

**UNIVERSITÄT
BAYREUTH**

**Re-thinking Energy Markets in Times of the Energy Transition:
Implications for Market Design and Regulation**

Dissertation

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

Vorgelegt
von
Lisa-Maria Hanny
aus
Altötting

Dekan:
Erstberichterstatter:
Zweitberichterstatter:
Tag der mündlichen Prüfung

Prof. Dr. Claas Christian Germelmann
Prof. Dr. Jens Strüker
Prof. Dr. Björn Häckel
04. Dezember 2025

“I didn’t fail a thousand times. The light bulb was an invention with a thousand steps.”

Thomas A. Edison

Acknowledgments

This thesis was made possible through the support and guidance of many individuals. I would like to express my sincere gratitude to my supervisors, Jens Strüker, and Björn Häckel, for their academic guidance, constructive feedback, and mentorship throughout this research. Their expertise and support were invaluable in shaping the direction and quality of this work.

I would also like to extend my heartfelt thanks to my former supervisor, Martin Weibelzahl, who first introduced me to the research field of energy markets and market design. His guidance, encouragement, and enthusiasm for the subject were instrumental in shaping my early academic development and igniting my long-standing interest in these topics. The insights and perspectives I gained under his supervision provided a strong foundation for both, my professional and personal growth in this field.

I also thank my colleagues and co-authors at Branch Business & Information Systems Engineering (Fraunhofer FIT), the Research Center for Information Management (FIM), the Technical University of Applied Sciences Augsburg, and the University of Bayreuth for their collaboration, contributions, and their continuous support.

Finally, I acknowledge the support of my family, whose encouragement has been important throughout my academic journey.

Abstract

Modern energy systems are undergoing a profound transformation. The traditional model of centralized power plants delivering electricity to largely passive consumers is giving way to a decentralized and participatory landscape. Rooftop solar panels, electric vehicles, storage devices, and smart household technologies are shifting the flow of energy and information, creating new opportunities for market participation and trading products such as flexibility services. At the same time, these developments introduce unprecedented complexity: balancing variable renewable generation, coordinating millions of distributed energy resources, and ensuring grid stability are challenges that demand re-thinking existing system and market structures.

In this context, energy flexibility emerges as a key mechanism, enabling participants to actively shape supply and demand, respond to market signals, and integrate low-carbon technologies. In this sense, electricity consumers or "prosumers" become active market participants, providing flexibility services that stabilize the system while benefiting economically. Yet flexibility alone is insufficient without clear incentives, reliable monitoring, and transparent reward structures embedded in a suitable market design.

Digital technologies provide the critical bridge between market design goals and real-world behavioural changes. They help operationalize incentive schemes, monitor the behaviour of a growing number of market participants, and make economic rewards, e.g., from flexibility provision, tangible. Hence, these technologies transform energy from a passive commodity into an interactive service, allowing markets, regulators, and consumers to interact in small time intervals and exchange a broad portfolio of energy-related goods and services.

This dissertation explores how decentralization, sustainability, and digitalization intersect to reshape energy systems. It highlights how digital technologies can operationalize incentives, enhance system resilience, and make energy markets more transparent, efficient, and participatory. Ultimately, it argues that the energy transition is not just a technical challenge, but a societal one requiring an interdisciplinary consideration of policy goals and regulations as well as digital technologies.

Table of Contents

1	Introduction	1
1.1	Motivation	1
1.2	Research objectives	2
1.3	Structure of the dissertation and embedding of the research papers	3
2	Re-Thinking Energy Markets to integrate Distributed Energy Resources	5
2.1	Facilitating market access for distributed energy resources in a consumer-centric market environment	6
2.1.1	The need for a more consumer-centric market design	6
2.1.2	Six design principles for consumer-centric market design	7
2.1.3	Definition of a consumer-centric market design	9
2.2	Resilience in distributed energy systems	9
2.2.1	Energy-related application of the term "resilience"	10
2.2.2	Constructing a resilience index for energy systems	11
2.2.3	Case study: Testing the resilience index for the German energy system . . .	16
3	Re-Thinking Energy Regulation to enhance Sustainability	18
3.1	The role of grid charges in promoting sustainability: The case of energy-intensive industries	19
3.1.1	Policy failures in the German grid charges regulation	20
3.1.2	Using grid charges to promote sustainable behaviour in energy-intensive industries	21
3.2	Market-based and regulatory incentives for flexibility from less energy-intensive consumers	22
3.2.1	Local Flexibility Markets (LFMs)	23
3.2.2	Policy failures in German energy regulation impede the development of LFMs	24
3.2.3	Implementing LFMs to create sustainability incentives in the distribution grid	27
4	Leveraging the Impact of digital Technologies in Energy Markets	29
4.1	The role of digital technologies in closing the flexibility gap	30
4.1.1	Artificial Intelligence (AI) as an enabling technology for energy trading . .	31
4.1.2	An algorithmic AI framework for multi-market flexibility trading	32

4.2	The role of digital technologies in addressing the "market for lemons" problem in voluntary carbon offsets	35
4.2.1	Plethora of available digital technologies for Monitoring, Reporting, and Verification (MRV) processes	36
4.2.2	A method for selecting digital technologies in MRV processes	36
5	Conclusion	41
5.1	Summary	41
5.2	Limitations and Outlook	42
	Bibliography	45
A	Overview of research papers	57
A.1	Research papers included in this dissertation	57
A.2	Index of further papers	58
A.3	Individual contribution to the included research papers	59
B	Research Paper P1: Consumer-centric electricity markets: Six design principles	61
C	Research Paper P2: Resilience, the long forgotten? Analyzing the Resilience of the German Electricity System	62
D	Research Paper P3: On the progress in flexibility and grid charges in light of the energy transition: The case of Germany	63
E	Research Paper P4: Marktbasierter Flexibilitätseinsatz im Verteilnetz: aktuelle Herausforderungen und Lösungsvorschläge zur Umsetzung europarechtlicher Vorgaben	64
F	Research Paper P5: How to trade electricity flexibility using artificial intelligence – an integrated algorithmic framework	66
G	Research Paper P6: When voluntary carbon markets give you lemons, make lemonade: a method for selecting digital technologies in MRV processes	67

List of Figures

Figure 1.1: Structure of this dissertation along major developments on energy markets . . .	4
Figure 2.1: Six Design Principles (DPs) for a consumer-centric electricity market design; Source: Research paper #1	9
Figure 2.2: Methodological approach for index construction; Source: Research paper #2 . .	11
Figure 2.3: Structure and indicators of the proposed CI for electricity system resilience as- sessment; Source: Research paper #2	13
Figure 2.4: Change of the resilience index within the study period 2010 - 2023; Source: Re- search paper #2	17
Figure 3.1: Participants in local flexibility markets; Source: Research paper #3	23
Figure 4.1: Integrated Machine Learning (ML) framework for multi-market flexibility trad- ing; Source: Research paper #5	33
Figure 4.2: Overview of the method 's activities and elements; Source: Research paper #6 .	37
Figure 4.3: Activity 1; Source: Research paper #6	38
Figure 4.4: Activity 2; Source: Research paper #6	38
Figure 4.5: Activity 3; Source: Research paper #6	39
Figure 4.6: Activity 4; Source: Research paper #6	40
Figure 4.7: Activity 5; Source: Research paper #6	40

List of Tables

Table 2.1: Fundamental scale of pairwise comparison. Adopted from (Saaty, 1990).	14
--	----

Copyright Statement

*The following chapters are partly comprised of content taken from the research articles in this thesis.
To improve the readability of the text, I have omitted the standard labelling of these citations.*

1 Introduction

1.1 Motivation

Not long ago, energy systems operated largely in the background of industrial society — centralized and scarcely visible to the general public. Electricity moved unidirectionally from a limited number of large-scale generators to millions of passive consumers (Cramton, 2017; Defeuilley, 2019). Fossil fuels such as oil, coal, and natural gas powered factories, enabled mass mobility, and heated private households. This system was efficient and predictable, yet fundamentally rooted in unsustainable resource extraction and greenhouse gas emissions (Defeuilley, 2019; Solomon & Krishna, 2011).

Former centralized energy systems are now undergoing a fundamental transformation. The 21st century has elevated energy from a technical infrastructure to a central societal concern: how to sustain economic development without exceeding planetary boundaries. Climate change is no longer a distant hypothesis but a lived reality, manifesting in extreme weather events, failed harvests, and heat-induced health crises (Lahsen & Ribot, 2022; Zhao et al., 2022). Parallel to ecological urgencies, geopolitical instability and volatile energy prices have intensified demand for energy security and affordability (Emiliozzi et al., 2025).

International policy frameworks aim to address these concerns. The Paris Agreement, for example, commits nearly all nations to limit global warming to well below 2 °C (United Nations Framework Convention on Climate Change, 2015). The United Nations’ Sustainable Development Goals (SDGs) place “Affordable and Clean Energy” (SDG 7) alongside objectives on health, poverty reduction, and inequality (United Nations, 2015). For the European Union (EU), the Green Deal sets the ambition of climate neutrality by 2050, coupling decarbonization with industrial progress, digital modernization, and enhanced consumer participation in energy markets (European Commission, 2019a).

Realising these ambitions, however, requires more than substituting traditional power plants with Renewable Energy Sources (RES). It demands a systemic reconfiguration of how energy is produced, distributed, consumed, and governed. The traditional paradigm of centralized, top-down energy provision is increasingly being replaced by decentralised, interactive, and digitally managed ecosystems. For instance, Distribution Energy Resources (DER) such as rooftop photovoltaics transform households into distributed generators. Electric vehicles act as mobile storage units. Smart meters and Internet of Things (IoT) infrastructures render consumption transparent in real time. Energy is no longer merely supplied — it is transacted, forecasted, aggregated, and optimized.

One key ingredient in integrating DER in energy systems and fostering their active participation is energy flexibility — the ability of consumers, devices, or industrial facilities to adapt their consumption or production in response to system needs (Barth et al., 2018; Heffron et al., 2020).

Flexibility turns participation into a service: an electric vehicle delaying its charging, a heat pump shifting its operation, or a household battery feeding electricity back into the grid becomes an active contributor to system stability. Yet this transformation depends on regulatory frameworks and market designs that reward such behaviour, allowing households, industries, and even small devices to participate fairly and profitably in energy markets (Heffron et al., 2020).

At this intersection, digitalization becomes a key enabler. For instance, digital technologies such as Artificial Intelligence (AI) may anticipate consumption and generation patterns, allowing flexible loads to shift in time without compromising comfort (Shahzad & Jasińska, 2024; Ukoba et al., 2024). Blockchain technologies enable secure and transparent tracking of flexibility contributions, making even small-scale actions — such as delaying a washing cycle or exporting battery power — traceable and tradable (Karumba et al., 2023; Y. Wu et al., 2022). Digital twins simulate system responses to flexible behaviour before interventions occur, reducing operational risks for grid operators (Song et al., 2023). Aggregation algorithms bundle thousands of individual devices into coordinated flexibility portfolios (Rodrigues et al., 2025). By the use of digital technologies, flexibility becomes not just a technical characteristic but a marketable resource, opening the energy system to new actors, services, and business models.

Re-thinking energy systems is therefore not only a technological question but one of governance, regulation, and institutional market design. It demands infrastructures and markets that are not merely low-carbon, but transparent, resilient, and well-governed. In this sense, this dissertation aims at making a contribution to translating global policy ambitions such as the SDGs and the Green Deal into tangible improvements in current and future energy systems and markets.

1.2 Research objectives

This dissertation aims to integrate the perspectives of a decentralized and distributed energy system with the overarching objective of advancing sustainability. Both developments – decentralization and sustainability – require a fundamental rethinking of existing energy systems, markets, and institutional frameworks. As discussed in the motivation, regulatory adjustments and market design reforms alone are often insufficient to drive meaningful behavioural change or investment. While incentive structures exist and function in theory, they must be made tangible and actionable for the intended market participants. In this context, digital technologies emerge as critical enablers, translating theoretical incentives into practical outcomes and facilitating the real-world transformation of energy systems and markets. Building on this, the dissertation investigates the digitalization of energy systems and markets as a conceptual framework, within which decentralization and sustainability are embedded.

1.3 Structure of the dissertation and embedding of the research papers

This cumulative dissertation explores current developments and changes in the energy landscape and their implications for regulation, market design, and digitization initiatives. It combines different perspectives from information systems research, economics, and legal studies. Such an interdisciplinary approach is necessary, as the energy transition cannot solely be regarded an engineering challenge, but involves a broader socio-technical transformation. This cumulative dissertation comprises six research papers that touch upon the different perspectives and academic disciplines.

Section 2 describes the transformation of the energy landscape from former supply monopolies to a more *distributed and decentralized energy system* with high shares of RES. It outlines the challenges associated with this development and provides solution approaches to ensure the continued functioning and reliability of the energy system in times of the energy transition. One of these solution approaches is presented in Section 2.1 and proposes to grant wholesale market access for DER in a more consumer-centric market environment. This approach follows the underlying logic that only if DER are allowed to participate in market activities and express their preferences, they can be accounted for in market results (Research paper #1). Section 2.2 takes this logic one step further and develops an index that evaluates the effects of the energy transition and related transformational developments, such as a more diversified and variable energy supply, not only on market outcomes but also on the (physical) resilience of energy systems. The index incorporates 27 indicators covering, for example, the energy mix or supply structures, and applies country-specific weightings to derive an aggregated resilience score (Research paper #2).

Section 3 captures the sustainability shift in energy systems and markets. While the energy transition sets clear goals for creating more *sustainable energy systems* in terms of, e.g. emission reduction targets, markets and regulation must set appropriate incentives to actually achieve these targets. Section 3.1 addresses this issue from a transmission-level perspective and proposes adjustments to the grid charges regulation for energy-intensive consumers, aiming to actively support – or at least facilitate – flexibility services (Research paper #3). Section 3.2 expands this problem to the distribution grid level and outlines market-based and regulatory flexibility incentives for less energy-intensive consumers (Research paper #4). Among others, this involves establishing Local Flexibility Markets (LFMs) to comply with European regulatory requirements.

Section 4 synthesizes the preceding developments by proposing strategies to capitalize on *digital technologies in energy markets*, supporting both the integration of decentralized assets into the energy system and enhanced sustainability outcomes. For instance, Section 4.1 proposes an algorithmic framework based on AI that trades energy flexibility across multiple energy markets. Hence, the algorithm aims to support enhanced market integration and harmonization of economically traded and physically delivered energy quantities, ultimately contributing to the well-functioning of decentralized energy systems and enhanced sustainability. The corresponding

research paper (Research Paper #5) has been nominated for the best paper award at the 55th Hawaii International Conference on System Sciences (HICSS) in the Resilient Networks Track. Furthermore, Section 4.2 presents a method for selecting suitable technologies to facilitate digital Monitoring, Reporting, and Verification (MRV) processes on Voluntary Carbon Markets (VCMs) (Research paper #6). Again, the presented method synthesizes the developments of decentralized environments and sustainability concerns by capturing a broad range of offset measures and more by more reliably evaluating their effect.

In summary, this dissertation covers three major developments that affect the energy markets of our times: First, there is a clear shift away from centralized monopolies to a more distributed and decentralized energy landscape, which puts current energy markets and physical grid infrastructures to the test. Second, the energy transition demands a more sustainable energy landscape, including not only reduced emissions but also a more efficient use of energy resources in terms of flexibility. And third, technological progress and digitization offer promising ways to account for these developments and harness existing potentials, e.g., in the form of flexibility services or carbon offset measures, on the different energy markets or VCMs. Figure 1.1 provides an overview of the described developments and their connections, thereby representing the structure of this dissertation.

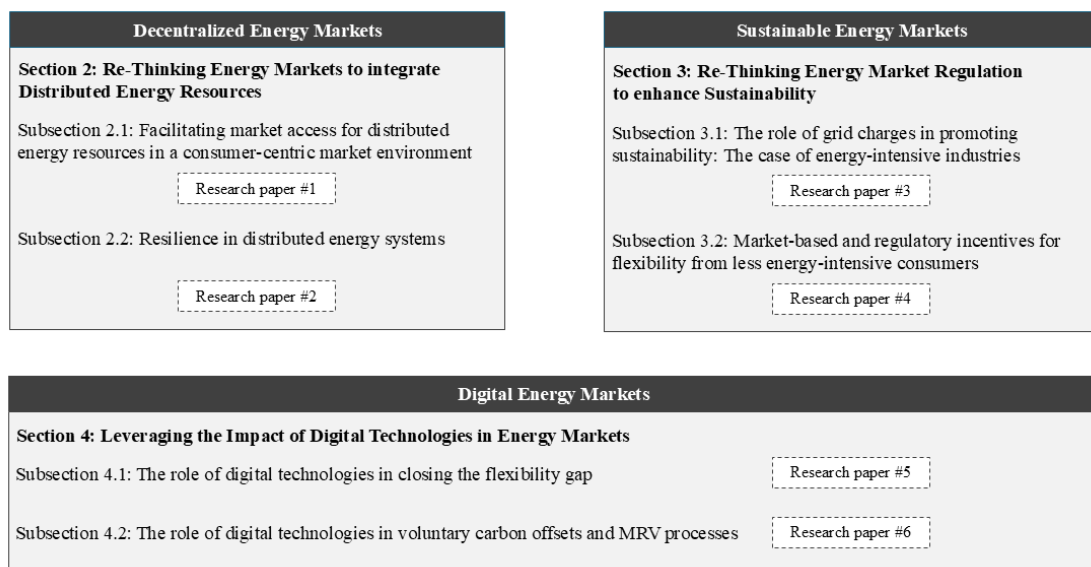


Figure 1.1: Structure of this dissertation along major developments on energy markets

2 Re-Thinking Energy Markets to integrate Distributed Energy Resources

Over the past decades European energy markets have undergone a profound transformation, evolving from highly centralized, state-controlled monopolies into increasingly liberalized, competitive, and decentralized systems (Pepermans, 2019). In the post-war era, most European countries relied on vertically integrated national utilities that controlled every stage of the value chain: generation, transmission, distribution, and retail (Penttinen, 2020; Pepermans, 2019). These monopolies, often state-owned, were responsible not only for ensuring security of supply but also for pursuing broader socio-economic objectives such as industrial development, regional cohesion, as well as the affordability of electricity and gas for households (Penttinen, 2020). Energy was therefore regarded a state responsibility and, thus, excluded from competition and market forces to a large extent.

This paradigm began to shift in the late 20th century under the influence of broader European integration, economic liberalization, and a growing awareness of the inefficiencies tied to monopoly structures. Starting in the 1990s, the EU released a series of legislative packages that aimed to open energy markets to competition. The First Energy Package (1996 for electricity, 1998 for gas) laid the groundwork by requiring the unbundling of energy organizations and granting third-party access to transmission networks (European Commission, 2025). Subsequent reforms, including the Second and Third Energy Packages, deepened this process by mandating structural unbundling of transmission system operators, establishing independent regulators, and creating a single European energy market (European Commission, 2011).

At the same time, environmental concerns and alternative generation sources like RES started their rise. While liberalization initially aimed at creating competition among large conventional generators, the accelerating deployment of wind, solar, and other RES fundamentally shapes the market landscape until now (Urishev, 2019). Unlike centralized power plants, renewables are often decentralized, small-scale, and connected directly to distribution grids (Singh & Singh, 2024). As a result, the structure of energy markets has shifted from a few dominant players towards a far more diverse ecosystem of producers, prosumers, aggregators, and other DER.

Today's European energy markets are characterized by a diverse energy landscape, where consumers are no longer passive recipients of energy but are increasingly active participants, capable of producing, storing, and trading electricity themselves (Michaelis et al., 2024; Pelka et al., 2022). The push towards decarbonization, embodied in the European Green Deal and the "Fit for 55" package (European Commission, 2021), further accelerates this trend by prioritizing renewable integration, smart grids, and sector coupling.

2.1 Facilitating market access for distributed energy resources in a consumer-centric market environment

The energy transition and the increasing spread of DER present challenges to energy systems worldwide. In particular, integrating high shares of DER like RES requires appropriate flexibility resources that can account for their intermittency and dependence on external factors like weather conditions, seasonality, or time of day. Flexibility resources, in the context of electricity, are understood as an instrument to assist in balancing intermittent electricity supply and demand at all times in the network (Heffron et al., 2020). A broad range of these flexibility resources already exists today, including controllable electricity generators, storage technologies, sector coupling, grid expansions, and controllable loads such as consumer devices or industrial processes (Fridgen et al., 2020). Demand-side flexibility is especially gaining attention due to its relatively low cost compared to large-scale storage technologies or grid expansions (Söder et al., 2018). Moreover, demand flexibility does not face public acceptance challenges or protracted administrative approval processes. The flexibility potential of households and consumer devices, including electric vehicles and heat pumps, is projected to reach up to 162.4 TWh by 2050 in Germany (Öko-Institut e.V., 2022). Despite this huge potential, only a small fraction of flexibility resources are actually used for system or grid stabilizing purposes (see research papers #1, #3, #4, and #5). This is the case, as many small-scale electricity consumers in Europe, especially households or individual devices, remain sidelined from market interactions due to outdated regulations or market designs (Öko-Institut e.V., 2022; Pedro et al., 2023). In particular electricity consumers “behind the meter” remain largely outside the competitive space in electricity markets in Europe (Yazdani et al., 2022), resulting in “lost” flexibility potentials.

2.1.1 The need for a more consumer-centric market design

The design of electricity markets plays a crucial role in addressing existing barriers to consumer participation, as it has the potential to broaden access to small-scale electricity consumers and reduce entry barriers, particularly in the context of providing flexibility. Future-oriented market design could treat flexibility as an explicit service, thereby creating financial incentives for electricity consumers to adjust their consumption in response to market and system needs (see research papers #1, #3, and #4). However, effective market design goes beyond mere market access: it must also establish appropriate signals and incentives that encourage active engagement and enable a substantial provision of flexibility. In this discussion, the term “market design” primarily refers to the architecture of European electricity spot markets, while also acknowledging potential implications for related markets such as balancing or futures markets. More broadly, market design encompasses the set of rules that govern interactions and information exchange to facilitate efficient transactions (Bichler et al., 2022). Although some electricity consumers, notably energy-intensive industries, already participate in electricity markets, their behaviour highlights the limitations of current market design: despite market access, a significant proportion of such

companies in Germany refrain from providing active flexibility due to market distortions caused by levies, taxes, and outdated regulations, which in some cases even penalize flexibility provision (see research paper #3). Consequently, granting market access to small-scale consumers, including households and DER will not automatically unlock their full flexibility potential unless market design actively incentivizes participation and supports investments in flexibility technologies. Accordingly, electricity market design should adopt a consumer-centric approach, emphasizing not only access but also targeted incentives that foster proactive engagement and flexibility provision in both the short and medium term.

