Data-driven techno-economic evaluation of energy-flexible hydrogen technologies

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„Flexibility is the key to stability."

John Wooden

Der Abschluss meiner Promotion markiert zugleich das Ende einer intensiven, lehrreichen und prägenden Zeit. Diese Gelegenheit möchte ich nutzen, um zu reflektieren und allen zu danken, die mich in dieser Phase begleitet und unterstützt haben.

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Abschließend möchte ich festhalten, dass mir die Promotion und die damit verbundenen Erfahrungen, trotz aller Anstrengungen und mühsamen Etappen, auch eines geschenkt haben: große Freude.

Augsburg, November 2025

Copyright Statement

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

Declaration

I confirm that I am the author of this cumulative dissertation and that I take full responsibility for its content. To enhance readability and ensure grammatical precision, this dissertation was reviewed using different large language models and language editing software (ChatGPT, DeepL, and Grammarly). I conducted a comprehensive review to ensure accuracy and adherence to academic standards and edited the content of this thesis as necessary.

Abstract

The accelerating momentum and magnitude of negative environmental disruptions emphasize the necessity to significantly reduce greenhouse gas emissions and limit the adverse consequences of climate change. Renewable hydrogen is considered a pivotal component for holistic greenhouse gas emission mitigation. Despite manifold strategies, such as REPowerEU and the German National Hydrogen Strategy, establishing a sustainable hydrogen economy poses considerable techno-economic challenges for involved energy policymakers, investors, and operators who must reach informed decisions in highly complex and multifaceted contexts. Given the need for energy-flexible operation to sufficiently utilize fluctuating renewable electricity, increasingly complex and hybrid technology stacks, and regulatory uncertainties, significant techno-economic hurdles for hydrogen production are not adequately addressed. Embedded in the Business and Information Systems Engineering discipline, this thesis focuses on techno-economic evaluation methodologies, as well as an energy policy perspective, to leverage information systems in the exploration of alternative regulatory frameworks that facilitate a sustainable hydrogen economy. The dissertation comprises five research papers that collectively develop methodological instruments and data-driven assessments to support decision-making among energy policymakers, investors in energy-flexible hydrogen technology, and system operators. First, it assesses the economic and ecological value of energy-flexible operation under volatile electricity prices. Second, it presents a techno-economic methodological framework for synergetic electricity procurement utilizing power purchase agreements with battery energy storage systems to reduce the levelized cost of hydrogen. Further, it introduces an optimization approach for the design and operation of multi-energy microgrids that simultaneously provide fast charging and on-site hydrogen production and refueling services for mobility applications. Finally, it explores alternative regulatory pathways for the Renewable Energy Directive by examining configurations for geographical correlation between renewable electricity generation and electrolysis, as well as wholesale market-integrated electricity procurement strategies. The major objective of this thesis is to advance both theoretical and practical knowledge towards energy-flexible operated hydrogen technologies embedded in not yet fully defossilized energy systems. Thus, this thesis provides a conceptual framework to conduct techno-economic evaluations of design and operational strategies for energy-flexible hydrogen infrastructures, supporting real-world decision-making for investments and deployment under evolving regulatory frameworks. By addressing these challenges, this research contributes to a sustainable hydrogen economy ramp-up and to mitigating greenhouse gas emissions, thereby aligning with international, European, and German policies.

Keywords: energy flexibility, renewable energy, hydrogen, smart sustainability, energy policy

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Abbreviations

BESS	Battery Energy Storage System
BEV	Battery Electric Vehicle
EU	European Union
FCEV	Fuel Cell Electric Vehicle
GHG	Greenhouse Gases
HSS	Hydrogen Subsystem
LCOH	Levelized Cost of Hydrogen
RES	Renewable Energy Sources
RFNBO	Renewable Fuels of Non-Biological Origin
RED	Renewable Energy Directive
PPA	Power Purchase Agreement

I Introduction

I.1 Motivation

The adverse consequences of climate change are no longer abstract projections but lived realities in the year 2025. The Copernicus Climate Change Service (2025) reported that 2024 was the warmest year on record and the first calendar year with the global mean temperature above 1.5 °C relative to pre-industrial levels. The World Meteorological Organization (2025) documented record-high ocean temperatures, accelerating sea-level rise, and escalating climate extremes. Europe experienced widespread flooding (Kate Abnett 2025), and global hydrological imbalance steadily intensifies with irregular drought and deluge patterns (Lee et al. 2023). These climatic developments not only seriously threaten the physical well-being of humanity (Janoš et al. 2025; Romanello et al. 2024) and the integrity of global ecosystems (Lee et al. 2023), but also lead to increased systemic risks and massive economic damage (Muinch RE 2025a), which will continue to grow as climate change progresses (Muinch RE 2025b).

These disruptive symptoms raise the necessity for evidence-based policy. The Paris Agreement stipulated ambitious targets, with 196 countries committing to reducing global Greenhouse Gas (GHG) Emissions and limiting the temperature increase to well below 2 °C (United Nations 2015). To achieve these targets and facilitate rapid, enduring, and scalable reductions in GHG emissions, global defossilization of the energy supply is essential. Thus, a transition to non-fossil fuel technologies, electrification, and the use of renewable hydrogen, particularly in hard-to-abate sectors and where electrification is not a viable alternative, is necessary (Zappa et al. 2019; Parra et al. 2019; Ameli et al. 2025). In the context of the European Union (EU), under the European Green Deal, the revised Renewable Energy Directive (RED) sets a target share of at least 42.5 % renewables by 2030, with an aspiration of 45 % (European Commission 2023c, 2023d). The REPowerEU initiative complements with a hydrogen production and import strategy, each of which aims to yield 10 million tons by 2030. (European Commission 2022). Hydrogen market formation is supported by the EU Hydrogen Bank, which conducts competitive auctions for subsidies on operating expenses in renewable hydrogen production plants (European Commission 2023b). In Germany, the updated National Hydrogen Strategy sets a target for domestic electrolysis capacity of at least 10 GW by 2030 (BMWK 2023), although the current administration relaxed these fixed targets in favor of flexible project-based targets (BMWE 2025). Collectively, these policy initiatives and instruments guide the integration and implementation of renewable electricity and renewable hydrogen markets.

However, delivering on these objectives requires technologies and operations that can cope with the volatile supply of renewable energy (Bichler et al. 2022; Sauer et al. 2022). Electricity-intensive technologies, such as electrolysers, are particularly effective, both economically and ecologically, when their operation is adapted to the temporal and spatial availability of low-carbon electricity from Renewable Energy Sources (RES) (Brandt et al. 2024; Park et al. 2023). Furthermore, certification schemes in the EU for renewable hydrogen in accordance with the specifications of Renewable Fuels of Non-Biological Origin (RFNBO) stipulate requirements regarding the additionality of renewable energy power plants and temporal as well as geographical correlation of electricity generation and consumption (European Commission 2023a, 2023c) which significantly shape electricity procurement portfolios and operational constraints (Ruhnau and Schiele 2023; Palmer et al. 2024; Schumm et al. 2025). The RFNBO-criteria make energy-flexible operation a mandatory element of system configuration, rather than an optional feature, for producing renewable hydrogen.

However, previously announced electrolyzer projects are reported to be postponed or terminated entirely in many cases, as the produced renewable hydrogen is not competitive with other alternative energy carriers and options for mitigating GHG emissions (Reuters 2025; IEA 2025). Consequently, due to considerable techno-economic challenges for involved energy policymakers, investors, and operators, the hydrogen market ramp-up is lagging (Brandt et al. 2024). Should this trend continue, the persistent implementation gap already evident regarding energy-flexible hydrogen production plants could increase further (Odenweller and Ueckerdt 2025). Continued slow progress of the market uptake would ultimately jeopardize the initial intention for renewable hydrogen adoption, which is to contribute to reducing GHG emissions and mitigate the negative consequences of climate change.

Scaling up investments and establishing long-term profitable operations for energy-flexible technologies requires intelligent integration and dispatch of individual system components to leverage synergies in complex and hybrid technology stacks. Therefore, it is imperative to develop and apply sophisticated data-driven methodological tools to reach informed decisions in highly complex and multifaceted contexts for energy-flexible operated hydrogen technologies within evolving market and regulatory environments. This cumulative dissertation aims to address these unmet requirements, as it introduces adequate methodological instruments and data-driven assessments to evaluate energy-flexible hydrogen technologies in evolving market and regulatory environments.

I.2 Research aim

As the negative effects of climate change continue to progress and previous energy policy measures to promote GHG emission reduction and the ramp-up of the hydrogen market are insufficient, research must provide adequate contributions to foster the implementation of energy-flexible hydrogen technologies. The implementation of energy-flexible hydrogen technologies is encompassed by multiple challenges that must be addressed to realize the associated benefits (Albadi and El-Saadany 2008). Leinauer et al. (2022) synthesize these challenges into economic, regulatory, technological, organizational, behavioral, information, and informational obstacles. Numerous studies highlight these challenges. Alcázar-Ortega et al. (2015) emphasize the critical importance to overcome technical, economic, and regulatory hurdles to promote energy-flexible operation. The legacy regulatory framework may have a detrimental impact on energy-flexible operation, therefore, existing policies must be revised in accordance with evolving requirements (Richstein and Hosseinioun 2020; Hanny et al. 2022). Annala et al. (2018) conclude, that energy policy in the EU should prioritize removing regulatory barriers to energy-flexible operation. Eventually, even synergies may be leveraged between technology configurations and regulatory frameworks as barriers are removed (Wohlfarth et al. 2020). Olsthoorn et al. (2015) conclude that the most critical challenge to energy-flexible operations is the impact on production and product quality. In this vein, proton exchange membrane electrolysis in particular may be suitable for energy-flexible operation, offering a wide dynamic operating range without significantly compromising system efficiency and hydrogen purity (Grigoriev et al. 2020; Megía et al. 2021).

Regarding energy-flexible hydrogen electrolysis, previous literature concurs on three aspects that motivate and align with the envisaged research objectives of this thesis. First, competitive renewable hydrogen production is significantly dependent on low-cost electricity supply (El-Emam and Özcan 2019; Droessler and Leach 2024). Second, optimizing energy-flexible electrolyzer operation yields operational cost reductions by accommodating high-volatility, low-cost renewable electricity (Chang and Rajuli 2024; Lux and Pfluger 2020). Third, hybrid technology configurations can raise capacity utilization and lower specific hydrogen costs even further (Glenk and Reichelstein 2019; Gulay et al. 2025; Mößle et al. 2025).

Strict regulatory frameworks to produce renewable hydrogen further limit its economic feasibility (Veenstra and Mulder 2024; Wang 2024). In particular, specific electricity sourcing criteria stipulated in the RED of the EU impose regulatory and economic barriers to energy-flexible hydrogen production (Egerer et al. 2024; Schlund and Theile 2022; Thaler et al. 2025). Related studies examine geographical correlation design choices that shape the feasible space for electricity procurement under evolving markets and policies (Stolte et al. 2024; Brandt et al. 2024). Casas Ferrús et al. (2024) find that spatial diversification of electricity procurement options may lead to beneficial economic performance. In the related literature, a common theme is the focus on temporal correlation and the recognition of a significant trade-off. Stricter simultaneity requirements reduce the GHG emission intensity of electrolytic hydrogen, yet raise the Levelized Cost Of Hydrogen (LCOH), while less stringent temporal correlation yields the contrary (Brandt et al. 2024; Ruhnau and Schiele 2023; Schlund and Theile 2022). Giovanniello et al. (2024) therefore argue for alternative trajectories that enable broader temporal matching and gradually move toward stricter temporal alignment as the hydrogen market matures.

To address research gaps and contribute to common research themes, this cumulative dissertation aims to develop data-driven methodological tools and conduct data-driven assessments to support decision-making on design and operation strategies of energy-flexible hydrogen systems under real-world market conditions and evolving regulatory frameworks. The thesis addresses technical, economic, and regulatory challenges faced by policymakers, investors, and operators in energy-flexible hydrogen technologies. The research included in this dissertation focuses on empirical electricity market analyses, techno-economic evaluation methods, and policy assessments with a particular emphasis on EU regulatory criteria to produce renewable hydrogen. In this vein, this cumulative dissertation aims to address three research objectives.

(1) *Quantify how energy-flexible operation of energy-intensive technologies may influence economic and ecological performance to calibrate stakeholder expectations and provide evidence for subsequent technology configuration and policy analysis.*

(2) *Develop, validate, and demonstrate methodological instruments to enable techno-economic evaluations of complex and hybrid technology stacks for energy-flexible operated hydrogen production.*

(3) *Assess alternative regulatory design elements regarding temporal and geographical correlation and their implications on the economic and ecological performance of energy-flexible hydrogen technologies.*

The major objective of this thesis is to contribute to both theoretical and practical knowledge regarding energy-flexible operated hydrogen technologies. Collectively, the research included in this cumulative dissertation provides conceptual frameworks to conduct techno-economic evaluations of alternative design and operational strategies for energy-flexible hydrogen infrastructures within evolving regulatory frameworks. The results of this work contribute to facilitating data-driven real-world decision-making for investors, operators, and energy policymakers regarding energy-flexible hydrogen technologies.

I.3 Structure of the thesis and embedding of the research papers

This cumulative dissertation consists of five research papers that collectively develop methodological instruments and data-driven assessments to support decision-making among energy policymakers, investors, and operators of energy-flexible hydrogen technologies. The structure of the thesis, illustrated in Figure 1, organizes the individual research articles according to the research objectives, contributing to the overall goal of the dissertation, which is to facilitate a conceptual framework to conduct techno-economic evaluations and support real-world decision-making for energy-flexible hydrogen infrastructures.

