Fostering Distributed Flexibility Options in the Dynamic Transition Toward a Sustainable Energy System

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Copyright Statement

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

Abstract

This doctoral thesis explores the impact of external shocks on Germany's energy transition and the potential of distributed flexibility options. It highlights how distributed flexibility options can address challenges arising from integrating renewable energy sources while maintaining sustainability, affordability, and security of supply. Germany's energy system recently faced external shocks, including the COVID-19 pandemic and the European gas crisis. These crises exposed vulnerabilities, such as dependencies on natural gas imports and exposure to volatile energy markets, while accelerating the shift to renewable energy and electrification. The COVID-19 pandemic underscored the need for the interconnected European energy systems to jointly manage demand and generation fluctuations. At the same time, the gas crisis highlighted the importance of diversifying energy sources and accelerating the introduction of renewable energy sources to adapt to supply-side disruptions. Distributed flexibility solutions are crucial for addressing these challenges. They can contribute to balance intermittent renewable electricity generation, reduce grid congestion, and enhance system stability. Therefore, this thesis examines the contributions distributed flexibility options in the distribution grid can bring for systemic flexibility needs like redispatch, balancing energy, and residual load management. Further, a flexibility score is developed to quantify the revenue and associated risk of industrial flexibility measures and offers a practical tool for industrial consumers to uncover promising flexibility options. The score allows industrial consumers to estimate revenue and associated risk with minimal effort by evaluating the degrees of freedom of flexibility measures. Further, this thesis covers community-based approaches to promote the local synchronization of electricity generation and consumption to reduce electricity costs and support renewable energy integration. While effective, these approaches often face regulatory barriers that hinder their realization. The thesis emphasizes integrating distributed flexibility options into national energy policies and investment in digitalization to enhance coordination and scalability. This thesis provides a step toward effectively utilizing distributed flexibility options that can help bridge the gap between renewable energy integration and system stability, offering pathways to a sustainable, affordable, and secure energy future.

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I Introduction

I.1 Motivation

Climate Change and the subsequent need to counter, and ideally stop, its effects pose the greatest challenges of modern times. Due to burning fossil fuels, deforestation, and livestock farming, humanity is, next to the naturally occurring greenhouse gases, severely affecting the earth's temperature and climate. The increasing global temperature has a severe effect on livelihood, manifesting in, amongst others, frequent extreme weather situations like heat, floods, aridities, decreased biodiversity, or crop productivity (Abbass et al., 2022). Therefore, with the Paris Agreement (United Nations, 2015), the member countries of the United Nations committed themselves under international law to tackle climate change using appropriate measures. The overarching goal is to hold the global average temperature below two degrees celsius above the pre-industrial level characterized by the years 1850 to 1900 and make assiduous efforts to limit the increase to 1.5°C above the pre-industrial level (Chen et al., 2021; Falkner, 2016). Despite global efforts, in 2023, the global average temperatures reached a new high since the start of recording at 14.98°C, marking an increase of 1.48°C compared to the pre-industrial level (Copernicus Climate Change Service, 2024). Combined with a shortfall in set goals, the need to drive solutions and mitigation strategies to limit global warming remains pressing.

In Germany, the energy sector comprises the most emissions, with 205 million metric tons of CO_2 equivalent, equalling 30.5 % of the German emissions in 2023. It is followed by the industrial sector (23.0 %), the transportation sector (21.6 %) and the building sector (15.2 %) (Agentur für Erneuerbare Energien e.V., 2024; Umweltbundesamt, 2024). To reduce emissions, the German government passed the Klimaschutzgesetz in 2019 with a stricter amendment in 2024, where greenhouse gas neutrality is stipulated as a goal for 2045 (Bundes-Klimaschutzgesetz, 2019; Bundes-Klimaanpassungsgesetz, 2024). Key actions include promoting renewable energy, encouraging the electrification of transportation and heating, and electrifying industrial processes to reduce reliance on natural gas and other conventional energy sources (Ibrahim et al., 2024; Wiese et al., 2022). Traditionally, the German electricity grid was characterized by large conventional power plants located near densely populated areas or energy-intensive industrial companies to minimize the distance electricity needed to be distributed downstream. Electricity generation was typically dispatched according to forecasted demand, with fast-ramping power plants, such as gas-fired units, offering the necessary adaptability to account for any forecast errors (Haas et al., 2023). However, the rise of renewable energy and its intermittent nature, particularly PV and wind, is shaping the electricity grid. A significant share of renewable capacity, especially PV, is installed at the distribution grid level. By 2024, 57 GW of the total 82 GW of installed PV capacity in Germany is connected at this level (Bundesnetzagentur, 2024d; Reuther & Kost, 2024). In addition to distributed generation, new assets such as electric vehicles (EVs) and heat pumps (HPs) are also being introduced at the distribution grid level, increasing the demand for electricity and adding to the grid's load (Alanazi, 2023; Appen et al., 2014; Burger & Weinmann, 2014). These distributed energy resources (DERs) propel the need to manage increased load and the fluctuating input from renewable sources. Instead of the traditional unidirectional flow from centralized power plants to consumers, electricity increasingly flows bidirectionally from distributed generation sources and flexible devices like battery storage systems (BSS) or EVs at the distribution level back into the grid (Appen et al., 2014; Damianakis et al., 2023; Dik et al., 2023). At the same time, renewable energy sources (RES), like wind generation units, are often located far from major consumption centers. As a result, electricity must be transmitted over longer distances (Eising et al., 2020). These extended transmission routes and the intermittent factor of renewable energy generation introduce new challenges, including congestion, on the transmission grid. This necessitates costly interventions such as redispatch, curtailment of renewable generation, or balancing energy (Bundesnetzagentur, 2024c; Joos & Staffell, 2018). These measures increase grid fees for consumers and restrict the potential to reduce emissions in the electricity sector.

As the integration of renewable energy and distributed resources accelerates, the need for greater flexibility within the electricity system becomes paramount (Andersen et al., 2023; Göke et al., 2023; Kamali Saraji & Streimikiene, 2023). This challenge is called the "flexibility gap" (Alhelou et al., 2018; Heydarian-Forushani et al., 2017; Laugs et al., 2020). Degefa et al. (2021) define flexibility as the ability of energy systems and assets to modify their regular operation in response to (external) signals of scarcity without causing disruptions. Flexibility allows the grid to adapt to fluctuating generation from intermittent sources like wind and PV while maintaining the balance between supply and demand. Flexibility options can be categorized into four main types: grid, storage, supply-side, and demand-side flexibility (Lund et al., 2015; Papaefthymiou et al., 2018). This thesis will mainly focus on distributed flexibility options like demand-side management of residential or industrial assets, EVs, HPs, BSSs, or supply-side flexibility from a distributed renewable generation, which, especially on the demand side, bear an untapped potential (R. Heffron et al., 2020; Sauer et al., 2022). To foster the flexibility of distributed flexibility options, digitalization plays a critical role in managing the complexities arising, such as the need to coordinate these assets effectively, the harmonization of scarcity signals, proof of provision of flexibility, or managing data complexity (Körner et al., 2022; Lin & Huang, 2023; Loock, 2020). On the supply side, it allows verification of electricity origin, ensuring the value of "green" electricity (Körner et al., 2024). On the demand side, digitalization provides insights into electricity flows and grid usage, improving forecasting and preventive measures. By enabling end-to-end digitalization, DERs can respond dynamically to scarcity or price signals and provide proof of provision, efficiently providing flexibility to the electricity system (Babel et al., 2024). This transparency is a prerequisite for unlocking distributed flexibility potentials essential to ensure that the energy sector can continue to meet its three critical objectives: sustainability, affordability, and security of supply (Bauknecht et al., 2024; Wu & Sansavini, 2021). Various approaches have emerged in recent years to leverage distributed flexibility in research and practice. These approaches tackle the challenges of integrating distributed electricity generation and flexibility options into existing grid infrastructure by providing mechanisms that enable system operators, prosumers, and consumers to optimize energy use dynamically, thereby creating value for all participants. Key strategies identified in research and practice include aggregator-led pooling of flexibility. Aggregators bundle small-scale consumer resources, such as household BSSs and EVs, allowing these aggregated resources to participate as a unified asset in energy markets (Stede et al., 2020). Virtual power plants present a similar approach, where DER are coordinated to mimic the operation of a traditional power plant, delivering reliable power to the grid and participating in balancing markets (Venegas-Zarama et al., 2022). Additionally, variable grid fees and time-of-use electricity tariffs serve as economic instruments designed to incentivize consumers to adjust their energy usage in response to grid needs or price signals, thus reducing peak demand and alleviating grid congestion (Schmidt et al., 2018). Emerging approaches, such as energy communities, peer-to-peer trading, and local energy markets, further decentralize energy management by enabling prosumers to sell excess power to neighbors or local grids, fostering local energy resilience and consumer empowerment (Okwuibe et al., 2022; Pena-Bello et al., 2022).

The increasing penetration of renewable generation and DERs presents opportunities to leverage innovative flexibility solutions, addressing challenges like grid stability and renewable integration. However, external factors, such as economic shocks and geopolitical crises, make the energy transition dynamic. This dynamic nature demands adaptation and provides opportunities to expedite progress toward a resilient and sustainable energy future.

I.2 Research Aim

Given the identified opportunities, this thesis seeks to contribute in two aspects. First (1), this thesis aims to provide insights into external factors and their influence on the energy transition regarding European interaction, consumer behavior, and market dynamics. To this end, this thesis examines recent shocks, the COVID-19 pandemic and the European gas crisis, that have significantly affected the German electricity system. Secondly (2), the thesis focusses on distributed “bottom-up” flexibility options like small-scale BSSs, EVs, HPs, rooftop PV, or flexibility from demand-side management using household appliances, aiming to illustrate how these options can enhance the effective integration of RES, particularly in light of inherent grid constraints, regulatory barriers, and uncertain revenue and risk.

The need to explore aspect (1) results from the influence of recent shocks on Germany's energy transition and energy policies. The COVID-19 pandemic and the European gas crisis have disrupted ways in the German energy system and introduced a critical reassessment of established priorities (Bersalli et al., 2024). As Germany copes with the imperatives of ensuring energy security and advancing sustainability while maintaining affordability, these crises stress the necessary balance between short-term responses and long-term objectives (Belaïd et al., 2023; Jamasb et al., 2024). The COVID-19 pandemic initially showcased the potential for rapid behavioral change and highlighted the role of science-based policy in facilitating a swift transition to low-carbon energy sources (Geels et al., 2022; Halbrügge et al., 2021; Hodges et al., 2022). Further, the European gas crisis has illustrated the vulnerabilities of energy systems that remain dependent on fossil fuels, leading to concerns over energy dependency and market stability (Konopelko et al., 2023). As policymakers began prioritizing affordability and security of supply over sustainability, investments in renewable energy have been deprioritized, possibly leading to new lock-ins hindering progress toward climate goals (Babić & Mertens, 2024). This underscores the importance of understanding the interplay between these external shocks and their implications on the energy system and its transition toward sustainability. Therefore, aspect (2) critically examines these crises to shed light on their effects on European interaction, consumer behavior, and market dynamics. By analyzing how these events have reshaped the German energy system this thesis seeks to provide actionable insights derived from past dynamics and dependencies in the German energy system. It demonstrates how these external factors and crises have exposed vulnerabilities, such as the reliance on gas imports, while simultaneously highlighting opportunities to use these dynamics as a catalyst for driving the energy transition, e.g., adoption of energy efficiency measures and seeking energy alternatives due to high energy prices. The analysis underscores the need for measures that reduce the system's susceptibility to future external shocks, such as diversifying energy sources, accelerating renewable energy investments, and building robust market structures that protect consumers from price surges. By integrating these findings into planning, the German energy transition can not only withstand future disruptions but also leverage them as opportunities to drive transformative change, ensuring the balance between energy security, sustainability, and affordability (Meo et al., 2024).

To investigate aspect (2), it is essential to recognize that DERs have traditionally been viewed as load contributors without playing an active role in the German electricity system. In contrast, flexibility has predominantly been derived from fast-ramping generation units, such as pumped-hydro storage and gas power plants. However, the evolving German energy transition has shifted this imperative, creating a notable flexibility gap that necessitates the effective integration of DERs to support grid stability and RES utilization (cf. Section I.1). As the integration of intermittent RES increases, fostering distributed flexibility options has become paramount (Derksen & Weber, 2017; Pearson et al., 2022). These options offer the potential to provide much-needed responsiveness and adaptability to the German electricity system, yet they also present a range of challenges that must be addressed. Regulatory barriers, such as industry grid-charge regulations, the inertia of national regulatory adaptations to European legislation, and uncertainties surrounding revenue and associated risks, complicate the deployment of these flexibility options (Babilon et al., 2024; Hanny et al., 2022; Leinauer et al., 2022). Additionally, a coordination dilemma arises: determining which demands these flexibility options can be utilized most effectively for while complying with local grid constraints (Bauknecht et al., 2021; European Commission, 2022). In response to these challenges, regarding aspect (2) this thesis assesses the value of distribution grid flexibility for systemic applications to measure the value and temporal alignment of these flexibility options. Further, a flexibility score is developed as a practical tool for evaluating with minimal financial and temporal investment, allowing for a more straightforward comparison of potential revenue and associated risk. The thesis then shifts focus to community-based approaches, examining the impact of residential energy communities on grid performance. Furthermore, the potential of industrial energy communities is investigated in the context of navigating existing regulatory challenges imposed by Germany’s asymmetric grid charge regulations. Exploring aspect (2) aims to help understand the interplay between DERs and the need for system flexibility to address immediate challenges and provide a building block for an energy system capable of adapting to future developments. By aligning community-based initiatives with broader energy policy objectives, aspect (2) further aims to contribute to understanding how aspects of distributed flexibility options can influence grid stability and support Germany's transition toward a sustainable energy future.

This thesis aims to gain insights into the external factors influencing the energy system and the potential of distributed flexibility options in supporting the vital balance between energy security, affordability, and sustainability and overcoming the rising challenges of the energy transition. Ultimately, this thesis aspires to contribute to a more sustainable and adaptable energy system, ensuring that the lessons learned from recent challenges inform robust policy recommendations that advance a low-carbon energy future.

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

This doctoral thesis is cumulative and comprises six research articles contributing to the research aim. Figure 1 accordingly illustrates the structure of the thesis and the embedding of the research articles.

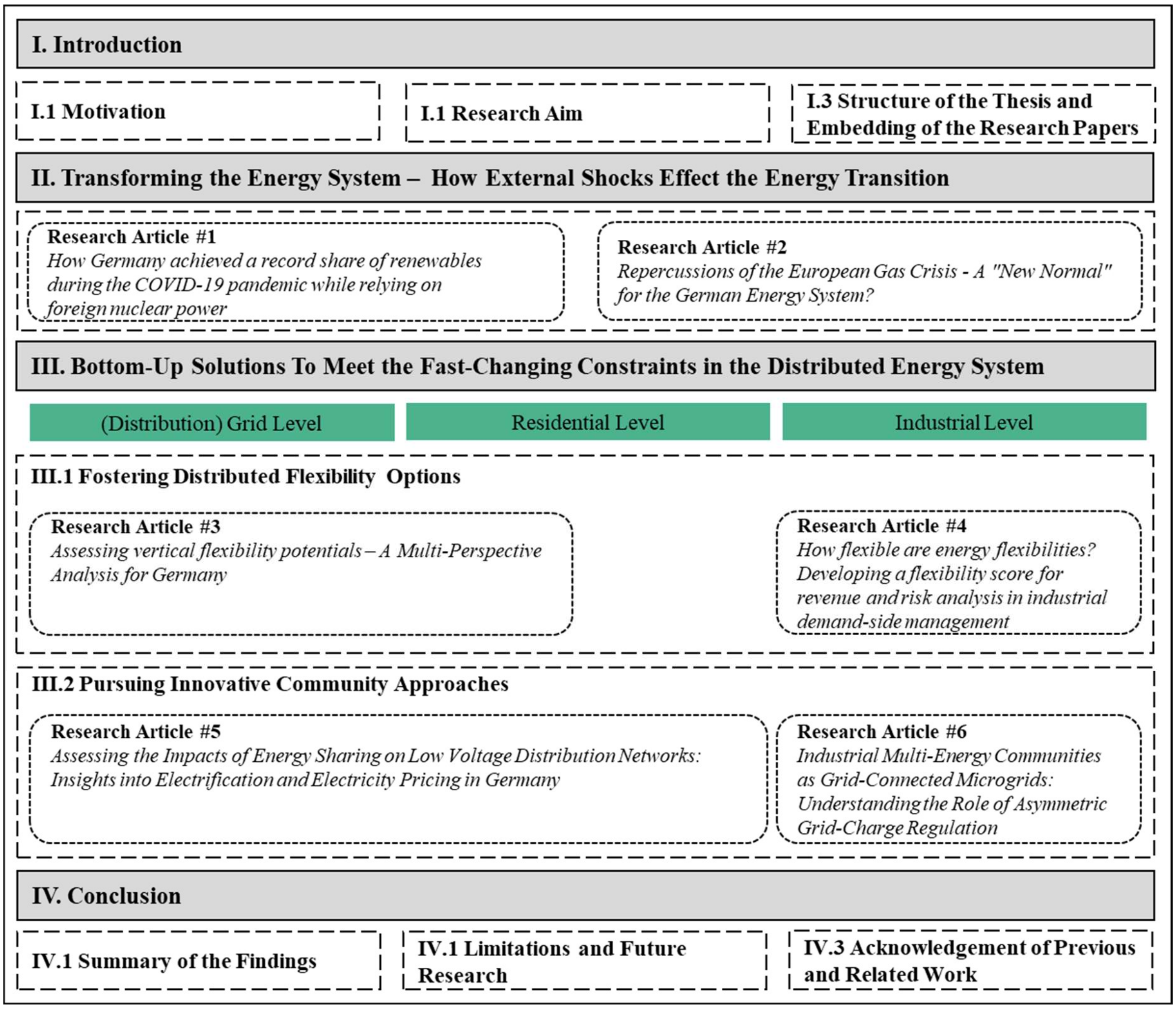

Figure 1: Structure of the Doctoral Thesis and classification of the embedded Research Articles.