2.1.2 Six design principles for consumer-centric market design

To harness the full potential of DER, it is essential that electricity markets are open to all consumers and ensure consumer-centricity. Such openness and centricity enables consumers to sell their self-generated electricity and/or offer flexibility in their electricity consumption. In this regard, the specific design for a consumer-centric electricity market must be carefully chosen to ensure the right incentives are in place. This dissertation presents six DPs for a consumer-centric electricity market design. According to the underlying methodology presented in research paper #1, DPs are formulated in the following form:

Design Principle Name: For an *Implementer* to achieve or allow for an *Aim* for a *User* in a *Context*, employ *Mechanisms* $M_1, M_2, \dots, M_n$ involving *Enactors* $E_1, E_2, \dots, E_n$.

For the sake of readability, the descriptions included in this dissertation mainly focus on *Mechanisms* and *Enactors*, as they represent clear calls for action.

DP 1: Openness to new market players, low market entry barriers, and low transaction costs

The first DP of a consumer-centric market design emphasizes openness to new market participants by minimizing entry barriers and transaction costs. This requires low thresholds for participation, limited complexity, and minimal financial and knowledge requirements to encourage consumer engagement. Practical measures include granting small consumers and automated devices access to wholesale markets (M1), fostering the participation of aggregators (M2) and prosumers (M3), and ensuring transparency through accessible market information (M4). To enable this, regulatory adjustments are needed, such as legally empowering consumers to participate (E1), supporting digital tools like smart meters (E2), and applying behavioural economics to anticipate market behaviour (E3).

DP 2: Expression of consumer preferences

The second DP highlights the importance of enabling consumers to express their preferences and constraints in electricity markets. This requires suitable bidding languages (M1) and diverse trading products (M2) that reflect different consumption patterns and values, such as temporal

flexibility or green electricity use. Digital technologies (E1) are essential to support these processes, while market-clearing mechanisms must adapt accordingly (E2).

DP 3: Insurance against sudden and unexpected price spikes and system imbalances

The third DP focuses on protecting consumers from extreme price volatility and system imbalances, which is essential for broad and sustainable participation in electricity markets. A consumer-centric market design should therefore include insurance mechanisms (M1) to guarantee affordable basic supply for vulnerable consumers and ensure security of supply through emergency measures (M2). This requires analysing consumer risk preferences (E1), improving price forecasting (E2), and developing scenario models for extreme events (E3). Risk-sharing mechanisms are also necessary, with aggregators potentially taking on the role of shielding small consumers from price peaks, a function historically performed by traditional electricity suppliers (E4).

DP 4: Exposure to price signals

The fourth DP stipulates that a consumer-centric market design should empower consumers to react to wholesale price signals, which is often not possible today. This requires new business models (M1), incentives for investments in behind-the-meter technologies such as photovoltaics, electric vehicles, storage, and heat pumps (M2), and strong reliance on digital tools like smart meters and automated energy management (E1). Additionally, tariff structures may need reform to enhance transparency and introduce dynamic or peak-time pricing (E2, E3).

DP 5: High temporal and regional granularity of electricity prices

Another DP for a consumer-centric market design is the consideration of high temporal and spatial granularity in electricity prices. This is particularly crucial given the decentralized and variable nature of renewable generation. One approach is to reflect transmission and distribution constraints directly in prices (M1), while also ensuring that prices are determined on a fine-grained temporal scale (M2). To achieve this, several strategies may be applied, such as introducing shorter trading products closer to real time (E1), adopting nodal pricing (E2), or increasing the frequency of intraday auctions (E3). These measures are vital for integrating DER effectively and for reducing risks associated with forecast uncertainty.

DP 6: Interoperability with other (related) markets

The final DP of a consumer-centric market relates to ensuring interoperability with other markets. In this context, it is important to link back to the first principle — facilitating consumer participation — since ease of access must also be preserved when connecting markets. Potential mechanisms include interoperability with balancing markets (M1), local flexibility markets (M2), local energy markets or peer-to-peer platforms (M3), as well as with other European spot

markets (M4). To explore such interconnections, approaches like agent-based modelling or other simulation methods can be applied (E1). At the same time, it is crucial that these interactions do not introduce excessive complexity for participants.

The outlined DPs provide essential pillars for facilitating the integration of DER in the energy system and re-thinking energy markets in the DER era.

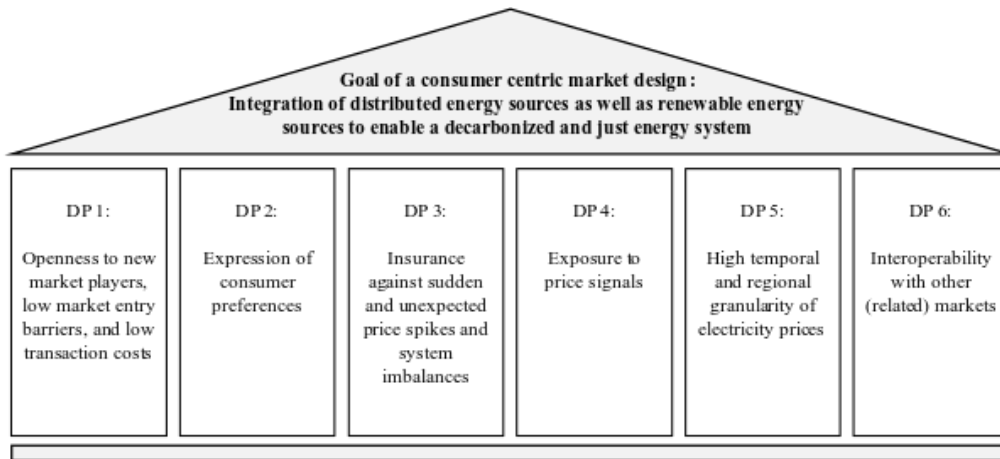


Figure 2.1: Six DPs for a consumer-centric electricity market design; Source: Research paper #1

2.1.3 Definition of a consumer-centric market design

Building on the six DPs, the following definition can be derived for a consumer-centric market design (see research paper #1). It incorporates the characteristics of a future-proof consumer-centric market design as a key building block for a deep decarbonization:

Consumer-centric electricity market design is a set of market rules that are consistent with the rules of other relevant energy markets and allow efficiently matching electricity demand and supply, with consumers having nondiscriminatory market access, being exposed to fine-grained price signals, being able to express their preferences, and having sufficient possibilities to protect themselves against unexpected price spikes.

2.2 Resilience in distributed energy systems

While the active participation of consumers and small-scale DER in energy markets is crucial for enhancing their integration into the energy system and unlocking flexibility potentials, a more distributed energy landscape simultaneously raises concerns about overall system reliability (Groissböck & Gusmão, 2020; Röpke, 2013). For example, in the electricity system, these concerns stem not least from the intermittency and variability of RES, but also from the increasing decentralization and diversification of assets and the need to transport electricity over longer distances and across different grid levels. Also, flexibility measures themselves do not necessarily involve constant and reliable electricity supply, but rather interrupt generation and/or consumption patterns in a controlled – but still "flexible" – manner. Against this backdrop, the traditional

paradigm of ensuring uninterrupted supply at all times (and at all costs) is gradually giving way to a resilience-oriented perspective (Beyza & Yusta, 2022; Wender et al., 2017). This approach acknowledges that short-term interruptions may occur, for example when providing flexibility, yet emphasizes the ability of the system to recover quickly and return to predefined generation or consumption patterns in a timely and controlled manner.

2.2.1 Energy-related application of the term "resilience"

The term resilience originates from the Latin verb *resiliere*, meaning “to jump back” or “to rebound” (Alexander, 2013; Hosseini et al., 2016). Initially introduced in the 19th century within the field of material science (Tredgold, 1818), it has since been adopted across numerous disciplines. Despite its widespread use, the literature still lacks a universally agreed-upon definition of resilience (Arghandeh et al., 2016; Z.-K. Gao et al., 2021). Commonly, resilience is understood as “*the ability to prepare and plan for, absorb, recover from, and more successfully adapt to adverse events*” (National Academies of Sciences, 2017). Accordingly, a resilient system is not only capable of withstanding both anticipated and unforeseen short-term disruptions but also of adjusting to long-term structural changes (Sharifi & Yamagata, 2016). From this perspective, resilience can be regarded as a form of “insurance” against rare, unexpected, and severe disturbances with potentially unobserved consequences (Baumgärtner & Strunz, 2014).

Similar to certain components in material science that must withstand external stress without permanent failure, modern energy systems must cope with shocks—ranging from sudden supply-demand imbalances to long-term structural disruptions — while continuing to provide essential services. In energy systems, this translates into the ability to maintain critical supply during unforeseen events such as extreme weather, cyberattacks, or geopolitical crises, and to evolve in response to long-term transitions such as a changing energy landscape in times of decarbonization (Gasser et al., 2021). By extending the material sciences metaphor of “bending without breaking” to the energy system, resilience offers a powerful framework to understand and design energy systems that are fit for the future.

More precisely, resilient electricity systems are characterized by four dimensions: anticipation, absorption, recovery, and adaptation (Ahmadi et al., 2021; Bajwa et al., 2019; Molyneaux et al., 2016; Sharifi & Yamagata, 2016; Umunnakwe et al., 2021):

- **Anticipation:** Preparing for potential disruptions by taking measures to prevent large-scale outages – in the sense of controlling the controllable. This requires foresight capabilities (e.g., identifying risks from political instability or natural disasters), creativity (e.g., technological and non-technological innovation), as well as efficiency and robustness.
- **Absorption:** Withstanding and mitigating the effects of disturbances while preventing cascading failures. Core elements include flexibility (e.g., storage capacities), redundancy (e.g., backup generation), and diversity (e.g., a mix of generation technologies).
- **Recovery:** Restoring system functionality after a disruption. Effective recovery depends on adequate physical resources (e.g., fossil fuel reserves), human and financial capacities,

flexibility (e.g., storage), and institutional agility (e.g., fast governmental processes).

- **Adaptation:** Learning from past events and adjusting the system—incrementally or transformatively to improve preparedness for future disruptions. Key principles are adaptability (e.g., long-term infrastructure investment) and diversity (e.g., diversification of energy imports).

2.2.2 Constructing a resilience index for energy systems

To evaluate resilience in electricity systems, research paper #2 develops a Composite Index (CI) designed to help policymakers adopt a multidimensional perspective on system resilience. A CI essentially describes the mathematical combination of individual indicators, measuring an underlying multidimensional phenomenon that cannot be captured by a single indicator (El Gibari et al., 2019; Joint Research Centre of the European Commission, 2008; Mazziotta & Pareto, 2013). The construction process follows a seven-step methodological approach, illustrated in Figure 2.2, and is based on the Handbook on Constructing Composite Indicators published by the Joint Research Centre of the European Commission, 2008. The underlying indicators are derived from a structured literature review and subsequently validated and refined through focus group sessions with a diverse set of energy experts. For determining the relative importance of indicators, the Analytical Hierarchy Process (AHP) is applied as the weighting methodology.

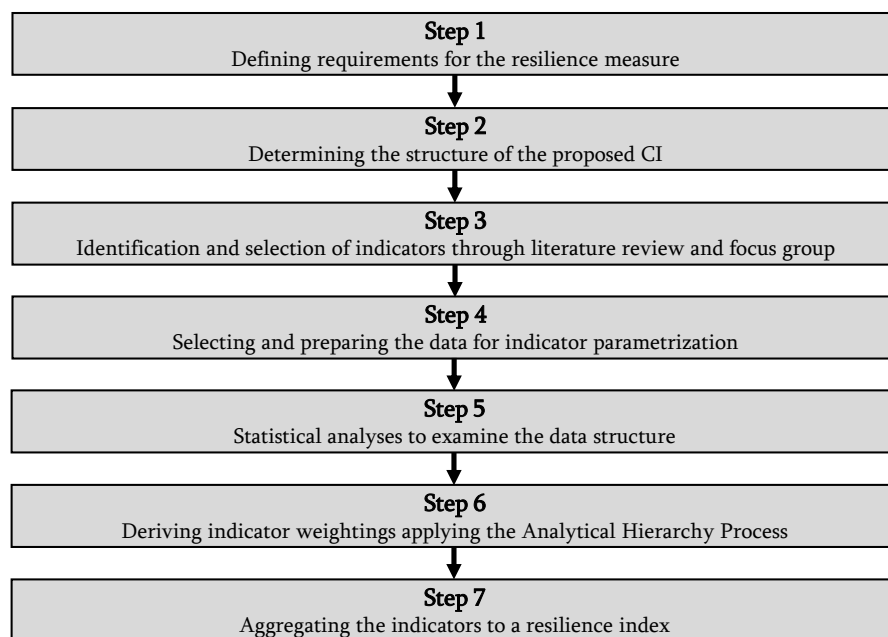


Figure 2.2: Methodological approach for index construction; Source: Research paper #2

Step 1: Requirements of resilience measures

To ensure the quality of the constructed index, which is commonly defined as “fitness for use” in terms of user needs (Joint Research Centre of the European Commission, 2008), the first step aims to set requirements for the CI. With the need to identify fields for action to improve resilience and to derive policy recommendations, the resilience index should therefore meet general requirements for CI and fulfill the following properties (Ahmadi et al., 2021; Bhusal et al., 2020; Chanda & Srivastava, 2016; Das et al., 2020; Joint Research Centre of the European Commission, 2008; Jufri et al., 2019; Najarian & Lim, 2019; Raoufi et al., 2020; Vugrin et al., 2017):

- **Completeness:** The CI should to a large extent capture the multidimensional and dynamic nature of resilience in electricity systems, accounting for potential risks and uncertainties.
- **External validity:** The CI should be applicable to a wide range of electricity systems worldwide.
- **Robustness:** Small variations in input parameters should not significantly alter the index outcomes.
- **Transparency:** Both the design and calculation methodology should be fully documented, and results must be traceable.
- **Measurability:** The CI should provide a quantitative assessment of resilience based on credible, openly accessible, and well-documented data to ensure reliability.
- **Usefulness:** The CI should effectively inform policymakers about the current state of resilience, highlight areas for improvement, and accommodate country- or region-specific conditions.

Step 2: Determining the index structure

The proposed index is structured around the four key dimensions of resilient electricity systems — anticipation, absorption, recovery, and adaptation — which collectively capture their capacity to withstand and respond to disruptions (Ahmadi et al., 2021; Bajwa et al., 2019; Molyneaux et al., 2016; Sharifi & Yamagata, 2016; Umunnakwe et al., 2021).

Step 3: Indicator selection

The indicators used in the CI are derived from an extensive literature review in research paper #2 and evaluated through focus group sessions with experts in the field of electricity system research. After removing duplicates, 143 resilience indicators could be identified in the literature review. The variety of indicators is mainly because some studies investigate resilience from an energy security perspective, but lack sufficient differentiation between resilience and energy security. This leads to many indicators originally proposed for energy security considerations also being used for resilience assessments (Gasser et al., 2020; Jasiūnas et al., 2021). To refine the selection, indicators were screened according to three criteria: (1) each indicator must be directly related to at least one of the four resilience dimensions, (2) it must have a demonstrable positive

or negative impact on resilience, and (3) it must align with the objectives of the index, providing meaningful insights into the current state of system resilience and supporting informed energy policy decisions. The combined outcomes of the literature review and focus group discussions are summarized in Figure 2.3, which illustrates the assignment of the selected indicators to their respective resilience dimensions.

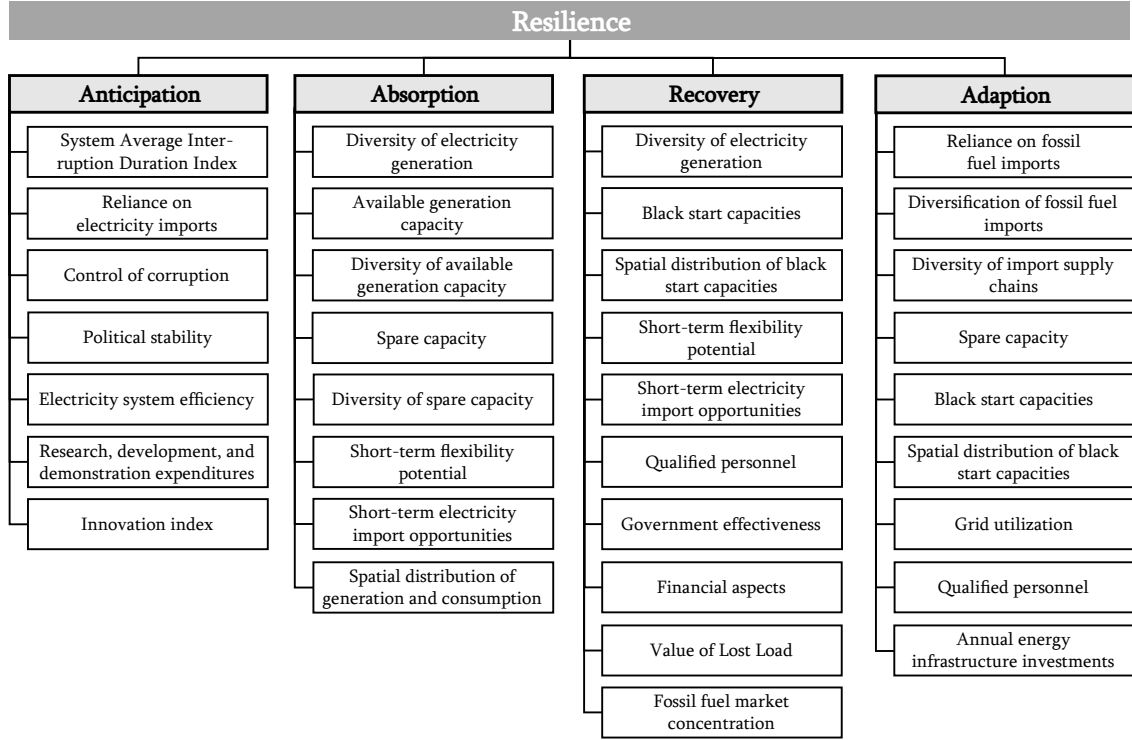


Figure 2.3: Structure and indicators of the proposed CI for electricity system resilience assessment; Source: Research paper #2

Step 4: Data selection and preparation

To ensure reliable results, indicator data must be credible, transparent, complete, and publicly accessible (Gasser et al., 2020; Joint Research Centre of the European Commission, 2008). Indicators are normalized to a common scale and aligned so that higher values consistently indicate greater resilience — for example, while high grid utilization decreases resilience, diversified generation increases it. Standardization is applied to transform each indicator to a mean of zero and a standard deviation of one.

$$NI_i = \frac{x_i^t - \bar{x}_i}{\sigma_i} \quad (2.1)$$

where x_i^t is the value of indicator i in year t before standardization, $\bar{x}_i$ is the mean of all values of indicator i within the period studied, and σ_i represents the standard deviation of the data set for indicator i . To apply standardization, at least five values per indicator are required (Sharifuddin, 2014).

Step 5: Statistical analyses

In step 5, the data structure is assessed for its suitability in index construction. Pearson's correlation coefficient is used to examine relationships between indicators, with a generally positive correlation within each dimension indicating meaningful links to resilience (Gasser et al., 2020; Schober et al., 2018). Multicollinearity is evaluated using the variance inflation factor (VIF), applying a standard threshold of 10 (O'Brien, 2007).

Step 6: Assigning weightings to the indicators

Indicator weightings reflect the relative importance of each criterion for the concept under evaluation (Greco et al., 2019), which is the resilience of the electricity system. To determine these weightings, the AHP is employed. The AHP is particularly well-suited for decomposing hierarchical structures and addressing complex problems, as it allows the integration of both quantitative and qualitative considerations within the assessment (J.-J. Wang et al., 2009).

At the core of the AHP is the pairwise comparison of indicators, where experts from the focus group sessions evaluate the relative importance of each indicator against others, expressing the strength of this preference numerically on a nine-point scale (see Table 2.1).

Table 2.1: Fundamental scale of pairwise comparison. Adopted from (Saaty, 1990).