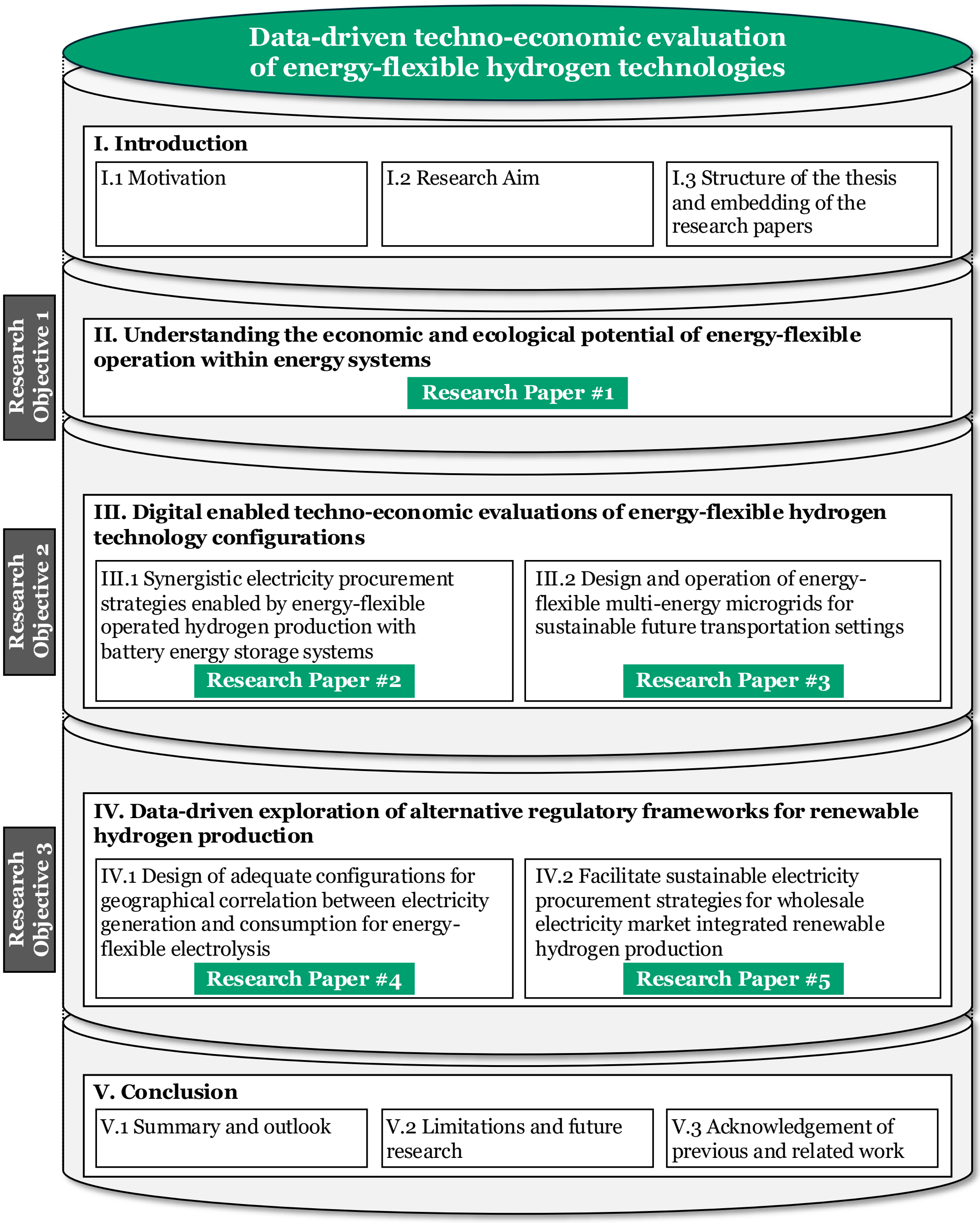

Figure 1: Overview and embedding of the research papers within the thesis.
Source: Own illustration.

After this introductory chapter, Section II establishes the analytical and empirical foundation for understanding the economic and ecological potential of energy-flexible operation. In this context, Research Paper #1 quantifies how market-based dynamic electricity tariffs translate into electricity procurement cost savings and reductions in associated GHG emissions. Consequently, the quantitative results substantiate that volatility in electricity generation from RES and the resulting market prices for electricity create beneficial opportunities for energy-flexible technologies. Section II thereby addresses a key research aim of this thesis by establishing a data-driven baseline for the dual value proposition of energy-flexibility in both economic and environmental aspects, which subsequent sections draw upon as they progress from generic flexible loads to focus on hydrogen technologies.

Building on this foundation, Section III turns to digital enabled techno-economic evaluations of energy-flexible hydrogen technology configurations. The section is divided into two complementary subsections that collectively address the research objective to develop and evaluate design and operational strategies of energy-flexible hydrogen infrastructures. In Section III.1, Research Paper #2 introduces a methodological framework for synergetic electricity procurement strategies for renewable hydrogen production, incorporating Power Purchase Agreements (PPAs) and Battery Energy Storage Systems (BESS). The study evaluates design and operational strategies for multiple BESS and PPA configurations to leverage electricity procurement portfolios characterized by increased volatility and reduced costs, and thus minimize the LCOH. In Section III.2, Research Paper #3 expands the scope from design and operational strategies for renewable hydrogen production towards hybrid multi-energy microgrids with BESS. It introduces an operational model for application in the mobility sector, in which fast-charging services for Battery Electric Vehicles (BEV) and on-site hydrogen production and refueling for Fuel Cell Electric Vehicles (FCEV) are cooperatively integrated at a single location. The study identifies that BESS and energy-flexible operation primarily serve to reduce peak loads under prevailing grid charge regulations. Limiting the ecological benefits of other operational strategies besides grid charge optimization, the results highlight the necessity for further evolution within the regulatory framework to access the complete potential of the insights presented in Section II.

Consequently, Section IV then focuses on data-driven exploration of alternative regulatory frameworks for renewable hydrogen production, with a particular focus on the RED. The section is structured according to the analysis of the geographical correlation and the temporal correlation of renewable hydrogen production based on the RED. Collectively, the research papers covered in Section IV address the research objective of transferring methodological tools towards policy-related assessments and provide guidance for alternative regulatory pathways that enable energy-flexible operation of hydrogen technologies. Within Section IV.1, Research Paper #4 examines geographical correlation, as it proposes and evaluates alternative specifications between renewable electricity generation and electrolysis to understand how different correlation specifications affect operating costs of energy-flexible electrolysis as well as electricity system costs. Section IV.2, covered by Research Paper #5, analyzes how wholesale spot market integrated electricity procurement strategies can be designed under evolving temporal correlation to advance the currently rather limited options outlined in the RED. The study evaluated the implications of combining PPAs and spot market electricity procurement beyond the current scope of the regulatory framework regarding the associated GHG emission intensity and the LCOH.

Section V concludes and reflects the content of this cumulative dissertation. Section V.1 summarizes the contributions on techno-economic evaluations of energy-flexible hydrogen technologies. Section V.2 highlights limitations and opportunities for future research. Section V.3 acknowledges previous and related work and clarifies how the included research papers expand these research streams.

In Section VI, references applied within this thesis are listed. Section VII provides further information on the research papers included in this thesis and my individual contribution to each of these research papers. Additionally, the supplementary material contains the full text of all published research papers, as well as the full text of all research papers that are not yet intended for publication.

II Understanding the economic and ecological potential of energy-flexible operation within energy systems

The accelerating integration of volatile renewable electricity generation has shifted the energy-flexible operation of energy-intensive technologies, such as electrolyzers, from an option to a system necessity (Albadi and El-Saadany 2008; Bichler et al. 2022; Sauer et al. 2022). When electricity prices reflect scarcity, dynamic tariffs may reward electricity consumers who shift their consumption toward low-price periods with reduced electricity procurement costs (Sensfuß et al. 2008; Schreiber et al. 2015). Previously, academic literature examined demand response regimes, flexible tariffs, and economic and ecological implications, establishing both technical feasibility and overall system benefits (Gils 2016; Pape et al. 2016; Menke et al. 2016). Existing studies further address isolated elements of electricity tariff design and demand response mechanisms, finding positive economic and ecological effects associated with energy-flexible operation (Calver and Simcock 2021; Choi and Thomas 2012; Golmohamadi 2022). However, the quantification of these beneficial effects under variable energy system and electricity market conditions has remained underdeveloped, despite its relevance for operators and policy instruments that seek to optimize affordability and decarbonization (Eicke and Schittekatte 2022; Leinauer et al. 2022; Kim and Shcherbakova 2011). The sensitivity towards the temporal range of flexibility, from short-term to multi-day operations, has not been systematically modelled and evaluated. Nevertheless, the time horizon may be a key factor in understanding the interaction of flexible technologies within the context of economic objectives in the electricity market. Furthermore, the European energy crisis of 2021–2022, characterized by unprecedented wholesale price spikes and volatility, created conditions that differed significantly from those observed in much of the pre-crisis empirical work (Steffen and Patt 2022). Thus, significant gaps remain for adequate data-driven decision support.

These research gaps motivate the design and synthesis of Research Paper #1, which anchors this section on understanding the economic and ecological potential of energy-flexible operation of hydrogen technologies within energy systems. Research Paper #1 investigates whether real-time electricity pricing enables flexible industrial loads to reduce electricity costs and GHG emissions associated with electricity consumption, particularly under the market conditions prior to and during the European Energy crisis in the years 2019–2022. The study formulates a mixed-integer linear optimization that schedules energy-flexible operation as a load increase over several hours, immediately followed by a symmetric decrease of equal magnitude. The model minimizes electricity procurement costs under a dynamic tariff equal to the EPEX SPOT Day-Ahead electricity price in the Germany/Luxembourg bidding zone (DE-LU) and computes associated GHG emissions using hourly average emission factors for Germany. The dataset spans the years 2019–2022, enabling a contrast between pre-crisis and crisis conditions (cf. Figure 2). The results of the optimization study are provided as relative cost reductions in EUR/kW and emission reductions in kg-CO2-e/kW, aggregated by quarter within each year to highlight seasonal variations.

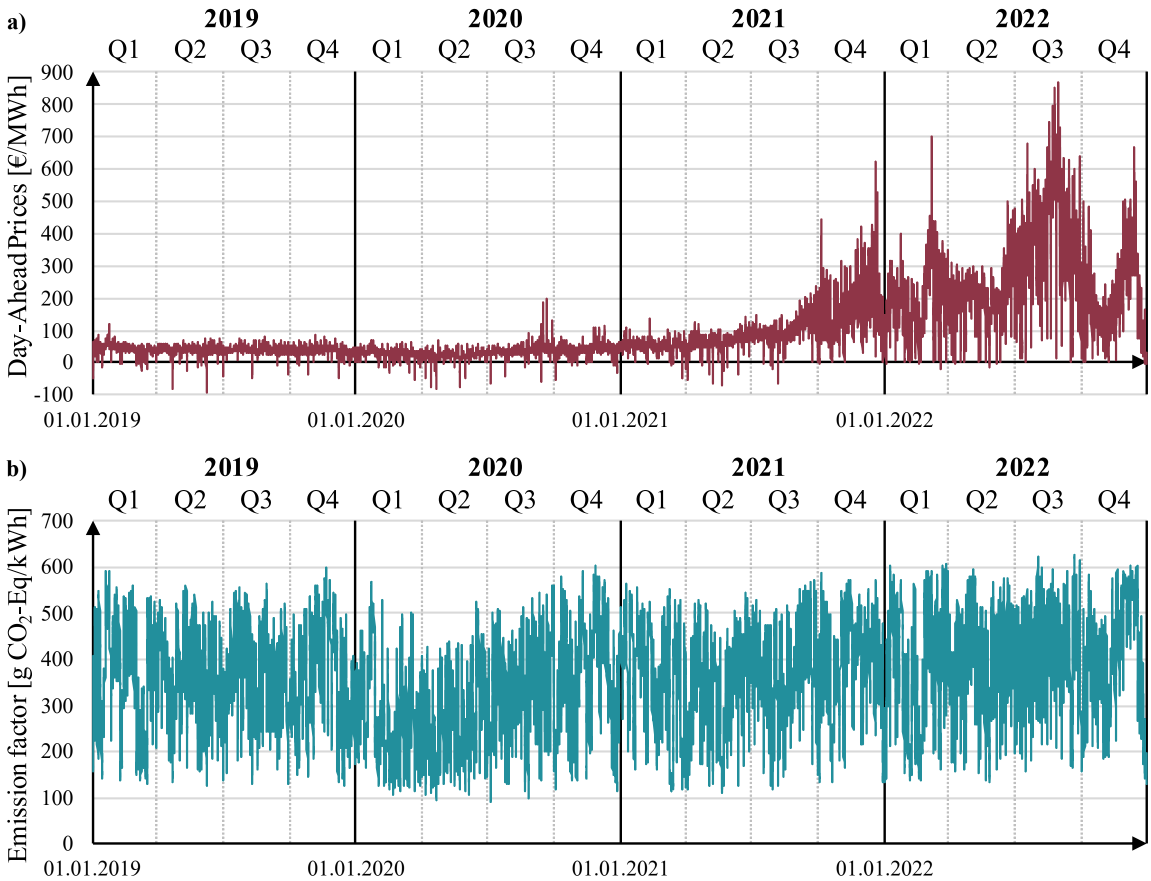

Figure 2: Illustration of EPEX SPOT hourly Day-Ahead prices for BZN|DE-LU (a) and associated emission factors (b) in Germany between 2019 and 2022.
Source: Own illustration, data from (ENTSO-E 2022b; Lauf et al. 2021).

The results indicate that energy-flexible operation in real-time electricity tariffs simultaneously reduces electricity procurement costs and associated GHG emission reductions. Additionally, it is evident that the economic potential of flexibility significantly increases during market crisis situations. Across flexibility durations, relative cost savings average roughly 10 EUR/kW between the first quarter of 2019 and the second quarter of 2021, increasing to approximately 50 EUR/kW between the second half of the year 2021 and the end of the year 2022. Peak values for the cost reduction potential appear in the third quarter of 2022, with a six-hour flexibility yielding 129.13 EUR/kW. However, even the shortest flexibility of one hour exhibits a ten-fold increase between its lowest of 2.21 EUR/kW in the first quarter of 2020 and its highest cost reduction potential of 22.88 EUR/kW in the third quarter of 2022. The findings of electricity procurement cost savings generally align with reductions in associated GHG emissions. Yet, the intensity of this synergetic effect depends on the duration of flexible operation and underlying market conditions. In the first quarter of

2022, one hour of flexible operation reduces approximately 2.84 kg-CO_2-e/kW, while 48 hours of flexible operation achieves a reduction of 71.49 kg-CO_2-e/kW. Despite the significant potential for cost reductions, no exceptionally high reduction in associated emissions have been identified between the third quarter of 2021 and the fourth quarter of 2022. Furthermore, there are exceptions, as evidenced by the higher level of emissions in the third quarter of 2019, despite cost reductions, indicating that simultaneous alignment of electricity procurement costs and emission reductions is not achieved in every case.

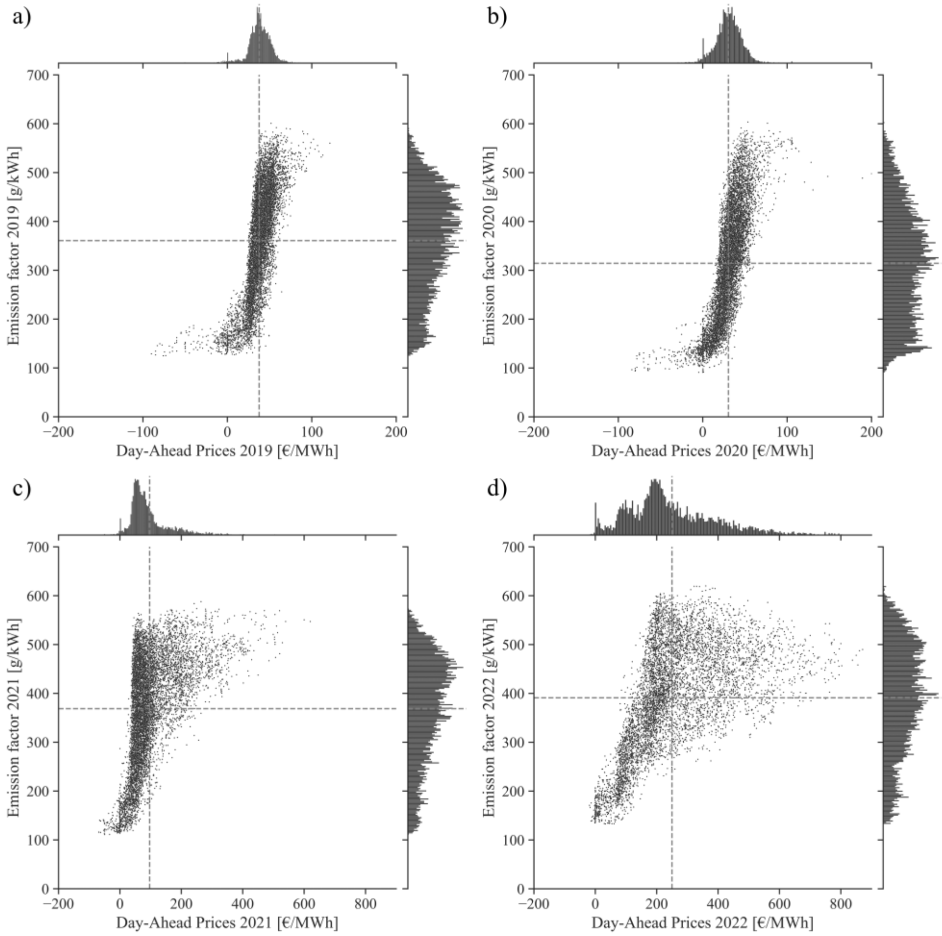

Figure 3: Correlation analysis between EPEX SPOT hourly Day-Ahead prices for BZN|DE-LU and GHG emission factors of the years 2019 (a), 2020 (b), 2021 (c), and 2022 (d) in Germany.
Source: Own illustration, data from (ENTSO-E 2022a, 2022b).