Following the introduction (Section I), where the motivation, research aim, and thesis structure are given, Section II delves into recent external factors and their effect on the transformation of the energy system toward sustainability while maintaining the security of supply and affordability. Accordingly, Research Article #1 explores Germany’s shift toward increased electricity imports as a flexibility measure in response to its growing share of intermittent renewable energy, especially during the COVID-19 pandemic. The article provides insights into how this shift impacted Germany's energy system by analyzing market dynamics, environmental factors, and the use of interconnection capacities within Europe to achieve a record share of renewable energy generation. Further, Research Article #2 examines the response of the German energy system to the shock triggered by the Russian-Ukrainian war, which began in February 2022, and the subsequent natural gas shortages. This disruption highlights the importance of understanding the sensitivity of energy systems, particularly in Germany. The sharp rise in natural gas prices led to a supply-side shock by driving up electricity production costs, influencing behavior in the German electricity market. In response, measures had to be taken on both the supply and demand sides to alleviate the surge in electricity prices. To assess the impact, gas and electricity consumption, supply trends, and gas and electricity market data before and after the war outbreak are analyzed to answer the question of whether the shock was a short-term disruption or introduced a "new normal" into the German energy system.

Section III aims to explore bottom-up solutions to efficiently integrate distributed flexibility options to face the challenges stated in Section I.1. Subsection III.1 particularly aims to contribute to the understanding of the value of distributed flexibility and to provide a straightforward measurement of the economic value of industrial flexibility without requiring high setup costs and temporal effort. First, the distributed flexibility potential available from the distribution grid to enhance flexibility on the system level is explored and matched to the flexibility demand from redispatch, balancing energy, and the integration of renewable generation exceeding electricity demand, so-called residual load (Research Article #3). To foster energy flexibility in the industrial sector and overcome high effort in flexibility audits and complex optimization models to quantify the economic potentials, a flexibility score is developed in Research Article #2 to provide a simple way to analyze the economic potential as an initial indicator of successful flexibility implementation that requires little data. The flexibility score describes the degrees of freedom (DOFs) of individual energy flexibility measures, i.e., how flexible a flexibility measure is. It allows industrial companies to approximate the economic value and associated revenue risk of flexibility measures with little effort. Subsection III.2 explores the benefits of community-based approaches in fostering the local synchronization of electricity generation and demand at both residential and industrial level. In this context, Research Article #5 examines the impact of energy sharing and variable electricity tariffs on the distribution grid. While residential energy sharing has already been discussed in academic literature and tested in pilot projects, industrial communities also hold significant potential in promoting the local integration and utilization of renewable energy. Hence, Research Article #6 investigates the advantages that industrial companies in industrial energy communities (IEC) can leverage under Germany's grid regulations, which currently pose challenges to providing flexibility.

Finally, section IV concludes with a summary of the key findings (cf. subsection IV.1) and outlines relevant limitations along with directions for future research (cf. subsection IV.2). It also discusses earlier related works and publications completed during the writing of the thesis in subsection IV.3. Section V lists the references used in the thesis. Section VI, the appendix, provides further details on the six research articles included in the thesis (cf. Section VI.1), followed by an account of the author's contributions to each article in Section VI.2. The abstracts of all research articles published as well as extended abstracts for the submitted research articles are presented in Section VI.3. The supplementary material not intended for publication contains the full texts of all research articles.

II Changing External Factors Influencing the Energy Transition

The urgent need to address climate change has triggered a fundamental transformation of the German energy system to meet sustainability goals. This transformation, however, presents complex challenges as both the conditions and objectives within the energy sector are evolving, demanding adaptability and resilience (Ketsopoulou et al., 2021). Moreover, energy systems remain highly susceptible to external influences, including economic crises, geopolitical conflicts, and other global events (Zakeri et al., 2022). These can either accelerate or hinder progress, often creating lock-in effects reinforcing existing dependencies (Fouquet, 2016). These external factors also reshape the balance between priorities such as energy security and economic growth, influencing decision-making and investment within the energy system (Banna et al., 2023). To explore these dynamics, recent crises, such as the COVID-19 pandemic and the European gas crisis following the Russia-Ukraine conflict, provide valuable insights into the external factors the energy system has to cope with.

Research Article #1: How Germany Achieved a record share of renewables during the COVID-19 pandemic while relying on foreign nuclear power

The COVID-19 pandemic exemplified both the adaptability and vulnerabilities of modern electricity systems. During the COVID-19 pandemic, electricity consumption in several European countries decreased alongside a larger share of RES (Jiang et al., 2021; Prol & O, 2020). This led to lower Day-Ahead market prices and higher negative electricity prices than previous years. In 2020, Germany reached a share of 50.5 % of renewables in the electricity generation mix (Fraunhofer ISE, 2021). Even though this implies a more volatile generation profile and, consequently, a higher risk of security of supply, according to Halbrügge et al. (2021), the German electricity system exhibited no irregularities in terms of grid frequency or redispatch volumes. These conditions reduced the short-term profitability of conventional power plants and potentially hindered new investments in generation capacity but promoted the attractiveness of investments in flexibility options.

During the COVID-19 pandemic, represented by the weeks 12 to 52 of 2020, Germany achieved a record share of renewable electricity generation in 2020. It shifted from a net electricity exporter to a net electricity importer, as depicted in Figure 2. Therefore, the interconnected European electricity system supported Germany’s increased electricity imports, addressing pandemic-related shifts (R. J. Heffron et al., 2021; Osorio et al., 2020). Research Article #1 consequently analyzes German electricity imports as a flexibility option during the pandemic, considering the market, environmental, and grid perspective to answer how German electricity imports influenced the decrease in greenhouse gas emissions in 2020.

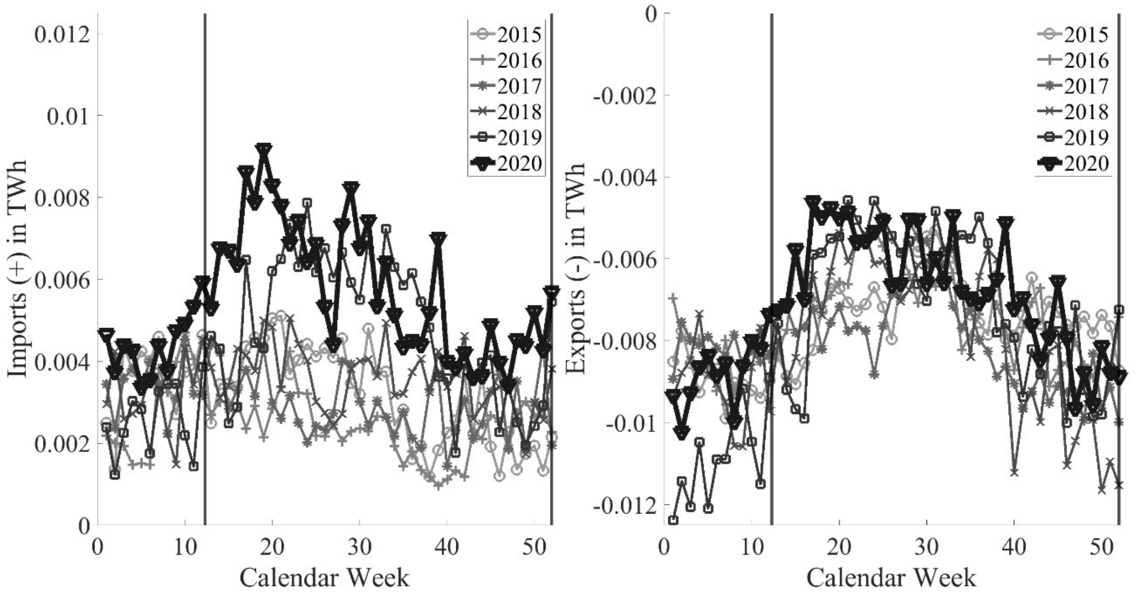

Figure 2: Profile for imports and exports of the German bidding zone for 2015 to 2020. The vertical lines represent the start of our period of interest (start of the partial lockdown in Germany from the 17th of March until the end of 2020). Own illustration, data from ENTSO-E.

The market perspective is examined in Research Article #1 to determine whether Germany was required to import the flexibility needed to accommodate a high share of renewable energy generation at higher prices than in previous years during the COVID-19 pandemic. Using data on Day-Ahead electricity market prices, the hourly difference in price between the German bidding zone and each neighboring bidding zone is determined and weighted by the actual amount of electricity imported (cf. Table 1). Positive values in Table 1 indicate that Day-Ahead prices in Germany were higher, whereas negative values reflect lower Day-Ahead prices in Germany than in the neighboring bidding zone.

Table 1: Specific costs for electricity imports of Germany for each neighboring bidding zone from 2015 to 2020 in EUR per MWh. Data from ENTSO-E.

Year	AT	BE	CZ	DK	FR	NL	NO2	Pl	SE4	CH
2015	n.a.	n.a.	0.03	10.11	-0.58	-1.80	n.a.	3.95	14.44	0.65
2016	n.a.	n.a.	0.21	3.41	-0.62	-0.43	n.a.	4.29	5.46	0.65
2017	n.a.	n.a.	-0.02	6.28	-1.94	0.86	n.a.	5.60	9.79	1.32
2018	-2.87	n.a.	0.54	3.92	-0.72	-4.46	n.a.	1.82	6.46	-0.43
2019	-0.40	n.a.	0.00	1.67	2.08	-0.17	n.a.	-1.65	6.14	1.77
2020	-1.08	0.31	0.05	7.52	2.03	2.19	22.32	-7.64	11.86	1.38

Table 1 shows no consistent pattern across all years and neighboring bidding zones. However, since 2018, Germany has generally imported electricity when prices in Austria were higher than in Germany. A similar trend is observed for France (until 2019) and the Netherlands (until 2020). The table shows positive values for Sweden, indicating that Germany imported electricity when its prices exceeded those in Sweden. In 2020, most values were positive, except for Austria and Poland, meaning Germany typically imported when its prices were higher than those of exporting countries. Compared to 2019, the year 2020 shows decreased values for Austria, France, Poland, and Switzerland, suggesting higher costs for German imports from these zones in 2020 than in 2019. In contrast, values increased for the Czech Republic, Denmark, the Netherlands, and Sweden, reflecting lower import costs for Germany from these zones compared to 2019. Overall, the prices for international transmission flexibility for Germany in terms of flexibility imports did not show a clear upward trend.

To examine the environmental perspective, whether Germany imported electricity exhibiting a lower share of renewable generation than the electricity generated in Germany, Research Article #1 examines data on the electricity generation in the neighboring bidding zones. The analysis first identifies the countries where Germany imported electricity from and examines the share of RES in these exporting countries. Here, RES includes renewable generation technologies such as biomass, geothermal, hydro pumped storage, hydro run, hydro water reservoir, PV, waste, wind offshore, and wind onshore. Further, the difference in RES share during import periods is assessed in Germany and the exporting countries. Figure 3 shows the amount of electricity imported to Germany, which is related to the difference in the share of renewable electricity generation between Germany and the exporting country. The x-axis indicates the share of renewable electricity generation in Germany minus the weighted share of RES in all exporting countries for the times of electricity imports to Germany. Negative values on the x-axis indicate that at this point in time, the share of renewable electricity generation in

Germany was lower than the weighted average in the exporting countries and vice versa. The marked point on the left and right-hand side of the vertical line represents the average share of renewable electricity generation and the average amount of imports for each section.

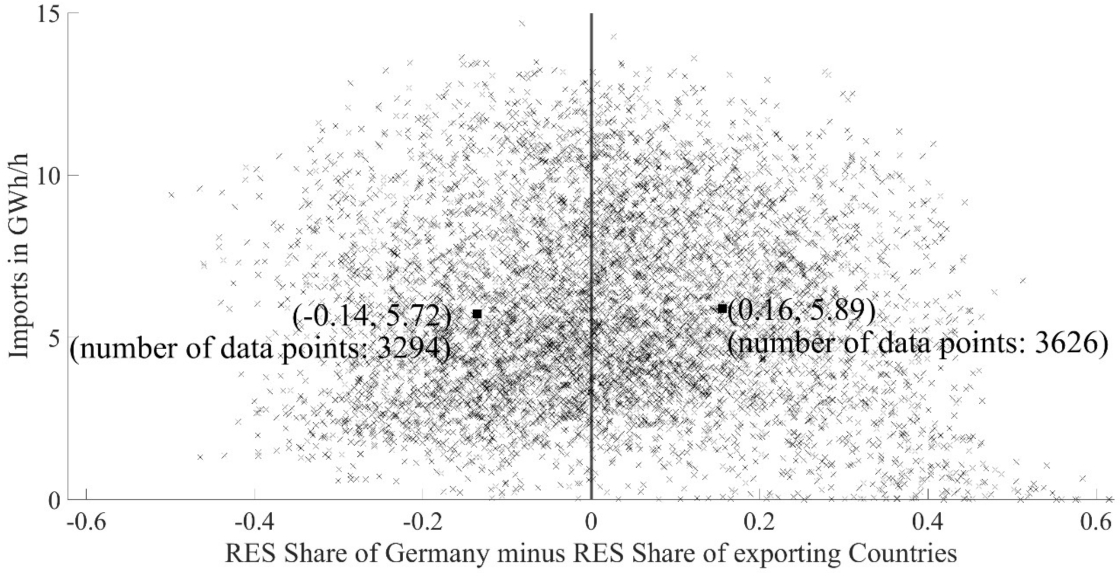

Figure 3: Difference in the share of renewable electricity generation between Germany and the corresponding exporting country for the times of imports to Germany (commercial imports/exports). Own illustration, data from ENTSO-E.

Figure 3 shows that Germany's electricity imports in 2020 predominantly stemmed from countries with a lower RES share than Germany's at those times, represented by the data on the right side of the vertical line. Consequently, the electricity imported by Germany in 2020 to meet flexibility demands and achieve a high renewable energy share generally contained a lower share of RES. A closer look at the generation sources in Research Article #1 reveals that, during the COVID-19 pandemic, nuclear power from France (15.44 % of Germany's total imports) and Switzerland (12.12 %), natural gas (7.62 %) and other conventional power (4.16%) from the Netherlands, onshore wind (6.61 %) and offshore wind (4.61%) from Denmark, and hydroelectric power from France (3.25 %) and Switzerland (6.26%) were the primary sources of imported electricity.

In conclusion, the results show that large parts of German electricity imports during the COVID-19 pandemic stemmed from nuclear power plants in France and Switzerland, providing the transmission flexibility to achieve a record share of renewable energy generation in Germany. This, however, did not reflect on the prices for transmission flexibility, which did not exhibit a clear trend. Research Article #1 highlights the need for a coordinated, interconnected European electricity system to manage the increasing share of intermittent RES. European policies must consider the interdependencies within the interconnected grid, requiring aligned national strategies to meet climate targets and manage cross-border coordination. Germany illustrates these challenges, as it increasingly relied on electricity imports during the COVID-19 pandemic due to its high RES share. Although transmission flexibility supports this reliance, future pressures on interconnection capacities, particularly as other countries adopt similar RES goals and phase out conventional electricity sources, may limit Germany's ability to depend on imports.