Scale	Definition	Explanation
1	Equal importance	Both indicators contribute equally to resilience
3	Moderate importance	Experience and judgment slightly favour one indicator over another
5	Strong importance	Experience and judgment strongly favour one indicator over another
7	Very strong importance	An indicator is strongly favoured over another, and its dominance demonstrated in practice
9	Absolute importance	The evidence favouring one indicator over another is of the highest order possible of affirmation
2, 4, 6, 8	Intermediate values	Used to represent compromises between the aforementioned preferences
$\frac{1}{3}, \frac{1}{5}, \frac{1}{7}, \frac{1}{9}$	Reciprocal values	If indicator C_i has one of the above numbers assigned to it when compared with indicator C_j , then C_j has the reciprocal value when compared with C_i

This assessment results in a $n \times n$ judgment matrix $\mathbf{A}$ for each dimension, defined as

$$\mathbf{A} = \begin{bmatrix} 1 & c_{12} & \dots & c_{1n} \\ c_{21} & 1 & \dots & c_{2n} \\ \vdots & \dots & \ddots & \vdots \\ c_{n1} & c_{n2} & \dots & 1 \end{bmatrix}, \quad (2.2)$$

where c_{ij} is the relative importance of indicator C_i over indicator C_j and n is the number of indicators within the considered dimension. The AHP assumes that a person arrives at an inverse judgment when comparing indicator C_j to C_i and indicator C_i to C_j (Saaty, 1990). Hence, the energy system expert has to give only one judgment for each indicator pair, while the reciprocal value is calculated according to Equation (2.3):

$$c_{ji} = \frac{1}{c_{ij}} \quad \forall i \neq j \text{ and } i, j = 1, 2, \dots, n \quad (2.3)$$

The indicators' relative weighting is extracted by solving the eigenvalue problem of matrix $\mathbf{A}$

$$\mathbf{A} \cdot \mathbf{w} = \lambda_{max} \cdot \mathbf{w} \Leftrightarrow \begin{bmatrix} 1 & c_{12} & \dots & c_{1n} \\ c_{21} & 1 & \dots & c_{2n} \\ \vdots & \dots & \ddots & \vdots \\ c_{n1} & c_{n2} & \dots & 1 \end{bmatrix} \cdot \begin{bmatrix} w_1 \\ w_2 \\ \vdots \\ w_n \end{bmatrix} = \lambda_{max} \cdot \begin{bmatrix} w_1 \\ w_2 \\ \vdots \\ w_n \end{bmatrix}, \quad (2.4)$$

where $\mathbf{w}$ is the maximal eigenvector of matrix $\mathbf{A}$, and λ_{max} is the maximal eigenvalue of matrix $\mathbf{A}$. Assuming consistent judgments, λ_{max} is equal to n , i.e., if indicator C_i is twice as important as indicator C_j and C_j is three times as important as indicator C_k , C_i has to be six times as important as C_k (Belton, 1986).

$$c_{ij} \cdot c_{jk} = c_{ik} \quad \forall i, j, k \quad (2.5)$$

In reality, however, inconsistencies are a natural phenomenon (May, 1954). Saaty argued that applying the AHP is possible as long as the inconsistency is sufficiently low. To check the inconsistency level, the consistency ratio (CR) is calculated according to Equation (2.6)

$$CR = \frac{ConI}{RI}, \quad (2.6)$$

with the consistency index ($ConI$) defined as

$$ConI = \frac{\lambda_{max} - n}{n - 1}. \quad (2.7)$$

The literature recommends using a cut-off consistency ratio of 0.10 (Saaty, 2001).

Individual expert weightings are averaged to form group weightings for each indicator (Aczél & Saaty, 1983; Saaty, 2008). The number of experts is derived from analysing the change of each indicator resulting from the inclusion of another expert assessment. Interviewing additional experts is terminated when all indicators converge. Research paper #2 defines convergence when in three consecutive interviews, the deviation of all indicator scores for all years does not exceed the threshold of 5%. At least five interviews are performed to obtain a balanced spectrum of opinions and avoid convergence too early.

Step 7: Indicator aggregation

Finally, the indicators within each dimension are combined to produce a single score. A geometric aggregation function is employed, which aligns with the axioms of the AHP (Saaty, 2001) and reduces compensatory effects between indicators. Because geometric aggregation requires all normalized indicators to be strictly positive (Greco et al., 2019), values of zero or negative values would invalidate the calculation. To address this, the normalized data are rescaled through a monotonic transformation by adding a constant (+3) to all values. The index I^D of dimension $D \in \{\text{anticipation, absorption, recovery, adaption}\}$ is obtained by Equation (2.8).

$$I^D = \prod_{i=1}^n (NI_i^D)^{w_i^D} \quad \text{with} \quad \sum_{i=1}^n w_i^D = 1 \quad \forall D, \quad (2.8)$$

where NI_i^D is the i -th normalized indicator weighted by w_i^D , and n is the number of indicators in dimension D .

2.2.3 Case study: Testing the resilience index for the German energy system

Figure 2.4 illustrates that the resilience index of the German electricity system has increased overall from 2010 to 2023. After an initial rise between 2010 and 2011, the index experienced its largest decline in the study period, dropping from 15.3 in 2011 to 12.2 in 2012. This decrease was driven by negative developments across all indicators, particularly reductions in available generation capacity, spare capacity, and black start capability. From 2012 to 2016, improvements in the index were supported by lower System Average Interruption Duration Index (SAIDI) values, increased generation capacity, and greater diversification of electricity sources, among other factors.

Between 2016 and 2018, resilience largely stagnated. While continued diversification, sufficient generation capacity, and flexibility contributed positively, these gains were offset by rising SAIDI values, declines in political stability and black start capacity, and higher grid utilization. A notable improvement occurred between 2018 and 2020, primarily driven by increased spare capacity, with resilience maintaining relatively high levels thereafter. Fluctuations at the end of the study period reflect specific challenges: the decline in 2021 was mainly due to reduced capacity reserves and higher import risks, while the 2023 drop resulted from lower scores in control of corruption and political stability, increased grid utilization, and decreased investment in grid infrastructure. The highest resilience value during the study period is observed in 2022.

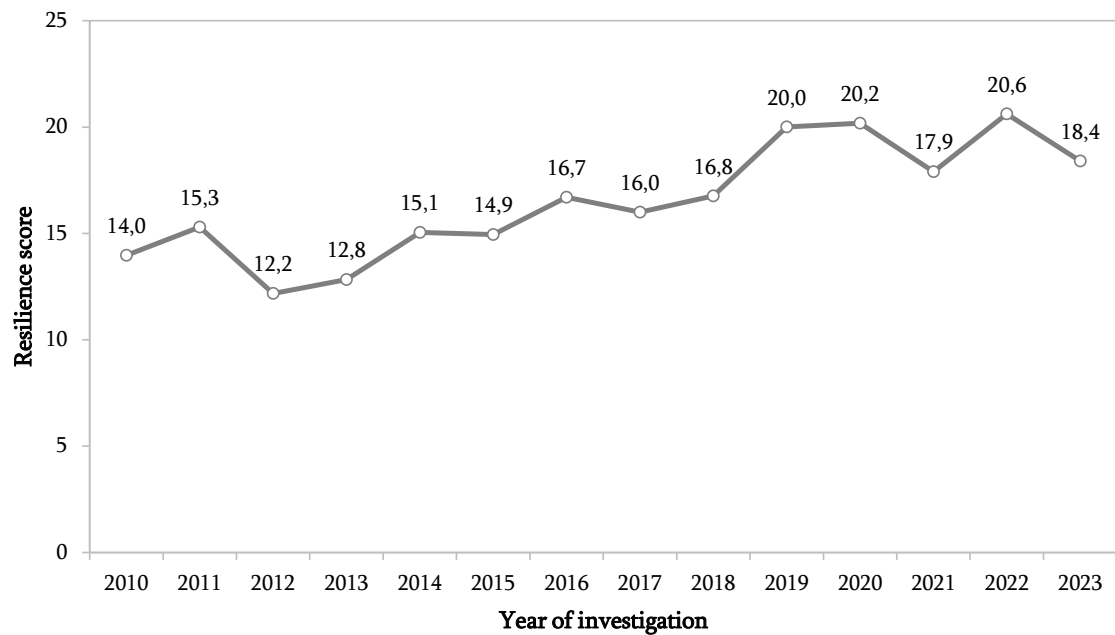


Figure 2.4: Change of the resilience index within the study period 2010 - 2023; Source: Research paper #2

The trend described for the German electricity system indicates that resilience has generally increased over time, but remains sensitive to specific stressors such as capacity reductions, political instability, and grid constraints. In a system with a growing share of DER — such as rooftop solar, small-scale wind, and battery storage — the resilience challenge may become even more pressing in the future making close and objective monitoring indispensable.

3 Re-Thinking Energy Regulation to enhance Sustainability

Closely linked to the decentralization of the energy landscape (see Section 2) is the need to create sustainable energy systems. This need stems, among other things, from the urgency to fight climate change, the declining cost and higher availability of sustainable technologies like RES, and a growing societal preference for clean energy (Moustakas et al., 2020). Sustainability, in this context, is understood as the principle of meeting present needs without compromising the ability of future generations to meet their own (Emina, 2021; Ruggerio, 2021). Back in 1713, Carl von Carlowitz – the "founder" of the sustainability principle – illustrated this principle by the metaphor of cutting trees (Grober, 2017): If a community cuts down trees at the same rate that the forest can naturally regrow, the resource remains available for generations. The forest continues to provide wood, shade, oxygen, and biodiversity without being depleted. But if trees are cut faster than they can regrow, the forest is eventually destroyed – undermining both the environment and the community that depends on it. In the same way, sustainability in energy means using resources and designing systems within their natural limits, so that today's consumption does not compromise the ability of future generations to meet their needs (Grigoroudis et al., 2021).

With technological advancements, for example, in RES, battery storage, electronic or "smart" consumer devices, the shift toward sustainability is no longer a mere technological possibility, but also a policy imperative. Yet, the pace of change is often slowed not by technical limitations but by outdated energy policies or regulatory frameworks (Lu et al., 2020; Painuly & Wohlgemuth, 2021; Tsangas et al., 2022). Current regulation, designed in the era of centralized, fossil-fuelled generation, often inhibits the deployment and scaling of sustainable technologies. Electricity markets, grid management, and tariff structures were largely built around predictable, controllable supply from large power plants (Glachant & Ruester, 2014).

Research papers #3 and #4 illustrate, for example, how electricity markets struggle to accommodate variable RES and DER as well as flexible demand. Both research papers outline that electricity pricing and market rules often fail to reward flexibility services provided by storage or demand response, even though these are crucial for balancing renewable supply. Interconnection fees and grid access regulations may disadvantage small-scale producers, discouraging prosumers from contributing to the system (see research papers #1 and #4). Subsidies and capacity mechanisms that still support fossil-based generation can distort competition, making it harder for renewables to thrive on a level playing field (Özdemir et al., 2020; Timperley, 2021). Moreover, lengthy permitting and approval procedures delay investment in wind, solar, and transmission infrastructure, even as policymakers call for rapid expansion (Oduro et al., 2024).

The result is a misalignment between regulatory structures and the technological realities of a sustainable energy system (Glachant & Ruester, 2014). To unlock the full potential of sustain-

able technologies, regulation must evolve. For instance, market design must actively incentivize flexibility, energy efficiency, and decarbonization (Conejo & Sioshansi, 2018; Parag & Sovacool, 2016). Grid regulations must adapt to a decentralized energy landscape, where millions of small-scale consumers or prosumers, energy communities, or storage providers play an active role in shaping market outcomes (Parag & Sovacool, 2016). Permitting processes must be streamlined, while fossil subsidies must gradually be phased out (Oduro et al., 2024; Timperley, 2021). In summary, regulation must shift from enabling incumbent technologies to enabling sustainable ones, reflecting the reality that clean energy is no longer experimental but essential.

In the following, this dissertation examines potential amendments to existing energy regulations with the aim of steering market participants toward sustainable behaviour through targeted market incentives. Regulations concerning administrative procedures, such as permitting processes or infrastructure investments like grid expansions, fall outside the scope of this analysis, as they are already addressed in related work (Oduro et al., 2024; Steinbach, 2013; Winter & Johnson, 2025).

3.1 The role of grid charges in promoting sustainability: The case of energy-intensive industries

The grid charges regulation plays a crucial role in shaping the incentives for sustainable practices within energy systems (Bergaentzlé et al., 2019; Richstein & Hosseinioun, 2020). By determining how costs for grid usage are allocated among energy consumers and generators, grid charges influence investment decisions, consumption behaviour, and the successful integration of variable and intermittent RES (Bergaentzlé et al., 2019). When designed appropriately, they can encourage efficient use of infrastructure, stimulate decentralized generation, and reward environmentally beneficial practices like the deployment and use of "green technologies" (Bergaentzlé et al., 2019).

For instance, grid charges that reflect the temporal and locational value of energy with high accuracy, may induce sustainable behaviour in the form of energy flexibility. By aligning cost signals with actual grid conditions, grid charges may encourage consumers and generators to adapt their behaviour in ways that support system stability and sustainability (Hennig et al., 2023; Yang et al., 2024). Time-differentiated or capacity-based grid charges, for instance, reward consumers who shift demand away from peak periods, thereby reducing congestion and deferring costly infrastructure investments (Hennig et al., 2023). Similarly, they create economic incentives for storage operators to absorb excess renewable generation during low-demand periods and release it when the system is strained (Bergaentzle & Gunkel, 2022).

Research paper #3 underlines that such incentives are particularly important for energy-intensive industries, where grid charges influence not only total energy costs but also international competitiveness and site selection decisions (Richstein & Hosseinioun, 2020). Consequently, these industries are especially sensitive to changes in the grid charges regulation, as such adjustments directly shape their cost structure and business model. At the same time, they hold substantial

potential to provide system flexibility, owing to their large and adaptable energy demand compared to smaller consumers or households (Richstein & Hosseinioun, 2020). For these reasons, energy-intensive industries are central to policy debates on grid charges reforms and constitute the main focus of the following analysis.

3.1.1 Policy failures in the German grid charges regulation

In general, a *policy failure* refers to the gap between governmental objectives and actual outcomes, ultimately resulting in the non-fulfilment of those objectives (McConnell, 2015). Along similar lines, Sokołowski and Heffron, 2022 emphasize the goal-oriented nature of policies and define energy policy failure as any policy that fails to achieve local, national, or international energy and climate objectives across the energy life cycle, while also neglecting to deliver just outcomes.

Research paper #3 finds that the current grid charge regulation represents a case of *policy failure*, as it is not adequately designed for the energy transition and lags behind recent developments such as demand-side flexibility. It also remains tied to uncertainties, for instance regarding the future of exemption rules for energy-intensive industries. Following the categorization proposed by Sokołowski and Heffron, 2022, grid charges exemplify *policy failure* through both collapsed incentives – particularly for demand-side flexibility – and misguided pathways in the course of the energy transition. Moreover, research paper #3 attributes this failure primarily to regulatory inconsistencies at both national and European levels, as well as to a lack of political will.

As outlined above, the case of energy-intensive industries is particularly noteworthy, since energy costs often determine both their overall profitability and their international competitiveness. For this reason, such industries are frequently granted individual (i.e., reduced) grid charges, which are typically linked to stable and predictable electricity consumption patterns, e.g., §19 (2) sentence 2 Electricity Network Fee Ordinance (StromNEV) (see research paper #3). However, when providing demand-side flexibility, these industries face the risk of losing this legal privilege and, consequently, being subject to higher grid charges. More precisely, research paper #3 finds that positive or negative load peaks arising from flexibility provision can lead either to the withdrawal of individual grid charges or to an increase in capacity-based charges. As a result, a significant portion of existing flexibility potential remains untapped, since energy-intensive industries are economically disincentivized from exploiting it. In many cases, §19 (2) sentence 2 StromNEV effectively functions as a “penalty” for electricity consumers with the highest demand-side flexibility potential — that is, the energy-intensive industry. This underutilization of flexibility not only limits the possibilities for efficient congestion management in the grid, but also reduces overall sustainability of energy systems by hampering the integration of RES and the corresponding reduction of greenhouse gas emissions. As a result, the potential of energy-intensive industries to support a low-carbon, cost-effective energy transition remains largely untapped, representing a clear case of *policy failure*.

3.1.2 Using grid charges to promote sustainable behaviour in energy-intensive industries

As the previous examples illustrated, grid charges play a crucial role in incentivizing – or discouraging – the use of flexibility and related investments, particularly in the German context of an energy-only market. Research paper #3 identifies four measures that could help reduce current barriers to the activation of industrial demand-side flexibility in Germany:

- First, a fundamental *redesign of grid charges* is required. This may involve either a general reduction — potentially financed through taxes or CO₂ pricing — or a shift toward dynamic tariff structures. In the case of dynamization, grid charges should not only vary over time but also reflect local grid conditions, for example through the introduction of a congestion index (Freier et al., 2019). Alternatively, temporal differentiation could be combined with the implementation of local marginal pricing, allowing electricity prices to signal grid congestion directly (Cramton, 2017). However, the design of dynamic grid charges must also incorporate fairness considerations to ensure access to affordable electricity for all consumers and to uphold principles of energy justice (Neuteleers et al., 2017).
- Second, policymakers should amend § 19 *StromNEV* to ensure that the provision of grid- and system-stabilizing flexibility does not disadvantage industrial consumers in the allocation of individual grid charges. Under the current regulation, grid charges are designed solely to reflect each consumer’s contribution to annual peak capacity. As a result, energy-intensive industries that deviate from their constant load profiles to provide flexibility risk losing their entitlement to reduced charges. This creates a regulatory paradox, where actors who behave in a grid-friendly manner are financially penalized. To resolve this conflict, the regulation should be revised so that load peaks resulting from grid- or system-stabilizing flexibility provision are excluded from the calculation of the final electricity price, including grid charges (Hanny, Wagner, et al., 2022). In practice, this could be implemented by “neutralizing” positive or negative load peaks caused by flexibility provisions.
- Third, policymakers should establish *legal certainty and transparency* concerning the future development of grid charges to promote investments in industrial demand-side flexibility. This applies, among other aspects, to the methodology for calculating the physical path – meaning the specific route that electricity physically takes through the grid from the point of generation to the point of consumption – as well as to the continuation of exemption rules in the *StromNEV* (e.g., §19 (2) sentence 2) for energy-intensive industries (see research paper #3).
- Fourth, policymakers should consider introducing *flexibility incentives* that complement wholesale market signals and grid charges. One option is the establishment of (local) flexibility markets, which can provide additional remuneration for flexibility after wholesale markets have cleared (Jin et al., 2020; Torbaghan et al., 2016). In this sense, wholesale and flexibility markets operate synergistically in unlocking flexibility potentials. Further complementary mechanisms include peer-to-peer electricity trading models (Park et al., 2021) or the aggregation of flexible loads into joint portfolios to access balancing or ancillary ser-

vice markets (Eid et al., 2015). While such measures may also apply to energy-intensive consumers, they primarily target less energy-intensive households and consumer devices connected at the distribution grid level. These consumer groups constitute the focus of research paper #4 and are discussed in greater detail in the following section.

3.2 Market-based and regulatory incentives for flexibility from less energy-intensive consumers

While energy flexibility in the past focused primarily on industrial consumers at the transmission grid level (see Section 3.1), flexibility in the distribution grid is becoming increasingly important as DER such as heat pumps, electric vehicles, and rooftop photovoltaics proliferate. Unlike industrial flexibility, flexibility on the distribution grid level is inherently decentralized, relying on millions of small-scale actors at different grid locations (Arboleya et al., 2022; Masiello et al., 2024). Due to their widespread adoption and growing share in total energy consumption, demand-side flexibility from DER can now exert a substantial influence on grid load, for instance, by mitigating local congestion, reducing peak loads, and supporting voltage stability (Resch et al., 2021; Rinaldi et al., 2022; Shahzad & Jasińska, 2024). Thereby flexibility from DER has the potential to effectively decrease the need for costly and time-consuming grid reinforcements on the distribution level (Rinaldi et al., 2022; Shahzad & Jasińska, 2024). However, current tariff structures, including grid charges, as well as wholesale market signals, are often too aggregated in space and time to mobilize flexibility precisely where and when it is needed (see research papers #2, #3, and #4). Moreover, as highlighted in research paper #1, wholesale market signals typically do not reach small-scale consumers and DER with sufficient strength to create meaningful behavioural incentives (see Section 2.1). Hence, these energy assets need other (market) mechanisms that cast a direct and undistorted impact on their remuneration from flexibility to create an incentive structure that effectively promotes sustainable behaviour.

LFMs offer a promising solution to this problem, by enabling consumers and aggregators to offer their flexibility directly to Distribution System Operators (DSOs) (Jin et al., 2020). Hence, these markets allow local grid constraints to be managed in a targeted and cost-efficient manner. Instead of relying solely on passive price signals or rigid grid reinforcement planning, flexibility is treated as an active resource that competes with infrastructure investments (Eid et al., 2016; Jin et al., 2020). Moreover, LFMs can provide transparent, market-based remuneration for small-scale flexibility providers, thereby increasing participation and confidence to further invest in flexible technologies (Eid et al., 2016). In this way, LFMs form a crucial bridge between a more decentralized energy landscape and the system-wide need for coordinated flexibility provision to enhance the successful integration of DER and promote overall sustainability.

3.2.1 Local Flexibility Markets (LFMs)

LFMs represent a market-based approach to managing congestion in energy systems (Bouloumpasis & Steen, 2019). They complement existing energy and balancing markets — such as spot markets, balancing capacity markets, or redispatch markets — and offer the potential to effectively and efficiently manage grid congestion (Kornrumpf et al., 2016; Severin et al., 2019). In this way, LFMs supplement current market structures and regulations for controllable loads at the distribution grid level (Bons et al., 2019).

LFMs can be defined as regionally limited marketplaces for flexibility, with a focus on grid- and system-stabilizing use (Olivella-Rosell, Bullich-Massagué, et al., 2018; Ramos et al., 2016). Flexibility is primarily deployed to maintain grid stability, which requires access to and processing of local information, such as grid utilization. Beyond system support, LFMs can also serve market-oriented purposes, for example by exploiting price differences for temporal arbitrage under volatile energy prices, thereby reducing price volatility and enhancing market stability (Olivella-Rosell, Lloret-Gallego, et al., 2018).

In LFMs, flexibility providers and consumers interact to trade various flexibility products. These products differ in adjustment direction (energy injection or withdrawal), start time, duration, and offered capacity (Villar et al., 2018). Flexibility can serve system-, grid-, or market-stabilizing purposes; this dissertation focuses on the grid-stabilizing deployment. The overarching objective is to better integrate decentralized renewable generation into the electricity system, to reduce the need for costly grid expansion at the distribution level, and promote overall sustainable energy systems (Bouloumpasis & Steen, 2019).