The results of the study further reveal positive correlations between EPEX Spot Day-Ahead electricity prices and hourly GHG emission factors associated with electricity generation. Within Figure 3, each plot depicts the electricity prices on the x-axis and the emission factors on the y-axis. At the top and right of each diagram, a histogram is provided to illustrate the distribution of prices and emissions. The correlation weakens in the crisis but remains positive. Correlations drop from 71.84 % in 2019 and 76.05 % in 2020 to 53.23 % in 2021 and 59.12 % in 2022. This correlation between electricity prices and hourly GHG emission factors associated with electricity generation constitutes a vital factor in the beneficial deployment of energy-flexible technologies, as it determines whether cost-minimizing operational strategies also lead to emission reductions. These results substantiate a fundamental principle of energy-flexible operated technologies, as flexibility is economically and ecologically more valuable when prices are more volatile. Thus, flexibility may be utilized as an instrument of insurance against price risks, effectively exploiting market volatility to generate arbitrage opportunities.

Research Paper #1 serves as the empirical foundation for the thesis. First, it calibrates stakeholder expectations regarding the potential benefits of energy-flexible operation. Second, by simultaneously evaluating electricity procurement cost and emission performance, it contributes a fundamental methodology for subsequent assessments within this cumulative dissertation. Furthermore, this study yields several implications for energy policy, as well as for investors and operators of energy-flexible technologies. First, energy-flexible operation may provide a financial hedge against the volatility of dynamic electricity wholesale prices. As the share of renewable energies in the energy system and, consequently, the volatility of electricity generation continues to increase, market disruptions comparable to those seen during the European energy crisis between 2021 and 2022 may reemerge. Investors and operators should therefore acknowledge and leverage energy-flexible operation to mitigate future exposure to electricity price risks. Meanwhile, policymakers should establish regulatory frameworks that enable utilities to implement dynamic electricity tariffs and incentivize companies to invest in flexible technologies as part of a comprehensive risk management strategy. Secondly, the identified ecological benefits encourage the broad implementation of market-based dynamic tariffs for energy-flexible operation, rather than static price regimes. By enabling operational strategies aimed at minimizing electricity procurement costs and simultaneously reducing associated GHG emissions, dynamic tariffs facilitate the adaptation of electricity consumption towards renewable electricity sources. Investments in energy-flexible technologies thus contribute to achieving climate goals while improving the economic position of companies within an energy system with a high share of renewable electricity. Third, the positive correlation between economic and ecological benefits may not be generalizable and should therefore be reinforced by appropriate policy instruments. During the European market crisis in Germany, the use of inexpensive but emission-intensive coal-fired electricity generation reduced the correlation between prices and emissions. Therefore, action beyond the implementation of dynamic electricity tariffs is required, as wholesale electricity prices must adequately reflect ecological impacts associated with electricity generation to effectively translate emission intensity into price signals. The adjustment of the limit on emissions allowances under the EU Emissions Trading System, as well as incorporating stricter carbon pricing into future electricity tariff designs, represents approaches to achieving this alignment.

III Digital enabled techno-economic evaluations of energy-flexible hydrogen technology configurations

III.1 Synergetic electricity procurement strategies enabled by energy-flexible operated hydrogen production with battery energy storage systems

Renewable hydrogen production will only scale if operators of electrolyzers can offer hydrogen at competitive offtake prices and if regulatory requirements are met, along with certification regarding sustainability standards. However, various challenges impede the realization of hydrogen electrolysis systems in practice. Achieving GHG emission reduction in line with EU energy policy objectives requires that electricity used for hydrogen production be supplied exclusively from RES (Brandt et al. 2024). This facilitates energy-flexible operation of electrolysers (Parra et al. 2019), since flexible dispatch is the practical means to accommodate the intermittency of solar and wind and to align electrolytic hydrogen production with RES availability (Stöckl et al. 2021; Kojima et al. 2023; Huber et al. 2014). Besides energy-flexible operation, related literature discusses the integration of energy storage technologies within hydrogen production systems to cope with the volatility of RES (Gholami and Ghaleh Jough 2025; Mößle et al. 2025). At the same time, water electrolysis is electricity-intensive, making the techno-economic optimization of electricity procurement portfolios essential to reduce operating expenses and to allocate high capital costs efficiently (Ueckerdt et al. 2024; Al-Qahtani et al. 2021). Furthermore, previous literature argues that energy-flexible hydrogen electrolysis can also reduce operating costs by efficiently utilizing otherwise curtailed renewable energy (Gholami and Ghaleh Jough 2025; Yan et al. 2024). Previous studies explored electricity procurement strategies for electrolysis plants to achieve lower hydrogen production costs. (Casas Ferrús et al. 2024; Glenk and Reichelstein 2019). However, the set of permissible electricity procurement strategies for renewable hydrogen production in the EU, as well as for hydrogen imports into the EU, is constrained by the RED and the accompanying delegated acts (European Commission 2023c, 2023a; Brandt et al. 2024). These constraints induce further operational complexity by imposing requirements on additionality, temporal matching, and geographical correlation. However, an integrated assessment of energy-flexible operated renewable hydrogen production with integrated BESS and a focus on PPA electricity procurement strategies in line with the RED regulatory framework remains to be addressed.

To cope with these unsolved challenges, Research Paper #2 introduces a mixed-integer linear programming model for a grid-connected microgrid that optimizes the electricity procurement strategy and hourly operation of a proton exchange membrane electrolyzer with integrated BESS. The topology of the proposed technological configuration is illustrated in Figure 4 and features a single grid-coupling point, as-produced physical and virtual PPAs from solar, wind, and hydropower, as well as a Hydrogen Subsystem (HSS) with compression and storage. The optimization enforces RED-consistent hourly temporal matching of renewable electricity generation and hydrogen production, based on PPA electricity procurement, and minimizes total annual operational costs. Within the scope of an optimization study, several BESS capacities and utilization rates for the electrolyzer are evaluated in the context of a real-world case study on a representative instance in Germany.

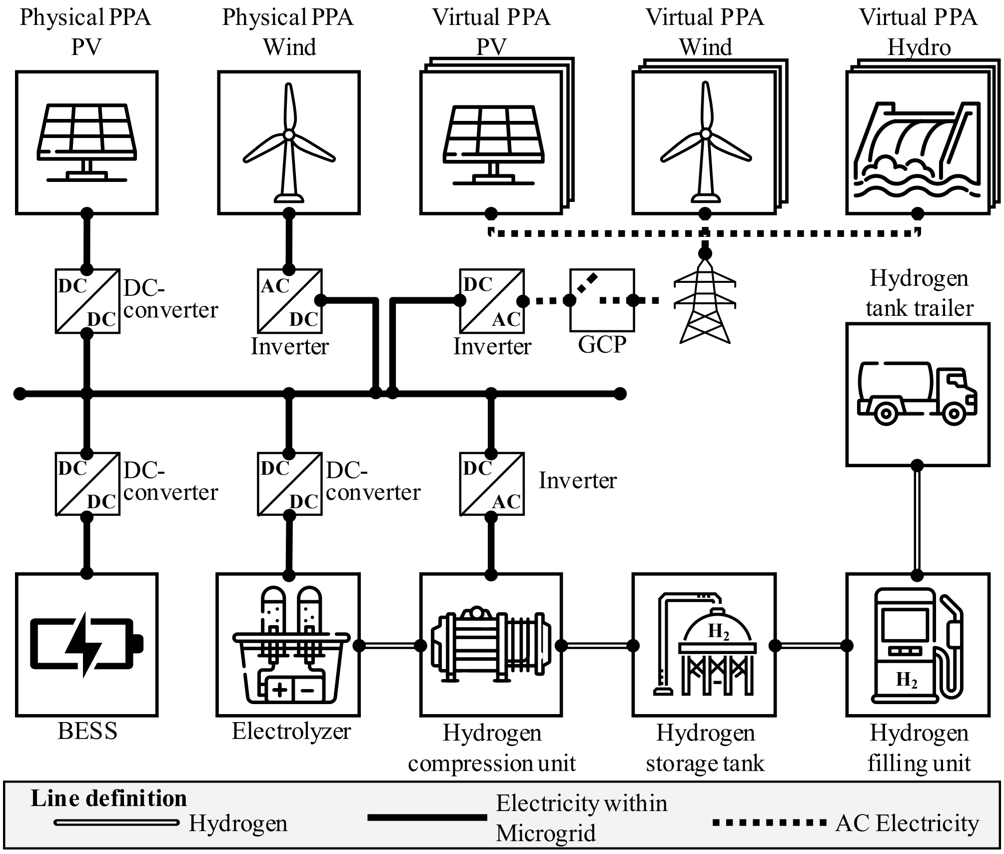

Figure 4: Illustration of the design of the microgrid topology for energy-flexible operated electrolysis powered by PPAs with integrated BESS.
Source: Own illustration.

The results of Research Paper #2 delve into the design of electricity procurement portfolios for the individual optimization cases. To this end, Figure 5 illustrates the allocation of the optimized shares for the respective PPA alternatives across various BESS capacity configurations and electrolyzer utilization scenarios based on full-load hours. At low utilization, for example 1,500 full load hours, the optimized portfolio relies predominantly on PV PPAs, while physical wind PPAs play a minor role. As utilization rises to 4,000 full load hours, the mix shifts significantly. The share of physical PV PPAs falls to approximately 5 %, and wind PPAs expand to a combined 72 % of the portfolio, split into 43 % virtual wind PPAs and 29 % physical wind PPA contracts. From 3,500 full load hours onward, hydro PPAs are placed within the optimized electricity procurement portfolios. At 4,000 full load hours and above, the share of hydro PPAs continues to grow and progressively replaces wind and PV for all given BESS capacity. For utilization of 4,500 full load hours and higher, increasing BESS capacity shifts the portfolio toward wind and solar PPAs, as the share of hydro PPAs declines.

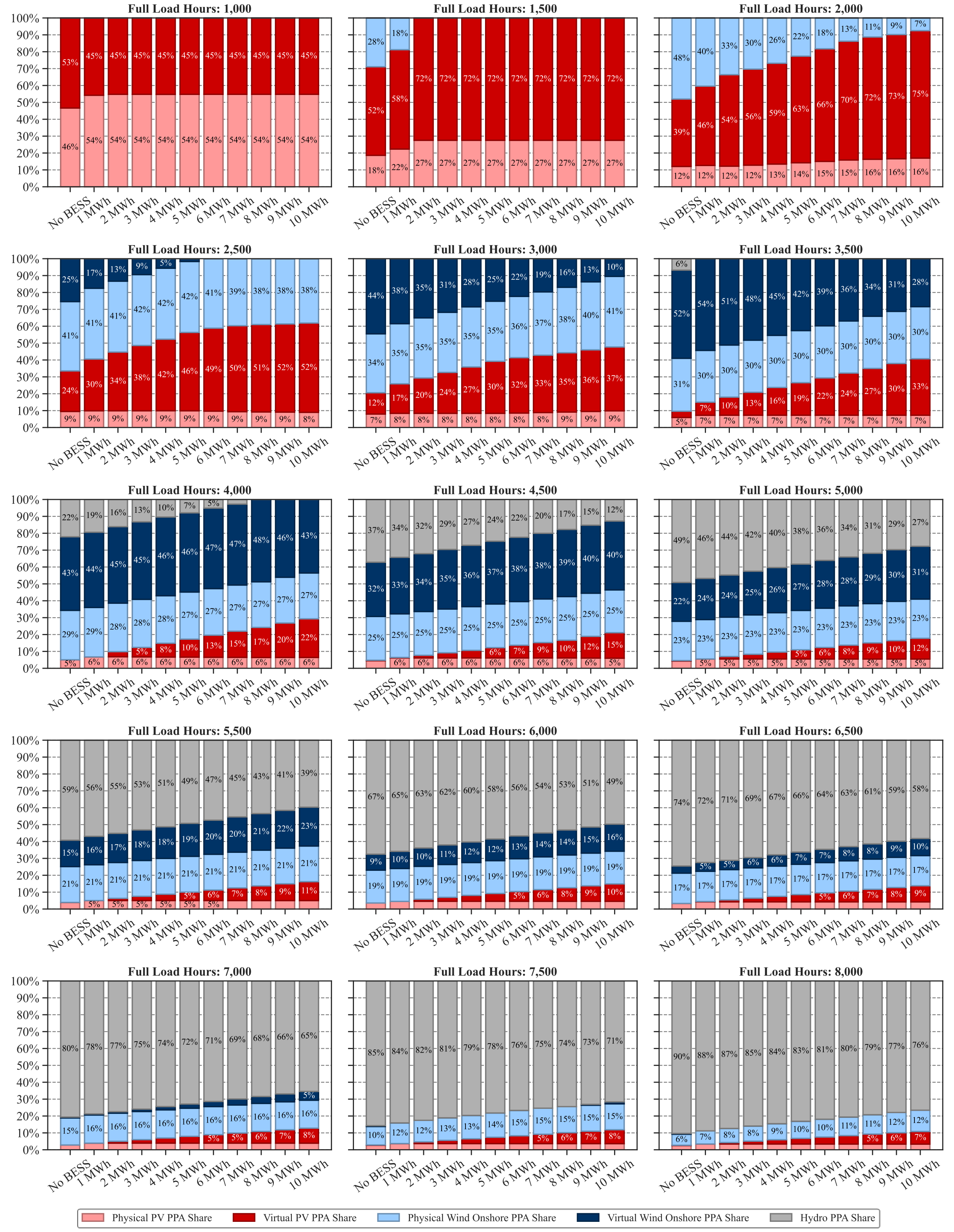

Figure 5: Illustration of optimized electricity procurement portfolios for various electrolyzer utilization rates and their sensitivity to different BESS capacities.
Source: Own illustration.

