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Decarbonizing the Industry Sector and its Effect on Electricity Transmission Grid Operation - Implications from a Model Based Analysis for Germany

*Martin Lieberwirth**, and *Hannes Hobbie***

ABSTRACT

Integrating large amounts of electrolyzer capacities poses particular challenges for grid operators along the entire hydrogen value chain. This research examines how hydrogen production capacities that support the decarbonization of German industrial sectors impact the electricity transmission grid. The operation of electrolyzer capacities and the production of green hydrogen result in increased electricity demand that stresses the power grids beyond conventional electricity load levels. The question arises to what extent electrolyzer capacities cause additional grid congestion and how flexible operation of electrolyzers can contribute to efficient management of future power grids. A scenario framework is created, differing in the decarbonizing strategy of industry sectors, operation mode of electrolyzers, and penetration levels of electrolyzer installations for a market projection of the future European electricity system. Model-based research is performed by applying a fundamental electricity market and congestion management optimization model of the European electricity systems for the set of scenarios. Results of the model-based investigation highlight the importance of integrating electrolyzer capacities into congestion management practices, primarily if corresponding decarbonized industries feature a more distributed allocation throughout Germany, such as the chemical, paper and printing industries. The findings of this work provide policymakers, system operators, and regulators with meaningful insights for designing future congestion management frameworks.

Keywords: Electricity, Green hydrogen, Congestion management, Grid modeling, Germany

JEL: L94, L51, D51, D41, C61, Q41

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1. INTRODUCTION

With the latest federal election in Germany in late 2021, the newly formed government decided to accelerate the deployment of renewable energies and increase the targeted renewable amounts. Formulated in the national Climate Protection Act, Germany is now aiming at a renewable penetration level of up to 80% of the total electricity demand until the year 2030 (Federal German Parliament, 2022). Parallel to the decarbonization of electricity generation, green hydrogen is considered a favorable option to reduce carbon emissions in fossil fuel-intensive industries.

While green hydrogen can be regarded as an essential pillar of the German energy transition, integrating large amounts of electrolyzer capacities poses particular challenges for system operators along the entire hydrogen value chain. The operation of electrolyzer capacities and production of

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green hydrogen imputes increased electricity demand, stressing electricity grids above the conventional electricity load level. Also, it requires a massive restructuring of the gas transportation and storage system. The question arises to which extent electrolyzer capacities cause additional grid bottlenecks and how a flexible operation of electrolyzers can contribute to efficiently managing future electricity grids. Since energy-intensive industries are distributed heterogeneously throughout Germany, the specific order in which they are decarbonized impacts the change of electricity loads and thus affects grid congestions differently. This research investigates the effects of the geographic distribution of electrolyzer capacities on the future transmission grid operation, focusing on how different decarbonization orders of specific industries impact individual grid bottlenecks and the efficiency of congestion management.

The remainder of this paper is structured as follows. The first chapter provides an overview of relevant studies addressing electrolyzers as a flexibility option in transmission grid operation. The following chapters motivate the research carried out in this work and describe the mathematical representation of the congestion management model used. Chapter 4 calibrates the applied market model against future market projections for 2030 and creates a scenario framework to investigate effects on transmission grid operation connected with decarbonizing German's energy-intensive sectors. Results of the model-based research presented in this paper are summarised in chapter 5 and discussed to assist policymakers in efficiently designing future congestion management frameworks in light of decarbonizing the German energy intensive industries in chapter 6.

2. MOTIVATION

Decarbonizing the energy-intense industry sectors has been a much-addressed topic in the German research landscape in recent years. Several studies emphasized that replacing fossil fuels and feedstocks with products from Power-to-X (PtX) or Power-to-Gas (PtG) technologies can hold a substantial potential to mitigate carbon emissions in energy-intensive industries (Nurdiawati and Urban, 2021). In this context, hydrogen electrolysis is considered one of the most promising technologies for providing needed low-carbon fuels. Heitel et al. (2021) showed that carbon emission for the European industry sector could be significantly reduced by switching to hydrogen as an energy carrier in specific processes like the blast-furnace route in steel production or ammonia and methanol production in the chemical industry. The newest German energy legislation partly reflects these findings in the parliament's decision to expand electrolyzer capacities up to 10 GW until 2030 to promote the development of domestic green hydrogen production for decarbonizing the industry sector (Federal German Parliament, 2022).