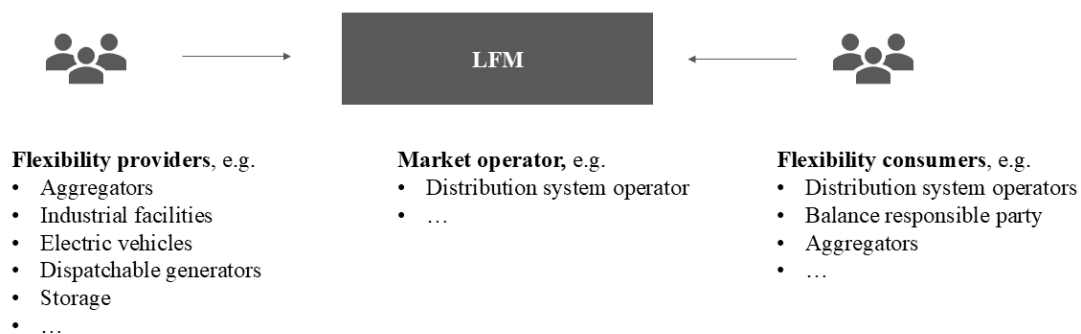


Figure 3.1: Participants in local flexibility markets; Source: Research paper #3

3.2.2 Policy failures in German energy regulation impede the development of LFMs

Research paper #3 defines a *policy failure* as the gap between governmental objectives and actual outcomes, ultimately resulting in the non-fulfilment of those objectives (McConnell, 2015). In the case of Germany, the implementation of LFMs provides a prime example for this term. While overarching European law explicitly mandates the market-based procurement of grid- and system-stabilizing flexibility across all interconnected energy markets, national implementation remains significantly behind these ambitions. To date, LFMs have scarcely progressed beyond early pilot phases within research projects (Bogensperger et al., 2019; enera, 2023; Schäfer-Stradowsky & Kalis, 2019). Although national policymakers formally recognise the importance of LFMs for future energy systems in a law amendment (Bundesgesetzblatt / Federal Law Gazette, 2021), their practical implementation faces barriers from incumbent regulation as well as a vague design of new or revised regulations. In the following, this misalignment between European and national law is outlined in greater detail.

Overarching European legal framework for LFMs

For implementing LFMs on the national level, e.g., in Germany, the overarching legal framework at the European level must first be examined. To enable market-based procurement and marketing of flexibility, the European legal framework imposes binding requirements on national legislature for the implementation of the relevant European legal acts. For instance, the EU may impose *Regulations* that, upon entry into force, automatically apply in a uniform manner across all EU member states without requiring transposition into national law (Article 288(2) of the Treaty on the Functioning of the European Union (TFEU)). By contrast, *Directives* set a specific objective for EU member states but leave them free to decide how to achieve it. Consequently, member states must adopt the necessary legislative measures to meet the target, i.e., transpose the Directive into national law (Article 288(3) TFEU). If a member state violates an applicable EU Regulation or fails to properly implement an EU Directive at the national level, the European Commission may initiate infringement proceedings against that country under Articles 258 and 259 TFEU.

LFMs offer the opportunity to practically implement the market-based approach to congestion management promoted by the EU in the Clean Energy Package (European Commission, 2019b) on the national level. The central legal basis for promoting and improving market-based mechanisms is the provision on redispatch procurement set out in Article 13(2) of the Electricity Regulation. It obliges member states to select and financially compensate resources eligible for redispatch using market-based mechanisms from existing generation facilities, energy storage, or demand response. Non-market-based redispatch is therefore permitted only where no market-based alternative is available, all available market-based resources have already been deployed, or insufficient competition or strategic bidding behaviour is to be expected — for example due to structurally recurring grid congestion or a limited number of resources eligible for redispatch

(Article 13(3) of the Electricity Regulation). Directly related to Article 13 of the Electricity Regulation is also Article 32(1) of the Electricity Directive, which governs not only whether but primarily how market-based flexibility procurement should be implemented at the national level. Accordingly, member states are explicitly called upon to establish an appropriate regulatory framework that enables and incentivizes DSOs to procure flexibility services for the purpose of congestion management in their networks. Such regulation is intended to ensure that DSOs can make use of flexibility services provided by DER, demand response, or energy storage, where these services can cost-effectively reduce the need for grid reinforcements and support the efficient and secure operation of distribution grids (Article 32(1), second sentence, Electricity Directive).

Due to the nature of the act as a Directive, it is binding for member states with respect to the objectives to be achieved but must be implemented separately through national legislation (Article 288(3) TFEU). The transposition deadline for the Electricity Directive was 31 December 2020. This deadline was addressed through the German federal government's draft law on the "Implementation of European Union Requirements and the Regulation of Pure Hydrogen Networks in Energy Law", which explicitly provides for the transposition of the Electricity Directive (Lange & Hofmann, 2022). This draft was subsequently consolidated into the law on the "Implementation of European Union Requirements and the Regulation of Pure Hydrogen Networks" of 16 July 2021 and is now in force (Bundesgesetzblatt / Federal Law Gazette, 2021). However, despite efforts to transpose EU regulations into national law, the implementation of LFMs remains largely a future prospect rather than a practical reality. This is because both existing national legislation and the recently enacted law continue to constrain the practical deployment of LFMs, representing a clear case of *policy failure*.

National legal framework fails to implement EU regulation and LFMs

For the case of Germany, research paper #4 observes that the national legal framework, while in principle allowing the procurement of flexibility through LFMs (§13(1) sentence 1 no. 2 Energy Industry Act (EnWG) in conjunction with §14(1) sentence 1 EnWG), often does not provide DSOs with sufficient incentives to make actual use of this possibility. This regulatory drawback demonstrates the need for an appropriate regulatory framework that not only permits market-based flexibility but explicitly incentivizes DSOs to make use of it. At the EU level, such a framework has been established under Article 32(1) of the Electricity Directive, which stipulates that flexibility for congestion management should, in principle, be procured on a market-based basis and that corresponding provisions must be implemented in national law. The amended provision in §14c EnWG represents an initial step toward implementing EU requirements for market-based flexibility. Additional barriers to market-based flexibility and to the practical implementation of LFMs remain in the areas of grid charges and incentive regulation.

Concerning the *EnWG*, the regulatory framework in principle does provide some opportunities for flexibility procurement, for example through individual and potentially market-based agreements. In particular, the general provision on system responsibility in §13(1) no. 2 EnWG forms the legal basis for load and generation management by allowing DSOs to conclude individual

contractual arrangements with consumption and generation facilities for the purpose of grid-stabilizing load and generation shifting. While the measures listed in §13 EnWG are partially applicable to DSOs via the reference norm in §14(1) sentence 1 EnWG, DSOs are entirely excluded from the scope of certain flexibility measures, such as switchable loads or switchable capacity. Only with §14a EnWG the legislator has taken a concrete step toward enabling flexibility services at the low-voltage level by introducing the grid-stabilizing operation of controllable consumption units and controllable grid connections in return for reduced grid charge. However, due to the lack of detailed implementation this option remains largely unused.

Similarly, the amended §14c EnWG leaves certain questions open, for example regarding the precise design of trading processes and the allocation of regulatory responsibilities in market-based flexibility procurements. For example, §14c(1) sentence 1 EnWG does not provide further detail on how a “transparent, non-discriminatory, and market-based procedure” for procuring flexibility services should be designed and monitored in practice. Moreover, the wording of §14c(1) sentence 1 EnWG does not clearly indicate the extent to which flexibility services are to be procured, as procurement is only required to the extent that it “contributes to increased efficiency in the operation and expansion of the distribution grid.” Although §14c(2) sentence 1 EnWG provides some clarification by stating that “specifications” for the procurement of flexibility services can be established to ensure effective and non-discriminatory participation of all market participants, these specifications are not further defined. Further uncertainties arise from §14c(4) EnWG, which provides an exemption from the obligation to procure flexibility services on a market-based basis if “[...] such procurement is not economically efficient or would lead to serious market distortions [...]”. The wording of §14c(4) EnWG, however, does not clearly state which flexibility services are covered, nor does it define in detail what is meant by “not economically efficient” or “market distortions.”

As far as *grid charges* are concerned, the amendment of §14a EnWG provides DSOs with significantly greater discretion in the calculation of grid charges for private households. For example, flexibility on the consumer side can be specifically incentivized through an “incentive module” and an associated offering of time-varying grid charges. In return, DSOs are authorized to selectively switch controllable loads on or off for corrective purposes, for instance to relieve the grid on short notice. While the flexibilization of grid charges on the consumer side is generally welcome, preventive flexibility procurement by DSOs, e.g., through LFM or pursuant to §14c EnWG, must increasingly take priority. Similarly, the proposed regulatory changes for industrial consumers regarding the granting of individual grid charges (see research paper #3 and Section 3.1) primarily reduce barriers on the consumer side but do not create concrete incentives for DSOs to actively utilize available flexibility potentials or to procure them through a market-based procedure.

Further obstacles to market-based flexibility procurement can be found in the *Incentive Regulation Ordinance (ARegV)*. When examining the standard examples in §11(2) sentence 1 ARegV, it is immediately apparent that flexibility measures are not explicitly listed as permanently uncontrollable cost components. By contrast, costs arising from the legally mandated curtailment of conventional and renewable generation facilities are included in the list. According to the reg-

ulation, DSOs have no influence over the costs incurred from such curtailment. Consequently, these curtailment costs are treated as uncontrollable costs — or pass-through cost items — in efficiency comparisons and in the determination of the revenue cap that serves as the basis, e.g., for the calculation of grid charges. As a result, for DSOs, it is ultimately irrelevant whether or to what extent they implement such measures. Instead, DSOs are incentivized to prioritize curtailment as a congestion management measure over market-based flexibility measures, which may indeed enter the calculation for efficiency comparisons and grid charges revenues. By contrast, all flexibility measures carried out on the basis of an individual contract between DSOs and a third party are treated differently; in such cases, DSOs can, to some extent, influence the resulting costs. However, this implies that any flexibility procurement that is individually agreed between DSOs and a flexibility provider is always considered less economical from the perspective of DSOs than curtailing generation capacity.

3.2.3 Implementing LFMs to create sustainability incentives in the distribution grid

Incentivizing market-based procurement of grid- and system-stabilizing flexibility, for instance through LFMs, is crucial for making flexibility deployment in the distribution grid economically viable — particularly for DSOs — while also reducing renewable energy curtailment and enhancing the overall sustainability of energy systems. At the European level, Article 32(1) of the EU Electricity Directive sends a clear signal in favour of market-based flexibility procurement. At the national level, however, there is still a lack of fundamental incentives for DSOs to utilize flexibility from DER (e.g., within the regulatory framework of the EnWG and the ARegV). Although EU requirements for market-based flexibility have been transposed into national law, they have not been further specified (e.g., in the context of §14c EnWG). To fully translate the effect of these EU requirements into national law and leverage the full sustainability impact, it is therefore necessary to remove existing and persistent barriers to flexibility, which, among other factors, hinder the practical implementation of market-based flexibility procurement over LFMs. To implement LFMs in practice and to create incentives, for example for DSOs, to actively participate in LFMs, research paper #4 proposes the following regulatory options:

- The wording of §14c EnWG, which implements EU requirements for the introduction and promotion of market-based flexibility procurement, does not make the precise meaning of the legal terms used or the allocation of responsibilities sufficiently clear. To ensure transparent and legally secure application, §14c EnWG should be supplemented with concrete legal definitions. This concerns, for example, §14c(2) sentence 1 EnWG and the “specifications” it contains for effective and non-discriminatory procurement of flexibility services, as well as the exemption provision in §14c(4) EnWG in cases of “market distortions.”
- To at least achieve parity between the cost components of curtailing conventional and renewable generation and those of grid-stabilizing flexibility procurement, the ARegV must be amended so that costs resulting from the provision of flexibility services pursuant to §14c EnWG are also included in the catalogue of permanently uncontrollable cost components

under §11(2) sentence 1 ARegV. This would at least indirectly remove the incentive for DSOs to favour curtailment solely due to the cost categorization. However, such alignment does not automatically create an incentive for DSOs to prioritize market-based flexibility procurement over other measures, such as curtailing generation capacity.

- A key challenge in implementing LFM lies in potential feedback effects on upstream energy markets, such as wholesale markets (Hirth et al., 2019). For example, generators in scarcity regions may withhold energy from the wholesale market or submit high bids to gain higher profits on downstream LFM, while generators in surplus regions may submit low bids to sell excess energy profitably or reduce output. This so-called "inc-dec gaming" can systematically alter bidding behaviour on wholesale markets, potentially exacerbating congestion in scarcity regions and increasing oversupply in surplus regions (Cramton, 2022; Hirth & Schlecht, 2019; Hirth et al., 2019). For this reason, regulation must actively consider such arbitrage possibilities in the future, as it is currently not illegal to exploit them. Additionally, market design must address this problem by reducing profits and, thus, incentives, to engage in "inc-dec gaming", e.g., by introducing more fine granular bidding zones on wholesale markets to resemble the local character of LFM (Cramton, 2022).
- Lastly, LFM need to exploit the technological possibilities in the digital era to facilitate market-based flexibility trading and the active participation of both DSOs and decentralized assets. For instance, LFM need to make use of intelligent metering and measurement systems, along with associated digital and statistical methods, to accurately calculate the economic "value", i.e., price, of flexibility services. Only by involving digital technologies, flexibility-relevant data can be recorded with sufficient accuracy to determine the actual deviation of generation or load, i.e., flexibility, compared to a validated "baseline" (Jahns et al., 2023). Only on this basis, the "true" value of the offered flexibility can be calculated and, thus, priced.

This last point already indicates the central role of digital technologies in practically implementing the market design and regulatory changes proposed in research papers #3 and #4. In this context, digital technologies act as direct enablers of a more sustainable energy system, by facilitating flexibility provision, minimizing the curtailment of RES, and reducing the need for costly and ecologically harmful grid expansions. The next section integrates the perspectives of a more decentralized energy landscape (see Sections 2.1 and 2.2 or research papers #1 and #2, respectively) with the need to promote sustainability in energy systems outlined in this section, highlighting how digital technologies can support and accelerate these developments.

4 Leveraging the Impact of digital Technologies in Energy Markets

The ongoing transformation of the energy sector is driven by two mutually reinforcing developments: a structural shift from centralized power generation toward decentralized, consumer-driven systems, and a growing demand for sustainability. These developments involve the coordination of millions of distributed assets — such as RES, electric vehicles, heat pumps, and battery storage systems — and introduce unprecedented complexity in energy systems (see research papers #1 and #2). Moreover, the sustainability potential of these assets remains largely untapped, as they are often operated inflexibly or not to the sufficient extent, for example in cases of RES curtailment (see research papers #3 and #4). These challenges make it evident that traditional grid planning and market mechanisms are no longer sufficient to manage an increasingly dynamic and distributed energy landscape. Digital technologies thus emerge as key enablers, both for the effective integration of DER and for the development of next-generation sustainable energy systems (Bañales, 2020; Wei et al., 2023).

Digital technologies may assist the development of energy systems across different layers: *hardware*, *software*, and *data*. For instance, smart meters, sensors, and IoT devices provide the hardware foundation for capturing real-time information on consumption, generation, and grid status (Ahmad & Zhang, 2021; Avancini et al., 2019). Additionally, software solutions — such as energy management systems, automated trading algorithms, and flexibility aggregation tools — process and act upon this information (Khorasany et al., 2022). Underlying both is data, which forms the critical layer that enables forecasting, optimization, and decision-making across millions of distributed assets (Devaraj et al., 2021).

However, it is not the individual contribution of hardware, software, or data that unlocks the full potential of digital technologies in energy systems — it is their seamless integration. Smart devices without interoperable software remain underutilized, and even the most advanced algorithms are ineffective without high-quality, real-time data. Only when hardware infrastructure, intelligent software, and data flows are tightly interconnected can decentralized resources be coordinated efficiently, flexibility be traded autonomously, and sustainability outcomes be measured accurately. Thus, the true value of digital technologies in energy systems lies not within each layer alone but in their convergence into a *digital ecosystem* (Devaraj et al., 2021; Hack et al., 2021; Immonen & Kalaoja, 2019).

In the following, this dissertation outlines possible applications for digital technologies in energy systems that enhance both, the integration of DER and sustainability outcomes. In particular, the applications focus on utilizing flexibility potentials in the form of automated flexibility trading in a multi-market setting (see research paper #5) as well as a method to select suitable technologies to digitize MRV processes for voluntary carbon offsets (see research paper #6).

4.1 The role of digital technologies in closing the flexibility gap

As the energy transition advances, the growing share of RES renders energy supply increasingly decentralized and intermittent, introducing new challenges for system stability (see research paper #2). Ensuring a reliable and future-proof energy system under these conditions requires a diverse set of flexibility options (see research papers #3 and #4). The shortfall between available and required flexibility is commonly referred to in the literature as the *flexibility gap* (Papaeftymiou et al., 2018). Digital technologies play a crucial role in bridging this gap by enabling efficient information exchange among market participants and enhancing the visibility of actual flexibility needs (Körner et al., 2019; Zhang et al., 2019). Moreover, they support faster market interactions and the automation of near real-time trading, thereby improving the responsiveness and efficiency of the energy system (Zhang et al., 2019). As a result, digital technologies and corresponding trading algorithms may exploit flexibility potentials with higher speed and better temporal and spatial accuracy than human traders and, thereby, contribute to overall system stability.

Although algorithmic trading has the potential to significantly enhance market efficiency — for instance, by improving transparency — only about half of the trades on European energy spot markets are executed automatically via algorithms (Vizjak, 2020). In this regard, energy markets clearly lag behind financial markets where algorithmic trading is much more common (Malcenić et al., 2019). Furthermore, only a limited number of trading algorithms explicitly account for energy flexibility exploitation, resulting in a partial decoupling of energy and flexibility trading and, thus, a misalignment between traded energy and actual system needs. While some initial algorithmic solutions for flexibility exploitation exist, these are predominantly restricted to passive decision-support functions and do not yet engage actively in market participation (Badami et al., 2020; Esmat et al., 2017; Ottesen et al., 2018).

The active and autonomous participation on both energy markets and dedicated flexibility markets (see research paper #4) would enable algorithms to develop strategies that simultaneously maximize profits across multiple markets, thereby promoting enhanced market integration and overall system efficiency. Current approaches to flexibility trading, however, are largely based on single-market optimization, which increasingly struggles to handle the complexity of near real-time, multi-market environments (see research paper #5) (Dall’Anese et al., 2017; Golmohamadi et al., 2021; Moreno et al., 2017). Consequently, conventional optimization models may produce suboptimal flexibility-marketing outcomes. For this reason, algorithms based on AI represent a promising solution, as they may actively learn and refine trading strategies through direct interaction and experimentation within the market environment.

4.1.1 Artificial Intelligence (AI) as an enabling technology for energy trading

Research paper #5 finds that AI-based algorithms represent a promising solution to deal with high-frequency interactions in a multi-market environment and to engage in autonomous trading and experimentation regarding bidding strategies. This section provides a detailed overview of the most common AI algorithms employed in energy flexibility trading, which will subsequently serve as the foundation for the algorithmic framework developed as part of this dissertation in research paper #5.

- **Reinforcement Learning (RL):** Large part of existing research on energy trading is centred around RL. RL is a subfield of ML in which an agent learns optimal behaviour through continuous interaction with its environment, gradually improving its decisions in pursuit of a defined objective (Sutton & Barto, 2018). For example, in the context of energy trading, González et al., 2019 apply Q-learning agents in the form of electricity consumers that jointly develop trading strategies to maximize individual profits across different markets, including retail, wholesale, and balancing markets. Similarly, W. Wang and Yu, 2019 propose an ML-based bidding strategy for participation in multiple electricity markets, namely the day-ahead and real-time market. Thus, while RL agents have been extensively studied in the context of integrating multiple energy markets, their application to trading energy flexibility across these markets remains largely unexplored.
- **Nature-Inspired Intelligence (NI):** Further approaches to facilitating energy trading through algorithmic methods draw on NI. These approaches draw inspiration from natural processes — such as the evolution of individuals within a population or the collective behaviour of biological swarms — and translate them into search algorithms that iteratively identify optimal or near-optimal solutions (Beheshti & Shamsuddin, 2013). In the context of energy trading, several studies apply such algorithms to determine optimal bidding strategies for electricity suppliers in day-ahead markets. For example, Shah and Chatterjee, 2020 and Sedeh and Ostadi, 2020 employ a Genetic Algorithm (GA), while Y. Gao et al., 2018 combine GA with Particle Swarm Optimization. In another approach, Sun et al., 2020 integrate GA with a hybrid Particle Swarm Optimization and an enhanced Firefly Algorithm. Similarly, Lezama et al., 2019 and Shah and Chatterjee, 2020 also adopt more sophisticated Nature-Inspired Intelligence (NII) techniques for strategy optimization.
- **Artificial Neural Network (ANN):** The previous example already illustrates that several of the identified algorithms are augmented with an additional layer of intelligence. More precisely, traditional RL- or NI-based approaches are often combined with neural networks to improve their decision-making performance. For instance, in the RL domain, Liang et al., 2020 and Cao et al., 2020 apply a Deep Deterministic Policy Gradient (DDPG) algorithm — an actor-critic framework that integrates RL with neural networks — to derive profit-maximizing bidding strategies for electricity suppliers. Similarly, Reddy et al., 2017 combine NI with ANN by using an artificial bee colony algorithm as the core optimizer, while the neural network dynamically tunes its parameters to enhance performance.

The identified algorithms offer a selected snapshot of existing approaches to energy trading. However, most of them focus exclusively on day-ahead, intraday, or wholesale energy markets, without accounting for the possibility of flexibly adjusting consumption schedules or providing flexibility services across different markets. The full-length literature review in research paper #5 only identifies a few studies that explicitly consider prosumers capable of providing flexibility to the grid from both the supply and demand side. In addition, some publications explore Peer-to-Peer (P2P) trading models, where small energy volumes are exchanged locally. While such local trading inherently enables flexibility provision, these approaches primarily focus on energy exchange and largely overlook the costs and benefits associated with shifting generation or load profiles.

4.1.2 An algorithmic AI framework for multi-market flexibility trading

To trade flexibility across multiple markets, flexibility providers must follow a structured decision process. First, they need to determine the quantity and time intervals during which flexibility can be offered. This requires accounting for the interdependence between providing flexibility at a given moment and the subsequent need to recover from deviating from the planned generation or consumption baseline (Schott et al., 2019). Second, providers must assess the available markets in which their flexibility can be traded, taking into account the potential costs and operational implications of adjusting their baseline profile. Finally, based on expected revenues and market-specific constraints, such as minimum bid sizes, they must decide on which market to place their bid.