While Research Article #1 focuses on the effects of the COVID-19 pandemic and analyzes the contribution of European transmission flexibility for Germany to reach a record share of renewable electricity generation in 2020, Research Article #2 focuses on the recent Russian-Ukrainian war.

Research Article #2: Repercussions of the European Gas Crisis – A "New Normal" for the German Energy System?

Russia's aggressive invasion of Ukraine on February 24, 2022, triggered a drastic reduction in Russian natural gas exports to European countries, including Germany (Halser & Paraschiv, 2022; Krebs, 2022). In response to this cut in supply, many European Union (EU) nations turned to liquefied natural gas (LNG) as a partial substitute. However, the shortfall of gas supply from Russia and limited import terminal capacities across Europe caused European natural gas prices to surge sharply (Ruhnau et al., 2022). The Year-Ahead Future prices for natural gas in Germany rose from 32 EUR/MWh in November 2021 to 129 EUR/MWh by November 2022 (Bundesnetzagentur, 2024a). Due to the German electricity market design, where the marginal electricity generation unit determines the price for all participants according to the merit order principle, this gas price spike drove electricity prices to unprecedented highs, adding significant volatility and uncertainty about future electricity pricing (ENTSO-E; Uribe et al., 2022). After this shock to the German energy system, Day-Ahead and year-ahead natural gas prices eased to 43 EUR/MWh by November 2023, suggesting that the European gas crisis, though initially a sharp shock, has introduced lasting elevated price levels and constraints to the German energy systems. Accordingly, Research Article #3 seeks to answer the question of to what extent the European gas crisis has established a "new normal" in the German energy system and potentially accelerates the energy transition. To assess the impact of the Russian-Ukrainian war on Germany, gas supply and consumption are analyzed in Research Article #2, followed by the Day-Ahead, Intraday, and Future electricity market. The analysis draws on data from 2018 to 2023 to assess gas consumption and imports to Germany, sourced by the German Federal

Network Agency for Electricity, Gas, Telecommunications, Post, and Railway (Bundesnetzagentur, 2024a) from Trading Hub Europe (Trading Hub Europe). For the electricity market in Germany, volume and price data provided by the European Energy Exchange (EEX) (European Energy Exchange AG) are utilized. Data on the Day-Ahead electricity spot market is sourced from the ENTSO-E Transparency Platform (ENTSO-E). In contrast, Future and Intraday market data is gathered from the EEX and EPEX Spot (EPEX Spot; European Energy Exchange AG).

Until the invasion in February 2022, Russian gas initially comprised 35.5 % of Germany's total daily gas imports. Following a first decrease in June 2022, Russian gas imports stopped completely on September 1st, 2022. As a result, Germany's total daily gas imports declined by 44 % over the year, from 4,73 GWh/day at the onset of the Russian invasion of Ukraine in February 2022 to 3,26 GWh/day by November 2nd, 2022. After Russia ceased all gas exports, Germany sought to compensate with gas from Switzerland and France and constructed LNG terminals. By the end of 2023, four LNG terminals were in use (Bundesnetzagentur, 2024b), enabling Germany to import around 70 GWh of LNG, which comprised 7 % of its total gas imports that year. In terms of supply sources in 2023, Norway, Belgium, and the Netherlands became Germany's primary suppliers, accounting for 44 %, 26 %, and 22 % of imports, respectively. The daily German gas imports in 2023 average 2.7 GWh/day, representing an even lower level than in 2022. Hence, Germany could not fully compensate for the shortfall in Russia's gas supply with LNG or other import options. These new constraints on the gas supply side led to vast fluctuations in German gas prices. After the Russian-Ukrainian war began in February 2022, German market prices for gas surged up to 316 EUR/MWh on the Day-Ahead market and 337 EUR/MWh on the Future market for the month ahead. However, by 2023, German gas prices had relaxed, averaging 39 EUR/MWh for the Day-Ahead market and 40 EUR/MWh for the Future market for the month ahead (Bundesnetzagentur, 2024a; European Energy Exchange AG).

Furthermore, Research Article #2 examines gas consumption in Germany before and after the breakout of the Russian-Ukrainian war. Figure 4 depicts the gas consumption in Germany, stemming from households, trade, and commerce on the left and industry on the right. The grey corridor indicates the gas consumption between 2018 and 2021, with the upper bound representing the maximum daily gas consumption and the lower bound representing the minimum daily gas consumption. The black line represents the average daily gas consumption between 2018 and 2021. The red line indicates the gas consumption in 2022, and the blue line shows the gas consumption 2023. The left-side vertical line represents the start of the Russian invasion on the 24th of February 2022. The maintenance start of the Nord Stream 1 pipeline from Russia to Germany and, therefore, the start of the reduction in gas imports to Germany is indicated by the right-side vertical line in Week 24.

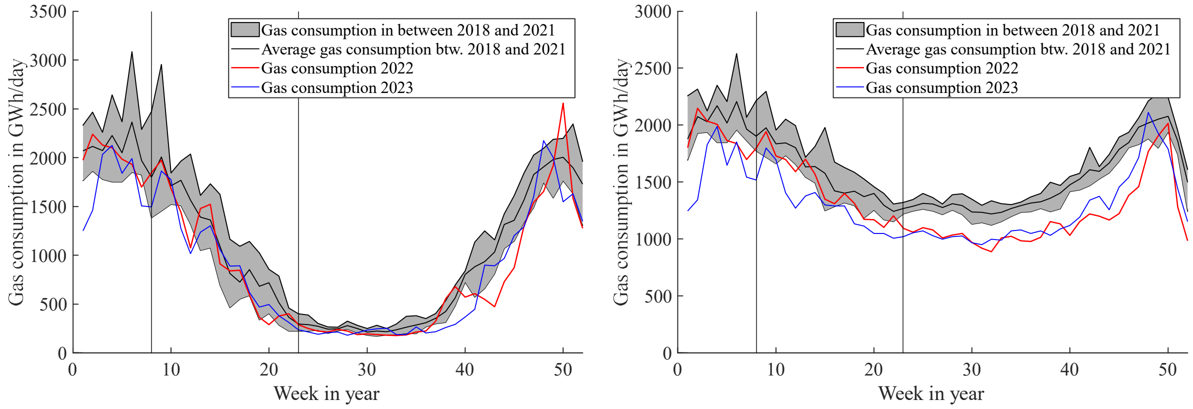

Figure 4: Gas consumption of households, trade and commerce (left), and industry in 2022 and 2023 compared to 2018 until 2021 in Germany. Own illustration, data from Bundesnetzagentur (2024a).

For the gas consumption of households, trade, and commerce, the left side of Figure 4 shows that the demand for gas did not change substantially in 2022 and 2023 on first sight. A shortfall can be depicted between weeks 36 and 45 in the years after the invasion, leading to a 11 % reduction in 2022 and 16 % reduction in 2023 compared to the average from 2018 to 2021. For the industrial sector (cf. right side of Figure 4), gas demand in 2022 generally falls short compared to 2018 to 2021 until the week before the start of maintenance work of the Nord Stream 1 pipeline. From this point in time onwards, gas consumption of the industry sector is up to 27 % lower (for Week 45) compared to previous years. Therefore, the industry has lowered its demand significantly. This trend continues in 2023, exhibiting an even lower gas consumption in the year's first half and a comparable gas consumption to 2022 in the second half. On average, the gas consumption of the industrial sector in Germany decreased by 15 % in 2022 and even further to 18 % in 2023 compared to the average of 2018 to 2021.

The unprecedented price surge and concerns over supply shortages have sparked a reevaluation of national energy strategies (Schramm, 2023; Verbraucherzentrale, 2024). Natural gas, historically a cornerstone of industrial energy supply, is increasingly seen as a high-risk energy source. The European gas crisis prompted initiatives to diversify energy portfolios and reduce reliance on it. For residential consumers, the energy crisis – amplified by recent legislation on energy savings and renewable heating (Gebäudeenergiegesetz, 2020) – has fueled a shift toward alternative heating systems. Notably, sales of HPs surged past one million units in 2023, according to the Bundesverband der Deutschen Heizungsindustrie, underscoring a clear trend toward renewable heating solutions (Bundesverband der Deutschen Heizungsindustrie). However, the continued demand for gas heating systems, favored because of their cost-effectiveness under current regulations, highlights the need to challenge and adapt current regulations to promote a sustainable energy transition.

Soaring gas prices due to the Russian-Ukrainian war also directly impacted electricity markets in Germany. To analyze changed behavior and conclude whether the gas crisis introduced a “new normal” to the German electricity markets and its stakeholders, Research Article #2 analyzes the traded volumes on the German Day-Ahead and Intraday electricity markets. Figure 5 depicts the volumes and prices of German Day-Ahead and Intraday electricity markets before the invasion (2018 to February 2022), for the year 2022 after the invasion, and for the year 2023 as boxplots and histograms to illustrate the levels and volatility of the data.

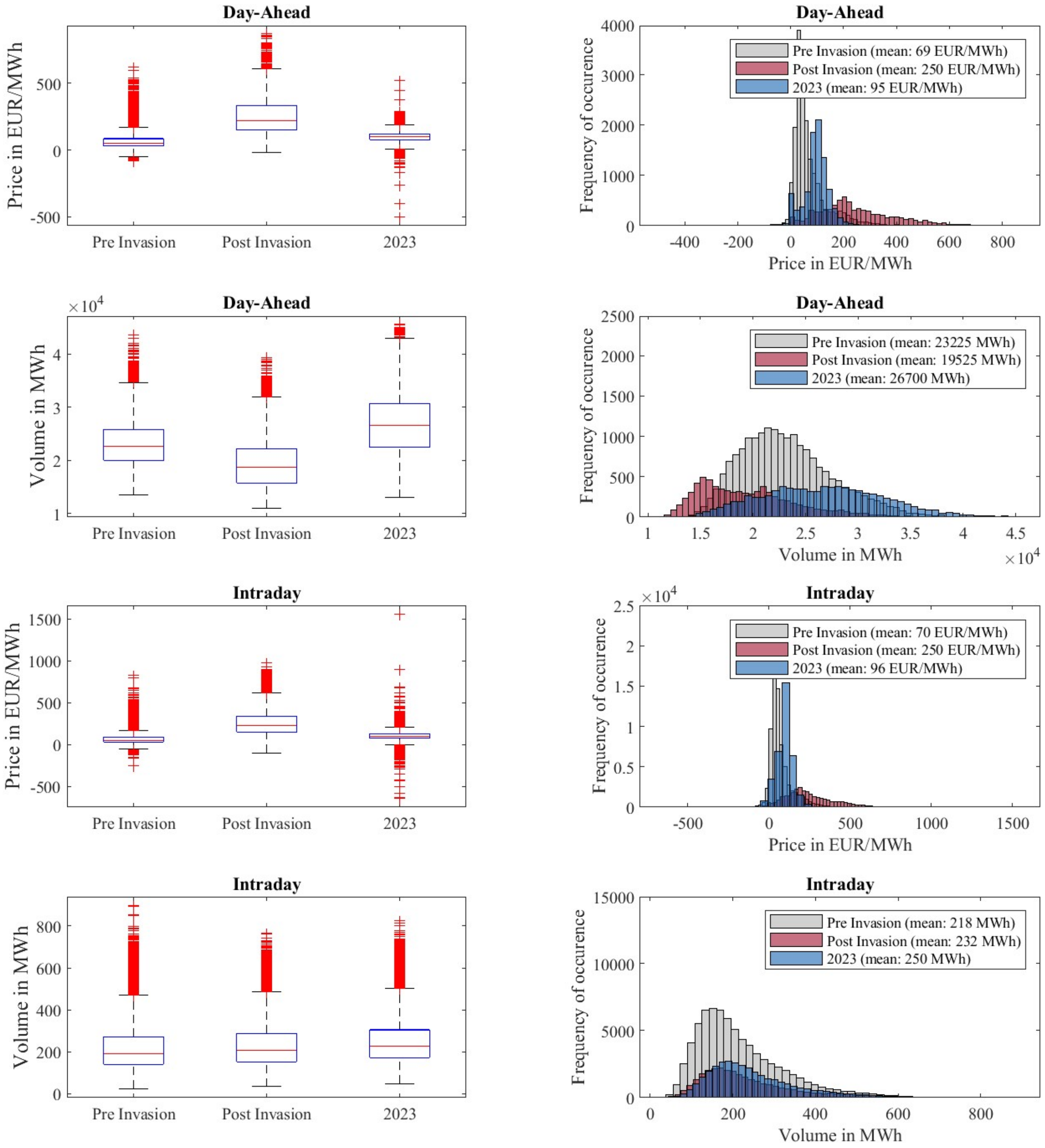

Figure 5: Boxplots and histograms depicting price and volume development on the Day-Ahead and Intraday market. Own illustration, data from EPEX Spot and ENTSO-E.

Figure 5 highlights the shifting dynamics in price levels and trading volumes within the German Day-Ahead and Intraday electricity markets. In the Day-Ahead market, average prices in 2023 stabilized at 95 EUR/MWh – a significant reduction from the volatile highs of 250 EUR/MWh in 2022 post-invasion, but an increased level compared to pre-invasion price levels averaging 69 EUR/MWh. Price volatility also declined in 2023, notably from 2022 levels, as illustrated in the histogram in the top left corner of Figure 5, returning to comparable volatility as pre-invasion prices. Traded volumes on the Day-Ahead market surged to unprecedented levels in

2023, reaching 26,700 GWh, marking a 37 % increase from 2022 and a 15 % rise from the average volumes traded pre-invasion. The Intraday market mirrored the Day-Ahead trend regarding price levels, with average prices settling at 96 EUR/MWh in 2023 after surging post-invasion to an average of 250 EUR/MWh in 2022 and comprising similarly reduced volatility. However, the rise in traded volumes on the Intraday market was less pronounced, with an 8 % increase from 2022 levels and a 15 % increase from volumes traded in the pre-invasion period. Additionally, the frequency of negative price hours in both markets rose again to 3.7 % in 2023 after decreasing in 2022 post-invasion from 3.9 % of the hours pre-invasion to 1.9 % in 2022 post-invasion. On the Future electricity market, average traded volumes dropped sharply between the start of the Russian invasion and December 2022 by 44 % to 2.7 TWh per day. This decrease likely reflected buyers' reluctance to secure electricity at high prices amid expectations of future price declines and rising inflation, underscoring a growing uncertainty about future price trends. In 2023, however, traded volumes rebounded to pre-invasion levels, occasionally surpassing them at the end of 2023 (European Energy Exchange AG). Futures prices (year-ahead) mirrored the dynamics of Day-Ahead market prices across 2022 and 2023. From an average of 70 EUR/MWh in 2021, after heavy fluctuation and peaks with 985 EUR/MWh in 2022, futures prices nearly doubled by 2023 compared to pre-invasion levels, reaching an average of 138 EUR/MWh. Electricity generation from gas power plants remained stable. From 2018 to 2021, gas power plants contributed an average of 10.2 % to Germany's electricity generation. This share remained steady at 10.6 % in 2022 but rose 11.2 % in 2023. This underscores the continued importance of gas power plants and Germany's dependency on them to meet the electricity demand despite the growing capacity of RES.

Overall, Research Article #2 highlights how Russia's invasion of Ukraine and the resulting disruptions to gas imports have fundamentally reshaped Germany's energy landscape. The introduction of LNG and increased imports from alternative suppliers could not fully compensate for the pre-invasion gas supply levels. However, a significant reduction in gas consumption, particularly in the industrial sector, coupled with strategic actions to stabilize markets, allowed gas prices to relax in 2023 to a "new normal". The industrial sector, heavily reliant on affordable and stable gas prices, accelerates the transition toward low-carbon alternatives and increasingly implements energy efficiency measures. Similarly, electricity prices have stabilized at higher levels, signaling a more persistent structural adjustment. With limited flexibility in demand for both gas and electricity, households, trade, and commerce must adapt to new price realities through demand reduction, efficiency improvements, or investment in sustainable solutions. From a political perspective, the shock of high and volatile energy prices underscores the urgency of investing in RES and flexible infrastructure. This crisis could be a powerful catalyst for advancing the energy transition, fostering a resilient and low-carbon energy system in Germany, and paving the way for more sustainable future.