Simultaneously, PtX technologies, e.g., electrolyzers, are considered a necessary flexibility option to facilitate the system integration of renewable energies (Zöphel et al., 2018). While market implications of PtX technologies have been studied a lot, only a few studies have examined the effects of green hydrogen production on transmission grid operation in Germany. By applying a market and transmission grid model, Larscheid et al. (2018) evaluated different business opportunities for electrolyzer operators. In addition to cross-commodity arbitrage trading, electrolyzers can provide system services for managing transmission grids. When electrolyzer capacities are located near electricity grid nodes facing high renewable curtailment rates, findings from their study indicate higher electrolyzer utilization amounts compared to a scenario in which operators can only profit from arbitrage trading. Focusing on hydrogen production costs, Grube et al. (2018) analyzed the potential for PtG applications in Germany under different grid expansion scenarios using a three-stage modeling approach. Like Larscheid et al. (2018), they scaled the nominal electrolyzer capacity based on modeled curtailment volumes of renewable energy and distributed them over a few selected locations.

Findings from this study show that an electricity network extension reduces transmission congestion, indicated by a decrease in curtailment-driven utilization of electrolyzer capacities. Although both studies acknowledge the mitigating effects of electrolyzers on grid congestions, the overall changes in redispatch and curtailment volumes are not explicitly analyzed. Furthermore, the model-endogenous operation of electrolyzer capacities for congestion management is not considered in their grid modeling setups.

Mueller et al. (2020) used a load flow simulation approach considering transmission constraints with PtG plants serving as flexible loads to carry out congestion relief in the modeled electricity grid. They placed a set of PtG plants exogenously at geographically intersecting electricity and gas grid nodes with significant amounts of installed wind turbines. In their simulation, 6.7 GW installed PtG capacities could decrease total redispatch and curtailment volumes by 4 TWh during the modeled timeframe in the year 2016. Xiong et al. (2021) considered PtG facilities as a redispatch option in a load flow optimization model for Germany. Results of their study indicate that electrolyzers can serve as a valuable flexibility option to reduce curtailment from renewable generation. When positioned near wind and solar generation capacities, electrolyzer operators benefit from the available electricity surplus, effectively reducing curtailment amounts by 12%. Further implications from the spatial distribution of electrolyzers are drawn by vom Scheidt et al. (2022), applying a nodal pricing model to select the locations for electrolyzer installations. Compared to a benchmark scenario with no hydrogen production capacities, the congestion management costs increase by 11% if an allocation of electrolyzer capacities is performed demand-oriented. The opposite effect can be observed if nodal price signals are utilized for site selection. In this case, congestion management costs decrease by almost 24%. Despite the assumed nodal market clearing that is not according to current German market clearing procedures, the study highlights the interrelationship between different geographical electrolyzer expansion pathways and resulting congestion management requirements.

The above-discussed literature demonstrates that green hydrogen production significantly affects transmission grid operation. Especially installations of electrolyzer capacities nearby renewable generation plants decrease total curtailment and redispatch volumes. Even though this installation strategy seems plausible from a grid service perspective, until now, no regulatory framework nor incentive systems for operators have been established to favor a grid-effective placement of electrolyzers (Fraunhofer Roadmap, 2019). Studies even emphasized that definite recommendations toward a near-demand or near-supply production of green hydrogen are not possible since the large-scale operation of electrolyzers is still an emerging market (Heitel et al., 2021). Moreover, decarbonizing energy-intensive industry sectors require hydrogen supply at the location of the facilities, and hydrogen transportation infrastructures are yet to be developed. Existing research works so far did not study effects related to a demand-oriented distribution of electrolyzers capacities. This work thus contributes to the existing research by evaluating the effects of near-demand green hydrogen production on transmission grid operation in Germany. To this end, we deliberately distribute electrolyzer capacities close to energy-intensive industries within the transmission grid network and investigate how the order in which different sectors with similar hydrogen technology readiness levels are decarbonized impacts electricity grid operation and congestion management.

3. MODELING CONGESTION MANAGEMENT OPTIMIZATION

Market Clearing Problem

Modelling congestion management can be done in vastly different ways. This work applies the fundamental market model ELMOD developed at the Chair of Energy Economics, TU Dresden

and newly integrates the modelling of hydrogen production and corresponding flexibility provision for congestion management in addition to the ELMOD base version. The following model description strips down the equation system to a minimum to foster an increased understanding of the model exercise carried out in this research. A full description of the base version of ELMOD herein applied is provided in Schönheit et al. (2020). Further reading on modelling congestion management can be found in Hobbie et al. (2022).

