparungen bei der Strombeschaffung führen.

Schlüsselwörter:

Risikomanagement, Portfoliooptimierung, Energieflexibilität, Industrielle Dekarbonisierung

VII.7 Research Paper 5: Risk Mitigation Capability of Flexibility Performance Contracts for Demand Response in Electricity Systems

Authors:

Florian Jäckle; Michael Schöpf; Jannick Töppel; Felix Wagon

Published in:

Proceedings of the 27th European Conference on Information Systems (2019)

Abstract:

The transition of the energy system increases the urgency to cope with the intermittency of renewable energy sources to keep the electricity network balanced. Demand Response (DR) measures are a promising approach to align the electricity consumption, especially of industrial consumers, with current electricity supply. While adequate information systems (IS) are already in place to dynamically adapt electricity consumption patterns, industrial consumers are still reluctant to implement DR measures due to uncertainty of their financial performance. Nevertheless, studies on risk transfer instruments related to DR investments are still scarce. To contribute to the closure of this research gap, we examine the risk transfer capability of Flexibility Performance Contracts (FPC). We derive cash flow structures for representative FPC designs, calculate risk premiums and enable the comparison of corresponding risk profiles. Presented FPCs are evaluated based on a real-world industrial use case. Thereby, the financial performance is modeled stochastically, taking electricity price fluctuation, industrial process characteristics, and IS-backed decisions into account. Our results reveal that FPCs represent well-suited risk transfer instruments for DR measures. Thus, FPCs have the potential to accelerate the application of DR measures and therefore to complement existing capabilities of IS in the context of electricity networks.

Keywords:

Financial Risk Mitigation; Demand Side Management; Demand Response; Energy Management System Aggregators

VII.8 Research Paper 6: For Better or for Worse? On the Economic and Ecologic Value of Industrial Demand Side Management in Constrained Electricity Grids

Authors:

Patrick Rövekamp; Michael Schöpf, Felix Wagon; Martin Weibelzahl

Published in:

Energy Policy (2023)

Abstract:

Electricity systems are in dire need to scale up volatile decentralized renewable electricity supply (RES), reducing the dependency on fossil fuels and drastically cutting carbon emissions. Industrial demand side management (DSM) is a key enabler of the energy transition, as it allows to align large shares of electricity consumption with (renewable) supply. We present a short-term market model to evaluate the economic value (i.e., reduced system costs) and ecologic value (i.e., reduced carbon emissions) of industrial DSM within a constrained electricity grid, incorporating conventional electricity supply (flexibility) and RES. A model evaluation yields four key findings: (1) Grid-capacity constraints determine whether and to what extent industrial DSM may contribute economic and ecologic value. (2) Both the economic and ecologic value of industrial DSM are determined by the location within a capacity-constrained electricity grid. (3) DSM might even increase carbon emissions depending on local merit orders. (4) Carbon emission pricing may resolve a potential conflict between ecologic and economic DSM-value maximization. Based on these findings, energy policy should (i) establish an electricity market design that provides sufficient local price signals for industrial DSM and (ii) ensure that local merit orders incentivize industrial DSM to contribute both economic and ecologic value based on appropriate carbon prices.

Keywords:

Industrial Demand Side Management; Congestion Management; Renewable Energies; Nodal Pricing; Carbon Emissions

VII.9 Research Paper 7: Designing Electricity Markets of the Future: On the Role of Information for Social Acceptance of a Transition in the Electricity Market Design

Authors:

Domink Eble; Felix Wagon; Martin Weibelzahl

Extended Abstract[5]:

In the global effort to combat climate change, numerous countries are engaged in a widespread energy transition to scale up the integration of renewable electricity generation. The fluctuations in electricity generation and geographical dispersion of renewable energy sources severely challenge electricity markets and necessitate wide-ranging reforms of current electricity market designs (Eicke & Schittekatte, 2022). An effective electricity market design encompassing targeted price signals is a critical element in providing incentives for energy flexibility on the supply and demand side, as well as targeted incentives for the expansion of renewable electricity generation (Cramton, 2017). Given that the current electricity market design in many countries was initially developed at a time when a limited number of dispatchable conventional power plants predominantly supplied electricity, there is an ever-growing need to examine and reform these market designs critically. However, reforming electricity market designs bears significant impacts on citizens, e.g., by means of changes in electricity prices or the expansion of renewable electricity generation in citizens' (direct) environment.