The results reveal two general trends that hold throughout the analyzed optimization instances. First, larger BESS capacities systematically raise the share of PV PPAs at most electrolyzer utilization levels. This is evident between 2,500 and 3,500 full load hours, as expanding BESS capacity reduces the share of virtual wind PPAs while the physical wind share remains roughly constant. Second, energy storage progressively substitutes hydro PPAs with cheaper, yet more volatile wind and solar PPAs at elevated electrolyzer utilization levels. Especially between 4,500 and 7,500 full load hours, where hydro PPAs are prominent within the electricity procurement portfolios, additional BESS capacity increases the share of virtual wind PPAs and reduces the share of hydro PPAs.

Next, the resulting LCOH for each electrolyzer utilization level, BESS configuration, and optimized electricity procurement portfolio are analyzed (cf. Figure 6). LCOH are exceptionally high at low electrolyzer utilization, specifically at 1,000 and 1,500 full load hours. As utilization increases, the LCOH declines significantly. Beyond 4,000 full load hours, the LCOH narrows between 8.67 EUR/kg for a 10 MWh BESS at 4,000 full load hours and 9.43 EUR/kg at 8,000 full load hours with no BESS. When comparing BESS sizes within utilization scenarios, higher BESS capacities result in marginal LCOH increases at low utilization up to 2,500 full load hours. Once utilization exceeds 3,000 full load hours, additional BESS capacity reduces LCOH. Sensitivity to BESS size diminishes from approximately 3,000 full load hours onward, especially at higher capacities. At 6,000 full load hours, for instance, the LCOH values for 10, 9, and 8 MWh BESS are tightly grouped at 9.00, 9.02, and 9.04 EUR/kg. Overall, the lowest LCOH values occur between 3,500 and 4,500 full load hours.

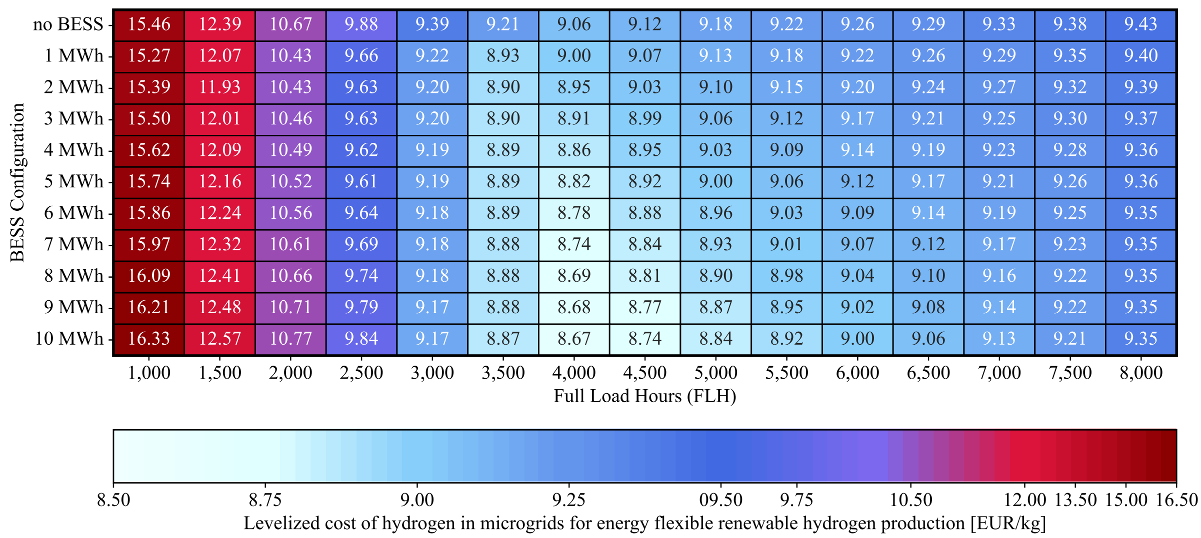

Figure 6: Illustration of the optimized LCOH for energy-flexible operated renewable hydrogen electrolysis for electrolyzer utilization scenarios and their sensitivity to varying BESS configurations. *Source: Own illustration.*

The study demonstrates that BESS may perform a pivotal role in lowering the LCOH under electricity sourcing requirements stipulated by the RED. Beneficial reductions in the LCOH performance emerge from the synergetic interaction of the as-produced PPA electricity supply, BESS capacity, and electrolyzer operation. Across the analyzed optimization instances, BESS integration primarily reshapes the PPA electricity procurement portfolios by enabling a shift toward lower-cost but more volatile PV PPAs, partially substituting higher-priced hydro and wind PPAs. The study restricts electrolyzer operation below 20 % of its nominal power and uses PPA electricity below this power threshold to charge the BESS instead. This increases overall utilization of contracted PPAs, allows subsequent BESS discharge to increase electrolysis production performance, and reduces the relative capital cost share by spreading fixed costs over an increased hydrogen output. Further sensitivity analyses underscore that the investment costs for BESS are crucial for reducing the LCOH effectively. As specific investment costs for BESS may decline through economies of scale in manufacturing or the utilization of second-life batteries, the beneficial economic potential of BESS integration in energy-flexible operated hydrogen production will continue to increase.

Within the scope of this dissertation, Research Paper #2 contributes a novel optimization model to analyze the design and operational strategies of energy-flexible hydrogen production systems that incorporate BESS to leverage the synergetic economic potential of low-cost and high volatility PPA electricity procurement portfolios. The paper develops a mixed integer linear optimization model that optimizes procurement and hourly operation for a grid-connected energy-flexible electrolyzer with integrated BESS operating conformant with the RED regulatory framework. The framework facilitates the development of techno-economic design guidelines and design of PPA based electricity portfolios to minimize LCOH while respecting technical and regulatory constraints. The study provides actionable decision support for investors and operators and identifies a viable role for second-life batteries.

III.2 Design and operation of energy-flexible multi-energy microgrids for sustainable future transportation settings

Road transportation is anticipated to be defossilized through a complementary coexistence of powertrain options with BEV for short- to medium-distance individual passenger mobility and FCEV for transportation requirements where heavy-duty, long distances, and quick refueling are decisive (Morrison et al. 2018; Michalski et al. 2019; Eberle and Helmolt 2010; Çabukoglu et al. 2019). This complementarity has not only been acknowledged in the literature but is also reflected in the EU´s "Fit for 55" package, which sets targets for a cross-European network of both fast-charging and hydrogen refueling stations (European Commission 2021a). National strategies, investment support, and corridor planning are aligned with this legislative framework (European Commission 2021b; European Parliament 2023). Yet, substantial hurdles persist for the economic viability of fast-charging and hydrogen refueling stations. The operation of fast charging and hydrogen infrastructure remains cost-intensive (Browne et al. 2012; Biresselioglu et al. 2018), a robust long-distance hydrogen distribution network within the EU is still lacking (Astiaso Garcia 2017), and electricity for both BEV charging and hydrogen production must be obtained from RES (Gustafsson et al. 2021). Grid-connected multi-energy microgrids that integrate decentralized renewable electricity generation, hybrid BESS and hydrogen storage systems, and hydrogen technologies to offer both charging and hydrogen refueling services address the challenges towards sustainable future energy supply for road transportation (Rose and Neumann 2020; Mansour-Saatloo et al. 2021). However, previous research has focused on design and operation in isolation, overlooking the potential synergies that arise from simultaneously supplying BEVs and FCEVs in hybrid microgrids. Haupt et al. (2020) evaluate BESS sizing for fast-charging hubs, whereas other contributions focus on hydrogen for medium to long-term energy storage (Valverde et al. 2013; Alam et al. 2019). Yassuda Yamashita et al. (2021) explore hybrid hydrogen and BESS microgrid configurations for self-sufficiency. The design and operation of hydrogen refueling stations further require acknowledgement of refueling demand behavior and renewable electricity availability (Grüger et al. 2018; Xu et al. 2022). Comparative assessments of BESS, hydrogen, and hybrid storage configurations demonstrate the trade-off between cost and GHG reductions (Dawood et al. 2020). Nevertheless, decision-makers still lack comprehensive techno-economic guidance for the design and operation of energy-flexible multi-energy microgrids in sustainable future transportation settings.

Research Paper #3 addresses these gaps and proposes a mathematical optimization model that minimizes total energy costs operating a grid-connected multi-energy microgrid with renewable electricity generation, hybrid BESS and hydrogen energy storage systems, and onsite hydrogen production to offer fast-charging and hydrogen refueling services at a shared station (cf. Figure 7). Within an optimization study, multiple design and operational strategies are considered, taking into account both economic and ecological performance. The real-world case study in Germany evaluates multiple BESS and hydrogen technology system configurations alongside two operating strategies, namely Day-Ahead market participation and self-consumption optimization without grid feed-in. The analysis covers the years 2019 to 2021 and yields six distinct scenarios.

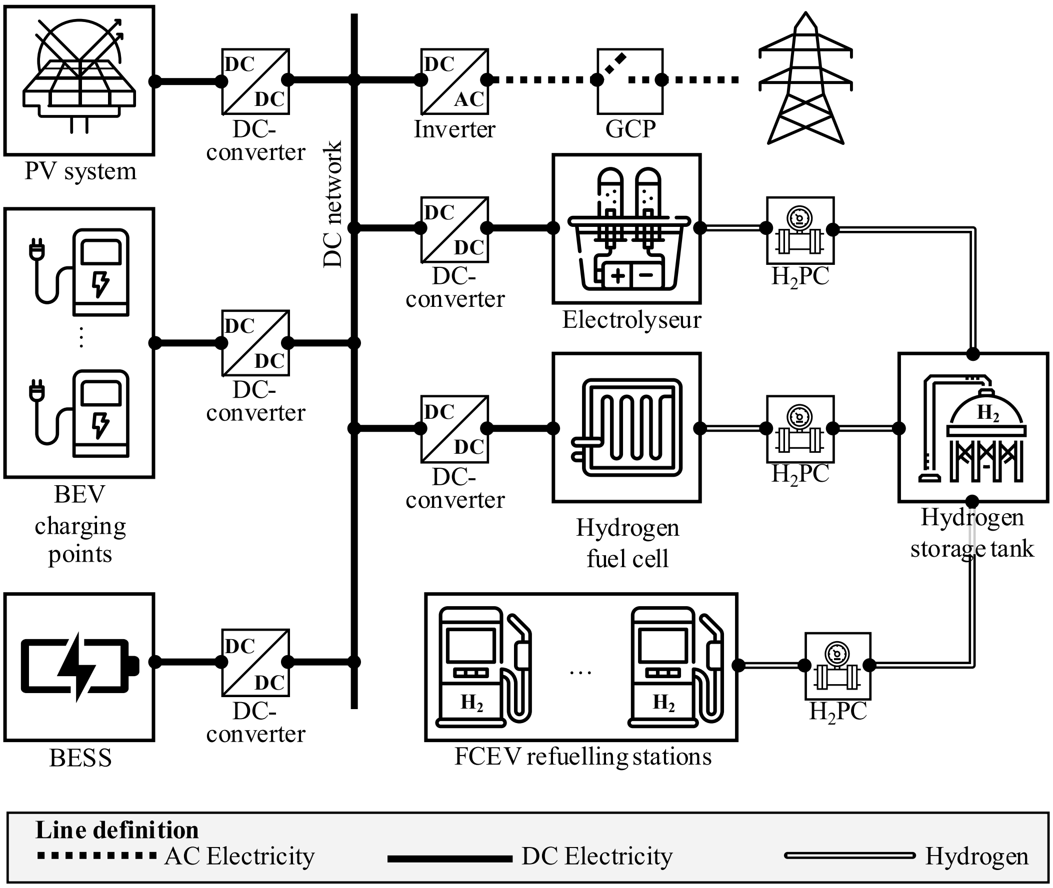

Figure 7: Illustration of the grid-connected multi-energy microgrid and its system modules.
Source: Own illustration.

The findings presented in Figure 8 indicate that incorporating BESS into a hybrid charging and refueling microgrid reduces both demand charge costs and total energy costs. BESS reduces grid electricity sourcing by enabling storage of photovoltaic surplus and facilitates charging in low Day-Ahead price periods. Following the strategy of self-consumption optimization, BESS maximizes the use of on-site generated electricity, and through Day-Ahead participation in electricity trading, it can further reduce total energy costs. In the year 2019, the difference between strategies is minor due to higher BEV charging demand. By 2020 and 2021, electricity feed-in gains leverage, and Day-Ahead participation becomes a more attractive option due to increased price levels. At the same time, performative hydrogen system configurations reduce total energy costs and improve the decarbonization potential. The electrolyser is the dominant electricity consumer, and increased production capacity enables more hydrogen to be produced during renewable peak generation or low-price hours in the Day-Ahead market. Fuel cell utilization is generally low, yet it increases under self-consumption in 2020, especially for smaller hydrogen storage setups. Excess photovoltaic generation can justify reconverting hydrogen to electricity to support charging during periods of low renewable availability. Outside such cases, fuel cell operation is often economically inefficient due to significant round-trip efficiency losses.