ELMOD can be interpreted as a sequence of two linear optimization problems: A day-ahead market clearing optimization and a congestion management optimization resolving all grid bottlenecks resulting from the market clearing dispatch. During the day-ahead clearing, the optimization model dispatches the generation capacities to serve the inelastic demand plus the electrical demands imputed by the electrolyzer operation and the net-exchange between the different markets in each time-step and market zone (Eq. 2). The assumed levels of hydrogen demands converted to equivalent electricity consumption amounts at the specific electricity nodes must be satisfied throughout the entire modelling time scope (Eq. 3). Net-transfer capacities constraint trade between market zones (Eq. 4). The objective function minimizes the total generation cost (Eq. 1) to serve the market's electricity demands. The installed power capacities constraint the generation dispatch (Eq. 5). In addition, assumed electrolyzer capacities limit the production of hydrogen at each facility (Eq. 6). The intersection of the merit-order supply curve with the total demand yields the day-ahead market equilibrium (power market balance). The electricity price can be derived from the dual variable of the power market balance (uni-form price). The following linear optimization problem represents the market-clearing optimization problem. All upper-case letters represent model-endogenous variables and are assumed positive and continuous. Lower-case letters represent parametric model inputs.

$$\min C^{da} = \sum_{p,t} G_{p,t}^{da} \cdot oc_p \quad (1)$$

subject to

$$- \sum_{p \in f(p,c)} G_{p,t}^{da} + d_{t,c} + \sum_{n \in f(n,c)} H_{n,t}^{da} + \sum_{cc \in f(c,cc)} (T_{t,c,cc} - T_{t,cc,c}) = 0 \quad \forall t, c \quad (2)$$

$$\sum_t H_{n,t}^{da} - d_n^H = 0 \quad \forall n \quad (3)$$

$$T_{t,c,cc} \leq c_{t,c,cc}^T \quad \forall t, c, cc \quad (4)$$

$$0 \leq G_{p,t}^{da} \leq c_p^G \quad \forall p, t \quad (5)$$

$$0 \leq H_{n,t}^{da} \leq c_n^H \quad \forall n, t \quad (6)$$

Congestion Management Problem

The cost-minimising wholesale market clearing dispatch serves as input for the congestion management optimisation problem ($G_{p,t}^{da}, H_{n,t}^{da}$). As the dispatch of generation stations and the operation of electrolyzer capacities are a model-endogenous result of the market clearing procedure, these variables are treated as given parameters during the congestion management optimization. The optimization problem performs upward, and downward adjustments of the generation dispatch and hydrogen production levels depending on the operation mode assumed, resolving electricity transportation congestion in the electricity grid, resulting from the wholesale market electricity feed-in (Eq. 8). Upward and downward adjustments are limited by the market operation and the installed generation and hydrogen production capacity of the specific technology (Eqs. 9-10, Eqs. 11-12). The nodal balance of the congestion management optimization yields a nodal electricity injection (net feed-in),

translating into power flows at each line. Power flows are constrained by the thermal line capacity (Eq. 13). Moreover, Eq. 14 enforces a voltage angle of zero at the slack node. The objective function of the congestion management optimization problem minimizes the total cost resulting from the net generation and electrolyzer operation adjustments considering the transportation capacity constraints existing at the different power lines (Eq. 7). The cost factors assumed for upward and downward adjustments do not solely reflect marginal operation costs. They also include penalty cost imposing a merit order of remedial actions according to the regulatory framework, i.e. ramping down renewable-based generators is performed with a lower priority than adjusting the generation levels of conventional units for environmental policy considerations. The congestion management optimization is represented with the following linear equation system. Again, all upper-case letters are model-endogenous variables and are assumed positive and continuous. Lower-case letters and the generation and hydrogen production variables from the wholesale market clearing represent parametric model inputs.

$$\min C^{rt} = \sum_{p,t} \left(G_{p,t}^{rt,+} \cdot mc_p^+ + G_{p,t}^{rt,-} \cdot mc_p^- \right) + \sum_{n,t} \left(H_{n,t}^{rt,+} \cdot mc_n^+ + H_{n,t}^{rt,-} \cdot mc_n^- \right) \quad (7)$$

subject to

$$\begin{aligned} - \sum_{p \in f(p,n)} \left(G_{p,t}^{da} + G_{p,t}^{rt,+} - G_{p,t}^{rt,-} \right) + H_{n,t}^{da} + H_{n,t}^{rt,-} - H_{n,t}^{rt,+} \\ + d_{n,t} + \sum_{n,nn} b_{n,nn} \cdot \delta_{nn,t} = 0 \quad \forall n, t \end{aligned} \quad (8)$$