The two articles collectively emphasize the impact of crisis and external shocks on the stability and resilience of energy systems. Article #1 highlights the strategic advantages of an interconnected European electricity system, which can provide stability and support during regional supply disruptions. In contrast, Article #2 underscores Germany’s vulnerability in its reliance on imported gas, which was exposed dramatically during the Russian-Ukrainian war. Together, these insights offer valuable lessons for a robust European energy transition. A joint European approach to energy security can maximize the benefits of shared resources and infrastructure, providing economic and stability advantages across member states. However, energy sources must be evaluated carefully to fully realize these benefits, emphasizing resilience to supply shocks and diversification. The gas crisis has redefined natural gas in the European context, positioning it as a risk but also a driver of the energy transition to abandon conventional energy sources relying on imports of resources. The shift toward alternative, low-carbon solutions, especially in sectors like heating and industry, shows promise but requires a reliable transition period. Policymakers must support this shift with effective regulation and long-term planning frameworks to enable sustainable investments. Long-term strategic planning and regulatory adjustments will be essential to navigate future uncertainties, ensuring that Europe’s energy systems remain robust, flexible, and aligned with climate goals.

III Bottom-Up Solutions To Meet the Fast-Changing Constraints in the Distributed Energy System

III.1 Fostering Distributed Flexibility Options

Distributed flexibility options are essential in tackling the challenges arising from the energy transition and the introduction of volatile renewable electricity generation (Strbac et al., 2019). At the beginning of the year 2024, approximately 450 thousand HPs (Bundesverband der Energie- und Wasserwirtschaft, 2024a) and 1.4 million EVs (Kraftfahrt-Bundesamt, 2024), and 1.1 million BSS (Fraunhofer ISE, 2024) are introduced into the German energy system. Yet, most of them are not integrated in such a way that fosters their flexibility potential and only act as additional loads in the energy systems (50Hertz Transmission GmbH et al., 2024; Burger & Weinmann, 2014). However, various concepts exist to tap into the unused potential. Legislatively, §14a EnWG enables distribution system operators (DSOs) under certain circumstances to tap into these resources directly by controlling flexible assets or through variable grid fees (Energiewirtschaftsgesetz, 2005/2024). Utilities are also increasingly required to offer time-of-use electricity tariffs to end consumers under §41a EnWG, allowing distributed flexibility to contribute by reacting to prices reflecting the electricity market situation (Energiewirtschaftsgesetz, 2005/2024). Focussing on the system level, aggregators exist that procure flexibility and market them on the German wholesale electricity markets or as balancing energy (Stede et al., 2020), complying with, e.g., minimum power requirements, by pooling the flexibility options. Also, transmission system operators (TSOs) increasingly recognize the value of distributed flexibility at the distribution grid level by using TSO-centered platforms to access flexibility from small, distributed flexibility assets after prior registration (Equigy). Such mechanisms promise a more coordinated approach to grid management, allowing for more efficient use of distributed flexibility.

Research Article #3: Assessing Vertical Flexibility Potentials – A Multi-Perspective Analysis for Germany

As decentralization continues to shape the future of the energy system, understanding how distributed flexibility can be effectively harnessed without compromising reliability or efficiency remains a critical challenge. Consequently, Research Article #3 addresses the question of the systemic value held by distributed flexibility options. Research Article #3 employs a two-step methodological framework to analyze flexibility potential in distribution grids. The first step determines the flexibility potential of DERs, such as PV systems, EVs, and

BSSs. A power flow simulation model evaluates grid conditions under varying load and generation scenarios, incorporating random assignments of DER installations to the available household connection points of the distribution grid. Key actions include grid configuration initialization, DER operation modeling, load flow calculations, congestion management, and flexibility quantification for higher grid levels (vertical flexibility). The grid setup, based on a rural distribution grid, incorporates detailed data on medium-voltage and low-voltage grid characteristics, DER distributions, and consumption and demand profiles. In the second step of the two-step framework, the available distributed flexibility is matched to the system's demand for redispatch, balancing energy, and residual load management. This step assesses the potential to integrate excess renewable electricity, reduce emissions, and enhance grid stability while analyzing the marketability of flexibility for operational purposes. Systemic flexibility needs are evaluated for redispatch, balancing energy, and residual load management, using real-world data from 2023.

The analysis of flexibility potential in the distribution grid highlights significant seasonal patterns and usage dynamics of distributed assets. Figure 6 demonstrates the seasonality of flexibility availability, with PV flexibility closely mirroring generation trends, rising in spring, peaking in summer, and declining in fall. Usability remains high, with 81.8 % of theoretical PV curtailment flexibility being available for systemic use, indicating that the distribution grid has yet to reach capacity constraints for distributed generation. Load-shedding flexibility, although exhibiting lower values in summer, is less influenced by seasonal variations, with an average monthly potential of 266 MWh and availability of 74.7 %. BSS flexibility reflects complementary seasonal behavior, with higher charging potential in colder months and increased discharging potential during warmer periods, balancing PV generation. Positive flexibility, such as load shedding and BSS discharging, is available for systemic applications 57.2 % of the time, while negative flexibility, including BSS charging and PV curtailment, is available at 70.2 %. These figures underscore the distribution grid’s capacity to adapt to varying electricity generation and demand conditions. The interplay between these sources results in a balanced level of flexibility throughout the year, with notable peaks aligning with PV output and consumption dynamics.

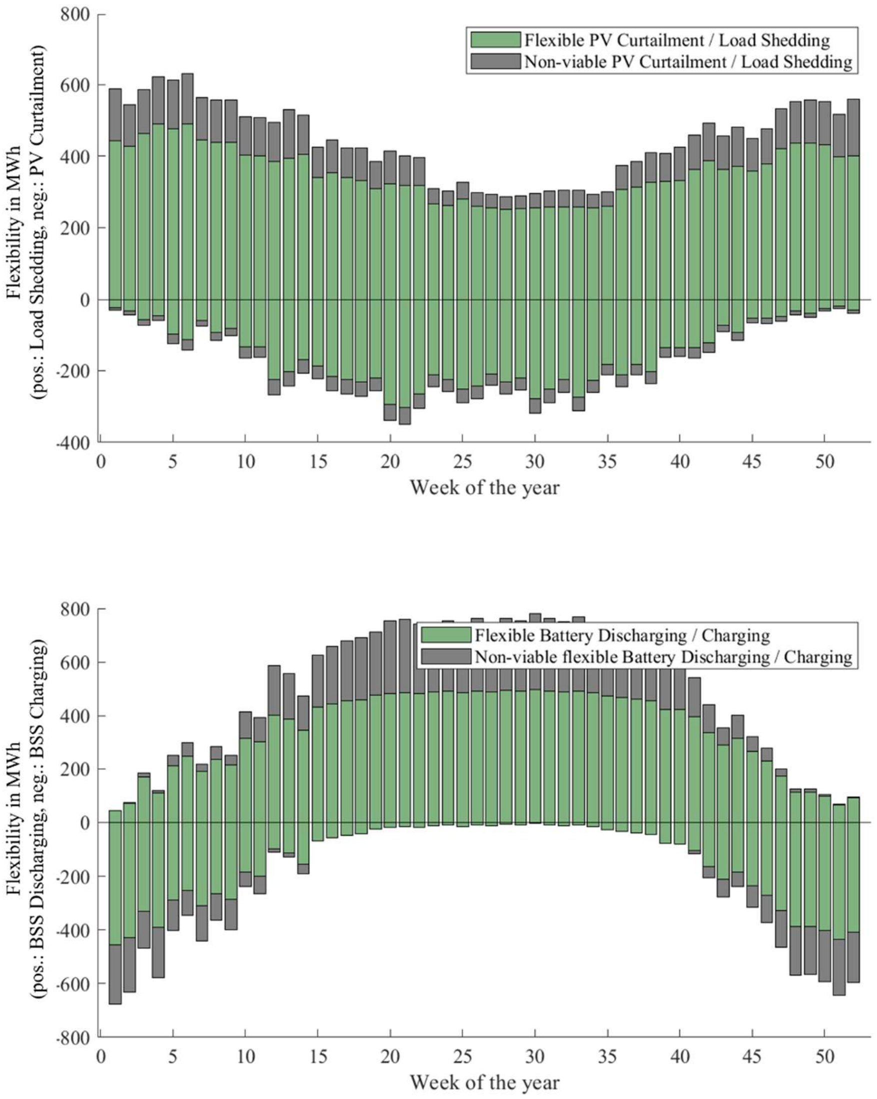

Figure 6: Viable and non-viable vertical flexibility from Load shedding, PV generation curtailment, and flexible BSS operation.

For redispatch purposes, distributed flexibility aligned well with positive redispatch needs, with load-shedding being available for 79 % of the hours redispatch is required and BSS discharging for 75 %. Negative redispatch needs exhibit less alignment, with PV curtailment available for only 42 % of the hours, and a negative redispatch is required compared to 73 % for BSS charging. While distributed flexibility could have met significant redispatch requirements, 21 % of the potential flexible energy remained unused due to temporal mismatches.

For balancing energy, distributed flexibility was strongly aligned with the needs of the Frequency Containment Reserve (FCR) and Automatic Frequency Restoration Reserve (aFRR). Load-shedding was available for 90 % of the hours of positive FCR needs and BSS discharging for 86 %, while negative FCR could have relied on BSS charging for 88 % of the required hours. PV curtailment, however, aligned with only 49 % of the hours with negative FCR needs due to temporal mismatches. Positive aFRR needs aligned well with load-shedding (89 %) and BSS discharging (85 %), while BSS charging matched 88 % of hours with negative aFRR needs. Utilization rates exhibit high values for both FCR and aFRR, with most of the available flexible energy from load-shedding and BSS resources utilized (78 % to 91 %). Conversely, Manual Frequency Restoration Reserve (mFRR) had a minimal alignment, with coverage below 2 % of the hours and similarly low utilization rates, reflecting its infrequent demand and limited overlap with distributed flexibility availability.

For residual load, positive residual load needs aligned well with available distributed flexibility. Load-shedding and BSS discharging were temporally matched with 96 % and 92 % of required hours, and nearly all available flexibility in these categories would have been utilized (98 % and 96 %). In contrast, negative residual load exhibited poor alignment, with PV curtailment and BSS charging matching only 2.5 % and 3.7 % of the required hours. Utilization rates for negative flexibility were similarly low, at 8 % for PV curtailment and 5 % for BSS charging. The average daily profiles reveal that positive residual load peaked during periods of low renewable generation, such as mornings and evenings, while negative residual load coincided with midday PV surpluses. Although positive residual load needs would have been effectively matched by available flexibility, negative residual load was only partially addressed.

This study underscores the untapped potential of distributed flexibility within distribution grids to support Germany’s evolving energy system. The research highlights the temporal alignment of flexibility supply from DERs with systemic needs, such as redispatch, frequency reserves, and residual load management. While the flexibility potential from PV systems, load-shedding, and BSS complements one another and ensures year-round availability, temporal mismatches limit its full utilization, particularly in negative flexibility from PV curtailment. The findings emphasize that leveraging distributed flexibility requires enhanced visibility, coordination, and digitalization across grid levels. Technologies such as digital twins, smart meters, and advanced distribution grid management are pivotal to bridge the gap between data collection and actionable control. Moreover, aggregators play a central role in pooling flexibility resources, coordinating signals, and aligning the contributions of DERs with grid needs. Effective coordination between DSOs, TSOs, and aggregators will be vital to unlock the full value of distributed flexibility. Integrating preventive and curative measures to manage flexibility will be essential to use the available vertical flexibility potential efficiently. Time-of-use pricing, local energy markets, and real-time intervention protocols represent promising approaches to incentivize the participation of DERs. Further, stable operation within distribution grids is a prerequisite for fostering vertical flexibility to support the transmission grid. Research Article #3 further stresses that the rollout of smart meters and other control mechanisms in Germany must be accelerated. Improved data collection can enable better transparency of electricity flows and grid bottlenecks, optimize flexibility utilization, and avoid unnecessary grid fees for consumers while ensuring affordability and maintaining the level of security of supply. Incorporating vertical flexibility into forecasting models and grid planning will amplify its benefits, allowing grid operations to more accurately anticipate short-term and long-term flexibility requirements.

In conclusion, distributed flexibility offers a scalable solution to integrate renewable energy, enhance grid stability, and reduce consumer electricity costs. By addressing current challenges and fostering regulatory and market innovations, distributed flexibility can become a building block of Germany's energy transition. Future efforts should focus on developing holistic models, advancing optimization strategies for DERs, and exploring emerging technologies to unlock the full potential of distributed flexibility.

While Research Article #3 underlines the potential of distributed flexibility options not only for the distribution grid but also for balancing energy and the electricity system in Germany, Research Article #4 focuses on the industrial sector. The industrial sector accounted for 43 % of German electricity consumption in 2023 (Bundesverband der Energie- und Wasserwirtschaft, 2024b) and is recognized to hold a substantial flexibility potential (Paulus & Borggrefe, 2011; Sauer et al., 2022) which is expected to grow further in the future (50Hertz Transmission GmbH et al., 2024; Rövekamp et al., 2023; Schoepf et al., 2018). Yet this potential remains underutilized mainly due to the high cost of investment, limited knowledge, uncertainty regarding the impact on production processes, and doubts about the overall profitability (Hanny et al., 2022; Leinauer et al., 2022). Nevertheless, studies indicate that industry could significantly contribute to closing the flexibility gap while simultaneously realizing economic benefits for companies that, among other things, face increasing price levels and volatility (Jäger et al., 2022; Löbbe et al., 2021).

Research Article #4: How flexible are energy flexibilities? Developing a flexibility score for revenue and risk analysis in industrial demand-side management

To support industrial companies exploiting their flexibility potentials, methods exist that accurately estimate potential revenues from industrial flexibility measures, such as energy audits (Tristán et al., 2020). Although there are specialized optimization techniques to assess the specific economic potential in certain sectors (e.g., cement production or heat transfer stations), they are limited to specific industries and processes (Kohne et al., 2021; Summerbell et al., 2017). These methods are costly and time-intensive, making them less accessible due to the financial burden and revenue uncertainties (Leinauer et al., 2022). Therefore, there is a need for a more streamlined, accessible approach that enables companies to assess the approximate economic potential and associated revenue risk of energy flexibility measures (EFMs) with minimal effort. This supports companies in gathering enough evidence to make informed investment decisions on EFMs, guiding them in prioritizing detailed analysis and reducing entry barriers for decision-making. To address these challenges, a flexibility score is developed in Research Article #4 using an Analytical Hierarchy Process (Repschläger et al., 2013; Zopounidis, 2010), which captures the DOFs of EFMs through a straightforward scaling system. In this context, an EFM's DOFs refers to its range of possible realizations determined by its specific characteristics. For instance, some processes may exhibit a low DOF due to constraints like a machine's fixed power consumption, while others may exhibit higher DOF. Using selected properties, industrial companies can apply this score to assess their flexibility measures. With this flexibility score, companies can estimate a specific flexibility measure's financial revenue potential and associated risks without detailed modeling or analysis.

The flexibility score is designed using a five-step methodological approach. Step 1 identifies relevant properties of flexibility measures to capture their DOFs. These properties, expressed through numeric or categorical values, indicate the practical flexibility of each measure. The selected properties must be broadly applicable across various industrial companies and simple to determine using existing data to avoid complex analyses. This step aims to develop a property portfolio that accurately describes flexibility measures' nature, behavior, and applicability, balancing precision with generalizability. For the case study conducted in Research Article #4, the activation duration, recovery time, activation frequency, and demand for compensation were selected. Step 2 defines a numerical rating scale to obtain the same format and units for all components of the flexibility score. Since the properties' projection onto the rating scale interval represents a strong influencing factor, a specific projecting normalization function must be formulated for each property. Next, all properties are aimed to be projected on a scale from 1 to 10, where 10 represents the maximal freedom in that property). As the identified properties have different relative importance for the explanatory power of the flexibility score, weights are assigned to the properties in the next step. To obtain these weights for the case study conducted in Research Article #4, research experts from the energy management field were interviewed, and normalized weights were obtained for the selected four properties. The normalized weight vectors from the multiple respondents were combined using an established method (Saaty, 1987), resulting in weights for four key properties of flexibility measures. These initial weights were then used to find the optimal solution for the four weights for corresponding properties. This was achieved using a regression analysis based on a natural exponential function, with the least squares estimator helping to refine the model. For this analysis, both revenue data and normalized properties of flexibility measures (calculated from case study data) were needed. The final optimized weights were tailored to the Day-Ahead and Intraday electricity markets, providing a more accurate prediction of revenue outcomes. The score's explanatory power is evaluated in the fifth step by applying it to a case study involving real-world data from 46 EFMs implemented by companies in Germany. Integer Linear Programming was used to identify the optimal scheduling for each flexibility measure, maximizing potential revenues based on historical electricity prices from Germany's Day-Ahead and Intraday markets. The case study provides two key results: the flexibility score of each energy flexibility measure considered and the revenue averaged over four weeks under optimal scheduling for both the Day-Ahead and the Intraday markets.