To address the complexity and price volatility across multiple markets and to derive corresponding trading strategies, research paper #5 finds that AI-based algorithms are particularly well-suited. Building on these insights, this dissertation proposes an integrated algorithmic framework for flexibility trading that combines ML- and NII-based approaches. The core objective of this framework is to determine an optimal multi-market flexibility trading strategy. To this end, a GA acts as a meta-learner, coordinating several market-specific Q-learning agents that generate tailored bidding strategies for individual markets. In addition, the framework accounts for interdependencies between baseline adjustments and market timing by applying different decision intervals, shorter ones for the market-level Q-learners and longer ones for the GA meta-learner. Figure 4.1 illustrates the proposed algorithmic framework:

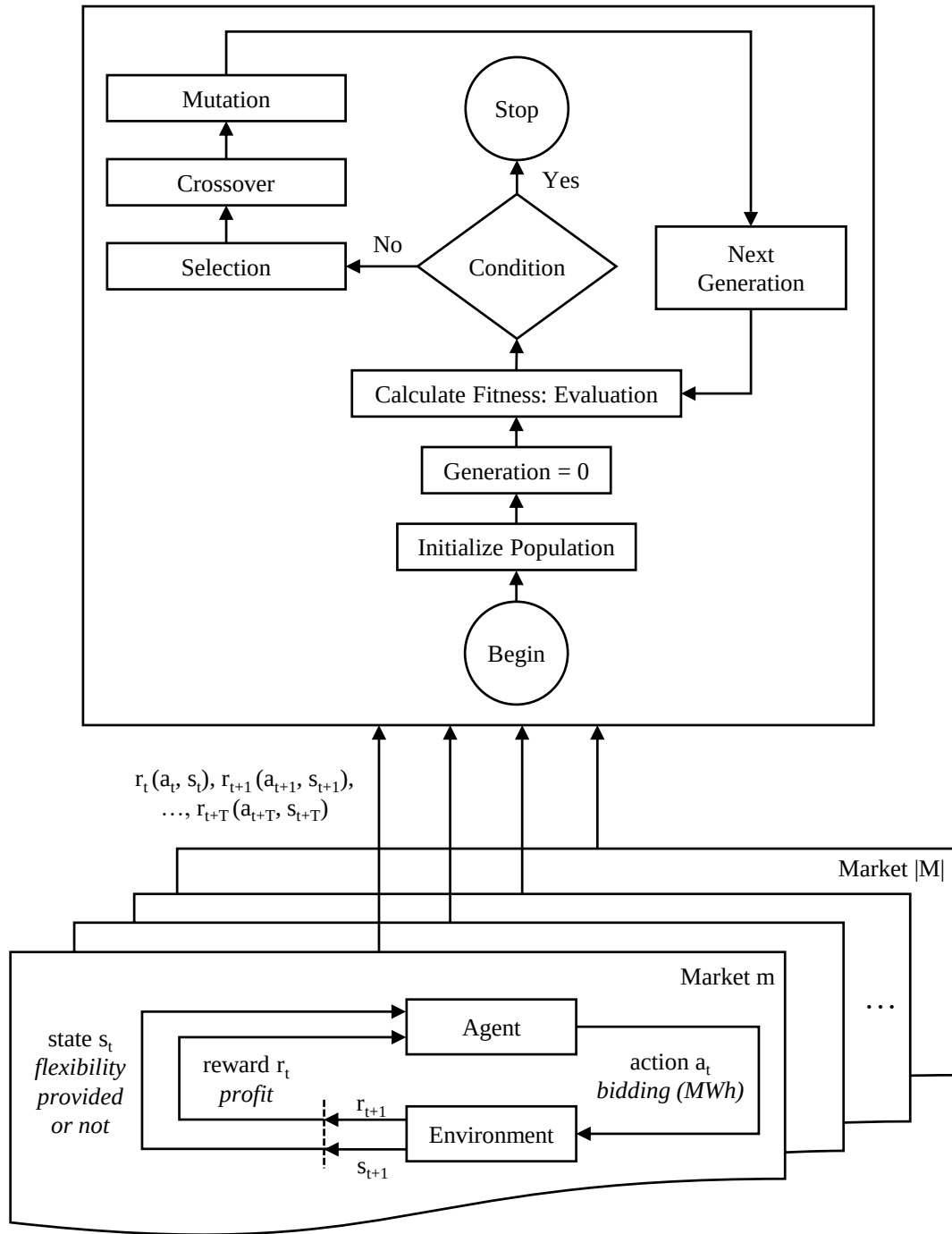


Figure 4.1: Integrated ML framework for multi-market flexibility trading; Source: Research paper #5

The framework relies on a set of RL algorithms that learn optimal bidding strategies across different markets in which flexibility can be traded (e.g., spot markets, balancing markets, or local flexibility markets). During the learning process, each RL agent interacts with its respective market environment by experimenting with different actions $a \in A$ (i.e., bidding strategies), observing the resulting transition to a new state s , and receiving an associated reward r . Actions that lead to higher rewards are reinforced over time. Through continuous interaction and feedback, the RL agents search for the bidding strategy that maximizes long-term cumulative rewards.

To solve the RL problem, the framework uses a set of Q-learning algorithms, each assigned to a specific energy or flexibility market. In line with the RL structure, each Q-learner links market signals to state-action-reward relationships. At each time step t , the agent observes the current market state s_t and executes a bidding strategy a_t . This action results in a transition to a new state s_{t+1} and yields a reward r_{t+1} , defined as the revenue from activating the submitted flexibility quantity minus the “inconvenience” cost and efficiency loss arising from baseline adjustments in generation or load.

Throughout this process, the agent stores the expected values of state–action pairs in a Q-table and continuously searches for the bidding strategy with the highest expected long-term return. Thus, each Q-learner aims to maximize Q-values and, consequently, the expected profit from its market participation. The update of Q-values follows the standard formulation by Sutton and Barto, 2018:

$$Q_i^{\text{new}}(s, ai) = (1 - \alpha) Q_i(s, ai) + \alpha \left[r_i + \gamma \max_{a'} Q_i(s', a') \right] \quad (4.1)$$

The above equation specifies how Q-learners update the Q-table at each time step. The learning rate $\alpha \in [0, 1]$ determines the weight assigned to new experiences (e.g., recent rewards), while the discount factor $\gamma \in [0, 1]$ reflects how far-sighted the agent is, i.e., the importance it places on future versus immediate payoffs.

During learning, Q-learners face an exploration–exploitation trade-off: they must decide whether to exploit the currently best-known action or explore seemingly inferior actions a_{t+1} to discover potentially better long-term gains. To balance this trade-off, this dissertation chooses an ϵ -greedy policy, selecting the action with the highest current Q-value with probability $1 - \epsilon$ and a random alternative action with probability ϵ . This enables experimentation with new bidding strategies while still favouring profitable behaviour.

To derive an optimal combination of bidding strategies across energy and flexibility markets, the framework further incorporates a meta-learner. NI-based optimization methods are suitable for integrating multiple decision layers. Therefore, an GA is added to the framework to determine an optimal flexibility trading strategy. This meta-learning approach not only captures heterogeneous market requirements, such as minimum bid sizes, but also accounts for temporal interdependencies in flexibility provision. This is particularly relevant for prosumers who can provide flexibility on both the supply and demand side across multiple time intervals.

4.2 The role of digital technologies in addressing the "market for lemons" problem in voluntary carbon offsets

One key pathway to improving the sustainability of energy systems is not only reducing emissions – for instance through the integration of RES — but also compensating for unavoidable emissions via offsetting schemes. While regulatory mechanisms such as the Emissions Trading Scheme (ETS) and reporting obligations under the Corporate Sustainability Reporting Directive (CSRD) and Corporate Sustainability Due Diligence Directive (CSDDD) already mandate emission reductions and compensation, many companies go beyond compliance and voluntarily pursue additional strategies to improve their carbon balance (Cadez et al., 2019; Herold et al., 2019). One such strategy is the purchase of carbon credits on VCMs. These credits are generated by projects that remove or reduce greenhouse gas emissions — such as reforestation or improved agricultural practices — and are certified by standards like Gold Standard or Verra (Kreibich & Hermwille, 2021).

Despite rising demand, carbon credit prices in VCMs remain relatively low compared to ETS certificates. Moreover, recurring scandals involving illegitimately issued credits reveal severe information asymmetries between project developers and buyers (Greenfield et al., 2023; Kreibich & Hermwille, 2021). As in Akerlof's *market for lemons* (Akerlof, 1978), buyers cannot reliably distinguish high- from low-quality credits, lowering their willingness to pay and crowding out high-quality offerings (Wongpiyabovorn et al., 2023).

Current, largely manual MRV practices can only partially address this information asymmetry (Comello et al., 2023). Buyers must either accept the risk of credit revocation or invest significant transaction costs to verify quality. Against this background, there is a clear need to apply digital technologies to reduce MRV-related transaction costs and alleviate information asymmetries (F. Wu et al., 2021). A digital transformation of VCMs could enhance data accessibility for all stakeholders (Granados & Gupta, 2013) and redefine roles within MRV processes (Weill & Woerner, 2015).

While digital transformation is known to reduce information asymmetries in markets (Nadkarni & Prügl, 2021), research on its systematic application in VCMs remains scarce. Existing work predominantly focuses on blockchain as a means to improve traceability of carbon credits (Hartmann & Thomas, 2020; Siphthorpe et al., 2022). Research Paper #6 offers an initial, more holistic perspective on how such technologies can be systematically applied to MRV processes in VCMs. More precisely, research paper #6 follows the Design Science Research (DSR) paradigm and designs a method based on Situational Method Engineering (SME) for selecting digital technologies for MRV processes in VCMs (Hevner et al., 2008). The method is iteratively evaluated in research paper #6 regarding usability, efficiency, generality, and practicality through a case study on soil carbon sequestration credits. The resulting artifact supports the (re)design of MRV processes and contributes to the digital transformation of VCMs by mitigating the *lemons problem*.

4.2.1 Plethora of available digital technologies for Monitoring, Reporting, and Verification (MRV) processes

As illustrated, VCMs currently rely predominantly on manual MRV processes, which are associated with inefficiencies, error susceptibility, mistrust in carbon assessments, information asymmetries, and high transaction costs (Krasikov & Legner, 2023; Lehner, 2023; Schletz et al., 2020; Woo et al., 2020). In the context of VCMs, digital transformation is often discussed with a focus on blockchain technology, particularly where trust in intermediaries or systems is limited (Feulner et al., 2022). Thanks to their immutability and tamper-proof characteristics, blockchains can facilitate the transformation of VCMs (Hartmann & Thomas, 2020; Kotsialou et al., 2022; Siphthorpe et al., 2022). However, most blockchain-based applications focus on post-credit issuance activities, such as marketplaces and trading, rather than on underlying MRV processes.

Emerging start-ups demonstrate a broader application of digital technologies in VCMs. For example, satellite imagery analysed via AI algorithms enables continuous forest monitoring, replacing labour-intensive field inspections (OCELL GmbH, 2023; Pina Technologies GmbH, 2023). This enhances data availability and monitoring frequency (Reis et al., 2019). Other technologies, such as Application Programming Interfaces (APIs), IoT devices, smart sensors, cloud computing, and automated drones, facilitate end-to-end digitalization and tighter integration between project monitoring and carbon credit trading (Toucan Toco, 2023; World Bank, 2022).

The diversity of these applications highlights the need for a systematic approach to digital transformation in VCMs. Given the rapid technological evolution and the complexity of digital solutions, projects and organizations with limited digital expertise often struggle to select appropriate technologies for specific MRV steps or for end-to-end digitalization. Accordingly, this dissertation proposes an artifact designed to systematically leverage digital technologies and guide researchers and practitioners in supporting the digital transformation of VCMs.

4.2.2 A method for selecting digital technologies in MRV processes

Research paper #6 develops a method to select suitable digital technologies for MRV processes. The method comprises five activities, each defined by specific *techniques*, *tools*, *roles*, and resulting *outputs* (Braun et al., 2005; Denner et al., 2018; Vanwersch et al., 2016). Rather than treating technology selection as an isolated task, the method integrates it with the assessment and adaptation of MRV processes and their requirements. Techniques describe how process improvements are generated, tools support their application, and roles specify the individuals or organizational units responsible for execution (Braun et al., 2005; Vanwersch et al., 2016).

To design the initial version of the method, research paper #6 draws on fragments from existing body of knowledge in scientific publications coupled with insights from industry collaborations and own research. Research paper #6 iteratively refines the method through workshops and expert interviews conducted as part of a case study on soil carbon sequestration, resulting in the final version, see Figure 4.2.

Activity	Technique	Tool	Role	Output
Activity 1: Determination of MRV process boundaries	– (Select standard framework) – Model all MRV process steps covered by standard <i>and related regulatory framework</i> – <i>Allocate roles and responsibilities to MRV process step</i> – Decide on sphere of interest – (Extend MRV process model by <i>additional</i> processes not covered by standard framework)	– Established process modelling language (e.g., BPMN, UML) – Multi-criteria decision analysis (e.g., AHP, MAUT)	– Process owner – Selected process participants – VCM standard expert (if available and necessary)	– Standard MRV process steps delineated to sphere of interest
Activity 2: Determination of quality objectives and evaluation criteria	– Determine quality objectives meeting <i>at least</i> minimum standard requirements – Derive evaluation criteria – Determine the relative importance of criteria	– (<i>Strategic analysis (e.g., PEST(EL), SWOT)</i>) – Feasibility analysis – Cost-benefit analysis – (<i>Value lever</i>)	– Process owner – Selected participants of top-level management – VCM standard expert (if available and necessary)	– List of evaluation criteria
Activity 3: Preselection of suitable digital technologies	– Derive minimum requirements for digital technology utilization from output in Activity 1 and 2 – Select suitable digital technologies appropriate for MRV process steps defined in Activity 1	– Requirement analysis	– Process owner – Technology experts	– List of digital technologies suitable for the defined MRV process steps defined in Activity 1
Activity 4: Determination of process change	– Combine suitable digital technologies of the defined MRV process steps to vectors – Model MRV process step modifications through digital technology vectors – Conduct comparative process analysis between process defined in Activity 1 and adjusted processes – <i>Exclude</i> digital technology vectors leading to <i>insufficient</i> process enhancements <i>in terms of quality objectives</i>	– Established process modelling language <i>used in Activity 1</i> (e.g., BPMN, UML) – <i>Design thinking workshops</i>	– Process owner – Selected process participants – Prospective users – Business Development	– Shortlist of digital technology vectors
Activity 5: Final assessment of digital technology vector	– Assess how the shortlist of digital technology vectors and the adjusted MRV process steps <i>meet</i> influence the evaluation criteria – Identify the digital technology vector that performs best across all evaluation criteria	– Multi-criteria decision analysis (e.g., AHP, MAUT, etc.)	– Process owner – Technology experts – Selected participants of top-level management	– Final ranking of preselected digital technology vectors

Figure 4.2: Overview of the method’s activities and elements; Source: Research paper #6

Before digital technologies can be selected and evaluated, the method first requires defining the boundaries of the MRV process in *Activity 1*. This involves developing a clear understanding of all MRV process steps covered either by the chosen standard framework or by the organization’s own scope of interest. Accordingly, the method may also extend to the subsequent trading phase on VCMs, as it is closely linked to MRV and can be significantly influenced by the use of digital technologies — for instance, when it comes to meeting process-related objectives.

Activity 2, the definition of quality objectives and evaluation criteria, focuses on establishing minimum (or additional voluntary) quality requirements for MRV processes. Only once both the MRV processes and their associated quality objectives are fully understood does *Activity 3* commence, involving the pre-selection of potentially suitable digital technologies.

The systematic application of digital technologies in MRV may entail process modifications, such as the automation or parallelization of certain tasks, which are examined in *Activity 4*. Finally, *Activity 5* comprises the overall assessment and selection of the most appropriate digital technologies for MRV processes within VCMs.

Activity 1: Determination of MRV process boundaries

Technique: Activity 1 starts with defining the boundaries of the MRV process. This requires modelling all relevant process steps, tasks, and actors — either based on a chosen standard framework (if adopted) or on a self-defined scope. A standard framework is optional but can enhance credibility and simplify process definition. Process modelling then clarifies the “sphere of interest”, i.e., the tasks that users of the method intend to influence. Regulatory constraints (e.g., impartiality) may limit this scope.

Tool: Established process-modelling languages such as Business Process Modell and Notation (BPMN) or Unified Modelling Language (UML) can be used to visualize tasks, workflows, and

actor relationships. If needed, multi-criteria decision-making tools such as AHP or Multi-Attribute Utility Theory (MAUT) can support decisions regarding the inclusion of standard frameworks or additional voluntary tasks.

Role: The activity involves the process owner (e.g., organizations coordinating MRV on VCMs), key process participants (e.g., verifiers), and — where necessary — experts on VCM standards.

Output: A structured overview of the MRV process and the defined scope of analysis (see Figure 4.3).

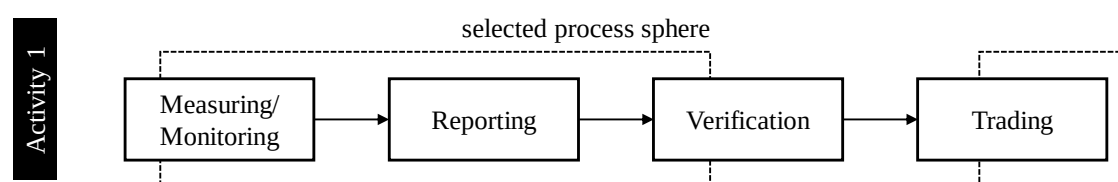


Figure 4.3: Activity 1; Source: Research paper #6

Activity 2: Determination of quality objectives and evaluation criteria

Technique: Activity 2 focuses on defining minimum and (optionally) additional quality objectives for MRV processes, aligned with or exceeding the selected standard framework. To later assess whether these objectives are met through digital technologies, users define evaluation criteria and may assign weightings to reflect varying importance across objectives or process steps (e.g., verification > reporting).

Tool: If quality objectives are not already defined within the organization, strategic tools such as Political, Economic, Social, Technological, Environmental, and Legal (PESTEL) or Strengths, Weaknesses, Opportunities, and Threats (SWOT) can support their derivation. Feasibility and cost-benefit analyses help determine whether objectives are realistic and proportionate. Additional non-monetary value criteria may be considered where relevant.

Role: The activity is primarily conducted by the process owner, supported by top-level management and experts on VCM standards.

Output: A set of quality objectives (including voluntary additions, if applicable) and corresponding evaluation criteria (see Figure 4.4).

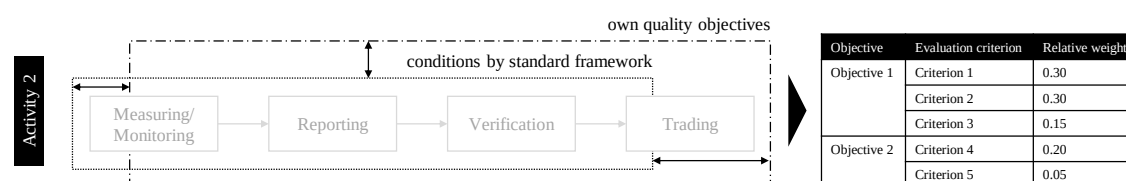


Figure 4.4: Activity 2; Source: Research paper #6

Activity 3: Pre-selection of suitable digital technologies

Technique: Based on the process model (Activity 1) and quality objectives (Activity 2), Activity 3 defines minimum technical and functional requirements for digital technologies. Only technologies that meet these requirements and support the defined MRV tasks are shortlisted.

Tool: A structured requirements analysis is recommended before shortlisting technologies. This includes documenting mandatory features from both a process and user perspective to ensure requirements are specific, measurable, and relevant.

Role: The process owner specifies and oversees the requirements. Technology experts identify and evaluate digital technologies against them.

Output: A preliminary list of digital technologies suitable for enhancing or extending MRV processes (see Figure 4.5).

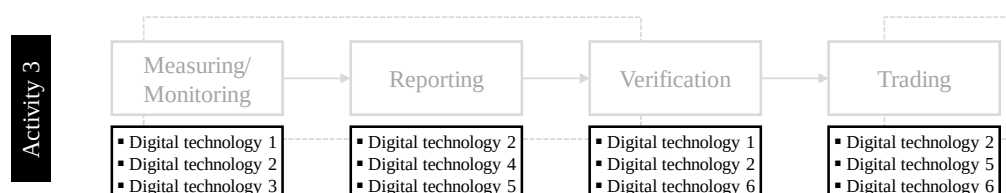


Figure 4.5: Activity 3; Source: Research paper #6

Activity 4: Determination of process change

Technique: Activity 4 evaluates how digital technologies affect the MRV value chain. Technologies are combined into “vectors” across process steps to assess potential changes. If the number of options is large, vectors may be reduced to a manageable subset. Comparative analysis of the process before and after adoption determines whether a vector meaningfully improves quality objectives. Vectors with insufficient impact are discarded.

Tools: Technology vectors can be modelled using the same process modelling language as in Activity 1. If necessary, multi-criteria decision analysis helps reduce combinations. Design thinking workshops may support qualitative assessment of desirability and feasibility.

Role: The process owner and MRV participants assess process impacts, while prospective users and business development provide input on usability and business relevance.

Output: A shortlist of viable technology vectors for final evaluation (see Figure 4.6).