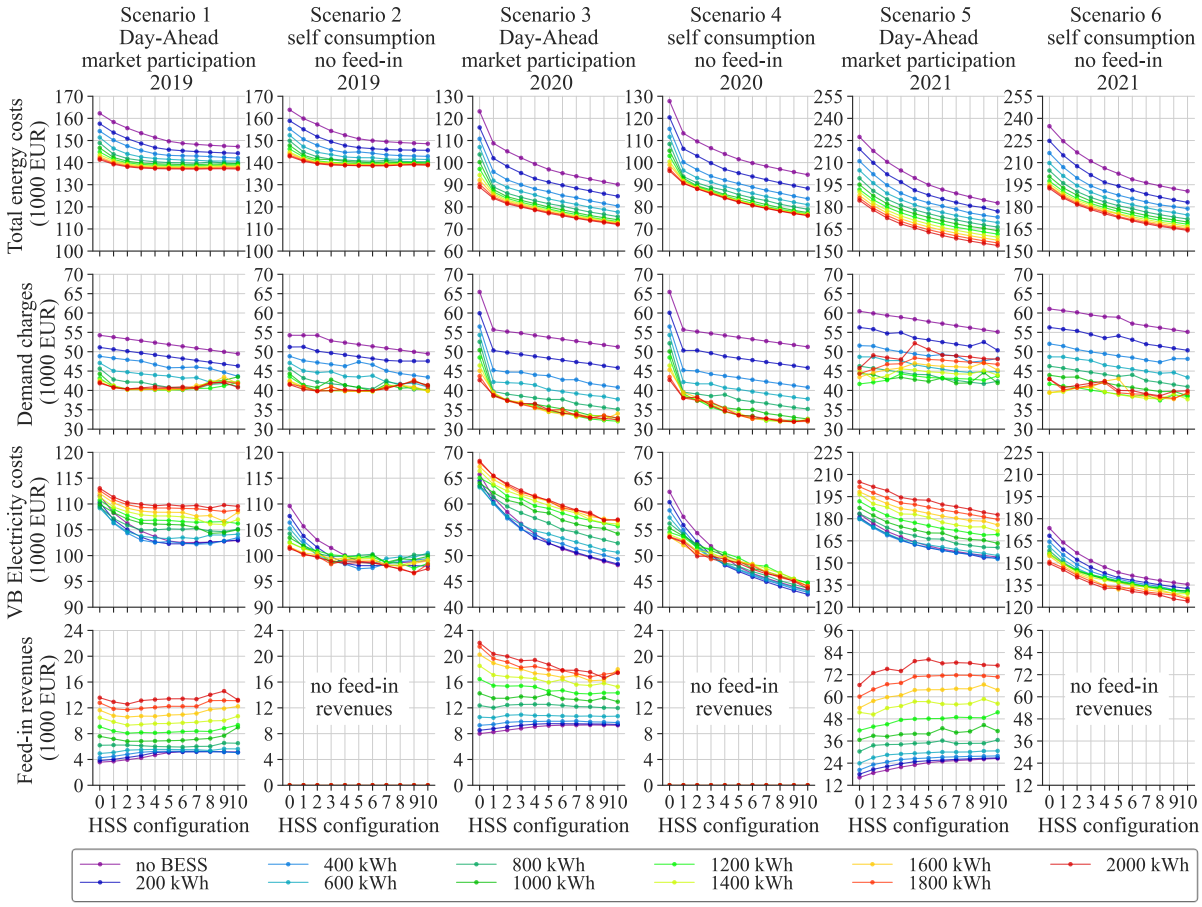

Figure 8: Optimization results for different BESS and HSS configurations and operational scenarios. *Source: Own illustration.*

Self-consumption optimization generally yields higher decarbonization than Day-Ahead participation. Day-Ahead market participation increases total grid electricity purchases as the average emissions factors of procured electricity rise, whereas on-site photovoltaic generation is associated with a lower emission factor. Figure 9 illustrates the resulting decarbonization impacts of BEVs and FCEVs compared with passenger cars and heavy-duty trucks with fossil fuel powered internal combustion powertrains. The analysis also uncovers a gap between cost-optimal operation and decarbonization progress. This is counterintuitive under Germany's merit-order, which prioritizes renewable feed-in over fossil plants (Sensfuß et al. 2008). As described in Section II, Day-Ahead prices and associated emission factors are positively correlated, and the correlation strengthens in 2020 relative to 2019, although rising price volatility by 2021 reduces the correlation. Due to the current grid charge regulation, operators minimize high electricity procurement load peaks and prefer steady electricity imports over frequent ramping of electricity procurement to exploit low-price intervals, thereby limiting the potential synergetic economic and ecological benefits from not fully materializing.

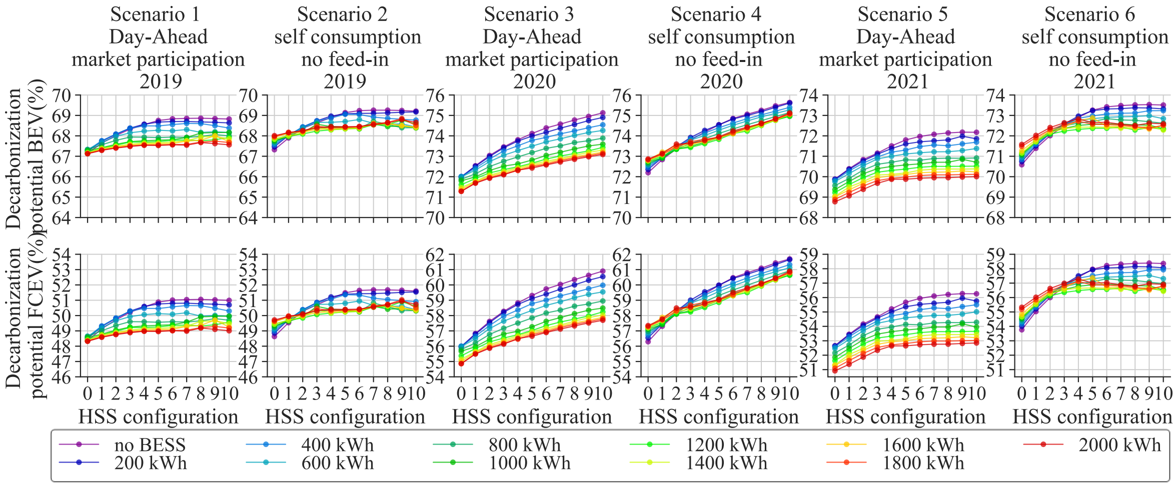

Figure 9: Illustration of the decarbonization potential of BEV and FCEV in comparison to passenger cars and heavy-duty trucks with fossil fuel powered powertrains.
Source: Own illustration.

In conclusion, the results of the study indicate that microgrid configuration, energy storage sizing, and operating strategy significantly influence both total energy costs and overall decarbonization potential. Consequently, several implications arise for policymakers, operators of energy-flexible technologies, and researchers. As current demand charge regulations impede the simultaneous reduction of total energy costs and associated GHG emissions, energy policy should align the regulatory framework to encourage energy-flexible operating strategies, enabling grid-connected microgrids to utilize otherwise curtailed renewable electricity effectively. Further, operational tax incentives could accelerate the deployment of hybrid charging and hydrogen refueling microgrids beyond infrastructure subsidies. Third, on-site power plants with low associated GHG emissions, such as photovoltaic and wind facilities, should be integrated with energy-flexible multi-energy microgrids for fast-charging and hydrogen refueling stations to facilitate sustainable transportation. This study contains specific limitations that encourage further research. As the case study focuses on Day-Ahead price dynamics and market design in Germany, future research may transfer the methodological approach to other regions with different regulatory and market conditions. Investigating varying electricity mixes or BEV and FCEV penetration rates, and incorporating long-term electricity prices and charging and refueling forecasts, would further support researchers, practitioners, and policymakers in their future decision-making processes.

IV Data-driven exploration of alternative regulatory frameworks for renewable hydrogen production

IV.1 Design of adequate specifications for geographical correlation between electricity generation and consumption for energy-flexible electrolysis

Geographical correlation in the context of the RED determines the spatial relationship between renewable electricity generation and electrolyzer operation for RFNBO confirmative hydrogen production and primarily focuses within the identical electricity market bidding zones (European Commission 2023a). However, in large bidding zones, extensive geographical distribution of RES power plants and electrolysis capacities result in novel requirements for the electricity transmission system, as grid congestion and redispatch demand may increase (vom Scheidt et al. 2022; Hordvei et al. 2025). The RED enables policymakers to implement more detailed geographical correlation specifications within individual bidding zones to anticipate the specific requirements of energy systems (European Commission 2023a). However, policymakers face challenges associated with determining how alternative geographic correlation specifications influence the electricity transmission system costs, as well as the location, utilization, and cost of hydrogen production via electrolysis. Prior studies indicate that the allocation of electrolysis capacity should concentrate in regions with high electricity generation capacities of RES and along corridors that relieve stress on the electricity transmission grid (vom Scheidt et al. 2022; Vargas-Ferrer et al. 2025; Stolte et al. 2024). However, geographical correlation in line with large uniform bidding zones can misalign objectives of private electrolysis investors and operators in contrast to energy system objectives, if either electricity procurement portfolios extensively rely on the electricity transmission system or local RES potentials are neglected (Ruhnau and Schiele 2023; Hordvei et al. 2025). Conversely, tightening of the geographical correlation within bidding zones may reduce electricity transmission system costs but raise hydrogen production costs by limiting access to high-capacity-factor sites for RES power plants and by increasing risks associated with surplus RES generation (Casas Ferrús et al. 2024). Energy policymakers therefore face the challenge of quantifying whether tightening the geographical correlation can serve as an adequate policy instrument to reduce the costs associated with integrating electrolyzers into the remaining electricity system and to characterize the associated trade-offs across sub-zonal geographical correlation specifications.

Research Paper #4 addresses these challenges by developing a methodological framework to derive and evaluate bidding zone-specific granular specifications for geographical correlation, as well as by validating and demonstrating the approach within Germany and its respective electricity market bidding zone. The study introduces a two-run optimization procedure using the modeling and optimization tools PyPSA and PyPSA-Eur. In the first optimization run, the renewable hydrogen production costs are minimized by optimizing the spatial allocation of electrolyzer capacities and RED-compliant electricity procurement strategies for electrolyzer operators. Thus, optimized locations, respective capacities, and electricity sourcing for electrolysis are determined to achieve production targets for renewable hydrogen. The second optimization run minimizes the expansion and operating costs of the electricity system required to meet the total electricity demand and supply the electricity procurement portfolios, taking into account the constraints of the electricity transmission grid. The methodological approach is validated and demonstrated in a case study for Germany, whereby 32 individual specifications for the geographical correlation are evaluated.

The results of the study indicate that tightening geographical correlation from a single large bidding zone to more granular configurations may reduce electricity system costs in some cases, as the results range from a 1.08 % reduction to a 1.32 % increase in electricity system costs. However, the results regarding hydrogen production costs indicate a contrary effect. By introducing more granular geographical correlation configurations, access to RES power plants outside the sub-zonal geographical correlation configuration is restricted. Consequently, the costs of hydrogen production increase between 0.40 % to 4.43 % relative to the single zone baseline scenario for the respective more granular configuration of the geographical correlation.

Throughout the evaluated geographical correlation configurations, the increase in hydrogen production costs exceeds any potential electricity system cost savings. Within a single large electricity market bidding zone and correlation specification, the optimized electricity procurement portfolios source PV predominantly in the south and southeast of Germany, while onshore wind is sourced from northern regions in the bidding zone. Tightening towards more granular geographical correlation specifications leads to a shift in electricity procurement portfolios, allocating the respective optimal solar and wind locations within the newly established regional boundaries. In addition, in tightened specifications for geographical correlation, it is increasingly frequent that the temporally correlated power output of RES power plants surpasses the installed electrolysis capacities. These surplus electricity volumes pose a potential economic risk if the electricity volumes are to be distributed to the public grid in periods when wholesale electricity prices are disadvantageous.

Research Paper #4 indicates that adequate specifications for geographical correlation between electricity generation and consumption for energy-flexible electrolysis can reduce RES electricity generation curtailment and requirements for the electricity transmission grid. For policymakers, the study provides guidance on the potential economic trade-offs of imposing restrictions across large, heterogeneous electricity market bidding zones. Nevertheless, energy policy decision-makers must acknowledge the associated trade-off associated with tightened geographical correlation specifications, whereby the subsequent costs for electrolyser operators increase considerably compared to the savings of expansion and operating costs of the electricity system. Following the third research objective of this cumulative dissertation, the findings and conclusions derived in Research Paper #4 support the advancement of alternative regulatory design elements for renewable hydrogen production by evaluating geographical correlation specifications beyond the current single bidding zone definition.

IV.2 Facilitate sustainable electricity procurement strategies for wholesale electricity market integrated renewable hydrogen production

The RED defines strict regulatory criteria for sourcing electricity to produce RFNBO-compliant renewable hydrogen, which enforce temporal matching with renewable electricity generation and electricity consumption by the electrolyzer (European Commission 2023a). Thus, electricity procurement for renewable hydrogen production primarily relies on PPAs (Moradpoor et al. 2023; Ruhnau and Schiele 2023). As a consequence, the integration of the wholesale electricity market is considerably restricted (Veenstra and Mulder 2024; Wang 2024). However, a slight exception applies, whereby temporal correlation is not required during hours when wholesale electricity spot market prices are less than or equal to 20.00 EUR/MWh (Langenmayr and Ruppert 2023; European Commission 2023a). These regulatory criteria for sourcing electricity reduce exposure to fossil-based and GHG-intensive electricity, as identified by the positive correlation between electricity market prices and associated GHG emissions (cf. Section II). Nevertheless, they also narrow the access to utilization periods of the electrolyzer when the market could supply additional power. Policymakers therefore face a fundamental trade-off in regulating renewable hydrogen. Relaxing the regulatory criteria for sourcing electricity to produce RFNBO-compliant renewable hydrogen may accelerate the deployment of electrolyzers through reduced LCOH while risking higher associated GHG intensity of produced hydrogen from additional electricity procurement through the public grid in not fully defossilized energy systems (Engstam et al. 2023; Ruhnau and Schiele 2023; Schlund and Theile 2022). In contrast, overly stringent regulatory criteria for electricity procurement limit GHG emission intensity but may contribute to increased LCOH, potentially hindering the market uptake of hydrogen (Frontier Economics 2021; Pototschnig 2021).

Research Paper #5 addresses this trade-off faced by energy policymakers by quantifying how controlled relaxation of the permitted maximum wholesale electricity market price affects the LCOH and the associated GHG intensity across multiple European bidding zones. For the qualitative study, a multi-step optimization procedure is introduced to determine the LCOH and GHG emission intensity for wholesale electricity market integrated electricity procurement for renewable hydrogen production (cf. Figure 10). In the first optimization step, the PPA electricity procurement portfolios are optimized. In the second optimization step, electricity procurement costs are optimized by utilizing wholesale market electricity, subject to the permitted maximum wholesale electricity market price. Within a sensitivity analysis, the 20.00 EUR/MWh price level is progressively relaxed in increments of 0.50 EUR/MWh, up to a price level of 100.00 EUR/MWh. To reflect the highly diverse characteristics of current, not fully defossilized energy systems, this methodology is applied to a total of 29 eligible bidding zones throughout Europe (cf. Table 1).

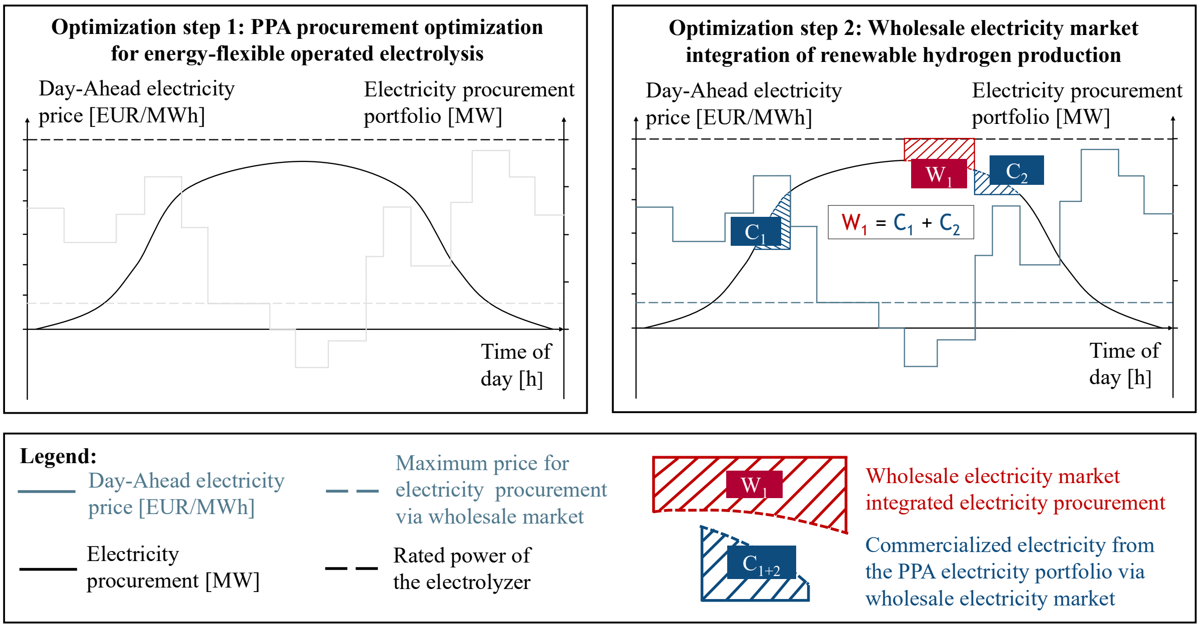

Figure 10: Illustration of the renewable hydrogen production with wholesale electricity market electricity procurement.
Source: Own illustration.