In Figure 7, the revenue potential on the Day-Ahead and Intraday market is plotted on the y-axis over the flexibility score for each of the 46 EFMs on the x-axis. Using regression analysis for both electricity markets, the numerical specification of the relationships is investigated using a natural exponential function, as shown in Figure 7.

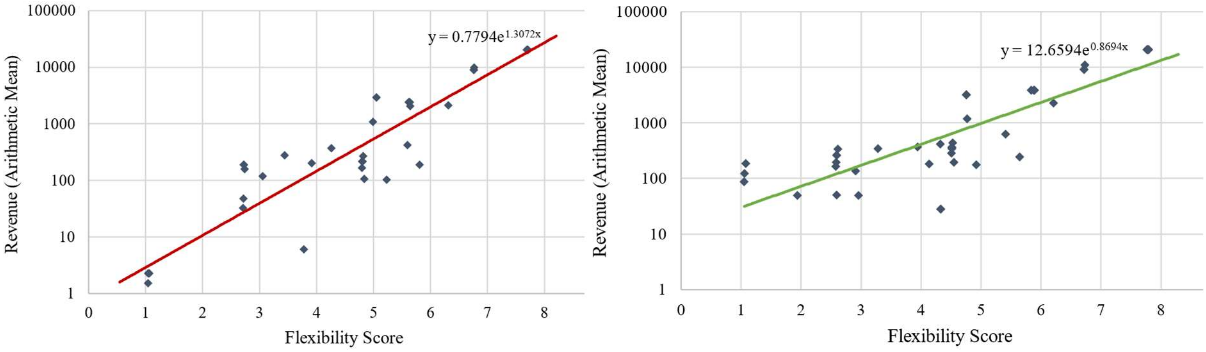

Figure 7: Estimated weekly revenue potential (EUR/MWh) for the Day-Ahead (left) and Intraday market (right).

The findings illustrated in Figure 7 depict a clear correlation between the flexibility score capturing the EFMs' DOFs and the generatable revenue for both spot markets. The results indicate that the basic level of revenue potential for the Intraday market is higher than that of the Day-Ahead market. At the same time, the revenue potentials of the investigated EFMs for the Day-Ahead market seem to be much more sensitive to changes in the DOF and, thus, in the flexibility score. Figure 7 hints that these two empirical effects almost balance out for high flexibility scores.

Regarding the revenue risk, the coefficient of variation VarK as a measure of dispersion or, in this case, risk, is used to describe the revenue risk while ensuring the comparability of heterogenous flexibility measures, whose revenue levels can differ considerably. The VarK of a given EFM is defined as the ratio of empirical standard deviation and the arithmetic mean of the associated revenue. The results are depicted in Figure 8, including the regression function's functional equation. A high VarK reflects a higher probability of diversion from the mean revenue and, therefore, higher revenue risk.

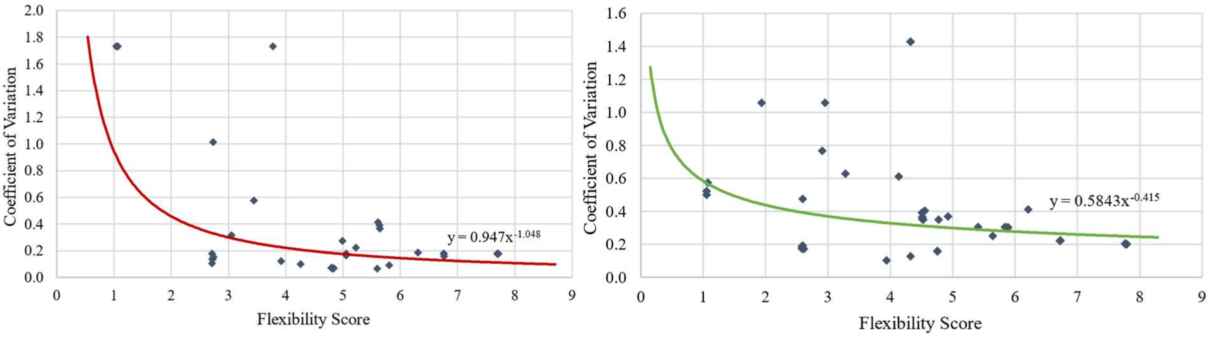

Figure 8: Estimated coefficient of variation of the revenue potential for the Day-Ahead (left) and Intraday market (right).

The results indicate a clear relationship between the flexibility score and the revenue risk. EFMs comprising a higher flexibility score are more likely to pose less revenue risk. Further analysis using the rate of change of the coefficient of variation regarding the flexibility score shows, in line with the observation of the empirical data points, that increasing the flexibility score by one unit for low initial values has a significantly more significant effect on the coefficient of variation, and therefore revenue risk, than for high initial values of the flexibility score. A comparison of risk between the Day-Ahead and Intraday markets showed no consistently higher risk. Flexibility measures with higher average FlexScores had lower risk in the Day-Ahead market, while those with lower FlexScores had lower risk in the Intraday market.

The developed flexibility score effectively links the EFM's DOFs to their potential revenue outcomes in both Day-Ahead and Intraday market scenarios. The findings reveal meaningful relationships between the flexibility score, expected revenue, and associated risk levels. Unlike traditional investments, increasing the flexibility score of EFMs tends to boost expected revenue while simultaneously lowering associated risk. This makes investments in EFM and measures to enhance the DOFs of EFMs particularly advantageous for industrial companies. The flexibility score offers a novel and practical tool for supporting investment decisions in industrial flexibility options, providing a way to quantify both revenue potential and risk for specific flexibility measures. Firstly, it offers a straightforward approach for estimating the economic potential and associated risk of flexibility measures without requiring time-intensive investigation. This makes it especially valuable in practical contexts, allowing industrial companies, aggregators, and energy consultants to assess viability early on and identify economically attractive projects. Its ease of use reduces barriers to entry, supporting informed decision-making for investments in flexibility measures. Additionally, the simplicity of the flexibility score makes it accessible to a range of users. For industrial companies, it aids in evaluating potential revenue from flexibility measures and production adjustments in early project stages. Aggregators and consulting agencies can also use it as a consulting tool, gaining insights into initial revenue opportunities during customer acquisition. Policymakers can leverage the score to identify and design subsidies, making flexibility investments more financially attractive by lowering costs and improving returns. Such support mechanisms could trigger further investments in flexibility measures.

III.2 Pursuing Innovative Community Approaches

The EU's Clean Energy Package (European Commission, 2019) establishes a legal framework that empowers consumers and communities to participate directly in the energy system and markets. Two key directives, the Electricity Market Directive (EU 2019/944, 2019) and the Renewable Energy Directive (EU 2018/2001, 2018), promote distributed energy production and consumption, emphasizing collective self-supply and energy communities. However, Germany has not integrated these EU mandates into national law, hindering new business models and innovation (Deutsche Energie-Agentur GmbH, 2022). In particular, the energy sharing envisioned by the EU – shared consumption of self-generated electricity through the public grid – is unfeasible in Germany, as existing models lack sufficient incentives for local renewable energy use and the growth of producer-consumer communities (Babilon et al., 2024). However, pilot projects have already delved into different forms of energy communities, energy sharing, and the utilization of distributed flexibility options in the distribution grid. The pebbles initiative, for example, aimed to establish Local Energy Communities that enable peer-to-peer energy trading, integrating local production, consumption, and storage to enhance sustainability and resilience using blockchains (Allgäuer Überlandwerk GmbH, 2022). With the Altdorfer Flexmarkt (ALF), on the other hand, a concept for a marketplace for energy flexibility on the distribution grid level for DSOs was developed, allowing the use of local flexibility potentials for congestion management (Forschungsstelle für Energiewirtschaft e.V., 2022). The real-world pilot Wunsiedel Energy Community encourages residents to generate and share renewable energy, fostering collaboration and enhancing community involvement in the energy transition (Deutsche Energie-Agentur GmbH, 2024). Lastly, the enera project focused on creating a virtual power plant that connects various energy producers and consumers, demonstrating local flexibility potential using digitalization to avoid wind power curtailment (Brommelmeier et al., 2021). According to multiple studies, energy communities and energy sharing inhibit numerous benefits: they promote local acceptance of renewable energy, drive the growth of renewable energy source installations, lower the need for subsidies, and enable economic participation in the energy transition. Additionally, they can help support the continued operation of post-subsidy renewable generation units and create incentives for new RES installations without subsidies (Barone et al., 2023; Rocha et al., 2023; Sousa et al., 2023).

Research Article #5: Assessing the Impacts of Energy Sharing on Low Voltage Distribution Networks: Insights into Electrification and Electricity Pricing in Germany

In the early stages of research on the evolving energy system, significant effort was devoted to analyzing the integration of DERs into Low-Voltage Distribution Networks (LVDNs). This research proposed traditional grid reinforcement measures, novel power quality control strategies, external incentives, and market signals to support distribution grid operation (Alboaouh & Mohagheghi, 2020; Coster et al., 2011; K. Kumar & G. B. Kumbhar, 2017; Karimi et al., 2016; Nour et al., 2020). However, as the concept of energy sharing emerged, the focus shifted toward the end-user perspective (Dynge et al., 2021), with much of the current research centering on the internal mechanisms of energy sharing among Renewable Energy Community (REC) members and the benefits it offers them (Gjorgievski et al., 2023; Tsaousoglou et al., 2022). Notably, only a few studies have explored the broader implications of energy sharing on the overall energy system, particularly its impacts on local LVDNs. Research Article #5 aims to fill that gap by examining how energy sharing affects network performance metrics, influenced by different pricing strategies and pathways to electrification. The article analyzes static network fees and electricity tariffs based on standard system cost assumptions alongside dynamic network fees and dynamic electricity tariffs that reflect the impacts of energy sharing on LVDNs. Additionally, future adoption rates of DERs are considered, including BSSs, EVs, and HPs, using projections from Germany’s electricity network development plan for 2023–2045 (50Hertz Transmission GmbH et al., 2024) to reflect the distributed and electrified nature of the future energy system. Research Article #5 presents a comprehensive methodology for integrating energy-sharing schemes within RECs in LVDNs. A sequential modeling approach is deployed, combining an energy-sharing model with a network model, allowing us to evaluate the impacts of energy-sharing on various network performance metrics using load flow calculations. Further. a case study using representative data for renewable generation, residential load profiles, EVs, and BSSs was used to gain valuable insights.

While Research Article #5 centers on evaluating the impact of energy sharing on grid performance, the effects of energy sharing and different tariff structures on the energy community are examined first. This analysis encompasses grid-community interactions within the energy-sharing framework, using grid imports and exports to represent electricity procured from and fed into the grid by the REC and REC-specific imports and exports to capture electricity shared among community members. The charged and discharged electricity of BSSs and EVs is also analyzed. Operational costs associated with REC activities are quantified, explicitly focusing on total electricity costs from the grid and community interactions, covering all imports and exports. The values for the performance metrics are presented in Table 2.

Table 2: Energy community performance metrics, including grid/REC interaction, DER operation, and costs.

	Business-as-usual			**Renewable energy community**		
	Static pricing	**Dynamic pricing**	**Dynamic grid fees**	**Static pricing**	**Dynamic pricing**	**Dynamic grid fees**
			2023			
Grid import /export [kWh]	629 /626	661 /626	675 /626	133 /70	133 /70	133 /70
REC import /export [kWh]	0/0	0/0	0/0	4172 /4172	4026 /4026	4013 /4013
BS charging /discharging [kWh]	560 /453	728 /590	802 /649	877 /710	877 /710	877 /710
EV charging /discharging [kWh]	0/0	0/0	0/0	0/0	0/0	0/0
REC costs [EUR]	107	106	104	23	21	21
			2037			
Grid import /export [kWh]	1731 /350	1731 /350	1731 /350	1365 /0	1365 /0	1365 /0
REC import /export [kWh]	0/0	0/0	0/0	7465 /7465	7416 /7416	7416 /7416
BS charging /discharging [kWh]	547 /443	855 /693	914 /740	450 /365	624 /505	574 /465
EV charging /discharging [kWh]	1305/ 102	1307 /103	1350 /137	1296 /116	1390 /210	1483 /245
REC costs [EUR]	295	288	281	232	225	221

Comparing scenarios with and without a REC highlights significant reductions in grid reliance when prioritizing energy sharing. REC scenarios show up to a 78 % decrease in grid imports and eliminate exports as community members meet their needs through self-consumption or energy sharing. This is incentivized by a community energy price set at 50 % of the retail rate, making local energy sharing more cost-effective. In 2037, energy sharing within the community becomes more pronounced with increased installations of DERs like PV systems, BSSs, and EVs. Households can store excess energy during high PV generation and share it later, supporting higher demand while reducing grid reliance. Dynamic pricing strategies cause slight variations in grid imports, especially during low retail price periods and with high DER installation. However, the stable community price consistently supports local energy interactions, leading to up to 80 % savings in electricity costs. These savings highlight the economic and resilience benefits of community-driven energy sharing in REC scenarios.

In the next step, Research Article #5 analyzes the grid's performance using metrics, including component loading, voltage magnitude, and grid reinforcement costs. Maximum loading for lines and transformers is set to 100 % of the nominal power to avoid disruptions or curtailment of DER electricity generation. The voltage limits are set to +/− 6 % of the nominal voltage, motivated by the current German standard DIN 50160 [59], which allows for a range of +/− 10 % at both LV and MV grid levels, allowing for a safety margin of +/− 4 % in line with (Beck et al., 2022; Candas et al., 2023; Deutsche Energie-Agentur GmbH, 2012). The necessities for new lines and transformers are examined to assess reinforcement costs. Following an iterative heuristic method, line overloading is first addressed by adding parallel lines, starting from the transformer. Transformer loading is evaluated in the next step, and upgrades are made to the next larger standard size if needed. Voltage magnitudes at all 906 buses are checked for violations of voltage boundaries, and if found, lines connected to affected buses are reinforced with additional parallels, starting from the transformer. No specific limit is set on the number of parallel lines, which may limit real-world applicability. After each step, a power flow simulation verifies that grid constraints are addressed, with steps repeated as necessary. Once all reinforcements are implemented, a final simulation ensures that previous upgrades are not compromised. While computationally efficient, this heuristic may not yield optimal solutions, and the given results should be regarded as indicative estimates. The results of the grid performance metrics are presented in Table 3.

Table 3: Grid performance metrics, including transformer and line loading, voltage magnitudes, and grid reinforcement measures.

	Business-as-usual			**Renewable energy community**		
	Static pricing	**Dynamic pricing**	**Dynamic grid fees**	**Static pricing**	**Dynamic pricing**	**Dynamic grid fees**
2023						
Max./Min. transformer loading [%]	29/15	70/34	91/45	25/12	27/13	29/14
Max. voltage for phases A/B/C [p.u.]	1.06/1.07/1.06	1.06/1.07/1.06	1.06/1.07/1.06	1.07/1.07/1.06	1.07/1.08/1.07	1.07/1.07/1.07
Overvoltage hours for phases A/B/C [%]	2/10/0	2/9/1	2/8/0	2/8/2	7/8/4	4/8/4
Min. voltage for phases A/B/C [p.u.]	1.03/1.03/1.04	1.02/1.00/1.03	1.01/0.99/1.03	1.02/1.02/1.04	1.01/1.02/1.03	1.02/1.02/1.02
Undervoltage hours for phase A/B/C [%]	0/0/0	0/0/0	0/0/0	0/0/0	0/0/0	0/0/0
Added transformer capacity [kVA]	0	0	0	0	0	0
Cost for added transformer capacity [kEUR]	0	0	0	0	0	0
Lines added [km]	1.7	1.3	1.3	1.6	2.1	1.6
Cost of lines added [kEUR]	95.6	76.8	76.8	92.1	123	93.4
2037						
Max./Min. transformer loading [%]	251/124	256/126	256/126	108/54	124/61	124/61
Max. voltage for phases A/B/C [p.u.]	1.07/1.07/1.06	1.07/1.07/1.06	1.07/1.06/1.06	1.09/1.10/1.07	1.07/1.09/1.07	1.07/1.07/1.08
Overvoltage hours for phases A/B/C [%]	2/2/1	1/3/0	1/2/1	1/7/10	2/4/14	3/7/11
Min. voltage for phases A/B/C [p.u.]	0.92/0.92/0.84	0.90/0.85/0.83	0.94/0.84/0.83	0.87/0.93/0.99	0.87/0.91/0.99	0.87/0.91/0.99
Undervoltage hours for phase A/B/C [%]	1/1/1	1/1/1	1/1/1	1/1/0	1/1/0	1/1/0
Added transformer capacity [kVA]	630	630	630	250	250	250
Cost for added transformer capacity [kEUR]	15.2	15.2	15.2	9.6	9.6	9.6
Lines added [km]	3.3	3	3	5.9	4.1	3.4
Cost of lines added [kEUR]	189	176	176	342	240	196

Table 3 depicts that energy sharing can effectively reduce grid stress, alleviating transformer and line loading by up to 68 % and 62 %, compared to Business-as-usual scenarios. By 2037, however, energy sharing alone may not fully mitigate transformer overloading, as increased DER deployment heightens grid utilization. While energy sharing decreases general asset loading, it does not significantly reduce the frequency of peak loading events, which often occur during low retail electricity prices and present a persistent challenge for grid stability. Scenarios incorporating dynamic pricing and grid fees reveal an unintended impact: rather than shifting consumer behavior to relieve grid stress, these pricing mechanisms sometimes marginally increase grid loading, particularly in the 2023 Business-as-usual scenario (cf. Table 3). This suggests the need for more refined pricing strategies to align consumer demand with (real-time) grid capacity constraints. All scenarios encounter voltage fluctuations, including instances where voltage levels breach upper and lower limits. The REC scenarios exhibit particularly variable voltage profiles due to the flexibility of community energy trading, which contributes to significant voltage deviations (cf. Table 3). This variability underscores the need for grid reinforcement, especially in line installations, to maintain voltage stability. Although energy sharing raises overall grid reinforcement costs – primarily due to additional lines to handle voltage issues – transformer upgrade expenses remain relatively low, with necessary capacities not exceeding 630 kVA.