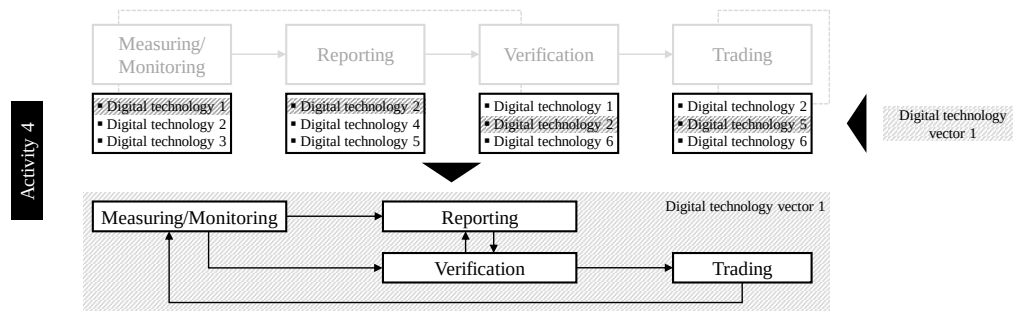


Figure 4.6: Activity 4; Source: Research paper #6

Activity 5: Final assessment of digital technology vector

Technique: Activity 5 selects the final technology vector by evaluating how each shortlisted option impacts the quality criteria defined in Activity 2. Users assess whether and to what extent each vector improves the MRV process. The highest-scoring vector is selected.

Tools: Multi-criteria decision analysis (e.g., pairwise comparison) supports structured ranking of technology vectors.

Role: The decision is made jointly by the process owner, technology experts, and authorized management representatives.

Output: A final ranking of technology vectors, serving as decision support for digital technology adoption in MRV processes (see Figure 4.7).

Activity 5	Shortlist					
	Relative weight	Evaluation criterion	Vector 1	Vector 2	Vector 3	Vector 4
	0.30	Criterion 1	1	3	4	3
	0.30	Criterion 2	5	4	5	5
	0.15	Criterion 3	5	1	2	5
	0.20	Criterion 4	4	2	4	4
	0.05	Criterion 5	2	1	3	1
		Weighted Sum	3,45	2,70	3,95	4,00

Shortlist	Ranking
Vector 1	3.
Vector 2	4.
Vector 3	2.
Vector 4	1.

Figure 4.7: Activity 5; Source: Research paper #6

Research paper #6 evaluated the presented method through a case study with a German-Austrian start-up developing soil carbon sequestration offset credits for listing with Gold Standard (Sonnenberg & Vom Brocke, 2012; Yin, 2017). Soil carbon projects enhance humus content and involve specific tilling and crop rotation practices to increase soil carbon (Lal, 2004). The method was applied to design new MRV processes with four practitioners from the start-up over four workshops (2–5 hours each) and supplemented by seven follow-up expert interviews.

The case study assessed the method against ease of use, efficiency, generality, and operability (March & Smith, 1995; Sonnenberg & Vom Brocke, 2012). Workshops confirmed its practical value and broad applicability for digital technology selection in VCMs, requiring only minor adjustments. Expert interviews further refined specific tools, roles, and formulations within the method, resulting in the final, validated version.

5 Conclusion

Modern energy systems are undergoing a profound transition. On the one hand, the growing share of DER is making these systems increasingly decentralized, which can introduce complexity and potential reliability challenges compared to traditional centralized grids. On the other hand, sustainability has become a guiding principle, driven by the need to conserve natural resources and ensure a livable planet for future generations. To address both challenges — the integration of DER and the pursuit of sustainability goals — digital technologies play a crucial enabling role. Among others, they support real-time monitoring, predictive maintenance, automated control, and data-driven decision-making, helping to maintain system stability while accelerating the shift toward cleaner and more resilient energy infrastructures.

Next to the infrastructure perspective, digital technologies also have the potential to fundamentally transform energy markets. For instance, consumers can turn into active market participants, as digital technologies enable the coordination of a much higher number of actors and transactions within increasingly short time intervals. Automated trading by household IoT devices is one concrete example. Additionally, new market roles are emerging – such as prosumers who sell surplus energy via P2P platforms or within local energy markets. Digital technologies further support the practical implementation of incentive schemes in energy markets, particularly for flexibility trading. As described in this dissertation, regulatory amendments are an important foundation for creating economic incentives — for example, through amended grid charges or the establishment of LFMs. However, regulatory adjustments alone are often insufficient to trigger real behavioural change. As demonstrated in the cases of grid charges and local flexibility trading, removing obstacles does not automatically lead to participation.

This is where digital technologies become essential: they translate regulatory incentives into tangible opportunities. They make economic rewards transparent and measurable, lower entry barriers through automation, and provide platforms on which flexibility or surplus energy can be traded in practice. In this way, digital technologies are not merely supportive tools but key enablers for turning market design into market reality — and thus indispensable for re-thinking energy markets in times of the energy transition.

5.1 Summary

This cumulative dissertation integrates the perspectives of a more decentralized and sustainable energy landscape with the evolution of modern, state-of-the-art digital technologies. It addresses current challenges that arise from these developments, e.g., in energy markets, and proposes possible solution approaches for market design and regulation assisted by digital technologies.

Research papers #1 and #2 focus on the decentralization of energy assets, as an increasing number of actors enter energy systems and markets as active participants. This contrasts with the

traditional model of centralized energy generation and distribution, where most consumers were passive. Research paper #1 offers a definition for such "consumer-centric" market design, thereby re-thinking existing market structures. The rise of active consumers and further decentralized assets introduces new challenges for energy system resilience and its continuous monitoring. The resilience index developed in research paper #2 provides a valuable starting point in addressing this challenge.

Research papers #3 and #4 concentrate more on the sustainability aspect of energy systems. They highlight the critical role of energy flexibility in integrating "green" energy technologies such as RES. Flexibility can also support the integration of further DER like IoT devices, electric vehicles, or storage systems, thereby linking back to the challenges of decentralization. Both research papers approach the topic from regulatory and market design perspectives, offering concrete policy implications through adjustments to frameworks like the StromNEV and EnWG.

Finally, research papers #5 and #6 introduce the digitization perspective. They provide concrete suggestions to implementing incentive schemes in energy markets and making rewards transparent. For instance, the proposed algorithm for flexibility trading continuously tracks rewards within an AI-based framework, providing direct monetary feedback to users. Likewise, the systematic selection of digital technologies in MRV processes ensures that participation in voluntary offsetting schemes is reliable, traceable, and credible for companies or other prospective traders.

5.2 Limitations and Outlook

Notwithstanding the contributions of this dissertation, several limitations should be acknowledged. First, the scope of this work is naturally constrained. For instance, the decentralization perspective primarily addresses the challenges associated with this development, rather than its potential benefits. In fact, decentralization could positively impact system resilience by reducing concentration and associated vulnerabilities of critical infrastructures. Similarly, the sustainability perspective is largely incentive-focused, leaving aside other relevant factors such as technological improvements in energy technologies or infrastructures, including carbon-capture technologies in industrial facilities or more energy-efficient consumer devices. Finally, the digitization perspective is limited to selected technologies, particularly AI, and specific applications, such as VCMs.

Second, the regulatory amendments proposed in this dissertation need to be tested in practice and carefully monitored for potential misuse. For example, the implementation of LFM may not only incentivize flexibility provision but also give rise to so-called "inc-dec" gaming (see Section 3.2.3). Such behaviour could undermine the stability of energy systems, posing risks to society while benefiting individual actors financially. Similarly, rewarding flexibility provision may lead market participants to overstate their contributions, for instance by misreporting baseline values or exaggerating the amount of flexibility provided. To address these risks, market authorities must evolve alongside regulatory frameworks and their potential exploitation to ensure proper enforcement and safeguard system integrity.

Third, the application of digital technologies in critical infrastructures like energy systems must be carefully handled. Quite obviously, digital technologies pose new vulnerabilities to the system, e.g., by providing intrusion points for cyber attacks. Additionally, digital technologies may evolve in ways not intended by their users or regulators. For instance, as energy market trades are increasingly carried out autonomously via “smart” devices, algorithms may identify strategies that maximize their own rewards while operating in legal gray areas. One notable example is “algorithmic collusion”, where algorithms anticipate and mirror the actions of other algorithms to collectively increase gains, akin to the classic prisoner’s dilemma. While not explicitly illegal, such behaviour can distort market outcomes and artificially inflate prices for traded commodities, such as energy flexibility.

In light of these limitations, future work could broaden the scope of this dissertation to related research fields. For instance, the incentive-based economic perspective on the flexible use of energy technologies could be complemented by engineering research, focusing on the development and evolution of these technologies. Furthermore, the regulatory adjustments proposed in this dissertation should be empirically tested in experimental settings, drawing on insights from behavioural economics. Finally, the application of digital technologies in autonomous energy trading warrants careful evaluation regarding cybersecurity and intended performance, for example, within controlled digital and regulatory “sandbox” environments.

Use of writing assistance Please note that I have utilized various writing assistance software programs (e.g., ChatGPT, DeepL, and Grammarly) to enhance the language and readability of this work. Nevertheless, I take full responsibility for its content and have thoroughly reviewed and edited the material as necessary.

Bibliography

- Aczél, J., & Saaty, T. L. (1983). Procedures for synthesizing ratio judgements. *Journal of Mathematical Psychology*, 27(1), 93–102.
- Ahmad, T., & Zhang, D. (2021). Using the internet of things in smart energy systems and networks. *Sustainable Cities and Society*, 68, 102783.
- Ahmadi, S., Saboohi, Y., & Vakili, A. (2021). Frameworks, quantitative indicators, characters, and modeling approaches to analysis of energy system resilience: A review. *Renewable and Sustainable Energy Reviews*, 144.
- Akerlof, G. A. (1978). The market for ‘lemons’. In P. Diamond & M. Rothschild (Eds.), *Uncertainty in economics* (pp. 235–251). Academic Press.
- Alexander, D. E. (2013). Resilience and disaster risk reduction: An etymological journey. *Natural Hazards and Earth System Sciences*, 13(11), 2707–2716.
- Arbolea, P., Kippke, M. A., & Kerscher, S. (2022). Flexibility management in the low-voltage distribution grid as a tool in the process of decarbonization through electrification. *Energy Reports*, 8, 248–256.
- Arghandeh, R., von Meier, A., Mehrmanesh, L., & Mili, L. (2016). On the definition of cyber-physical resilience in power systems. *Renewable and Sustainable Energy Reviews*, 58, 1060–1069.
- Avancini, D. B., Rodrigues, J. J., Martins, S. G., Rabêlo, R. A., Al-Muhtadi, J., & Solic, P. (2019). Energy meters evolution in smart grids: A review. *Journal of cleaner production*, 217, 702–715.
- Badami, M., Fambri, G., Mancò, S., Martino, M., Damousis, I. G., Agtzidis, D., & Tzouvaras, D. (2020). A decision support system tool to manage the flexibility in renewable energy-based power systems. *Energies*, 13(1), 153.
- Bajwa, A., Mokhlis, H., Mekhilef, S., & Mubin, M. (2019). Enhancing power system resilience leveraging microgrids: A review. *Journal of Renewable and Sustainable Energy*, 11.
- Bañales, S. (2020). The enabling impact of digital technologies on distributed energy resources integration. *Journal of Renewable and Sustainable Energy*, 12(4), 045301.
- Barth, L., Hagenmeyer, V., Ludwig, N., & Wagner, D. (2018). How much demand side flexibility do we need? analyzing where to exploit flexibility in industrial processes. *Proceedings of the Ninth International Conference on Future Energy Systems*, 43–62.

- Baumgärtner, S., & Strunz, S. (2014). The economic insurance value of ecosystem resilience. *Ecological Economics*, 101, 21–32.
- Beheshti, Z., & Shamsuddin, S. M. H. (2013). A review of population-based meta-heuristic algorithms. *Int. J. Adv. Soft Comput. Appl*, 5(1), 1–35.
- Belton, V. (1986). A comparison of the analytic hierarchy process and a simple multi-attribute value function. *European Journal of Operational Research*, 26(1), 7–21.
- Bergaentzle, C., & Gunkel, P. A. (2022). Cross-sector flexibility, storage investment and the integration of renewables: Capturing the impacts of grid tariffs. *Energy Policy*, 164, 112937.
- Bergaentzlé, C., Jensen, I. G., Skytte, K., & Olsen, O. J. (2019). Electricity grid tariffs as a tool for flexible energy systems: A danish case study. *Energy Policy*, 126, 12–21.
- Beyza, J., & Yusta, J. M. (2022). Characterising the security of power system topologies through a combined assessment of reliability, robustness, and resilience. *Energy Strategy Reviews*, 43, 100944.
- Bhusal, N., Abdelmalak, M., Kamruzzaman, M., & Benidris, M. (2020). Power system resilience: Current practices, challenges, and future directions. *IEEE Access*, 8, 18064–18086.
- Bichler, M., Buhl, H. U., Knörr, J., Maldonado, F., Schott, P., Waldherr, S., et al. (2022). Electricity markets in a time of change: A call to arms for business research. *Schmalenbach Journal of Business Research*, 74(1), 77–102. <https://doi.org/10.1007/s41471-021-00126-4>
- Bogensperger, A., Zeislmair, A., & Faller, S. (2019). Flexibilität in der niederspannung: Plattform oder eigenes system. *Energiewirtschaftliche Tagesfragen*, 69(11), 19–22.
- Bons, M., Creutzburg, P., & Schlemme, J. (2019). Energiewende in der industrie. potenziale und wechselwirkungen mit dem energiesektor [Abgerufen am 07.04.2022]. https://www.bmwi.de/Redaktion/DE/Downloads/E/energiewende-in-der-industrie-ap2b-executive-summary.pdf?__blob=publicationFile&v=4
- Bouloumpasis, I., & Steen, D. (2019). Congestion management using local flexibility markets: Recent development and challenges. *2019 IEEE PES Innovative Smart Grid Technologies Europe (ISGT-Europe)*, 1–5.
- Braun, C., Wortmann, F., Hafner, M., & Winter, R. (2005). Method construction-a core approach to organizational engineering. *Proceedings of the 2005 ACM Symposium on Applied Computing*, 1295–1299.
- Bundesgesetzblatt / Federal Law Gazette. (2021, July). Gesetz zur umsetzung unionsrechtlicher vorgaben und zur regelung reiner wasserstoffnetze im energiewirtschaftsrecht (novellierung des energiewirtschaftsgesetzes) [Inkrafttreten: 26.07.2021]. https://www.bgbl.de/xaver/bgbl/start.xav?startbk=Bundesanzeiger_BGBl&jumpTo=bgbl121s3026.pdf
- Cadez, S., Czerny, A., & Letmathe, P. (2019). Stakeholder pressures and corporate climate change mitigation strategies. *Business Strategy and the Environment*, 28(1), 1–14.
- Cao, D., Hu, W., Xu, X., Dragičević, T., Huang, Q., Liu, Z., Chen, Z., & Blaabjerg, F. (2020). Bidding strategy for trading wind energy and purchasing reserve of wind power producer—a drl based approach. *International Journal of Electrical Power & Energy Systems*, 117, 105648.
- Chanda, S., & Srivastava, A. K. (2016). Defining and enabling resiliency of electric distribution systems with multiple microgrids. *IEEE Transactions on Smart Grid*, 7(6), 2859–2868.

- Comello, S., Reichelstein, J., & Reichelstein, S. (2023). Corporate carbon reporting: Improving transparency and accountability. *One Earth*, 6(7), 803–810.
- Conejo, A. J., & Sioshansi, R. (2018). Rethinking restructured electricity market design: Lessons learned and future needs. *International Journal of Electrical Power and Energy Systems*, 98, 520–530. <https://doi.org/10.1016/j.ijepes.2017.12.014>
- Cramton, P. (2022). Local flexibility market. econtribute discussion paper [Abgerufen am 19.07.2023]. <https://www.econstor.eu/handle/10419/262344>
- Cramton, P. (2017). Electricity market design. *Oxford Review of Economic Policy*, 33(4).
- Dall’Anese, E., Mancarella, P., & Monti, A. (2017). Unlocking flexibility: Integrated optimization and control of multienergy systems. *IEEE Power and Energy Magazine*, 15(1), 43–52.
- Das, L., Munikoti, S., Natarajan, B., & Srinivasan, B. (2020). Measuring smart grid resilience: Methods, challenges and opportunities. *Renewable and Sustainable Energy Reviews*, 130.
- Defeuilley, C. (2019). Energy transition and the future (s) of the electricity sector. *Utilities Policy*, 57, 97–105.
- Denner, M. S., Püschel, L. C., & Röglinger, M. (2018). How to exploit the digitalization potential of business processes. *Business & Information Systems Engineering*, 60, 331–349.
- Devaraj, J., Madurai Elavarasan, R., Shafiullah, G., Jamal, T., & Khan, I. (2021). A holistic review on energy forecasting using big data and deep learning models. *International journal of energy research*, 45(9), 13489–13530.
- Eid, C., Codani, P., Chen, Y., Perez, Y., & Hakvoort, R. (2015). Aggregation of demand side flexibility in a smart grid: A review for european market design. *2015 12th International Conference on the European Energy Market (EEM)*, 1–5.
- Eid, C., Codani, P., Perez, Y., Reneses, J., & Hakvoort, R. (2016). Managing electric flexibility from distributed energy resources: A review of incentives for market design. *Renewable and Sustainable Energy Reviews*, 64, 237–247.
- El Gibari, S., Gómez, T., & Ruiz, F. (2019). Building composite indicators using multicriteria methods: A review. *Journal of Business Economics*, 89(1), 1–24.
- Emiliozzi, S., Ferriani, F., & Gazzani, A. (2025). The european energy crisis and the consequences for the global natural gas market. *The Energy Journal*, 46(1), 119–145.
- Emina, K. A. (2021). Sustainable development and the future generations. *Social Sciences, Humanities and Education Journal (SHE Journal)*, 2(1), 57–71.
- enera. (2023). Flexibilitätsmärkte für die netzdienliche nutzung – energiezukunft mit enera: Ziele und erkenntnisse [Abgerufen am 19.07.2023]. <https://projekt-enera.de/ueber-enera/>
- Esmat, A., Pinson, P., & Usaola, J. (2017). Decision support program for congestion management using demand side flexibility. *2017 IEEE Manchester PowerTech*, 1–6.
- European Commission. (2011). Third legislative package for an internal EU gas and electricity market [Accessed on 18.09.2025]. https://ec.europa.eu/commission/presscorner/detail/en/memo_11_125
- European Commission. (2019a). The european green deal. Retrieved September 28, 2023, from https://ec.europa.eu/info/strategy/priorities-2019-2024/european-green-deal_en

- European Commission. (2019b, June). Regulation (eu) 2019/943 of the european parliament and of the council of 5 june 2019 on the internal market for electricity (recast) [Electricity Regulation]. <https://eur-lex.europa.eu/eli/reg/2019/943/oj>
- European Commission. (2021). 'Fit for 55': delivering the EU's 2030 Climate Target on the way to climate neutrality [Accessed on 18.09.2025]. <https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:52021DC0550>
- European Commission. (2025). Fact Sheet: Internal energy market [Accessed on 18.09.2025]. <https://www.europarl.europa.eu/factsheets/en/sheet/45/internal-energy-market>
- Feulner, S., Guggenberger, T., Stoetzer, J. C., & Urbach, N. (2022). Shedding light on the blockchain disintermediation mystery: A review and future research agenda. *European Conference on Information Systems*.
- Freier, J., Arnold, M., & Hesselbach, J. (2019). Introduction of an approach to develop dynamic electricity prices for residential customers. *2019 16th International Conference on the European Energy Market (EEM)*, 1–6.
- Fridgen, G., Keller, R., Körner, M.-F., & Schöpf, M. (2020). A holistic view on sector coupling. *Energy Policy*, 147, 111913.
- Gao, Y., Zhou, X., Ren, J., Wang, X., & Li, D. (2018). Double layer dynamic game bidding mechanism based on multi-agent technology for virtual power plant and internal distributed energy resource. *Energies*, 11(11), 3072.
- Gao, Z.-K., Liu, A.-A., Wang, Y., Small, M., Chang, X., & Kurths, J. (2021). IEEE Access Special Section Editorial: Big Data Learning and Discovery. *IEEE Access*, 9, 158064–158073.
- Gasser, P., Lustenberger, P., Cinelli, M., Kim, W., Spada, M., Burgherr, P., Hirschberg, S., Stojadinovic, B., & Sun, T. Y. (2021). A review on resilience assessment of energy systems. *Sustainable and Resilient Infrastructure*, 6(5), 273–299.
- Gasser, P., Suter, J., Cinelli, M., Spada, M., Burgherr, P., Hirschberg, S., Kadziński, M., & Stojadinović, B. (2020). Comprehensive resilience assessment of electricity supply security for 140 countries. *Ecological Indicators*, 110.
- Glachant, J.-M., & Ruester, S. (2014). The eu internal electricity market: Done forever? *Utilities Policy*, 31, 221–228.
- Golmohamadi, H., Larsen, K. G., Jensen, P. G., & Hasrat, I. R. (2021). Optimization of power-to-heat flexibility for residential buildings in response to day-ahead electricity price. *Energy and Buildings*, 232, 110665.
- González, A. Y. R., Alonso, M. P., Lezama, F., Rodríguez, L., de Cote, E. M., Morales, E. F., Sucar, L. E., & Crockett, D. D. (2019). A competitive and profitable multi-agent autonomous broker for energy markets. *Sustainable Cities and Society*, 49, 101590.
- Granados, N., & Gupta, A. (2013). Transparency strategy: Competing with information in a digital world. *MIS Quarterly*, 37(2), 637–641.
- Greco, S., Ishizaka, A., Tasiou, M., & Torrisi, G. (2019). On the methodological framework of composite indices: A review of the issues of weighting, aggregation, and robustness. *Social Indicators Research*, 141, 61–94.