Table 1: Parameterization data for the analyzed European electricity bidding zones and the respective electrolyser locations. *Data from (Electricity Maps 2024; KYOS 2024; ENTSO-E 2024)*

Bidding zone	**Location**	**Hydro-PPA** $[€/MWh]$	**Solar-PPA** $[€/MWh]$	**Wind-PPA** $[€/MWh]$	**Annual mean Day-Ahead price** $[€/MWh]$	**Annual mean GHG emission intensity** $[g\ CO_2\text{-}Eq/kWh]$
Austria AT	Vienna	87.30	62.80	75.60	81.43	123.20
Belgium BE	Brussels	83.80	53.75	63.00	70.33	142.24
Bulgaria BG	Sofia	99.00	80.10	89.10	102.45	340.71
Croatia HR	Zagreb	88.00	67.15	77.30	94.58	229.32
Czech Rep CZ	Prague	89.30	63.70	76.30	85.02	476.72
Denmark DK1	Aalborg	71.10	45.80	44.00	70.75	118.55
Denmark DK2	Copenhagen	69.50	46.50	39.65	70.97	125.43
France FR	Paris	78.80	54.65	65.15	57.91	31.28
Germany Luxembourg DE_LU	Emden	76.70	39.35	52.40	78.56	332.07
Greece GR	Athens	86.30	55.90	71.45	100.77	338.67
Hungary HU	Budapest	87.00	64.35	75.35	100.71	236.93
Italy IT_CALA	Rossano	83.90	50.25	67.70	109.06	301.18
Italy IT_CNOR	Florence	95.90	75.60	86.75	109.36	246.29
Italy IT_CSUD	Rome	90.90	63.35	80.25	109.74	301.18
Italy IT_NORD	Milan	96.50	76.95	88.10	107.33	242.86
Italy IT_SARD	Cagliari	83.50	45.10	67.80	106.11	528.16
Italy IT_SICI	Palermo	85.20	53.45	70.55	112.13	315.14
Italy IT_SUD	Barletta	83.90	50.25	67.70	109.06	294.44
Netherlands NL	Amsterdam	78.80	41.85	51.50	77.30	272.79
Norway NO1	Oslo	73.10	57.15	57.45	42.07	26.05
Norway NO2	Stavanger	66.20	53.95	49.50	50.18	33.35
Norway NO5	Bergen	61.00	51.55	46.70	41.06	26.34
Poland PL	Warsaw	100.90	75.10	81.35	96.38	703.92
Portugal PT	Lisbon	67.70	43.40	48.75	63.25	104.21
Romania RO	Bucharest	82.60	61.55	70.35	103.42	319.25
Slovakia SK	Bratislava	86.90	63.90	74.00	92.79	238.05
Spain ES	Madrid	67.20	37.10	47.85	62.84	124.14
Sweden SE3	Stockholm	69.60	50.60	49.50	35.83	19.72
Sweden SE4	Malmö	72.20	49.35	46.80	49.79	37.64

Relaxing the permitted maximum wholesale Day-Ahead electricity market price yields a reduction in the LCOH in most analyzed bidding zones, although the magnitude varies. In Northern Europe, the most pronounced influence appears in the bidding zone of DK2, where the LCOH falls from 2.95 EUR/kg-H_2 at 20.00 EUR/MWh to 2.31 EUR/kg-H_2 at 61.00 EUR/MWh. At the same time, results for SE3 indicate no significant deviations, and SE4 reveals only a marginal reduction in LCOH, along with relaxing the permitted maximum wholesale Day-Ahead electricity market price. In NO5, the LCOH reduction saturates beyond 33.50 EUR/MWh, whereas NO1 and NO2 continue to yield LCOH reduction until about 34.00 and 44.00 EUR/MWh. In Eastern Europe, the LCOH levels are significantly higher than in Northern Europe, and reductions extend to increased relaxation thresholds, yet yield a similar pattern of steady decline with progressing relaxation that flattens once profitable purchases in the wholesale electricity market are exhausted with elevated price levels for the relaxation. In Western Europe, the trajectory of the LCOH reductions resembles that identified within the bidding zones of Eastern Europe. Yet, the LCOH reductions come to an earlier halt, from roughly 73.00 EUR/MWh, with the France bidding zone showing almost no LCOH reduction potential and stopping at a permitted maximum wholesale Day-Ahead electricity market price relaxation of approximately 50.50 EUR/MWh. Southern Europe also exhibits significantly diverse LCOH levels and reduction trajectories. Within Italy, a country composed of seven individual bidding zones, the lowest LCOH can be achieved in the bidding zone of Sardinia, and the highest LCOH are found within the most northern bidding zones.

Besides LCOH reductions, across all regional clusters, the associated GHG emission intensity of produced hydrogen generally rises as the permitted Day-Ahead price threshold is increased, again with significant heterogeneity by individual bidding zones. In Northern Europe, within the bidding zone of DK1, the GHG emission intensity increases from 1.14 kg-CO_2e/kg-H_2 at 20.00 EUR/MWh to 2.52 kg-CO_2e/kg-H_2 at 63.50 EUR/MWh, while hydrogen produced in the bidding zone of DK2 rises from 1.20 to 2.84 kg-CO_2e/kg-H_2 at 64.00 EUR/MWh. The results for SE4 and the Norwegian bidding zones indicate merely small GHG emission increases. In contrast, the resulting GHG emission intensity for hydrogen produced in SE3 remains unchanged, as no cost reduction was available. In Western Europe, the bidding zone of DE_LU yields the highest GHG emission intensities, moving from 1.54 kg-CO_2e/kg-H_2 at 20.00 EUR/MWh to 6.55 kg-CO_2e/kg-H_2 at 76.00 EUR/MWh and beyond, whereas FR starts at 0.87 and barely reaches 1.00 kg-CO_2e/kg-H_2 even as the permitted Day-Ahead price threshold is increased to 50.50 EUR/MWh. In Eastern Europe, GHG emissions intensities initially increase only slightly up to roughly 40.00 EUR/MWh but then diverge strongly, with the bidding zone of Poland ultimately plateauing at the highest GHG emission intensity of produced hydrogen throughout all analyzed bidding zones at 16.82 kg-CO_2e/kg-H_2 beyond a price threshold of 89.50 EUR/MWh. The results for the bidding zones in Southern Europe also indicate mixed outcomes, with Greece and Sardinia revealing a sharp increase in the associated GHG emissions at high permitted maximum wholesale Day-Ahead electricity market prices.

Relaxing the permitted Day-Ahead price progressively lowers the LCOH while increasing the associated GHG emission intensity. Yet the magnitude of both effects varies widely across the analyzed bidding zones. Figure 11 illustrates the results of the sensitivity analysis of permitted maximum prices regarding the relative LCOH reductions and respective relative increase in associated GHG emission intensity. Bidding zones with abundant low-cost hours and a favorable alignment between prices and emissions achieve meaningful cost reductions with simultaneous slight increases of the associated GHG emission intensities as the permitted maximum wholesale Day-Ahead electricity market price is increased. This is particularly evident in the analyzed bidding zones in Northern Europe, while other bidding zones such as PL, IT_SARD, and IT_CALA indicate a significant trade-off between reducing the LCOH while increasing the associated greenhouse gas emission intensity of the hydrogen produced.

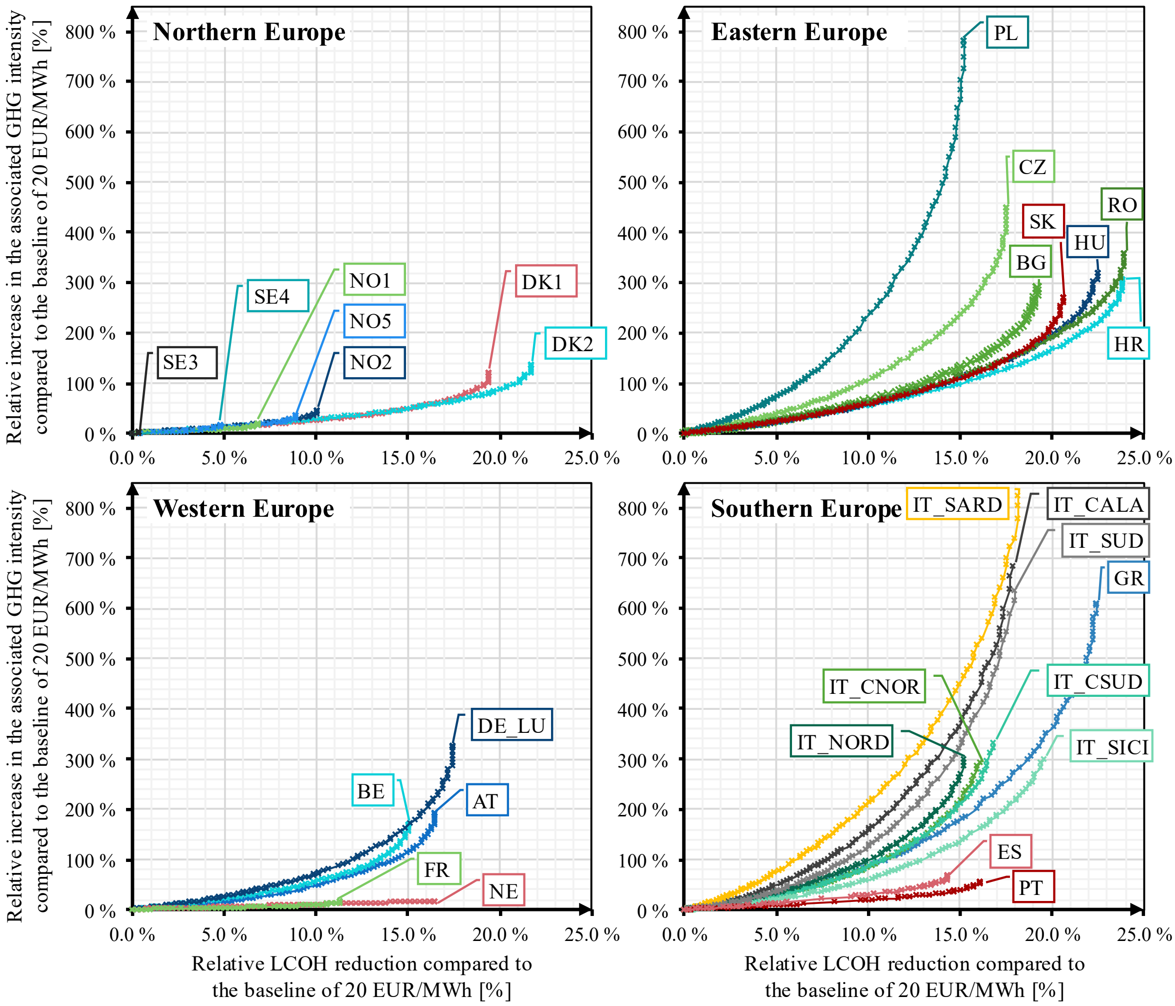

Figure 11: Illustration of the sensitivity analysis of permitted maximum price levels regarding the relative LCOH reductions and relative increase in associated GHG emission intensity.
Source: Own illustration.

The results for the geographical regions and included bidding zones reveal highly diverse trajectories for the relative LCOH reductions and corresponding relative increase in associated GHG emission intensities of produced hydrogen. The analysis highlights several bidding zones where the trajectory remains relatively shallow over large stretches of the relaxation thresholds, which indicate favorable trade-offs regarding LCOH reductions and GHG emission increases. In contrast, other bidding zones exhibit very steep trajectories as the relaxation threshold rises, which indicates that further wholesale market electricity purchases are associated with carbon-intensive electricity generation.

The interrelation between the LCOH reduction and the increase of the associated GHG emission intensity may be explained by the correlation between wholesale electricity market prices and associated GHG emission factors, as introduced in Section II. However, as the correlation factor may vary significantly across bidding zones, a general permitted maximum wholesale Day-Ahead electricity market price applicable to all bidding zones is not adequate. Furthermore, throughout all analyzed regions and bidding zones, the bidding zone-specific saturation points above further relaxation of the permitted maximum wholesale Day-Ahead electricity market price yields no further reductions in the LCOH reflect the price point at which the relaxation price threshold surpasses the PPA prices of the respective electricity procurement portfolios in the bidding zone that additional market purchases cease to improve the objective of minimizing the LCOH. Besides the GHG intensity of produced hydrogen, these saturation points indicate a key limit for the relaxation that matters to policymakers. Thus, in line with the third research objective of this cumulative dissertation, Research Paper #5 translates the insights developed in Sections II and III into the regulatory design and decision-making perspective relevant to energy policymakers.

V Conclusion

V.1 Summary

Mitigating the negative consequences of climate change involves the comprehensive integration of RES and the utilization of hydrogen in hard-to-abate sectors where electrification is not feasible. Thus, in defossilized, low-carbon energy systems, electricity-intensive technologies such as energy-flexible hydrogen technologies, which operate in accordance with variable renewable electricity supply, have particular significance. Nevertheless, prevailing economic, technical, and regulatory challenges have impeded the market adaptation of hydrogen technologies thus far. In this vein, three research objectives are pursued through five research papers comprised in this cumulative dissertation. To contribute to the market ramp-up of energy-flexible hydrogen technologies, this thesis develops, validates, and demonstrates methodological instruments for techno-economic evaluations and conducts data-driven assessments of alternative regulatory frameworks for renewable hydrogen production systems.

Section II establishes the analytical and empirical foundation by quantifying the economic and ecological potential of flexible operation, as covered in Research Paper #1. The analysis introduces a generalizable optimization model for energy-flexible operation and indicates relative cost and emissions reductions due to the positive correlation of wholesale electricity market prices and associated GHG emissions of electricity generation. A major implication of the study is that energy flexible operation serves as insurance against volatility in the electricity market. In the context of the European energy crisis, energy-flexible operation would yield twelvefold higher relative cost savings compared to regular market conditions. Research Paper #1 thus contributes to the thesis by calibrating stakeholder expectations with a data-driven baseline for the potentials encompassed by energy-flexible operation, which informs hydrogen-specific configuration and policy analysis.

Section III turns to techno-economic evaluation methodologies for energy-flexible hydrogen technology configurations. Within Section III.1, Research Paper#2 covers the optimization of design and operational strategies of energy-flexible operated electrolysis for onsite production of renewable hydrogen combined with BESS powered via PPAs. Thus, this study presents a novel methodological approach suitable for practical application in future electrolysis projects. The results of a case study in Germany indicate that BESS incorporated into energy-flexible renewable hydrogen production systems can leverage electricity procurement portfolios characterized by low-cost, high-volatility PPAs. Consequently, LCOH may be reduced through the strategic combination of diverse flexibility technologies. In this regard, the minimum LCOH of 8.67 EUR/kg at 4,000 full load hours are achieved with integrated BESS.