In conclusion, Research Article #5 shows that energy sharing can facilitate community-level cost savings and reduce asset loading on the grid. However, it also introduces increased voltage variability, possibly leading to additional reinforcement costs. Looking toward 2037, the impacts of DER installations are anticipated to intensify significantly. This underlines the need to incorporate energy community approaches into grid planning. Furthermore, it emphasizes the necessity for enhanced coordination at the distribution grid level, which can be achieved through comprehensive end-to-end digitalization. By prioritizing these strategies, a more resilient, efficient, and sustainable energy future that not only meets the growing electricity consumption but also copes with the transition to a distributed energy landscape can be achieved.

Community approaches traditionally focus on residential settings, yet substantial benefits also arise from their extension into industrial settings. IECs, which align with the EU's definition of Energy Communities (European Commission, 2019) represent an innovative model where industrial participants interconnect locally to exchange energy and are technically realized through grid-connected microgrids, enabling the synchronization of renewable energy supply with the electricity and heat demand of participating industrial companies. IECs are believed to enhance local renewable integration and support cost efficiency by reducing dependency on public energy infrastructure (Eslamizadeh et al., 2022; Kong et al., 2020; Rajamand, 2020).

Research Article #6: Industrial Multi-Energy Communities as Grid-Connected Microgrids: Understanding the Role of Asymmetric Grid-Charge Regulation

While a considerable body of literature examines how various assets of industrial companies are coordinated within an IEC, Research Article #6 delves into the economic and ecological impacts of asymmetric regulations through a microgrid lens. A significant aspect of this analysis highlights current German regulations concerning grid charges, which incentivize industrial energy customers to maintain a constant load profile (Hanny et al., 2022). This requirement presents a challenge, as it hinders the synchronization of electricity demand with the volatile electricity supply introduced by RES. Further, different companies within a microgrid experience the effects of these regulations in varying, asymmetric ways, depending on their electricity consumption profile. Understanding how these asymmetric regulations influence IEC behavior and how IECs can leverage them is crucial for successful implementation and design. Therefore, Research Article #6 focuses on the implications of asymmetric grid-charge regulations to assess the economic and ecological effects using a case study based on a representative IEC.

In Research Article #6, a mixed-integer linear program is developed to analyze the behavior of IECs under asymmetric German grid-charge regulation, representing multiple participating industrial companies in an underlying microgrid. The microgrid comprises different assets that generate, consume, or store electricity and heat over various periods. Within the microgrid, companies can freely share electricity and heat. In doing so, the participants jointly minimize the costs of the entire microgrid. In more detail, the modeled assets owned by the different industrial companies comprise PV systems for electricity generation, Combined heat and power plants (CHPs) units for heat and electricity generation, HPs, and Gas Heaters (GHs) for heat energy generation, as well as BSSs and heat storage units. In addition, electricity can be fed into or withdrawn from the public electricity grid through several grid coupling points (GCPs). Typically, every GCP is assigned to precisely one of the participating companies. The optimal grid-charge corridor for each GCP is selected in the optimization process to ensure minimal energy costs. The case data for three companies from a real-world industrial area was obtained for 2021. Company 1 (C1) represents an energy-intensive manufacturing company with a CHP unit, a heat storage unit, and a four-shift operation seven days a week. Company 2 (C2) represents a medium-sized company ("sustainable pioneer") with a PV system, a BSS, a heat storage unit, and an HP. Company 3 (C3) represents a large store open on weekdays and Saturdays, with a PV system and no further assets. The simulation is conducted over a whole year to consider seasonal effects. Three scenarios are analyzed to evaluate the IEC under asymmetric regulation. Scenario 1 is a benchmark, with each company independently minimizing operational costs, illustrating individual cost management, asset use, and emissions under current regulations. In Scenario 2, the companies form a joint IEC, coordinating assets to minimize total costs, with installed power lines and heat pipes enabling unrestricted energy sharing. Scenario 3 removes regulatory constraints, allowing the IEC to operate without limits on energy exchange, revealing the impact and potential inefficiencies of current asymmetric regulations. Figure 9 depicts the total energy costs for each scenario differentiated by the electricity procurement price (EPP), levies, volume-based and capacity-based grid charges (VBGC and CBGC), prices for natural gas, and feed-in revenue on the left and differentiated by the company and the costs for natural gas on the right.

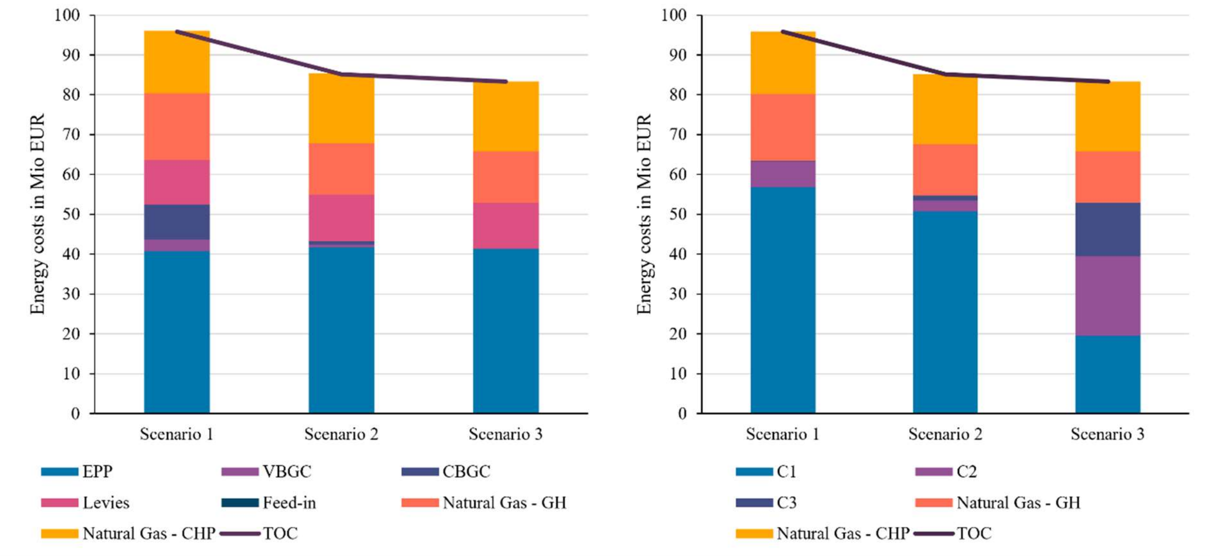

Figure 9: Distribution of energy costs by component (left) and company (right).

In Scenario 1, the optimal configuration resulted in total operational costs of 95,868,709 EUR, with energy procurement charges (EPCs) comprising 42.5 %, grid charges at 12.1 %, and levies at 11.7 % of the total energy costs (cf. Figure 9). Natural gas costs for heating and CHP units comprised 17.5 % and 16.3 %, respectively, while feed-in revenue had a minimal impact, reducing costs by just 0.2 % of the total energy costs. In Scenario 2, the optimal setup reduced total operational costs to 85,778,866 EUR, which describes an 11.2 % saving compared to

Scenario 1. EPCs accounted for 48.9 % of the total energy costs, with optimized grid charges decreasing to 1.9 %, exhibiting an 83.7 % decrease compared to Scenario 1 (cf. Figure 9). Heating and CHP gas costs comprised 35.7 % of total energy costs. Most of the most electricity costs were attributed to Company 1 (92.8 %). Scenario 3, not subject to regulatory constraints, achieved the lowest costs at 83,306,002 EUR – posing a 2.2 % reduction compared to Scenario 2. However, if the exact total grid charges for Scenario 2 are assumed to ensure comparability, the savings reduce to 0.3 %, with EPCs reduced by 0.7 % and gas costs by 0.1 % (cf. Figure 9). Removing the market premium regulation favored self-consumption, as PV-generated electricity was not fed into the grid due to the low feed-in revenue, underscoring the IEC's ability to optimize cost-effectively under minimal regulation. Examining the load profiles, in Scenario 1, each company's electricity withdrawal follows its time-dependent load profile, with minimal impact from energy generation, storage, or load flexibility. In Scenario 2, the IEC primarily uses GCP 1, benefiting from its lower grid charges. The model optimizes GCP 1's peak load to reach 8,000 hours, covering electricity demand up to this limit. GCP 2 and 3 are only used when the total electricity demand exceeds GCP 1's peak capacity. GCP 2 primarily consumes electricity outside peak load times to reduce capacity-based grid charges. In Scenario 3, withdrawals are evenly distributed without restrictions or pricing differences among GCPs.

In the next step, Research Article #6 examines the utilization of the shared IEC assets, focusing on PV system self-consumption and heat generation distribution. By sharing assets, the IEC enhances their utilization. Figure 10 depicts the self-consumption rates of PV-generated electricity across scenarios on the left side and the utilization of the heat-generating assets per scenario on the right side.

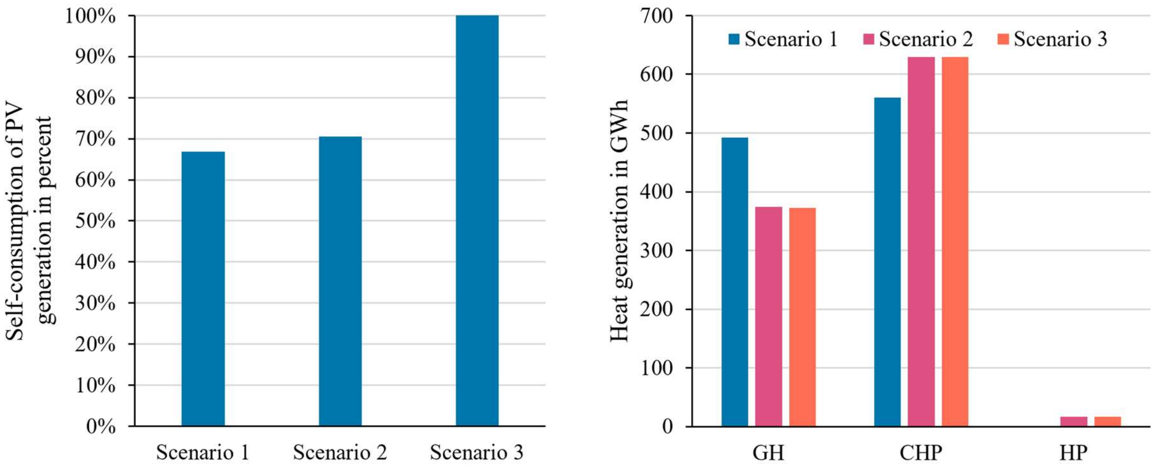

Figure 10: Self-consumption of PV-generated electricity (left) and heat generation per asset category (right).

In Scenario 1, overall PV self-consumption is 66.8 %, with Company 2 achieving nearly 100 % due to a high daytime load profile matching PV generation and BESS utilization on weekends. In contrast, Company 3, which exhibits lower weekday demand and is closed on Sundays, reaches only 44.7 % self-consumption. In Scenario 2, self-consumption becomes more dynamic. When grid feed-in offers a higher price than grid consumption, the IEC benefits from feeding excess electricity into the grid. Conversely, in times comprising high EPP, self-consumption can help reduce cost, leading to a higher overall self-consumption than Scenario 1. In Scenario 3, without grid charges or the market premium model, self-consumption reaches 100 % (cf. Figure 10), as grid consumption costs consistently outweigh feed-in revenues. The heat generation distribution further illustrates IEC optimization. In Scenario 1, gas heating is 32.2 % higher than for the optimized IEC setting in Scenario 2. In Scenario 2, the CHP and HP sharing substantially reduces gas usage, increasing CHP and HP utilization by 12.3 % and 74 times, respectively. Scenario 3 achieves an additional 0.6 % reduction in gas heating and a 4.7 % increase in HP usage, indicating that asset utilization is optimized further when regulatory constraints are removed.

In conclusion, Research Article #6 highlights the cost-saving potential and inherent limitations of IECs within the framework of current asymmetric regulatory conditions. The case study illustrates significant reductions in operational costs achieved through IECs. However, the extent of these benefits is heavily influenced by regulatory variables. In Scenario 1, individual companies struggle to fully capitalize on the advantages presented by asymmetric grid charges, even when they possess high energy demand and flexibility, as demonstrated by Company 1. Conversely, Scenario 2 reveals that IECs can optimize grid utilization by pooling their assets and leveraging different grid-charge regulations on different GCPs, resulting in an 85.9 %

reduction in grid-related costs compared to isolated operations. Scenario 3 further depicts that IECs can achieve additional cost savings by aligning energy consumption with market price fluctuations, free from regulatory constraints. Overall, the findings of Research Article #6 suggest that Germany's existing asymmetric grid-charge regulations significantly limit the operational flexibility of industrial companies and IECs, thereby constraining both renewable self-consumption and their ability to support grid stability dynamically. The results indicate that the current German regulations on grid charges pose multiple challenges. By incentivizing constant loads, industrial companies and IECs cannot leverage their flexibility to balance generation and load effectively in response to price signals. This leads to higher emissions due to electricity sourced from the GCPs within the IEC. Moreover, these regulations necessitate considerable redistribution of electricity among companies to comply, even when the overall load profile of the IEC remains relatively stable. In contrast, omitting asymmetric grid-charge regulation, Scenario 3 demonstrates that allowing IECs greater freedom to adapt to dynamic pricing could support grid stability and emissions reductions. This suggests a pressing need for regulatory frameworks that reconcile economic incentives with environmental objectives, promoting a more sustainable and flexible energy system in the future.

IV Conclusion

IV.1 Summary of the Findings

This doctoral thesis offers an in-depth perspective on external influences on the German energy transition and the potential of distributed flexibility and community-based approaches as essential elements to cope with the dynamics. These elements support a successful transition toward sustainability by maintaining affordability and security of supply. The six research articles presented in this thesis focus on examining the influence of the COVID-19 pandemic and the European gas crisis and subsequent implications on the energy transition and the multifaceted potential of distributed flexibility options.