- Greenfield, P., Ambrose, J., & Ormesher, E. (2023). Adverts claiming products are carbon neutral by using offsetting face uk ban. Retrieved March 8, 2024, from <https://www.theguardian.com/environment/2023/may/15/uk-advertising-watchdog-to-crack-down-on-carbon-offsetting-claims-aoe>
- Grigoroudis, E., Kouikoglou, V. S., Phillis, Y. A., & Kanellos, F. D. (2021). Energy sustainability: A definition and assessment model. *Operational Research*, 21(3), 1845–1885.
- Grober, U. (2017). Eternal forest, sustainable use: The making of the term “nachhaltig” in seventeenth- and eighteenth-century german forestry. In *Routledge handbook of the history of sustainability* (pp. 96–105). Routledge.
- Groissböck, M., & Gusmão, A. (2020). Impact of renewable resource quality on security of supply with high shares of renewable energies. *Applied Energy*, 277, 115567.
- Hack, T., Ma, Z., & Jørgensen, B. N. (2021). Digitalisation potentials in the electricity ecosystem: Lesson learnt from the comparison between germany and denmark. *Energy Informatics*, 4(Suppl 2), 27.
- Hartmann, S., & Thomas, S. (2020). Applying blockchain to the australian carbon market. *Economic Papers: A Journal of Applied Economics and Policy*, 39(2), 133–151.
- Heffron, R., Körner, M.-F., Wagner, J., Weibelzahl, M., & Fridgen, G. (2020). Industrial demand-side flexibility: A key element of a just energy transition and industrial development. *Applied Energy*, 269, 115026.
- Hennig, R. J., de Vries, L. J., & Tindemans, S. H. (2023). Congestion management in electricity distribution networks: Smart tariffs, local markets and direct control. *Utilities Policy*, 85, 101660.
- Herold, D. M., Farr-Wharton, B., Lee, K.-H., & Groschopf, W. (2019). The interaction between institutional and stakeholder pressures: Advancing a framework for categorising carbon disclosure strategies. *Business Strategy & Development*, 2(2), 77–90.
- Hevner, A. R., March, S. T., Park, J., & Ram, S. (2008). Design science in information systems research. *MIS Quarterly*, 28(1), 6.
- Hirth, L., & Schlecht, I. (2019). Market-based redispatch in zonal electricity markets: Inc-dec gaming as a consequence of inconsistent power market design (not market power) [Abgerufen am 19.07.2023]. <https://www.econstor.eu/bitstream/10419/194292/1/Market-Based-Redispatch-in-Zonal-Electricity-Markets.pdf>
- Hirth, L., Schlecht, I., Maurer, C., & Teerstegen, B. (2019). Kosten- oder marktbasiert? zukünftige redispatchbeschaffung in deutschland. schlussfolgerungen aus dem vorhaben „untersuchung zur beschaffung von redispatch“ [Abgerufen am 19.07.2023]. <https://www.bmwk.de/Redaktion/DE/Publikationen/Studien/zukuenftige-redispatch-beschaffung-in-deutschland.html>
- Hosseini, S., Barker, K., & Ramirez-Marquez, J. E. (2016). A review of definitions and measures of system resilience. *Reliability Engineering & System Safety*, 145, 47–61.
- Immonen, A., & Kalaoja, J. (2019). Requirements of an energy data ecosystem. *IEEE access*, 7, 111692–111708.

- Jahns, C., Stein, T., Höckner, J., & Weber, C. (2023). Prevention of strategic behaviour in local flexibility markets using market monitoring—concept, application example and limitations. *Energy Policy*, 174, 113427.
- Jasiūnas, J., Lund, P. D., & Mikkola, J. (2021). Energy system resilience – A review. *Renewable and Sustainable Energy Reviews*, 150.
- Jin, X., Wu, Q., & Jia, H. (2020). Local flexibility markets: Literature review on concepts, models and clearing methods. *Applied Energy*, 261, 114387.
- Joint Research Centre of the European Commission. (2008). *Handbook on constructing composite indicators: Methodology and user guide*. OECD publishing, Paris (France).
- Jufri, F. H., Widiputra, V., & Jung, J. (2019). State-of-the-art review on power grid resilience to extreme weather events: Definitions, frameworks, quantitative assessment methodologies, and enhancement strategies. *Applied Energy*, 239(100), 1049–1065.
- Karumba, S., Sethuvenkatraman, S., Dedeoglu, V., Jurdak, R., & Kanhere, S. S. (2023). Barriers to blockchain-based decentralised energy trading: A systematic review. *International Journal of Sustainable Energy*, 42(1), 41–71.
- Khorasany, M., Gazafroudi, A. S., Razzaghi, R., Morstyn, T., & Shafie-khah, M. (2022). A framework for participation of prosumers in peer-to-peer energy trading and flexibility markets. *Applied energy*, 314, 118907.
- Körner, M.-F., Bauer, D., Keller, R., Rösch, M., Schlereth, A., Simon, P., et al. (2019). Extending the automation pyramid for industrial demand response. *Procedia CIRP*, 81, 998–1003. <https://doi.org/10.1016/j.procir.2019.03.241>
- Kornrumpf, T., Meese, J., Zdrallek, M., Neusel-Lange, N., & Roch, M. (2016). Economic dispatch of flexibility options for grid services on distribution level. *2016 Power Systems Computation Conference (PSCC)*, 1–7.
- Kotsialou, G., Kuralbayeva, K., & Laing, T. (2022). Blockchain's potential in forest offsets, the voluntary carbon markets and redd+. *Environmental Conservation*, 49(3), 137–145.
- Krasikov, P., & Legner, C. (2023). Introducing a data perspective to sustainability: How companies develop data sourcing practices for sustainability initiatives. *Communications of the Association for Information Systems*, 53(1), 162–188.
- Kreibich, N., & Hermwille, L. (2021). Caught in between: Credibility and feasibility of the voluntary carbon market post-2020. *Climate Policy*, 21(7), 939–957.
- Lahsen, M., & Ribot, J. (2022). Politics of attributing extreme events and disasters to climate change. *Wiley Interdisciplinary Reviews: Climate Change*, 13(1), e750.
- Lal, R. (2004). Soil carbon sequestration to mitigate climate change. *Geoderma*, 123(1-2), 1–22.
- Lange, K., & Hofmann, N. (2022). Nutzung von flexibilitätpotentialen auf verteilernetzebene nach der reform des enwg vom juli 2021. *N&R*, (01), 13–18.
- Lehner, A. (2023). Mrv for durable carbon removals within the eu carbon removal certification framework (crcf). Retrieved March 16, 2024, from https://assets-global.website-files.com/64c2561d5d66d4d06dc24d47/653129e1e7c34db4daf25559_MRV_for_durable_carbon_removals_within_the_EU_carbon_removal_certification_framework.pdf

- Lezama, F., Soares, J., & Vale, Z. (2019). Optimal bidding in local energy markets using evolutionary computation. *2019 20th International Conference on Intelligent System Application to Power Systems (ISAP)*, 1–6.
- Liang, Y., Guo, C., Ding, Z., & Hua, H. (2020). Agent-based modeling in electricity market using deep deterministic policy gradient algorithm. *IEEE Transactions on Power Systems*, 35(6), 4180–4192.
- Lu, Y., Khan, Z. A., Alvarez-Alvarado, M. S., Zhang, Y., Huang, Z., & Imran, M. (2020). A critical review of sustainable energy policies for the promotion of renewable energy sources. *Sustainability*, 12(12), 5078.
- Malceniece, L., Malcenieks, K., & Putniņš, T. J. (2019). High frequency trading and comovement in financial markets. *Journal of Financial Economics*, 134(2), 381–399.
- March, S. T., & Smith, G. F. (1995). Design and natural science research on information technology. *Decision Support Systems*, 15(4), 251–266.
- Masiello, R., Pandey, S., Chatterjee, D., Harper, A., Jackson, A., & Takayesu, E. (2024). Understanding grid flexibility: Flexibility for integrated grid planning with distributed energy resources. *IEEE Power and Energy Magazine*, 22(2), 60–66.
- May, K. O. (1954). Intransitivity, utility, and the aggregation of preference patterns. *Econometrica: Journal of the Econometric Society*, 1–13.
- Mazziotta, M., & Pareto, A. (2013). Methods for constructing composite indices: One for all or all for one. *Rivista Italiana di Economia Demografia e Statistica*, 67(2), 67–80.
- McConnell, A. (2015). What is policy failure? a primer to help navigate the maze. *Public Policy and Administration*, 30(3-4), 221–242.
- Molyneaux, L., Brown, C., Wagner, L., & Foster, J. (2016). Measuring resilience in energy systems: Insights from a range of disciplines. *Renewable and Sustainable Energy Reviews*, 59, 1068–1079.
- Moreno, R., Street, A., Arroyo, J. M., & Mancarella, P. (2017). Planning low-carbon electricity systems under uncertainty considering operational flexibility and smart grid technologies. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, 375(2100), 20160305.
- Moustakas, K., Loizidou, M., Rehan, M., & Nizami, A. (2020). A review of recent developments in renewable and sustainable energy systems: Key challenges and future perspective.
- Nadkarni, S., & Prügl, R. (2021). Digital transformation: A review, synthesis and opportunities for future research. *Management Review Quarterly*, 71, 233–341.
- Najarian, M., & Lim, G. J. (2019). Design and Assessment Methodology for System Resilience Metrics. *Risk Analysis*, 39(9), 1885–1898.
- National Academies of Sciences. (2017). Enhancing the Resilience of the Nation's Electricity System.
- Neuteleers, S., Mulder, M., & Hindriks, F. (2017). Assessing fairness of dynamic grid tariffs. *Energy Policy*, 108, 111–120.
- O'brien, R. M. (2007). A caution regarding rules of thumb for variance inflation factors. *Quality & quantity*, 41, 673–690.

- OCELL GmbH. (2023). Forstmanagement. Retrieved June 6, 2023, from <https://www.ocell.io/forest>
- Oduro, P., Uzougbo, N., & Ugwu, M. (2024). Renewable energy expansion: Legal strategies for overcoming regulatory barriers and promoting innovation. *International Journal of Applied Research in Social Sciences*, 6(5), 927–944.
- Öko-Institut e.V. (2022). *Das technische flexibilitätspotenzial im stromsystem bis zum jahr 2050*. <https://www.flickr.com/photos/oekoinstitut/51971887527/in/photostream/>
- Olivella-Rosell, P., Bullich-Massagué, E., Aragüés-Peñalba, M., Sumper, A., Ottesen, S. Ø., Vidal-Clos, J., & Villafáfila-Robles, R. (2018). Optimization problem for meeting distribution system operator requests in local flexibility markets with distributed energy resources. *Applied Energy*, 210, 881–895.
- Olivella-Rosell, P., Lloret-Gallego, P., Munné-Collado, Í., Villafáfila-Robles, R., Sumper, A., Ottesen, S. Ø., et al. (2018). Local flexibility market design for aggregators providing multiple flexibility services at distribution network level. *Energies*, 11(4), 822.
- Ottesen, S. Ø., Tomasgard, A., & Fleten, S.-E. (2018). Multi market bidding strategies for demand side flexibility aggregators in electricity markets. *Energy*, 149, 120–134.
- Özdemir, Ö., Hobbs, B. F., van Hout, M., & Koutstaal, P. R. (2020). Capacity vs energy subsidies for promoting renewable investment: Benefits and costs for the eu power market. *Energy Policy*, 137, 111166.
- Painuly, J. P., & Wohlgemuth, N. (2021). Renewable energy technologies: Barriers and policy implications. In *Renewable-energy-driven future* (pp. 539–562). Elsevier.
- Papaefthymiou, G., Haesen, E., & Sach, T. (2018). Power system flexibility tracker: Indicators to track flexibility progress towards high-res systems. *Renewable energy*, 127, 1026–1035.
- Parag, Y., & Sovacool, B. K. (2016). Electricity market design for the prosumer era. *Nature energy*, 1(4), 1–6.
- Park, S.-W., Zhang, Z., Li, F., & Son, S.-Y. (2021). Peer-to-peer trading-based efficient flexibility securing mechanism to support distribution system stability. *Applied Energy*, 285, 116403.
- Pedro, A., Krutnik, M., Yadack, V. M., Pereira, L., & Morais, H. (2023). Opportunities and challenges for small-scale flexibility in european electricity markets. *Utilities Policy*, 80, 101477.
- Pelka, S., Chappin, E., Klobasa, M., & de Vries, L. (2022). Participation of active consumers in the electricity system: Design choices for consumer governance. *Energy Strategy Reviews*, 44, 100992.
- Penttinen, S.-L. (2020). Energy market liberalisation: From monopolistic to traded markets in the european union. In *Routledge handbook of energy law* (pp. 77–89). Routledge.
- Pepermans, G. (2019). European energy market liberalization: Experiences and challenges. *International Journal of Economic Policy Studies*, 13(1), 3–26.
- Pina Technologies GmbH. (2023). How pina earth makes forests future-proof. Retrieved June 6, 2023, from <https://www.pina.earth/en/concept>
- Ramos, A., De Jonghe, C., Gómez, V., & Belmans, R. (2016). Realizing the smart grid's potential: Defining local markets for flexibility. *Utilities Policy*, 40, 26–35.

- Raoufi, H., Vahidinasab, V., & Mehran, K. (2020). Power systems resilience metrics: A comprehensive review of challenges and outlook. *Sustainability*, 12(22).
- Reddy, V. M. S., Subramanyam, B., & Kalavathi, M. S. (2017). Bidding strategy in south region day-ahead demand model by improved artificial bee colony algorithm. *International Journal of Power and Energy Conversion*, 8(2), 204–224.
- Reis, B. P., Martins, S. V., Fernandes Filho, E. I., Sarcinelli, T. S., Gleriani, J. M., Leite, H. G., & Halassy, M. (2019). Forest restoration monitoring through digital processing of high resolution images. *Ecological Engineering*, 127, 178–186.
- Resch, M., Bühler, J., Schachler, B., & Sumper, A. (2021). Techno-economic assessment of flexibility options versus grid expansion in distribution grids. *IEEE Transactions on Power Systems*, 36(5), 3830–3839.
- Richstein, J. C., & Hosseinioun, S. S. (2020). Industrial demand response: How network tariffs and regulation (do not) impact flexibility provision in electricity markets and reserves. *Applied Energy*, 278, 115431.
- Rinaldi, A., Yilmaz, S., Patel, M. K., & Parra, D. (2022). What adds more flexibility? an energy system analysis of storage, demand-side response, heating electrification, and distribution reinforcement. *Renewable and Sustainable Energy Reviews*, 167, 112696.
- Rodrigues, L., Coelho, F., Mello, J., & Villar, J. (2025). Digital platforms to support the flexibility value chain, run flexibility markets, and manage energy communities. *Current Sustainable/Renewable Energy Reports*, 12(1), 15.
- Röpke, L. (2013). The development of renewable energies and supply security: A trade-off analysis. *Energy policy*, 61, 1011–1021.
- Ruggerio, C. A. (2021). Sustainability and sustainable development: A review of principles and definitions. *Science of the total environment*, 786, 147481.
- Saaty, T. L. (1990). How to make a decision: The analytic hierarchy process. *European Journal of Operational Research*, 48(1), 9–26.
- Saaty, T. L. (2001). *Decision making for leaders: The analytic hierarchy process for decisions in a complex world*. RWS publications.
- Saaty, T. L. (2008). Decision making with the analytic hierarchy process. *International Journal of Services Sciences*, 1(1), 83–98.
- Schäfer-Stradowsky, S., & Kalis, M. (2019). Innovationsgrad des energiewenderechts. *EnWZ*, (4), 104–110.
- Schletz, M., Franke, L. A., & Salomo, S. (2020). Blockchain application for the paris agreement carbon market mechanism—a decision framework and architecture. *Sustainability*, 12(12), 5069.
- Schober, P., Boer, C., & Schwarte, L. A. (2018). Correlation coefficients: Appropriate use and interpretation. *Anesthesia & Analgesia*, 126(5), 1763–1768.
- Schott, P., Sedlmeir, J., Strobel, N., Weber, T., Fridgen, G., & Abele, E. (2019). A generic data model for describing flexibility in power markets. *Energies*, 12(10). <https://eref.uni-bayreuth.de/49077/>

- Sedeh, O. M., & Ostadi, B. (2020). Optimization of bidding strategy in the day-ahead market by consideration of seasonality trend of the market spot price. *Energy Policy*, 145, 111740.
- Severin, Y., Mischinger, S., Müller, A., & Seidl, H. (2019). Regulatorischer handlungsbedarf zur erschließung und nutzung netzdienlicher flexibilität – dena-analyse [Abgerufen am 14.12.2022]. https://www.dena.de/fileadmin/dena/Publikationen/PDFs/2019/Dena-ANALYSE_Regulatorischer_Handlungsbedarf_zur_Erschliessung_und_Nutzung_netzdienlicher_Flexibilitaet.pdf
- Shah, D., & Chatterjee, S. (2020). Optimal genco's bidding strategy in a power exchange facilitating combined power and emission trading using intelligent programmed genetic algorithm. *International Transactions on Electrical Energy Systems*, 30(8), e12463.
- Shahzad, S., & Jasińska, E. (2024). Renewable revolution: A review of strategic flexibility in future power systems. *Sustainability*, 16(13), 5454.
- Sharifi, A., & Yamagata, Y. (2016). Principles and criteria for assessing urban energy resilience: A literature review. *Renewable and Sustainable Energy Reviews*, 60, 1654–1677.
- Sharifuddin, S. (2014). Methodology for quantitatively assessing the energy security of Malaysia and other southeast Asian countries. *Energy Policy*, 65, 574–582.
- Singh, S., & Singh, S. (2024). Advancements and challenges in integrating renewable energy sources into distribution grid systems: A comprehensive review. *Journal of Energy Resources Technology*, 146(9), 090801.
- Sipthorpe, A., Brink, S., Van Leeuwen, T., & Staffell, I. (2022). Blockchain solutions for carbon markets are nearing maturity. *One Earth*, 5(7), 779–791.
- Söder, L., Lund, P. D., Koduvere, H., Bolkesjø, T. F., Rossebø, G. H., Rosenlund-Soysal, E., Skytte, K., Katz, J., & Blumberga, D. (2018). A review of demand side flexibility potential in northern europe. *Renewable and Sustainable Energy Reviews*, 91, 654–664.
- Sokołowski, M. M., & Heffron, R. (2022). Defining and conceptualising energy policy failure: The when, where, why, and how. *Energy Policy*, 161, 112745. <https://doi.org/10.1016/j.enpol.2021.112745>
- Solomon, B. D., & Krishna, K. (2011). The coming sustainable energy transition: History, strategies, and outlook. *Energy policy*, 39(11), 7422–7431.
- Song, Z., Hackl, C. M., Anand, A., Thommessen, A., Petzschmann, J., Kamel, O., Braunbehrens, R., Kaifel, A., Roos, C., & Hauptmann, S. (2023). Digital twins for the future power system: An overview and a future perspective. *Sustainability*, 15(6), 5259.
- Sonnenberg, C., & Vom Brocke, J. (2012). Evaluations in the science of the artificial—reconsidering the build-evaluate pattern in design science research. *Design Science Research in Information Systems. Advances in Theory and Practice: 7th International Conference*.
- Steinbach, A. (2013). Barriers and solutions for expansion of electricity grids—the german experience. *Energy Policy*, 63, 224–229.
- Sun, G., Wang, X., Yang, L., Ma, B., He, L., & Zhang, R. (2020). A method for power suppliers' optimal cooperative bidding strategies considering network losses. *Global Energy Interconnection*, 3(4), 335–345.
- Sutton, R. S., & Barto, A. G. (2018). *Reinforcement learning: An introduction*. MIT press.

- Timperley, J. (2021). The fight to end fossil-fuel subsidies. *Nature*, 598(7881), 403–5.
- Torbaghan, S. S., Blaauwbroek, N., Nguyen, P., & Gibescu, M. (2016). Local market framework for exploiting flexibility from the end users. *2016 13th International Conference on the European Energy Market (EEM)*, 1–6.
- Toucan Toco. (2023). Api's overview. Retrieved October 30, 2023, from <https://public-api-docs.toucantoco.com/docs/intro>
- Tredgold, T. (1818). On the Transverse Strength of Timber. *The Philosophical Magazine: A Journal of Theoretical Experimental and Applied Physics*, Chapter XXXXVII.
- Tsangas, M., Zorpas, A. A., & Jeguirim, M. (2022). Sustainable renewable energy policies and regulations, recent advances, and challenges. *Renewable Energy Production and Distribution*, 449–465.
- Ukoba, K., Olatunji, K. O., Adeoye, E., Jen, T.-C., & Madyira, D. M. (2024). Optimizing renewable energy systems through artificial intelligence: Review and future prospects. *Energy & Environment*, 35(7), 3833–3879.
- Umunnakwe, A., Huang, H., Oikonomou, K., & Davis, K. (2021). Quantitative analysis of power systems resilience: Standardization, categorizations, and challenges. *Renewable and Sustainable Energy Reviews*, 149.
- United Nations. (2015). Transforming our world: The 2030 agenda for sustainable development [Accessed: 2025-10-06]. <https://sdgs.un.org/2030agenda>
- United Nations Framework Convention on Climate Change. (2015). Paris agreement [Accessed: 2025-10-06]. https://unfccc.int/sites/default/files/english_paris_agreement.pdf
- Urishev, B. (2019). Decentralized energy systems, based on renewable energy sources. *Applied Solar Energy*, 55(3), 207–212.
- Vanwersch, R. J., Shahzad, K., Vanderfeesten, I., Vanhaecht, K., Grefen, P., Pintelon, L., Mendling, J., van Merode, G. G., & Reijers, H. A. (2016). A critical evaluation and framework of business process improvement methods. *Business & Information Systems Engineering*, 58, 43–53.
- Villar, J., Bessa, R., & Matos, M. (2018). Flexibility products and markets: Literature review. *Electric Power Systems Research*, 154, 329–340.
- Vizjak, C. (2020). The role of algorithms in energy trading.
- Vugrin, E., Castillo, A., & Silva-Monroy, C. A. (2017). Resilience Metrics for the Electric Power System: A Performance-Based Approach.
- Wang, J.-J., Jing, Y.-Y., Zhang, C.-F., & Zhao, J.-H. (2009). Review on multi-criteria decision analysis aid in sustainable energy decision-making. *Renewable and Sustainable Energy Reviews*, 13(9), 2263–2278.
- Wang, W., & Yu, N. (2019). A machine learning framework for algorithmic trading with virtual bids in electricity markets. *2019 IEEE Power & Energy Society General Meeting (PESGM)*, 1–5.
- Wei, C., Li, C.-Z., Löschel, A., Managi, S., & Lundgren, T. (2023). Digital technology and energy sustainability: Recent advances, challenges, and opportunities.