In Section III.2, Research Paper #3 widens the scope towards hybrid multi-energy microgrids that provide fast charging for BEV and on-site renewable hydrogen production and refueling for FCEV. The methodological contribution is a design-and-operation model that interconnects electricity and HSS to leverage synergetic effects. The findings indicate that BESS primarily reduces demand-charge exposure and flattens the electricity procurement from the public grid. Yet, the ecological benefit of reducing associated GHG emissions strongly depends on operating strategy. The study sets practical sizing guidance for batteries, electrolysers, and hydrogen energy storage systems in future energy supply infrastructure for transportation. Furthermore, the results highlight the significance of adequately adjusting the design of grid charges to unlock the beneficial potential of energy-flexible operated electrolysis.

Section IV extends the evaluations from the perspective of technology configurations to alternative regulatory frameworks for renewable hydrogen production that can support the market uptake of hydrogen. Within Section IV.1, Research Paper #4, covers the analysis of the geographical correlation between renewable electricity generation and electrolysis. The study proposes alternative configurations that refine the geographical boundaries while balancing overall energy system costs and individual electrolyzer operator costs. The findings within Research Paper #4 imply that alternative geographical correlation definitions entail a trade-off between reduced operating costs for the electricity system and increased costs for hydrogen production. In addition to the findings of the case study within Germany, the methodological approach can be applied to further analyses in all affected bidding zones within the scope of the RED. Continuing in Section IV.2, the thesis focuses on wholesale-market-integrated electricity procurement strategies for energy-flexible renewable hydrogen production under alternative regulatory criteria. The findings of the study reveal that stricter requirements for simultaneity lead to lower GHG emission intensity in renewable electrolysis. However, relaxing the maximum permissible price limit for electricity procurement through wholesale markets can reduce the LCOH, whereby this involves the trade-off of increased emission intensity. As this trade-off varies significantly between the bidding zones analyzed within the European electricity system, energy policymakers should consider regularly reviewing and revising the relaxation criteria and introducing a more sophisticated level of differentiation in bidding zone-specific regulations. The bidding zone-specific cost-emission thresholds identified in this study may thus prove valuable to energy policymakers in future amendments to the RED.

Collectively, the research conducted in this cumulative dissertation advances both theoretical and practical knowledge on energy-flexible operated hydrogen technologies. The thesis consolidates the individual findings and contributions of five research papers into a coherent conceptual framework for techno-economic evaluation of alternative technological configurations and operating strategies. Along with further considerations under evolving regulatory regimes to produce renewable hydrogen, the obtained conclusions may be translated into viable decision-making support for investors, operators, and policymakers. Consequently, this cumulative dissertation contributes to the sustainable market ramp-up of energy-flexible hydrogen technologies and GHG emission mitigation, thus consistent with international, European, and German energy policy objectives.

V.2 Limitations and future research

This thesis, along with other research work, contains limitations while simultaneously opening novel pathways for future research. While specific limitations and future research avenues for each of the included research papers are provided within the papers themselves, this section outlines common limitations and future research potential.

In all the Research Papers included, data-driven linear optimization models and simulation case studies using real-world data, as well as sensitivity analysis on a subset of parameters, were conducted. While the findings and conclusions from these analyses may be considered robust, they leave partially unresolved aspects regarding the broader implications of non-linear dependencies, alternative datasets, and extensive sensitivity analyses. Consequently, future research should enrich the empirical basis established by this dissertation and include advanced model formulations, extend the evaluation across further locations, market design options, and regulatory contexts, and implement systematic global sensitivity analysis to strengthen validity and reveal nonlinear interactions that may affect the conclusions.

The analyses conducted in Research Papers #1, #2, #3, and #5 rely on average GHG emission factors based on the historical electricity mix within the public electricity network. While this allows to streamline the implementation, it may provide an incomplete representation of the implications of energy-flexible operation on the entire electricity system and electricity market mechanisms, particularly during periods when marginal power plants operate at significantly higher emission intensities than the average mix. Therefore, future research can integrate marginal emission factors with appropriate temporal and spatial granularity, benchmark the results relative to average emission factors, and quantify the significance of these differences with respect to the contributions of this thesis.

The mathematical optimization models applied within each of the included Research Papers operate under the assumptions of complete information and rational decision-making. These models perform analyses that incorporate historical parameters such as electricity prices, electricity generation, and hydrogen demand. However, this reliance on predetermined conditions represents a significant limitation in the transferability of the methodological instruments to real-world deployment. Therefore, the economic and environmental potentials assessed in this study should be considered as maximum achievable results, as real-world operating conditions frequently deviate, thereby potentially degrading the actual performance. Hence, to enhance the practical applicability of future approaches, the incorporation of stochastic and predictive elements into data processing is necessary. In this context, data-driven artificial intelligence methods may provide valuable tools for further research, potentially leading to improved data accuracy and applicability, thereby contributing to a holistic assessment of the real-world capability of the methodological tools and data-driven policy assessments outlined in this thesis.

Within the Research Papers #2, #4, and #5, the analyses focus strongly on RED-consistent electricity sourcing under the current regulatory framework. However, regulatory regimes are not inherently permanent and are internationally heterogeneous. In the EU, delegated acts and the implementation of member states are subject to periodic review, whereby member states retain a certain degree of autonomy in their implementation. Furthermore, temporal-matching rules and locational correlation across diverse market designs may evolve in the future beyond the scope of this thesis. Thus, future work should expand on this research and compare alternative implementations across Member States and evaluate interdependencies under regulatory uncertainty.

Despite these limitations, I am confident that the methodological tools and data-driven policy assessments presented in this thesis constitute a valuable contribution towards informed decision-making in energy policy, as well as for investors and operators of energy-flexible hydrogen technologies, to facilitate a sustainable hydrogen economy in the future.

V.3 Acknowledgement of previous and related work

In my research papers, I closely collaborated with colleagues at the FIM Research Centre for Information Management, Technical University of Applied Sciences Augsburg, the University of Bayreuth, and the Branch Business & Information Systems Engineering of the Fraunhofer Institute for Applied Information Technology (FIT) in Augsburg and Bayreuth. I therefore present how my work and the embedded research papers build on previous and related work.

Research Paper #1 was not based on a specific previous research article but rather emerged from dedicated working packages and fruitful discussions within the Kopernikus-project SynErgie, which is funded by the Federal Ministry of Research, Technology and Space (SynErgie 2025). The project setting and discussions shaped the paper's focus on the economic and ecological value of demand-side flexibility, as well as its evaluation under volatile electricity prices. Please note that Research Paper #1 has previously been included within the cumulative dissertation of Sebastian Lukas Harding titled "Data-driven Analysis of Energy

Policy Instruments to Advance Energy Efficiency and Energy Flexibility" (Harding 2024).

Research Paper #2 extends the work of Arias et al. (2024)and Mößle et al. (2025) on electricity-procurement strategies for energy-flexible hydrogen production by formalizing a novel optimization model for an electricity procurement framework based on PPAs in conformity with the RED. Furthermore, the previous research by Mößle et al. (2025) is further expanded with an optimization study on the integration of BESS with multiple capacity levels to steer the electricity procurement portfolio regarding the price level and electricity volatility of included PPAs, thereby reducing the LCOH. The optimization model and approach are based on previous formulations applied for electrolysis systems in Research Paper #3 and BESS in the research of Haupt et al. (2020).

Further, the microgrid model and optimization study approach introduced in Research Paper #3 is significantly influenced by the research of Haupt et al. (2020). Furthermore, the case study in Research Paper #3 was inspired by the ODH@SIZ project, funded by the Bavarian Ministry of Economic Affairs, Regional Development and Energy (Open District Hub e.V. 2025), which deals with a charging park in proximity to a TEN-T freeway and reflects the regional emphasis on real-world feasibility. Please note that Research Paper #3 has previously been included within the cumulative dissertation of Matthias Kaiser titled "Smart and cross-sectoral energy supply for sustainable mobility" (Kaiser 2025).

Research Paper #4 expands previous literature that addresses spatial regulatory instruments to link renewable electricity generation and electrolysis in the ramp-up of renewable hydrogen capacities. The work is embedded within a growing literature that interrogates how locational signals should be reflected in hydrogen regulation (vom Scheidt et al. 2022; Casas Ferrús et al. 2024). While the German case study provides precise guidance, the methodological approach applies to broader discussions about geographical correlation configuration throughout individual bidding zones (Vargas-Ferrer et al. 2025).

Research Paper #5 expands the scope of previous studies by Brandt et al. (2024), Giovanniello et al. (2024), and Ruhnau and Schiele (2023), as it explores RED-consistent and alternative wholesale electricity procurement strategies for wholesale-market-integrated renewable hydrogen production. The paper is situated within the regulatory trajectory set by the European Commission's 2023 Delegated Acts on RFNBOs, which specify the conditions under which electricity used for electrolysis qualifies as renewable for certification purposes (European Commission 2023a). Research Paper #5 applies these regulatory requirements to align the methodological approach and demonstrates how electricity procurement portfolios may be structured to ensure compliance while maintaining operational energy flexibility for renewable hydrogen production.

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VII Appendix:

VII.1 Research papers relevant to this thesis

Research Paper #1: Unleashing the economic and ecological potential of energy flexibility: Attractiveness of real-time electricity tariffs in energy crises

Förster, R., Harding, S., Buhl, H. U. (2024) „ Unleashing the economic and ecological potential of energy flexibility: Attractiveness of real-time electricity tariffs in energy crises", *Energy Policy*, 185, p. 113975, Available at: https://doi.org/10.1016/j.enpol.2023.113975.

(VHB-Ranking 2024: B.; SJR 2024: 2.692; CiteScore 2024: 29.1 / 98th Percentile)

Research Paper #2: Leveraging synergies for energy-flexible operated electrolysis: A techno-economic analysis of power purchase agreement procurement with battery energy storage systems for renewable hydrogen production

Förster, R., Eiser, N., Kaiser, M., Buhl, H. U. (2025) „ Leveraging synergies for energy-flexible operated electrolysis: A techno-economic analysis of power purchase agreement procurement with battery energy storage systems for renewable hydrogen production", Applied Energy, 393, p. 126029, Available at: https://doi.org/10.1016/j.apenergy.2025.126029.

(VHB-Ranking 2024: B.; SJR 2024: 2.902; CiteScore 2024: 20.1 / 98th Percentile)

Research Paper #3: Future vehicle energy supply - sustainable design and operation of hybrid hydrogen and electric microgrids

Förster, R., Kaiser, M., Wenninger, S. (2023) „Future vehicle energy supply - sustainable design and operation of hybrid hydrogen and electric microgrids", Applied Energy, 334, p. 120653, Available at: https://doi.org/10.1016/j.apenergy.2023.120653.

(VHB-Ranking 2024: B.; SJR 2024: 2.902; CiteScore 2024: 20.1 / 98th Percentile)

Research Paper #4: Tightening the geographical correlation of renewable hydrogen production via electrolysis? Validation through a case study in Germany

Eiser, N., Förster, R., Buhl, H. U. (2025) „ Tightening the geographical correlation of renewable hydrogen production via electrolysis? Validation through a case study in Germany", *Submitted (Energy Policy).*

(VHB-Ranking 2024: B.; SJR 2024: 2.692; CiteScore 2024: 29.1 / 98th Percentile)

Research Paper #5: Advancing the Renewable Energy Directive for wholesale electricity market integrated renewable hydrogen production: a recent case study on European bidding zones

Förster, R., Eble, D., Buhl, H. U. (2025) „Advancing the Renewable Energy Directive for wholesale electricity market integrated renewable hydrogen production: a recent case study on European bidding zones", *Submitted (Energy)*.

(VHB-Ranking 2024: B.; SJR 2024: 2.211; CiteScore 2024: 16.5 / 99th Percentile)

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

- Bockhacker, T., Förster, R., Kerpedzhiev, G., Buhl, H. U. (2024) „Stolperstein der Energiewende: Die Stromnetzentgeltverordnung in Deutschland - Erkenntnisse einer Fallstudie aus der Papierindustrie", Zeitschrift für Energiewirtschaft, 48, p. 34-57, DOI: 10.1007/s12398-024-1264-6. (VHB-Ranking 2024: C).
- Weigel, M., Förster, R., Wagon, F. (2023) „Risikomanagement in der Strombeschaffung unter Nutzung industrieller Energieflexibilität", Zeitschrift für Energiewirtschaft, 47, p. 26-45, DOI: 10.1007/s12398-023-0936-y. (VHB-Ranking 2024: C).
- Reith, N., Eiser, N., Förster, R., Buhl, H. U. (2025), „Assessing the interactions between grid tariff regimes and representative renewable energy profiles for energy-flexible operated renewable hydrogen electrolysis", *Working Paper*.
- Klinger, L., Heinrich, T., Förster, R., (2025), „Effects of fine-granular grid electricity procurement for renewable and low-carbon hydrogen production - a comparative analysis of production modes", *Working Paper*.
- Buhl, H. U., Eble, D., Eiser, N., Förster, R., Heinrich, T., Herrmann, L., Kreiml, S., Pichlmeier, M., Preis, V., Probost, F., Rusche, S., Veitengruber, F., (2026). Strategien zur Förderung industrieller Energieflexibilität. In A. Sauer, H. U. Buhl, A. Mitsos, & M. Weigold (Eds.), Energieflexibilität in der deutschen Industrie. Band 3: Energieflexibilität in der Praxis, Stuttgart, Deutschland: Fraunhofer Verlag, *in press*.
- Heinrich, T. M. S., Buhl, H. U., Förster, R., Reith, N., Zukunft, F. (2025), „Hemmnisse und Potenziale der Regelenergievermarktung in Deutschland", *Whitepaper*, Available at: https://synergie-projekt.de/wp-content/uploads/2025/10/20250930_Whitepaper_Regelenergievermarktung_final.pdf

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- Buhl, H. U., Pichlmeier, M., Eble, D., Förster, R. (2024), „Stellungnahme im Rahmen der Konsultation des Optionenpapiers zum Strommarktdesign der Zukunft", *Position Paper*, Available at: https://synergie-projekt.de/wp-content/uploads/2024/09/Stellungnahme_SynErgie_BMWK_Optionenpapier-2.pdf
- Weibelzahl, M., Buhl, H. U., Förster, R., Bollenbach, J. (2023), „Stellungnahme im Rahmen der Konsultation des Reallabore-Gesetzes", *Position Paper*, Available at: https://synergie-projekt.de/wp-content/uploads/2020/08/20230809_Stellungnahme_Konsultation_Reallabor-Gesetz.pdf

VII.2 Individual Contribution to the included research papers

This doctoral thesis is cumulative and comprises five research papers. All of them were developed in collaboration in teams and with multiple co-authors. In this section, I will provide specific information on my individual contribution to each of the five research papers.