The evolving energy system in Germany is significantly shaped by the integration of RES and influenced by recent geopolitical events. As highlighted in Research Article #1, the COVID-19 pandemic presented unique challenges to the interconnected European electricity grid, including temporary border closures that impacted the electricity sector. Despite these disruptions, Germany was able to leverage its interconnected transmission lines with neighboring countries, relying on electricity imports from conventional power plants to supplement its growing share of RES. This increased utilization of interconnection capacities as flexibility options facilitated a record share of renewables within Germany's electricity generation mix, underscoring the importance of a robust and coordinated European electricity system to manage the complexities of intermittent energy sources. These insights emphasize the need for flexibility within the interconnected European electricity system and highlight the value of aligned national strategies to maintain resilience. To achieve long-term climate goals, European policies should account for the impacts and benefits of this interconnected electricity system. Coordinated efforts across Europe are essential for addressing the challenges of the climate crisis and supporting a sustainable transition for the continent's future electricity system. Following the geopolitical shift due to Russia's invasion of Ukraine, Research Article #2 discusses the profound disruption to Germany’s gas imports, prompting a search for alternative energy sources and resulting in elevated energy prices and heightened volatility throughout 2022. With natural gas now perceived as a high-risk resource, adapted consumption patterns emerged, and energy prices showed signs of stabilization in 2023, introducing a “new normal” for the German energy system. This shock can accelerate the shift toward low-carbon alternatives and enhanced resilience while also signaling strong potential for investments in renewable energy, electrification, and flexible energy options. Moving forward, comprehensive policy initiatives and strategic infrastructure investments will be essential to address the interconnected challenges of energy security and climate change. Research Article #3 emphasizes the systemic value of DERs within Germany's distribution grid, revealing their potential role in managing redispatch, balancing energy, and residual load requirements. Through a two-step methodological approach, the flexibility potential of DERs such as PV curtailment, load-shedding using HPs, EVs or household appliances, and BSS operation are examined, highlighting complementary seasonal patterns. Despite significant untapped flexibility potential, Research Article #3 underscores the potential of digitalization, improved TSO-DSO coordination, and targeted incentives to fully leverage vertical flexibility. These insights contribute to understanding the critical role of DERs in stabilizing grids, optimizing renewable energy integration, and reducing reliance on conventional energy sources for a sustainable energy transition. Research Article #4 introduces a flexibility score that quantifies the economic viability and revenue risk of EFMs, providing a streamlined tool for industrial companies navigating the energy transition. This score assesses each measure’s expected revenue and revenue risk based on its DOFs – the range of operational adjustments possible. Measures with higher DOFs, such as shorter recovery times, show higher revenue potential and reduced risk, making them attractive for companies aiming to optimize electricity costs and stay competitive. Validated with data from Germany’s Day-Ahead and Intraday markets, the flexibility score correlates strongly with revenue potential and risk profiles, offering a simplified alternative to complex flexibility modeling approaches. While initially tested in the German context, the score can serve as a valuable tool in other industrial settings, supporting decision-making for sustainable and cost-effective energy management. Research Article #5 emphasizes the potential of community-level energy sharing as a tool for achieving cost savings and reducing grid impact. However, the integration of DERs introduces challenges such as increased voltage variability in the grid. With DER adoption projected to rise significantly by 2037, Research Article #5 underscores the importance of integrating energy communities into grid planning and enhancing coordination through digitalization to ensure grid stability and efficiency. Research Article #6 investigates the role of IECs under asymmetric regulatory conditions, demonstrating that IECs can substantially reduce operational costs by sharing energy resources within grid-connected microgrids and exploit current grid charge regulation. However, it highlights that current regulatory frameworks may misalign economic incentives with environmental objectives. Research Article #6 suggests that evolving these frameworks to better support IECs could encourage investments in renewable and flexible energy solutions, contributing to a more sustainable and adaptable energy system.

These insights underscore the complexities and interdependencies within Germany's energy transition, highlighting the critical need for coordinated policies, innovative flexibility solutions, and regulatory reforms to effectively integrate renewable energy generation and foster a resilient energy future.

IV.2 Limitations and Future Research

While this doctoral thesis sheds light on external influences on the German energy transition and the potential of distributed flexibility, it is not without limitations. This section provides an overview of these limitations and spotlights resulting avenues for future research. Further, the individual research articles provide a detailed perspective on the limitations of this research endeavor and their potential for future research (cf. Section VI).

The first notable limitation involves the availability of real-world data. While Research Article #1 provides valuable insights into Germany's electricity imports during the COVID-19 pandemic, it would be further enriched by examining the consumption patterns of neighboring countries. Additionally, Research Article #4 relies on data collected by industrial companies themselves, which may inhibit potential errors. Articles #3 and #5 utilize benchmark or synthetic grid data. However, including real-world distribution grid data could significantly enhance the robustness of their findings. This highlights the need for effective collaboration between research and practice to address the complexities surrounding data availability and quality. Establishing partnerships with industry stakeholders, such as grid operators, regulatory bodies, and industrial companies, can facilitate the sharing of high-quality data. Such collaborations would improve the accuracy and relevance of research findings and ensure that the insights generated are grounded in practical realities. Integrating digital technologies can also play a crucial role in this context. By e.g., leveraging digital platforms or data spaces, stakeholders can facilitate more effective data sharing and collaboration, enhancing the overall quality and utility of the information available for research and decision-making while allowing for data security. Future research endeavors could greatly benefit from the development of standardized datasets encompassing a diverse range of geographical areas and energy market conditions, thereby improving the generalizability and applicability of the results.

Furthermore, the case study nature of Articles #3, #5, and #6 introduces scalability and sensitivity analysis considerations. While these studies offer insightful snapshots of specific contexts, exploring how their findings can be extrapolated to a system perspective of the energy systems is essential. Future research could involve sensitivity analyses that assess the robustness of results under varying conditions, inter alia including different community structures or regulatory frameworks. This would validate the findings and clarify how the proposed solutions can be adapted to diverse scenarios and influence system-level outcomes.

A further limitation of this thesis concerns the assumptions made about energy consumption behavior. The study uses historical energy consumption patterns assuming that past behaviors can reliably forecast future trends. This overlooks the dynamic nature of consumer behavior, which evolves due to technological advancements, economic changes, and policy interventions. While historical data provides valuable insights, it does not account for shifts in behavior driven by external factors like increased climate awareness or changing energy costs. Additionally, the elasticity of consumer behavior adds complexity. Future research should address these limitations by incorporating adaptive scenarios and socio-economic variables to capture evolving consumption patterns better. This approach would enhance the robustness of energy system models under changing circumstances.

The complexities of regulatory frameworks and the rapid evolution of market dynamics also represent significant aspects of this research. As highlighted in Research Article #2, understanding the long-term implications of price fluctuations on various stakeholders is crucial. The fast-changing regulatory landscape necessitates continuous evaluation of policies to avoid lock-in effects that could hinder effective adaptation. Advanced digital tools can provide valuable insights by analyzing vast data to forecast potential impacts and inform policy adjustments. Future studies could employ advanced forecasting models to the research presented in this thesis to quantify the long-term impacts of regulatory changes and explore the path dependencies of various countermeasures, ensuring that adaptive policy frameworks remain relevant and effective.

Another area for further research is the specificity of the flexibility score developed in Research Article #4. While this score aims to simplify the evaluation of industrial flexibility options, its granularity may not fully capture the operational intricacies of energy systems. Future research could investigate the trade-offs between simplicity and detailed modeling, employing sensitivity analyses to evaluate the significance of various parameters on economic outcomes. Expanding the flexibility score to encompass a broader range of use cases, such as balancing energy or non-industrial flexibility options, could enhance its applicability and utility in real-world scenarios.

In summary, addressing the limitations related to data availability, scalability, consumer behaviour, regulatory complexities, and flexibility modeling can significantly enhance the robustness of the findings presented in this doctoral thesis. Exploring the implications of digitalization within these contexts will further enrich the research landscape. Such endeavors will contribute to developing innovative solutions and effective policy frameworks essential for navigating the challenges of a successful energy transition. Ultimately, this work serves as a foundation for future research to further examine the relationships within energy systems and enhance our understanding of effectively managing the transition toward sustainability.

IV.3 Acknowledgment of Previous and Related Work

In all research projects and papers presented in this thesis, I worked with colleagues at the Branch of Business & Information Systems Engineering of the Fraunhofer Institute for Applied Information Technology (FIT), University of Bayreuth, the University of Applied Sciences Augsburg, and the FIM Research Center for Information Management (FIM).

The foundation of the COVID-related analysis in this thesis is rooted in previous work by Halbrügge et al. (2021), which Research Article #1 builds upon. Research Article #2 emerged from the dynamics of the gas crisis and is closely aligned with the themes explored in the previous COVID-related papers. In addressing the obstacles identified by Cagno et al. (2013) and Leinauer et al. (2022), Research Article #4 was designed to enhance decision support for exploiting industrial flexibility options. This aim directly responds to the challenges outlined in their research, demonstrating the ongoing relevance of their findings in guiding further investigation. Additionally, the community approach presented in Research Article #5 and Research Article #6 is influenced by the research of Fridgen et al. (2018), Rieger et al. (2016), and Madler et al. (2023). Research Article #6 drew further motivation from the insights of Rövekamp et al. (2023) and the grid issues highlighted by Hanny et al. (2022). These previous works provide a critical context for understanding community energy initiatives' potential benefits and challenges, informing my approach to exploring these strategies.

Please note that I used writing assistance tools, including DeepL, Grammarly, and ChatGPT, to enhance this thesis's readability and language. However, all recommendations provided by these programs were critically evaluated, and I take full responsibility for the final content presented in this thesis.

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VI Appendix

VI.1 Research Articles Relevant to this Doctoral Thesis

Research Article #1: How Germany Achieved a record share of renewables during the COVID-19 pandemic while relying on foreign nuclear power

Halbrügge, Stephanie; Buhl, Hans Ulrich; Fridgen, Gilbert; Schott, Paul; Weibelzahl, Martin; Weissflog, Jan. How Germany Achieved a record share of renewables during the COVID-19 pandemic while relying on foreign nuclear power. *Energy* (2022). DOI: 10.1016/j.energy.2022.123303.

(VHB Publication Media Rating 2024 WI: Category B | Impact Factor (2024): 9.0)

Research Article #2: Research Article #2: Repercussions of the European Gas Crisis – A "New Normal" for the German Energy System?

Bühner, Volker; Michaelis, Anne; Weibelzahl, Martin; Weissflog, Jan. Repercussions of the European Gas Crisis – A "New Normal" for the German Energy System? *Submitted.*

Research Article #3: Assessing Vertical Flexibility Potentials – A Multi-Perspective Analysis for Germany

Weissflog, Jan; Strueker, Jens. Assessing Vertical Flexibility Potentials – A Multi-Perspective Analysis for Germany. *Submitted.*

Research Article #4: How flexible are energy flexibilities? Developing a flexibility score for revenue and risk analysis in industrial demand-side management

Rusche, Simon; Weissflog, Jan; Wenninger, Simon; Häckel, Björn. How flexible are energy flexibilities? Developing a flexibility score for revenue and risk analysis in industrial demand-side management *Applied Energy (2023).* DOI: 10.1016/j.apenergy.2023.121351.

(VHB Publication Media Rating 2024 WI: Category B | Impact Factor (2024): 10.1)

Research Article #5: Assessing the Impacts of Energy Sharing on Low Voltage Distribution Networks: Insights into Electrification and Electricity Pricing in Germany

Lersch, Jonathan; Tang, Rui; Weibelzahl, Martin; Weissflog, Jan; Wu, Ziyan. Assessing the Impacts of Energy Sharing on Low Voltage Distribution Networks: Insights into Electrification and Electricity Pricing in Germany. *Applied Energy (2024).* DOI: 10.1016/j.apenergy.2024.124743

(VHB Publication Media Rating 2024 WI: Category B | Impact Factor (2024): 10.1)

Research Article #6: Industrial Multi-Energy Communities as Grid-Connected Microgrids: Understanding the Role of Asymmetric Grid-Charge Regulation

Dautzenberg, Alexander; Kaiser, Matthias; Weibelzahl, Martin; Weissflog, Jan. Industrial Multi-Energy Communities as Grid-Connected Microgrids: Understanding the Role of Asymmetric Grid-Charge Regulation. *Journal of Cleaner Production (2024).* DOI: 10.1016/j.jclepro.2024.142738.

(VHB Publication Media Rating 2024 WI: Category B | Impact Factor (2024): 9.8)

I also co-authored further book chapters, white papers, and research papers throughout the dissertation, which are not part of this doctoral thesis. Articles published up to the submission of the doctoral thesis can be found in the following:

- Fabri, Lukas; Weißflog, Jan; Wenninger, Simon: **Unraveling the Complexity: A Taxonomy for Characterizing and Structuring Smart Energy Services**. *Journal of Cleaner Production, 2024.*
- Kaiser, Matthias; Stohr, Alexander; Strüker, Jens; Weibelzahl, Martin; Weissflog, Jan; Ali-Will, Fatuma; Hesse, Ewald; Trbovich, Anna; Tzavikas, Spyridon: **Das dezentralisierte Energiesystem im Jahr 2030**. *Whitepaper, 2023.*
- Bhuiyan, Rajon; Weissflog, Jan; Schöpf, Michael; Fridgen, Gilbert: **Indicators for assessing the necessity of power system flexibility: a systematic review and literature meta-analysis**. *Proceedings of the 18th International Conference on the European Energy Market (EEM), 2022.*
- Hanny, Lisa; Körner, Marc-Fabian; Leinauer, Christina; Michaelis, Anne; Strüker, Jan; Weibelzahl, Martin; Weissflog, Jan: **How to trade electricity flexibility using**

artificial intelligence: An integrated algorithmic framework. *Proceedings of the 55th Hawaii International Conference on System Sciences (HICSS), 2022.*

- Buhl, Hans Ulrich; Schöpf, Michael; Schott, Paul; Weibelzahl, Martin; Weissflog, Jan: **Bewertung von Flexibilitätsoptionen im deutschen Stromsystem 2021 bis 2035 unter Berücksichtigung der Holzverfeuerung**. *Studie im Auftrag des NABU, 2021.*
- Buhl, Hans Ulrich; Bollenbach, Jessica; Breiter, Katharina; Weissflog, Jan: **Schaufenster für Quartiere der Zukunft – Erfahrungen aus der Praxis.** *Whitepaper, 2024.*
- Buhl, Hans Ulrich; Gabrek, Nadine; Gerdes, Jan-Niklas; Kaymakci, Can; Rauland, Katrin; Richter, Fabian; Sauer, Alexander; Schneider, Christian; Schott, Paul; Seifermann, Stefan; Tristan, Alejandro; Wagner, Jonathan; Wagon, Felix; Weibelzahl, Martin; Weissflog, Jan; Zachmann, Bastian: **Industrial Flexibility Options and their Applications in a Future Energy System**. *Whitepaper, 2021.*
- Bachmann, Andreas; Bank, Lukas; Bark, Carlo; Bauer, Dennis; Blöchl, Bruno; Brugger, Martin; Buhl, Hans Ulrich; Dietz, Benjamin; Donnelly, Julia; Friedl, Thomas; Halbrügge, Stephanie; Hauck, Heribert; Heil, Joachim; Hieronymus, Aljoscha; Hinck, Torben; Ilieva-König, Svetlina; Johnzén, Carl; Koch, Carsten; Köberlein, Jana; Köse, Ekrem; Lochner, Stefan; Lindner, Martin; Mayer, Tim; Mitsos, Alexander; Roth, Stefan; Sauer, Alexander; Scheil, Claudia; Schilp, Johannes; Schimmelpfennig, Jens; Schulz, Julia; Schulze, Jan; Sossenheimer, Johannes; Strobel, Nina; Tristan, Alejandro; Vernim, Susanne; Wagner, Jonathan; Wagon, Felix; Weibelzahl, Martin; Weigold, Matthias; Weissflog, Jan; Wenninger, Simon; Wöhl, Moritz; Zacharias, Jan; Zäh, Michael: **Energieflexibel in die Zukunft: Wie Fabriken zum Gelingen der Energiewende beitragen können**. *VDI Verlag, 2021.*

VI.2 Individual Contribution to the Research Articles

This cumulative dissertation comprises seven research articles representing the main body of work. All articles were developed in teams with multiple co-authors. This section details the respective research settings and highlights my individual contributions to each article.

Research Article #1 was authored by a team of six. One of my co-authors had a lead role, while the other five contributed as sub-ordinate authors. I contributed to the preparation of the real-world data, the analysis of those data, and the visualization of the evaluations. Further, I took a supporting role in writing and revising the manuscript.

Research Article #2 was co-authored by a team of four. The responsibility for the initial idea, conceptualization, and manuscript writing and revising was shared with another author. I was also responsible for the preparation, analysis, and visualization of the data. The further two authors predominantly provided feedback on the conceptualization and the initial and revised manuscript.

Research Article #3 was authored by a team of two, and I took the role of lead author. In particular, I set up the research idea, conceptualized and programmed the simulation environment, prepared the input data, analyzed the results, and took the lead role in writing and revising the paper. The other author provided feedback, especially regarding conceptualizing the research project and the manuscript.

Research Article #4 was written by a team of four. I contributed to the research paper by developing the research idea with one co-author, preparing input data for the simulation, and developing parts of the simulation that another co-author built upon. Further, I was involved in writing and revising the manuscript and giving feedback on sections written by other authors. The fourth author had a subordinate role by providing feedback and guiding the research project.