- Weill, P., & Woerner, S. L. (2015). Thriving in an increasingly digital ecosystem. *MIT Sloan Management Review*.
- Wender, B. A., Morgan, M. G., & Holmes, K. J. (2017). Enhancing the resilience of electricity systems. *Engineering*, 3(5), 580–582.
- Winter, C., & Johnson, O. (2025). Facilitating a green future? permitting reforms and renewables on public lands. *Natural Resources & Environment*, 39(4), 4–8.
- Wongpiyabovorn, O., Plastina, A., & Crespi, J. M. (2023). Challenges to voluntary ag carbon markets. *Applied Economic Perspectives and Policy*, 45(2), 1154–1167.
- Woo, J., Kibert, C. J., Newman, R., Kachi, A. S. K., Fatima, R., & Tian, Y. (2020). A new blockchain digital MRV (measurement, reporting, and verification) architecture for existing building energy performance. *2nd Conference on Blockchain Research and Applications for Innovative Networks and Services (BRAINS) 2020*, 222–226.
- World Bank. (2022). *Digital monitoring, reporting, and verification systems and their application in future carbon markets*.
- Wu, F., Hu, H., Lin, H., & Ren, X. (2021). Enterprise digital transformation and capital market performance: Empirical evidence from stock liquidity. *Management World*, 37(7), 130–144.
- Wu, Y., Wu, Y., Cimen, H., Vasquez, J. C., & Guerrero, J. M. (2022). Towards collective energy community: Potential roles of microgrid and blockchain to go beyond p2p energy trading. *Applied Energy*, 314, 119003.
- Yang, X., Wang, X., Lu, Z., Liang, Z., Gu, C., & Li, F. (2024). Distribution network tariff design: Facilitate flexible resource under uncertain future energy scenarios. *Energy Policy*, 188, 114075.
- Yazdani, H., Doostizadeh, M., & Aminifar, F. (2022). Unlocking the value of flexibility of behind-the-meter prosumers: An overview of mechanisms to esteemed trends. *The Electricity Journal*, 35(5), 107126.
- Yin, R. K. (2017). *Case study research and applications: Design and methods, volume 5*. Sage publications.
- Zhang, S., May, D., Atrazhev, P., Gul, M., Leach, A., Weis, T., & Musilek, P. (2019). Etx: A flexible simulation framework for design of transactive energy systems. *2019 IEEE Canadian Conference of Electrical and Computer Engineering (CCECE)*, 1–4.
- Zhao, Q., Yu, P., Mahendran, R., Huang, W., Gao, Y., Yang, Z., Ye, T., Wen, B., Wu, Y., Li, S., et al. (2022). Global climate change and human health: Pathways and possible solutions. *Eco-Environment & Health*, 1(2), 53–62.

A Overview of research papers

A.1 Research papers included in this dissertation

Research Paper P1: Consumer-centric electricity markets: Six design principles

Michaelis, A., Hanny, L., Körner, M.-F., Strüker, J., & Weibelzahl, M. (2024). Consumer-centric electricity markets: Six design principles. *Renewable and Sustainable Energy Reviews* (VHB-JQ4¹: B)

Research Paper P2: Resilience, the long forgotten? Analyzing the Resilience of the German Electricity System

Hanny, L., Pichlmeier, M., & Weibelzahl, M. (n.d.). Resilience, the long forgotten? analyzing the resilience of the german electricity system [Submitted]. *Energy*

Research Paper P3: On the progress in flexibility and grid charges in light of the energy transition: The case of Germany

Hanny, L., Wagner, J., Buhl, H. U., Heffron, R., Körner, M.-F., Schöpf, M., & Weibelzahl, M. (2022). On the progress in flexibility and grid charges in light of the energy transition: The case of germany. *Energy Policy* (VHB-JQ3²: B)

Research Paper P4: Marktbasierter Flexibilitätseinsatz im Verteilnetz: aktuelle Herausforderungen und Lösungsvorschläge zur Umsetzung europarechtlicher Vorgaben

Hanny, L., Weibelzahl, M., Schöpf, M., & Hofmann, N. (2023). Marktbasierter Flexibilitätseinsatz im Verteilnetz: aktuelle Herausforderungen und Lösungsvorschläge zur Umsetzung europarechtlicher Vorgaben. *Zeitschrift für Umweltpolitik und Umweltrecht* (VHB-JQ3: B, VHB-JQ4: B)

Research Paper P5: How to trade electricity flexibility using artificial intelligence – an integrated algorithmic framework

Hanny, L., Körner, M.-F., Leinauer, C., Michaelis, A., Strüker, J., Weibelzahl, M., & Weissflog, J. (2022). How to trade electricity flexibility using artificial intelligence – an integrated algorithmic framework. In *HICSS 2022 Proceedings*. AIS Electronic Library (AISeL). https://aisel.aisnet.org/hicss-55/es/resilient_networks/4/ (VHB-JQ3: C, VHB-JQ4: B)

Research Paper P6: When voluntary carbon markets give you lemons, make lemonade: a method for selecting digital technologies in MRV processes

Leinauer, C., Hanny, L., Strüker, J., & Weibelzahl, M. (2024). When voluntary carbon markets give you lemons, make lemonade: A method for selecting digital technologies in mrv processes. In *ECIS 2024 Proceedings*. AIS Electronic Library (AISeL). https://aisel.aisnet.org/ecis2024/track12_digtrans/track12_digtrans/22 (VHB-JQ3: B)

¹VHB-JQ4: VHB Publication Media Rating 2024

²VHB-JQ3: VHB-JOURQUAL3

A.2 Index of further papers

Over the course of the dissertation, I also authored and co-authored the following research papers, studies, and reports. These papers are not part of this dissertation.

Ashour Novirdoust, A., Bichler, M., Bojung, C., Buhl, H. U., Fridgen, G., Gretschno, V., Hanny, L., Knörr, J., Maldonado, F., Neuhoﬀ, K., et al. (2021). Electricity spot market design 2030- 2050. <https://doi.org/10.24406/fit-n-621457>

Ahunbay, M. S., Ashour Novirdoust, A., Bhuiyan, R., Bichler, M., Bindu, S., Bjørndal, E., Bjørndal, M., Buhl, H. U., Chaves-Ávila, J. P., Gerard, H., et al. (2021). Electricity market design 2030-2050: Shaping future electricity markets for a climate-neutral europe. <https://doi.org/10.24406/fit-n-644366>

Ashour Novirdoust, A., Bhuiyan, R., Bichler, M., Buhl, H. U., Fridgen, G., Fugger, C., Gretschno, V., Hanny, L., Knörr, J., Neuhoﬀ, K., Neumann, C., Ott, M., Richstein, J. C., Rinck, M., Röhrich, F., Schöpf, M., Sitzmann, A., Wagner, J., & Weibelzahl, M. (2021). Electricity Market Design 2030-2050 : Moving Towards Implementation. <https://doi.org/10.24406/FIT-N-640928>

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. <https://eref.uni-bayreuth.de/id/eprint/71944>

Gimpel, H., Hanny, L., Ott, M., Wagner, J., Weibelzahl, M., Bichler, M., & Ober, S. (2021). Market success: The quest for the objectives and success factors of markets. In H. Gimpel, J. Krämer, D. Neumann, J. Pfeiffer, S. Seifert, T. Teubner, D. J. Veit, & A. Weidlich (Eds.), *Market engineering: Insights from two decades of research on markets and information* (pp. 21–44). Springer International Publishing. https://doi.org/10.1007/978-3-030-66661-3_2

A.3 Individual contribution to the included research papers

This cumulative dissertation comprises six research papers, all co-authored with multiple collaborators. This section details the context and outlines my contributions to the six papers.

Research Paper P1 entitled “Consumer-centric electricity markets: Six design principles” (Michaelis et al., 2024, Appendix B) was written by a team of five authors, all of whom made significant contributions. Under the leadership of one co-author, I contributed to specific parts of the research project and provided overall feedback. My work included gathering background information, establishing the theoretical foundations on Energy Justice, drafting selected sections of the manuscript, and actively engaging in research discussions. Three other co-authors supported the project by contributing to the theoretical framing, offering continuous feedback, and providing mentorship. While one co-author served as lead author and three others acted in supervisory roles, I contributed in a supportive capacity with a focus on theoretical development and writing.

Research Paper P2 entitled “Resilience, the long forgotten? Analyzing the Resilience of the German Electricity System” (Hanny et al., n.d., Appendix C) was written by a team of three authors. All authors contributed significantly to the paper. Together with one co-author, I co-initiated and co-developed the research project. My contributions included defining the framing and structure of the work, gathering background information on resilience in an energy-related context, supporting the case study, and deriving policy implications. Throughout the project, two authors, including myself, acted as lead authors, while the remaining co-author contributed in a supervisory role, providing feedback and guidance.

Research Paper P3 entitled “On the progress in flexibility and grid charges in light of the energy transition: The case of Germany” (Hanny, Wagner, et al., 2022, Appendix D) involved seven authors. I initiated and coordinated the research project and acted as a single lead author. My contribution spanned all phases of the work, including conceptualization, economic and legal analysis, writing, and overall management of the research project. While my primary focus was on generating results and deriving the corresponding policy implications, another co-author assisted in drafting the motivation and final conclusion of the paper. The remaining five co-authors provided supervision and scientific advice, offering feedback that helped refine the manuscript throughout the process. Accordingly, I served as the lead author, while the other co-authors contributed in supporting roles.

Research Paper P4 entitled “Marktbasierter Flexibilitätseinsatz im Verteilnetz: aktuelle Herausforderungen und Lösungsvorschläge zur Umsetzung europarechtlicher Vorgaben” (Hanny et al., 2023, Appendix E) was written by four authors. Together with one co-author, I initiated and coordinated the research project, ensuring its progress and alignment with the study’s objectives. My contributions spanned the conceptual development, writing, and overall coordination of the work. While one co-author concentrated on the legal aspects, I focused on the economic and technical perspectives. I was also heavily involved in the revision process following peer review, where I incorporated additional legal, economic, and technical details to strengthen the analysis. Accordingly, that co-author and I acted as lead authors. The remaining two co-authors provided

supervision and scientific feedback throughout the project, supporting the overall quality and coherence of the manuscript.

Research Paper P5 entitled “How to trade electricity flexibility using artificial intelligence – an integrated algorithmic framework” (Hanny, Körner, et al., 2022, Appendix F) was written by seven authors. The paper was a collaborative effort involving all authors. Together with one co-author, I initiated the research idea, shaped the overall concept, and co-led the project’s development. In particular, my work included establishing the theoretical foundations, organizing the structure of the paper, and developing significant portions of the algorithm presented in the results section. Two other co-authors contributed mainly by drafting parts of the text, assisting with the literature review, and supporting revisions during the peer-review process. The remaining three co-authors provided guidance and oversight, offering feedback and scientific mentoring that helped improve the manuscript.

Research Paper P6 entitled “When voluntary carbon markets give you lemons, make lemonade: a method for selecting digital technologies in MRV processes” (Leinauer et al., 2024, Appendix G) was written by four authors. All authors made significant contributions to the paper. Together with one co-author, I conceptualized the study, developed the method, conducted the case study evaluation, and contributed to the manuscript’s illustrations. During the review and editing phases, that co-author and I also took primary responsibility for writing and revisions. Based on these contributions, we served jointly as lead authors of the research paper. The remaining two co-authors complemented the team by providing valuable feedback during drafting and editing, facilitating contacts for the case study evaluation, and offering mentorship.

B Research Paper P1:

Consumer-centric electricity markets: Six design principles

Authors:

A. Michaelis, L. Hanny, M.-F. Körner, J. Strüker, and M. Weibelzahl

Published as:

Michaelis, A., Hanny, L., Körner, M.-F., Strüker, J., & Weibelzahl, M. (2024). Consumer-centric electricity markets: Six design principles. *Renewable and Sustainable Energy Reviews*

Abstract:

Key to the necessary decarbonization of energy systems is the large-scale expansion of renewable energy sources and their integration into the electricity system. This integration is challenging because the feed-in from renewable energy sources is highly intermittent and largely dependent on uncontrollable factors such as weather patterns. To maintain grid stability, which refers to the required balance between demand and supply in the electricity system, flexibility is key. Large flexibility potentials can be found on the electricity demand side. However, current electricity market design in Europe, while providing major flexibility incentives, often neglects small-scale electricity consumers and distributed energy resources. We contribute to shape future electricity markets with consumers at the heart by developing six design principles for a consumer-centric electricity market design. We proceed by conducting a systematic literature review and evaluate the findings by expert interviews. Based on the developed design principles, we define a consumer-centric electricity market design as a set of market rules that align with the rules of other relevant energy markets and allow for the efficient matching of electricity demand and supply, with consumers having nondiscriminatory market access, being exposed to fine-grained price signals, being able to express their preferences, and having sufficient possibilities to protect themselves against unexpected price spikes. By actively incorporating consumers into electricity markets, we contribute to the overarching goal of integrating renewable energy sources while promoting energy justice, i.e., supporting a balanced mix of economic, political, environmental, and social interests.

Keywords:

Energy Transition; Electricity Flexibility; Energy Justice; Consumer-centric Electricity Market; Consumer-centric Market Design; Consumer Participation; Demand-side Participation

C Research Paper P2: Resilience, the long forgotten? Analyzing the Resilience of the German Electricity System

Authors:

L. Hanny, M. Pichlmeier, and M. Weibelzahl

Published as:

Hanny, L., Pichlmeier, M., & Weibelzahl, M. (n.d.). Resilience, the long forgotten? analyzing the resilience of the german electricity system [Submitted]. *Energy*

Abstract:

Designing resilient electricity systems becomes increasingly important due to more frequent extreme weather events, geopolitical conflicts, or politically motivated attacks on critical infrastructures. Resilient systems are characterized by their anticipation, absorption, recovery, and adaptation capabilities, which enable a swift return to their pre-attack or shock status. Developing a comprehensive, multidimensional resilience index can help policymakers monitor and identify opportunities for building or expanding electricity system resilience. This paper conducts a structured literature review and develops a resilience index comprising 27 indicators. The country-specific weightings for the indicators are derived from assessments of national energy and electricity market experts using the Analytic Hierarchy Process. We apply the index in an empirical case study to analyze the electricity system resilience of Germany, one of Europe's central and largest countries, from 2010 to 2023. For Germany, we observe an overall increase in resilience between 2010 and 2023, with the highest score in 2022, despite, or possibly because of, the global energy crisis. Within the study period, both increasing and decreasing resilience trends can be observed, which can be attributed to different political decisions and various developments in the electricity system's environment. Our findings highlight that the continuous development of the electricity system requires close monitoring of potential changes in resilience to inform targeted policy measures that strengthen resilience.

Keywords:

Resilience; Electricity System; Energy System; Composite Index; Resilience Indicators; Analytical Hierarchy Process

D Research Paper P3: On the progress in flexibility and grid charges in light of the energy transition: The case of Germany

Authors:

L. Hanny, J. Wagner, H. U. Buhl, R. Heffron, M.-F. Körner, M. Schöpf, and M. Weibelzahl

Published as:

Hanny, L., Wagner, J., Buhl, H. U., Heffron, R., Körner, M.-F., Schöpf, M., & Weibelzahl, M. (2022). On the progress in flexibility and grid charges in light of the energy transition: The case of germany. *Energy Policy*

Abstract:

In the course of the energy transition, flexibility on the demand side is crucial to balance intermittent supply from renewable energy sources. In Germany, however, a large part of the demand side flexibility potential remains unused, especially due to an outdated and inappropriate grid charges regulation. In this respect, policymakers have failed to align their regulatory instruments, e.g., grid charges, to the flexibility requirements of the energy transition. Moreover, regulatory and planning uncertainties regarding the long-term vision for future electricity systems inhibit flexibility investments – marking another policy failure. Although the above issues are known to policymakers for quite some time, too little has been done to further develop corresponding regulation. This policy inaction results from a decision-making dilemma, in which policymakers did not reach a solution that benefits all stakeholders involved in the grid charges debate (e.g., energy-intensive and less energy-intensive electricity consumers). Solving the policy failure in the form of a revised and future-proof grid charges regulation will, however, increase the prospect of a just outcome for society and, more specifically, recognition and cosmopolitan justice. In this paper, we outline how grid charges inhibit demand side flexibility in Germany and which policy failures have ultimately contributed to stuck political decision-making. We further provide concrete suggestions of how existing policy failures may be corrected in order to ensure a successful energy transition as a policy guide for Germany and other countries all around the world.

Keywords:

Renewable Energy Sources; Grid Charges; Energy Policy; Flexibility; Energy-intensive Industry

E Research Paper P4:

Marktbasierter Flexibilitätseinsatz im Verteilnetz: aktuelle Herausforderungen und Lösungsvorschläge zur Umsetzung europarechtlicher Vorgaben

Authors:

L. Hanny, M. Weibelzahl, M. Schöpf, and N. Hofmann

Published as:

Hanny, L., Weibelzahl, M., Schöpf, M., & Hofmann, N. (2023). Marktbasierter Flexibilitätseinsatz im Verteilnetz: aktuelle Herausforderungen und Lösungsvorschläge zur Umsetzung europarechtlicher Vorgaben. *Zeitschrift für Umweltpolitik und Umweltrecht*

Abstract:

Für das Gelingen der Energiewende und das Erreichen klimaschutzpolitischer Zielvorgaben ist ein rascher und flächendeckender Zubau erneuerbarer Energien von zentraler Bedeutung. Die Abhängigkeit erneuerbarer Energien von externen Faktoren, wie z.B. Wetter und Tageszeit, sowie deren regionale Verteilung bringen jedoch auch neue Herausforderungen, insbesondere mit Blick auf die Netzauslastung, mit sich. Beispielsweise müssen aufgrund fehlender Leitungskapazitäten häufig große Mengen erneuerbarer Energien abgeregelt werden, um weiterhin für einen Ausgleich von Stromangebot und -nachfrage zu sorgen bzw. Netz- und Systemstabilität zu gewährleisten. Zur verbesserten Integration erneuerbarer Energien in das Stromsystem spielt neben dem Ausbau von Leitungskapazitäten die Nutzung von netz- und systemdienlicher Flexibilität – als kostengünstige Ergänzung zum Netzausbau – eine wesentliche Rolle. Flexibilität im Stromsystem kann dabei als eine Veränderung von Einspeisung oder Entnahme in Reaktion auf ein externes Signal (z.B. Preissignal) verstanden werden, mit dem Ziel, eine netz- oder systemstabilisierende Dienstleistung im Energiesystem zu erbringen (BNetzA, 2017). Um Flexibilitätpotenziale in der Praxis nutzbar zu machen und zielgerichtet zur Behebung von Netzengpässen einzusetzen, gibt die Europäische Kommission ein marktbasiertes Verfahren zur Flexibilitätsbeschaffung und -vermarktung vor. Die Schaffung lokaler Flexibilitätsmärkte, welche Flexibilitätsanbieter und -nachfrager auf einem Handelsplatz zusammenbringen, bietet dabei eine Möglichkeit, europarechtliche Vorgaben auch auf nationaler Ebene umzusetzen. Aktuell beste-

hen insbesondere im nationalen Recht jedoch wesentliche Hürden, welche einem marktbasierten Flexibilitätseinsatz und der Einrichtung lokaler Flexibilitätsmärkte entgegenstehen. Der nachfolgende Beitrag zeigt die bestehenden Hürden zur Umsetzung europarechtlicher Vorgaben auf und entwickelt, darauf aufbauend, regulatorische Handlungsempfehlungen zur Umsetzung europarechtlicher Vorgaben mittels lokaler Flexibilitätsmärkte.

Keywords:

Lokaler Flexibilitätsmarkt, Netzengpassmanagement, Regulatorik, Energiewende

F Research Paper P5: How to trade electricity flexibility using artificial intelligence – an integrated algorithmic framework

Authors:

L. Hanny, M.-F. Körner, C. Leinauer, A. Michaelis, J. Strüker, M. Weibelzahl, and J. Weissflog

Submitted to:

Energy

Abstract:

In course of the energy transition, the growing share of RES makes electricity generation more decentralized and intermittent. This increases the relevance of exploiting flexibility potentials that help balancing intermittent RES supply and demand and, thus, contribute to overall system resilience. Digital technologies, in the form of automated trading algorithms, may considerably contribute to flexibility exploitation, as they enable faster and more accurate market interactions. In this paper, we develop an integrated algorithmic framework that finds an optimal trading strategy for flexibility on multiple markets. Hence, our work supports the trading of flexibility in a multi-market environment that results in enhanced market integration and harmonization of economically traded and physically delivered electricity, which finally promotes resilience in highly complex electricity systems.

Keywords:

Electricity System; Flexibility; Algorithmic Framework; Artificial Intelligence

G Research Paper P6: When voluntary carbon markets give you lemons, make lemonade: a method for selecting digital technologies in MRV processes

Authors:

C. Leinauer, L. Hanny, J. Strüker, and M. Weibelzahl

Published as:

Leinauer, C., Hanny, L., Strüker, J., & Weibelzahl, M. (2024). When voluntary carbon markets give you lemons, make lemonade: A method for selecting digital technologies in mrv processes. In *ECIS 2024 Proceedings*. AIS Electronic Library (AISeL). https://aisel.aisnet.org/ecis2024/track12_digtrans/track12_digtrans/22

Abstract:

Companies increasingly commit to achieving 'net zero'. While sellers of carbon credits are facing increasing demand in Voluntary Carbon Markets (VCMs), buyers can still not reliably determine the quality of these credits. Such information asymmetries can lead to a 'market for lemons,' where buyers' willingness to pay remains under the expected price of high-quality credit sellers. Thus, these credits are driven out of the market. Information asymmetries in VCMs can be traced back to the underlying Monitoring, Reporting, and Verification (MRV). While digital technologies can reduce information asymmetries, only few start-ups focus on digital MRV. To refine existing and design new digital MRV processes, we apply Design Science Research (DSR) to propose a method for systematically selecting digital technologies. We evaluate our method via a case study on soil carbon credits and illustrate that our method may foster a tailored digital transformation of MRV to alleviate the lemons problem.

Keywords:

Voluntary Carbon Markets; Digital Transformation; Situational Method Engineering; Digital Technology Selection