Research Paper #1, titled "Unleashing the economic and ecological potential of energy flexibility: Attractiveness of real-time electricity tariffs in energy crises", was co-authored by a team of three. Two authors, including myself, were jointly responsible for writing the text of the originally submitted version and the revised versions of the article. As a team, we agreed that one of the co-authors and I should assume the roles of lead authors of the research article. The other co-author contributed as a subordinate author, mainly in the form of feedback during the submission and review process and in his role as a scientific supervisor and mentor. All lead authors jointly elaborated on the methodological approach to analyze the economic and ecological benefits of a market-based electricity tariff for flexible industrial consumers. Further, all lead authors contributed equally to the evaluation and analysis of the results and the derivation of policy implications on future electricity tariffs. I was particularly responsible for data curation, implementation, and conducting the optimization study.

Research Paper #2, titled "Leveraging synergies for energy-flexible operated electrolysis: A techno-economic analysis of power purchase agreement procurement with battery energy storage systems for renewable hydrogen production", was co-authored by a team of four. All authors, including myself, were jointly responsible for writing the text of the originally submitted version and the revised versions of the article. As a team, we agreed that I should assume the role of the sole lead author of the research article. Two other co-authors contributed as subordinate authors, primarily towards the development of the methodological approach, as well as revising the manuscript. The other co-author contributed as a subordinate author, mainly in the form of feedback during the submission and review process and in his role as a scientific supervisor and mentor. I was responsible for the supervision and management of the research project, writing the manuscript, literature work, graphical visualizations, data curation, implementation, and conducting the optimization study, evaluation, and interpretation of the results.

Research Paper #3, titled "Future vehicle energy supply - sustainable design and operation of hybrid hydrogen and electric microgrids", was co-authored by three team members. All authors, including myself, were jointly responsible for writing the text of the originally submitted version and the revised versions of the article. Further, all authors jointly elaborated on the methodological approach and contributed to the analysis and evaluation of the results and the derivation implications, as well as writing the manuscript. While all authors contributed equally to this paper, I was primarily responsible for the management of the research project, literature work, graphical visualizations, data curation, implementation, and conducting the optimization study.

Research Paper #4, titled "Tightening the geographical correlation of renewable hydrogen production via electrolysis? Validation through a case study in Germany", was co-authored by a team of three. Two authors, including myself, were jointly responsible for writing the text of the originally submitted version of the article. As a team, we agreed that one of the co-authors should assume the role of sole lead author of the research article. Therefore, he contributed significantly to the supervision and management of the research project, literature work, development of the methodological approach, graphical visualizations, data curation, implementation, and conducting the optimization study. The other co-author contributed as a subordinate author, mainly in the form of feedback during the submission and review process and in his role as a scientific supervisor and mentor. My main contribution to the research paper was the assessment of the methodological approach, evaluation, and interpretation of the results, as well as revising the manuscript.

Research Paper #5, titled "Advancing the Renewable Energy Directive for wholesale electricity market integrated renewable hydrogen production: a recent case study on European bidding zones", was co-authored by a team of three. Two authors, including myself, were jointly responsible for conceptualization, writing the text of the originally submitted version, and the revised versions of the article. As a team, we agreed that one of the co-authors and I should assume the roles of lead authors of the research article. The other co-author contributed as a subordinate author, mainly in the form of feedback during the submission and review process and in his role as a scientific supervisor and mentor. While all authors contributed equally to this paper, I was primarily responsible for management of the research project, data curation, implementation, and conducting the optimization study as well as the evaluation and analysis of the results towards the derivation of policy implications.

VII.3 Research Paper 1: Unleashing the economic and ecological potential of energy flexibility: Attractiveness of real-time electricity tariffs in energy crises

Authors:

Robert Förster, Sebastian Harding, Hans Ulrich Buhl

Published in:

Energy Policy (2024)

Abstract:

The European energy crisis in 2021 and 2022 emphasized the importance of energy flexibility to mitigate price peaks and manage increased market volatility. Dynamic electricity tariffs are key to unlocking the potential of energy flexibility, as they incentivize flexible consumers to reduce their costs by shifting their load to periods of low prices. We quantify the potential of dynamic tariffs and focus on their economic and ecological potential particularly in energy crises. Using German Day-Ahead spot market data covering 2019 to 2022 as basis for a dynamic tariff, we determine the cost and emission spread between non-flexible and flexible industrial processes. Our results show that energy flexibility together with the real-time electricity tariff lead to energy cost reductions, with relative cost reductions of flexible loads being up to 12 times higher in the energy crisis. Moreover, pre-crisis electricity costs and associated emissions were highly positively correlated, implying flexibilities in real-time electricity tariffs may minimize electricity costs while simultaneously reducing emissions. Based on our results, we conclude that real-time electricity pricing provides a suitable instrument to (1) incentivize necessary investments in energy flexibility, especially in energy crises, and (2) facilitate flexible consumers to reduce costs and emissions at the same time.

Keywords:

Demand Side Management; Dynamic tariffs; Decarbonization; Energy flexibility; Renewable energy; Energy crisis

VII.4 Research Paper 2: Leveraging synergies for energy-flexible operated electrolysis: A techno-economic analysis of power purchase agreement procurement with battery energy storage systems for renewable hydrogen production

Authors:

Robert Förster, Niklas Eiser, Matthias Kaiser, Hans Ulrich Buhl

Published in:

Applied Energy (2025)

Abstract:

To mitigate the increasingly adverse impact of climate change, policymakers foster the substitution of fossil energy sources with renewable hydrogen. However, considering market supply, procurement costs, and strict regulatory guidelines for renewable electricity sourcing to produce renewable hydrogen, electrolysis operators in the European Union (EU) encounter significant challenges. Intelligent design and operation of grid-connected energy-flexible operated renewable hydrogen electrolysis powered with renewable energy sources through Power Purchase Agreements (PPAs) with integrated Battery Energy Storage Systems (BESS) may be pivotal to overcome these challenges. To extend existing research literature, we evaluate the reciprocal effects of PPA procurement strategies and BESS configurations on the Levelized Cost Of Renewable Hydrogen (LCOH) in compliance with the EU regulatory framework. Our results from a single representative instance located in Germany show that BESS is beneficial in leveraging PPA electricity portfolios characterized by low costs and high volatility to minimize LCOH of renewable hydrogen electrolysis. Operators may profit from BESS integration if their electricity procurement strategy predominantly focuses on as-produced-PPAs for solar and wind. A sensitivity analysis of different BESS configurations reveals the relevance of adequately dimensioning the BESS to optimize economic results. Furthermore, we conclude that, based on a second sensitivity analysis of the investment costs of battery energy storage systems, complementing renewable hydrogen electrolysis systems may pose a viable business case for second-life batteries.

Keywords:

Renewable hydrogen infrastructure; Renewable energy directive; Power purchase agreements; Electricity procurement strategy; Battery energy storage systems; Microgrids

VII.5 Research Paper 3: Future vehicle energy supply - sustainable design and operation of hybrid hydrogen and electric microgrids[1]

Authors:

Robert Förster, Matthias Kaiser, Simon Wenninger

Published in:

Applied Energy (2023)

Abstract:

To decarbonise road transport, EU policymakers promote battery electric vehicle and fuel cell electric vehicle adaption and advocate the expansion of charging and hydrogen refuelling infrastructure in the Fit-for-55 package. However, infrastructure operators face cost-intensive operations and insufficient low greenhouse gas (GHG) hydrogen availability. Grid-connected hybrid hydrogen refuelling and electric vehicle charging microgrids with on-site hydrogen production, battery and hydrogen energy storages and renewable energy can help to solve these challenges. We investigate the influence of various microgrid design and operation strategies regarding their contribution to profitability and decarbonisation in an optimisation study. Our findings in a real-world case study within Germany indicate that the cost-effectiveness of designing and operating such microgrids does not contribute to the decarbonisation of road transportation under common operation strategies and current demand charge regulations. We advocate revising German demand charge regulations to support sustainable design and operation of future charging and hydrogen refuelling microgrids.

Keywords:

Microgrid, Hydrogen infrastructure, Electric vehicle charging, Hybrid energy storage systems, Decarbonization, Road transportation

[1] This research article is originally published in British English. Therefore, the language style in section differs from the rest of the thesis.

VII.6 Research Paper 4: Tightening the geographical correlation of renewable hydrogen production via electrolysis? Validation through a case study in Germany

Authors:

Niklas Eiser, Robert Förster, Hans Ulrich Buhl

Submitted to:

Energy Policy

Extended Abstract:

Renewable hydrogen is essential for defossilizing hard-to-abate sectors. To align its production with decarbonization objectives, the European Union's Renewable Energy Directive (RED) enforces strict electricity procurement criteria, including geographical correlation within the same bidding zone. Prior techno-economic studies predominantly focus on localized electrolysis costs, neglecting broader transmission system impacts (Brandt et al. 2024; Casas Ferrús et al. 2024; Stolte et al. 2024). In large bidding zones, unconstrained expansion of electricity generation and consumption can severely drive grid transmission costs if electrolyzers and their associated renewable energy sources (RES) are geographically segregated. Although literature notes that widespread RES generation capacities elevates electricity transmission grid expansion requirements (Hordvei et al. 2025; Ruhnau and Schiele 2023), integrated evaluations of electrolyzer operation under physical grid constraints remain scarce (Vargas-Ferrer et al. 2025; vom Scheidt et al. 2022). Consequently, energy policymakers lack quantified evidence on whether tightening geographical correlation to a sub-zonal level effectively reduces overall system costs and what economic trade-offs this imposes on hydrogen production economics.

To address this gap, this study develops a novel two model optimization framework utilizing the open-source transmission models PyPSA and PyPSA-Eur. The first model minimizes hydrogen production costs by optimizing electrolyzer site location and RED-compliant electricity procurement. Based on these portfolios, the second model minimizes electricity system expansion and operational costs under physical transmission grid constraints. The framework is validated via a German case study, which is characterized by a large bidding zone and ambitious hydrogen targets, while evaluating 32 distinct sub-zonal specifications of tightened geographical correlation.

The optimization results indicate that tightening geographical correlation reduces transmission system costs but elevates hydrogen production costs. Compared to a unified bidding zone, two-zone configurations alter system costs by -1.08 % (-53 million EUR) to +1.32 % (+65 million EUR), with savings halved when accounting for planned grid

development projects. Conversely, restricting regional RES access increases hydrogen production costs by 0.40 % (17 million EUR) to 4.43 % (189 million EUR). The increase in hydrogen production costs outweighs electricity system savings by at least 7 million EUR across all 32 specifications. While sub-zonal boundaries drastically lower grid expansion requirements and reduce RES curtailment by nearly 75 % due to more localized electricity procurement, minor layout adjustments can invert these benefits. Additionally, localized matching increases electricity resale risks for operators during periods where temporally correlated RES supply surpasses installed electrolysis capacities.

Although tightening geographical correlation limits RES curtailment and localized grid stress, it is inefficient from a total system perspective. The heightened hydrogen production costs systematically outweigh transmission system savings, potentially hindering the hydrogen market ramp-up. Since stricter sub-zonal rules shift economic burdens onto hydrogen operators and intensify their surplus electricity resale risks, policymakers should prioritize targeted transmission grid investments rather than imposing geographical restrictions.

Keywords: Renewable hydrogen; Renewable energy directive; Geographical correlation; Electricity procurement strategy; Electricity transmission grid

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VII.7 Research Paper 5: Advancing the Renewable Energy Directive for wholesale electricity market integrated renewable hydrogen production: a recent case study on European bidding zones

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Extended Abstract:

Renewable hydrogen is considered essential for mitigating greenhouse gas (GHG) emissions in hard-to-abate sectors. However, the regulatory framework of the European Union's Renewable Energy Directive (RED) enforces strict criteria for sourcing electricity to produce compliant renewable hydrogen. These criteria predominantly rely on Power Purchase Agreements (PPAs) and strictly limit the integration of the wholesale electricity market (Moradpoor et al. 2023; Ruhnau and Schiele 2023; Veenstra and Mulder 2024; Wang 2024). A key exception within the RED allows electrolyzer operators to procure electricity from the wholesale spot market during hours when prices are below 20.00 EUR/MWh (Langenmayr and Ruppert 2023). While these electricity sourcing criteria minimize exposure to fossil-based electricity and thus limit the GHG emission intensity, they also limi the operational hours of electrolyzers, ultimately increasing the levelized cost of hydrogen (LCOH). Energy policymakers therefore face a trade-off in relaxing the maximum permissible wholesale electricity price limit to accelerate the hydrogen market ramp-up by reducing the LCOH and simultaneously increasing the associated GHG emission intensity due to additional electricity procurement in not yet fully defossilized electricity systems (Engstam et al. 2023; Schlund and Theile 2022). Further, there is a lack of quantitative studies on the relaxation of this price limit and the effects on both the LCOH and the ecological impact across different European electricity systems.

To address this research gap, this study proposes a multi-step optimization procedure to determine the LCOH and the GHG emission intensity for wholesale electricity market integrated renewable hydrogen production. In the first step, the PPA electricity procurement portfolios are optimized for an energy-flexible operated electrolysis system. Building on these optimized portfolios, the second step minimizes the total electricity procurement costs by integrating wholesale market electricity, subject to a defined maximum permitted price limit. To quantify the economic and ecological trade-offs, a comprehensive sensitivity analysis is conducted. The status quo price level of 20.00 EUR/MWh is progressively relaxed in increments of 0.50 EUR/MWh up to a price limit of 100.00 EUR/MWh. Acknowledging the highly diverse characteristics of current European energy systems, the methodology is applied to a case study encompassing 29 individual electricity bidding zones across Europe.

The optimization results demonstrate that relaxing the permitted maximum wholesale Day-Ahead electricity market price yields a reduction in the LCOH in the majority of the analyzed bidding zones, though the magnitude varies substantially. In Northern European bidding zones, the LCOH decreases significantly, whereas bidding zones like SE3 show no relevant deviations. Conversely, Eastern and Western European bidding zones exhibit higher overall LCOH levels, with reductions flattening out once profitable purchases in the wholesale market are exhausted at elevated price limits. Simultaneously, the associated GHG emission intensity of the produced hydrogen systematically rises across all regional clusters as the permitted Day-Ahead price threshold is increased. Bidding zones with abundant low-cost hours and a favorable alignment between prices and emissions achieve meaningful cost reductions with only slight increases in GHG intensity. In contrast, other bidding zones like Poland, reveal a severe trade-off, where marginal LCOH reductions are accompanied by exponential increases in the associated GHG emission intensity, ultimately plateauing at exceptionally high emission levels.

Although relaxing the maximum permitted price for wholesale electricity market procurement proves to be an appropriate policy instrument to reduce the LCOH, the resulting economic and environmental trade-offs are highly heterogeneous. The underlying interrelation is driven by the varying correlation between wholesale electricity market prices and associated GHG emission factors within each specific bidding zone. Consequently, imposing a general, uniform maximum permitted wholesale Day-Ahead electricity market price across all European bidding zones is inadequate. Bidding zone-specific saturation points where further relaxation yields no additional LCOH reductions but continues to drive up emissions highlight relevant limitations. To facilitate an economically viable and ecologically suitable market ramp-up of renewable hydrogen, European energy policymakers should revise uniform regulations in favor of more sophisticated, bidding zone-specific differentiations of the permitted maximum wholesale electricity price.

Keywords:

Renewable hydrogen, Hydrogen policies, Renewable Energy Directive, Wholesale electricity market, Regulatory relaxation, Temporal correlation

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