Research Article #5 was co-authored by a team of five authors. Two of the authors took a subordinate rule by providing feedback on the research idea, conzeptualization, manuscript and revised manuscript. One author was responsible for the development of the simulation model as well as the analysis of the results. I contributed by co-developing the research idea and simulation concept. Further, I contributed by providing input data, contributing to the revision of the manuscript, and feedback throughout the research project.

Research Article #6 was co-authored by a team of four authors. Three authors equally contributed, while one had a subordinate rule by providing feedback and guidance throughout the research project. The three authors, including me, shared the responsibility for the research idea and conceptualization. One author did the manuscript draft, and my role was to give feedback and revise the manuscript for publication as well as in the revision process.

VI.3 Research Article #1

How Germany Achieved a record share of renewables during the COVID-19 pandemic while relying on foreign nuclear power

Authors: Halbrügge, Stephanie; Buhl, Hans Ulrich; Fridgen, Gilber; Schott, Paul; Weibelzahl, Martin; Weissflog, Jan

Published in: Energy (2022)

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

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

VI.4 Research Article #2

Repercussions of the European Gas Crisis - A "New Normal" for the German Energy System?

Authors: Bühner, Volker; Michaelis, Anne; Weibelzahl, Martin; Weissflog, Jan

Published in: Submitted to Energy

Extended Abstract[1]:

The European gas crisis, initiated by Russia's invasion of Ukraine on the 24th of February, has profoundly reshaped energy markets, presenting unprecedented challenges to supply, pricing, and policy frameworks (Grubb, 2022; Kröger et al., 2023; Ruhnau et al., 2023). This paper examines whether the crisis signifies a transient price shock or a transformative restructuring of the energy landscape. Focusing on Germany, the largest consumer of Russian natural gas in Europe up to February 2022, the paper provides an in-depth analysis of the crisis's impact on gas and electricity markets. Germany's experience offers critical insights into the evolving dynamics of energy systems under the pressures of geopolitical disruptions and the ongoing energy transition. The sudden reduction in Russian natural gas exports to Europe, combined with limited replacement capacities and global market constraints, caused gas prices to surge in 2022. In Germany, Day-Ahead gas prices peaked at over 300 EUR/MWh in 2022, far exceeding pre-crisis levels of approximately 30 EUR/MWh in 2021 (Trading Hub Europe). Although prices began stabilizing in 2023, they remain significantly elevated, suggesting a structural shift in baseline energy costs. This paper highlights the political and market-driven responses to this crisis, including diversifying supply sources through liquefied natural gas imports and accelerating renewable energy infrastructure development. However, these measures have only partially offset the supply shortfall, with liquefied natural gas imports accounting for a small fraction of total gas demand by 2023 (Bundesnetzagentur, 2024). On the demand side, industrial gas consumption in Germany experienced a notable decline, with usage dropping

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

by 15 % in 2022 and 18 % in 2023 compared to the 2018 to 2021 average (Bundesnetzagentur, 2024). This reduction underscores the adaptability of industrial sectors, which adopted efficiency improvements and alternative energy sources to mitigate rising costs. Conversely, households, trade, and commerce displayed limited responsiveness, reflecting challenges in achieving significant behavioral changes in energy usage. These findings highlight a key disparity in energy consumption flexibility across sectors. The crisis's effects extended beyond gas markets, profoundly impacting electricity markets due to Germany's reliance on the merit order principle, where the marginal cost of natural gas-fired power plants often determines electricity prices. Electricity spot markets experienced dramatic price spikes, with average Day-Ahead prices exceeding 250 EUR/MWh in 2022 (ENTSO-E). Traded volumes on the Day-Ahead market initially decreased as market participants reacted to high prices, while Intraday market volumes increased slightly, reflecting a growing reliance on short-term adjustments. By 2023, electricity trading volumes began recovering, but prices remained elevated compared to pre-invasion levels, signaling a "new normal" in market behavior characterized by heightened price levels. Further, the study examines the dynamics on the Future electricity market. Traded volumes on long-term markets, such as year-ahead and quarter-ahead contracts, decreased significantly in 2022 as uncertainty around future price developments discouraged market participation. However, volumes gradually rebounded in 2023, likely driven by increased reliance on contractual mechanisms like over-the-counter trading to hedge against price risks. This shift highlights the growing focus on market stability and risk management amid persistent energy market uncertainty. A key finding of the study is the limited substitution of natural gas in electricity generation. Despite efforts to reduce gas dependency, natural gas-fired plants continued to play a critical role in meeting electricity demand. The inability to rapidly replace these plants with alternative generation sources, such as renewables, reflects the structural constraints of Germany's energy system. This ongoing reliance underscores the importance of accelerating investments in renewable energy and enhancing system flexibility to reduce exposure to

future price shocks. The crisis also catalyzed broader changes in energy consumption patterns. Electricity demand in Germany showed only modest declines, with reductions in 2023 influenced by the warmer weather and the economic situation in Germany. This underscores the need for targeted policy measures to encourage more significant demand-side flexibility across all sectors. The paper argues that the European gas crisis has established a "new normal" for energy systems, characterized by sustained higher price levels, structural shifts in supply and demand, and evolving market behaviors. This includes accelerated efforts to diversify energy sources and increased investments in hydrogen-ready infrastructure for Germany. The implications of this "new normal" are multifaceted. Elevated energy prices present challenges for policymakers, requiring strategic interventions to stabilize markets and support the energy transition. While the crisis has imposed significant economic and social costs, it has also accelerated progress toward a more resilient and sustainable energy system. In conclusion, the European gas crisis has reshaped Germany's energy landscape, creating lasting changes in supply chains, price levels, and energy policy priorities. The European energy crisis uncovered the vulnerabilities and also opportunities in advancing the energy transition, ultimately steering Europe toward a more secure and sustainable energy future.

Keywords: Gas crisis, Energy markets, Price shock, Energy prices, Inflation, Energy transition

References: Grubb M. (2022). Navigating the Crises in European Energy: Price Inflation, Marginal Cost Pricing, and Principles for Electricity Market Redesign in an Era of Low-Carbon Transition. *Journal of Economic Literature 2022.*

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ENTSO-E. *Transparency Platform*. https://transparency.entsoe.eu/. Accessed: 25.10.2024.

VI.5 Research Article #3

Assessing Vertical Flexibility Potentials – A Multi-Perspective Analysis for Germany

Authors: Weissflog, Jan; Strueker, Jens

Published in: Submitted to Energy

Extended Abstract[1]:

Germany's transition to a renewable energy-driven system underscores the importance of flexibility to ensure grid stability (Andersen et al., 2023; Sabadini & Madlener, 2023; Holweger et al., 2023). As distributed energy resources (DERs) like photovoltaics (PV), battery storage systems (BSS), electric vehicles (EVs), and heat pumps (HPs) become increasingly introduced into the distribution grid, they offer significant potential for balancing supply and demand (Reuther & Kost, 2024; Agora Verkehrswende, 2024). As power flows become bidirectional, with DERs both consuming and generating electricity, Germany's grid faces challenges due to lagging infrastructure upgrades (Roncero, 2018). Flexibility has emerged as a critical solution, enabling the system to adapt to fluctuations and maintain stability (Papaefthymiou et al., 2018; Di Fazio et al., 2019). Vertical flexibility, leveraging distribution-level resources to support the transmission grid's flexibility requirements, is increasingly vital in bridging local and system-wide energy needs in light of the energy transition. This study evaluates the role of vertical flexibility in supporting redispatch, balancing energy, and residual load management, providing a detailed assessment of its alignment with systemic needs. The methodological approach follows a two-step process to quantify and evaluate DER flexibility. First, year-spanning load flow simulations use a synthetic distribution grid model incorporating grid constraints such as voltage limits, line capacities, and transformer thresholds. To ensure a robust assessment, 100 scenarios with randomized DER distributions are simulated to analyze the average flexibility potential across varying configurations. This step isolates the vertical flexibility potential by considering only the portions of

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

DER flexibility that remain unimpeded by local grid constraints and, therefore, is available for systemic use. The quantified flexibility potential is aligned with systemic requirements in the second step. Flexibility is categorized into positive (e.g., increased feed-in or reduced consumption) and negative (e.g., reduced feed-in or increased consumption) scenarios to assess its applicability for redispatch, balancing energy, and residual load management. This alignment helps determine how DERs can support broader grid stability. The findings highlight distinct seasonal trends in DER flexibility. PV curtailment flexibility peaks during summer, coinciding with maximum solar generation, whereas BSS discharging is more pronounced in the same period, reflecting its role in mitigating excess generation. Conversely, BSS charging flexibility is higher in winter, as reduced solar generation creates opportunities for storage systems to absorb surplus grid electricity. Load-shedding offers consistent flexibility throughout the year, largely unaffected by seasonal consumption patterns. The practical utilization of vertical flexibility varies across DER types and applications. Positive flexibility, particularly from load-shedding and BSS discharging, demonstrates high alignment with redispatch and balancing energy needs. However, negative flexibility, such as PV curtailment, faces limited utilization due to temporal mismatches between solar generation peaks and periods of high demand. Similarly, residual load analysis reveals a complementary relationship among DERs. Positive residual load periods – when demand exceeds renewable generation – benefit from load-shedding and BSS discharging, while negative residual load periods, characterized by renewable surpluses, see limited use of PV curtailment and BSS charging due to grid and temporal constraints. The study underscores the systemic value of vertical flexibility as a critical tool for balancing the grid. However, realizing its full potential requires addressing several challenges. Enhanced visibility and control of DERs are essential and achievable through digital technologies such as smart meters, digital twins, and advanced grid management. These tools enable precise monitoring and optimization of DER contributions. Policy measures, such as localized energy markets and dynamic pricing mechanisms, are crucial for incentivizing DER participation and fostering market-driven flexibility deployment. Aggregators are pivotal in coordinating distributed flexibility at scale, bridging the gap between DER owners and grid operators. Improved coordination among aggregators, distribution system operators, and transmission system operators is essential to integrate vertical flexibility into system-wide operations. Such coordination ensures that flexible contributions are dispatched efficiently and aligned with local and systemic needs. Despite the promise of vertical flexibility, challenges persist, including the temporal misalignment of certain resources with system needs. Addressing these gaps requires advanced optimization strategies, including real-time analytics, predictive algorithms, and dynamic dispatch models. Technological advancements such as bidirectional EV charging and dynamic HP operations also present untapped opportunities for enhancing vertical flexibility. This study emphasizes the complementary nature of DER flexibility, with PV systems, load-shedding, and BSS collectively supporting grid stability throughout the year. The findings demonstrate that vertical flexibility offers a scalable solution to support Germany's energy transition. By addressing current barriers and leveraging emerging technologies, Germany can unlock the full potential of its DERs, facilitating renewable integration, enhancing grid stability, and reducing reliance on conventional energy sources. Future research should focus on developing advanced dispatch strategies, incorporating real-time optimization, and exploring the system-wide integration of DERs into systemic flexibility frameworks.

Keywords: Vertical flexibility, Power flow Analysis, Flexibility demand, Distribution grid analysis

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Papaefthymiou G., Haesen E., Sach T. (2018). Power System Flexibility Tracker: Indicators to track flexibility progress towards high-RES systems. *Renewable Energy 2018, 127:1026–35.*

Di Fazio A.R., Russo M., Pisano G., Santis M. (2019). A centralized voltage optimization function exploiting DERs for distribution systems. *2019 International Conference on Clean Electrical Power (ICCEP): IEEE, 2019,* p. 100–109.

VI.6 Research Article #4

How flexible are energy flexibilities? Developing a flexibility score for revenue and risk analysis in industrial demand-side management

Authors: Rusche, Simon; Weissflog, Jan; Wenninger, Simon; Häckel, Björn

Published in: Applied Energy (2023)

Abstract: With rising and increasingly volatile energy prices, demand-side management (DSM) is becoming attractive within industry to optimize flexible electricity demand and to remain competitive. Despite economic and ecological benefits for companies, DSM implementation is not yet widespread. High effort in flexibility audits and complex optimization models to quantify DSM's economic potentials represent initial barriers in practice, raising the question whether there is a simple way to analyze economic DSM potential as an initial indicator of successful DSM implementation that requires little data on flexibility characteristics. To address this need, this study develops a flexibility score that describes the degrees of freedom of individual energy flexibility measures (EFMs), i.e. how flexible a flexibility measure is. The flexibility score is tested and validated in a risk-return analysis on 46 real-world industrial EFMs from Germany optimized with integer linear programming (ILP). Analyzing Germany's Day-Ahead and Intraday markets, the results show an increase in expected revenues and a simultaneous decrease in revenue risk with an increasing flexibility score, outlining DSM investments as attractive. Due to its ease of use, we see industrial companies, aggregators, energy service providers, and (energy) consultancy agencies as target users of the flexibility score. Policymakers can use the flexibility score to identify and design subsidies for energy flexibility investments.

Keywords: Industrial demand-side management, Energy flexibility, Flexibility score, Optimization model, Risk-revenue analysis, Flexibility modeling

VI.7 Research Article #5

Assessing the Impacts of Energy Sharing on Low Voltage Distribution Networks: Insights into Electrification and Electricity Pricing in Germany

Authors: Lersch, Jonathan; Tang, Rui; Weibelzahl, Jan; Weissflog, Jan; Wu, Ziyan

Published in: Applied Energy (2024)

Abstract: The shift towards renewable energy sources, which is especially significant in the residential sector, relies on distributed energy resources like PV systems, heat pumps, battery storage systems, and electric vehicles. Integrating DERs into low-voltage distribution networks presents challenges, including potential grid instabilities. Energy sharing is a consumercentric market approach, allowing consumers and prosumers to establish renewable energy communities (RECs) and share energy generated via DERs. Existing literature concerning energy sharing often prioritizes highlighting the benefits it offers to participants, rather than examining its direct impacts on established system boundaries such as distribution grid infrastructure. To this end, we employ a sequential modeling approach to study the integration of energy sharing schemes facilitated by RECs and their impacts on grid performance metrics, such as component loading, voltage magnitudes, and grid reinforcement costs. We examine twelve scenarios reflecting different REC configurations, DER adoption levels, and pricing strategies for both current (2023) and future (2037) contexts in Germany. Our findings indicate that implementing energy sharing not only results in considerable cost savings at the community level (with potential savings of up to 80% compared to scenarios without energy sharing) but also brings about significant reductions in grid asset loading (with decreases in transformer loading of up to 68% and line loading of up to 62%, compared to baseline scenarios). Conversely, we show that energy sharing can significantly influence voltage magnitudes at various nodes within the grid, potentially leading to substantial increases in grid reinforcement costs in future scenarios (i.e., 2037). Our research provides valuable insights for REC participants, regulators, and DSOs to understand the impacts of energy sharing on European low-voltage distribution networks and explore mitigation options, such as grid reinforcement measures.

Keywords: Energy sharing, Low voltage distribution grids, Microgrids, Renewable energy communities

VI.8 Research Article #6

Industrial Multi-Energy Communities as Grid-Connected Microgrids: Understanding the Role of Asymmetric Grid-Charge Regulation

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Abstract: The industrial sector is currently the leading emitter of greenhouse gases worldwide. Lowering emissions, the collaborative use of energy and storage technologies in Industrial Energy Communities (IEC) is a promising option, typically implemented as a grid-connected microgrid. To support successful implementations of IECs, it is essential to understand not only the interaction of different technical assets within an IEC but also the corresponding regulation that determines the IEC's economic and ecological performance. Similar to different technical capabilities of available assets, companies of an IEC are typically affected by regulation in different, asymmetric ways. To the best of our knowledge, we are the first to investigate the economic and ecologic effects stemming from asymmetric regulation, i.e., regulation that differs between different participating companies via a microgrid approach. By developing a novel linear model for German asymmetric grid charge regulation, we are able to optimize the economic operation of complex multi-energy microgrids under detailed regulatory conditions. In more detail, we formulate and implement a mixed-integer linear program to investigate the joint operation of a multi-energy IEC under asymmetric regulation. We conduct a real-world case study to evaluate the effects of German grid-charge regulation as a significant example of asymmetric regulation and compare the results of our IEC to a situation where every company of the IEC manages its assets individually. Our results indicate that IECs have the potential to significantly reduce the total operational energy costs under the current asymmetric German grid-charge regulation. While the shared assets see a higher utilization in the IEC, the impact on emissions is, however, limited.

Keywords: Energy community, Industrial microgrid, Grid-charge regulation, Multi-energy, Linear optimization