When considering policy measures entailing significant impacts on citizens, such as a transition in the electricity market design, it is imperative to understand how such policy decisions are supported and approved by society (Wolsink, 2012). This so-called social acceptance is recognized as a condition for the effective implementation of policy measures (van Meegeren, 2001). The absence of citizens' social acceptance can lead to local opposition, which may delay or prevent the implementation of policy measures and, ultimately, lead to public polarization and extremism (Sun et al., 2016). In general, social acceptance is characterized as a decision-making process wherein individuals weigh the trade-off between perceived benefits and perceived costs, which,

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in turn, are contingent upon the information available to them (Rapoport & Wallsten, 1972; Wolsink, 2012). However, individuals are bound to limited cognitive resources, hindering their ability to process information and anticipate the implications of decisions, especially in complex and unfamiliar contexts such as a transition in the electricity market design (Slovic, 1995; Sudo et al., 2013). Hence, citizens should have access to sufficient, comprehensible, and well-prepared information that supports citizens in learning about the impacts of policy changes (Dietz et al., 2003; Robertson, 2005). This, in turn, will allow policymakers to actively involve citizens in decision-making processes and to implement policy measures that are deeply grounded in social acceptance. However, nowadays, a considerable share of the population remains inadequately informed regarding electricity market design due to, e.g., complexity and limited transparency of information (Tabi & Wüstenhagen, 2017).

This study aims to examine the social acceptance of a transition in the electricity market design. For this purpose, we provide citizens with targeted information about the economic and ecological impacts of two exemplary electricity market designs to enable them to understand the characteristics of these electricity market designs comprehensively. In doing so, we integrate social acceptance research and electricity market design research.

The study follows a six-step research approach. The first three steps of this research approach include developing a quantitative market model and instantiating it by using data on electricity prices, electricity demand, and electricity generation in Germany to represent the German electricity market. The subsequent model analysis yields insights into electricity prices and generation expansion of RES for two exemplary electricity market designs. The following three steps of the research approach include designing an online experiment to investigate the social acceptance of a transition in the electricity market design, which builds on the results of the market model, as well as executing and assessing the online experiment with N=2,400 German citizens.

The findings of the online experiment suggest that German citizens generally accept a transition in the electricity market design towards a nodal pricing system and do not express outright opposition to such a transition. This insight is important for policymakers concerning a transition in the electricity market design, as nodal pricing is associated with significant changes, including locational electricity prices. Such factors could have resulted in opposition by the population. Our findings additionally indicate that citizens' attitudes exert the highest and statistically significant influence on social acceptance. To attain a positive attitude towards a transition in the electricity market design, perceived benefits and costs, inferred by citizens from the impacts associated with different electricity market designs, are crucial. It is imperative that the perceived costs should not outweigh the perceived benefits. Otherwise, it may be challenging to achieve a high level of social acceptance. Further, our findings indicate no significant influence of the information (e.g., economic or ecological characteristics of different electricity market designs) citizens received on social acceptance. Taking our experimental setup into account, this finding is particularly interesting. Two possible explanations arise: either citizens were not able to fully cognitively process the salient information presented in the experimental setup, or citizens' a priori beliefs and views prevented them from elaborating on the information. Both possible explanations represent intriguing starting points for future research, extending the investigations from this study.

Keywords:

Electricity Market Design; Uniform Pricing; Nodal Pricing; Economic and Ecological Information; Social Acceptance; Theory of Planned Behavior

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