$$0 \leq G_{p,t}^{rt,+} \leq c_p^G - G_{p,t}^{da} \quad \forall p, t \quad (9)$$

$$0 \leq G_{p,t}^{rt,-} \leq G_{p,t}^{da} \quad \forall p, t \quad (10)$$

$$0 \leq H_{n,t}^{rt,+} \leq H_{n,t}^{da} \quad \forall n, t \quad (11)$$

$$0 \leq H_{n,t}^{rt,-} \leq c_n^H - H_{n,t}^{da} \quad \forall n, t \quad (12)$$

$$-c_l^{th} \leq \sum_n h_{l,n} \cdot \delta_{n,t} \leq c_l^{th} \quad \forall l, t \quad (13)$$

$$s_{n^*} \cdot \delta_{n^*,t} = 0 \quad \forall n^*, t \quad (14)$$

4. DATA AND SCENARIO FRAMEWORK

Market Zone and Electricity Grid Representation

The market model applied in this work encompasses the European electricity markets on a high technical and spatial resolution. Figure 1 illustrates the considered market zones and electricity transmission grid.

Market equilibria in the European electricity markets are subject to trade activities between the market zones impacting electricity price formation. For this reason, ELMOD considers 16 European market zones influencing the German market interactions. No intra-zonal transmission limitations are assumed during market clearing according to NTC-based market clearing procedures. Future NTC-values for the scenario analysis conducted in this work are taken from ENTSO-E (2021) estimations. The congestion management optimization considers a detailed representation of the German electricity transmission grid. As solving the congestion management problem is highly computational demanding, neighboring countries of Germany are modeled as aggregated nodes

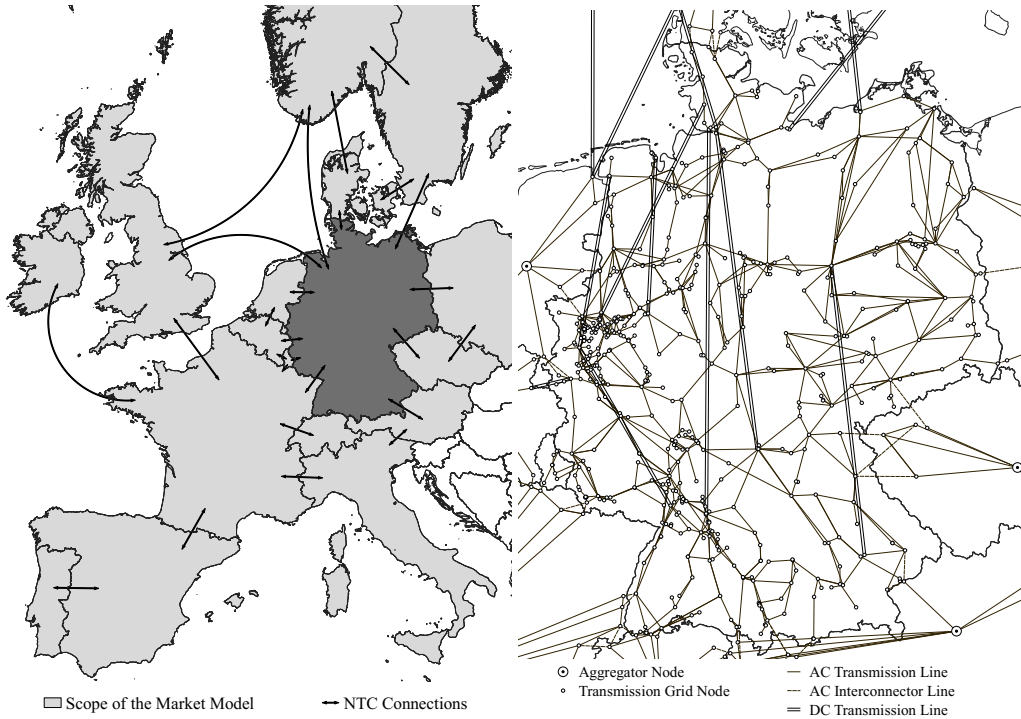


Figure 1: Scope of the Market Model

Figure 2: Transmission Grid of Germany in 2030

during the optimization of electricity transmission. Cross-border transmission limitations are still modeled with their physical transportation limitations, avoiding unintended cross-border electricity exchanges.

Optimizing congestion management requires detailed replicating of the electricity grid infrastructures. The structure of the German transmission network, depicted in Figure 2, is extracted from the static grid models published by German transmission grid operators (Joint Allocation Office, 2021). Static grid models contain comprehensive information about the transmission network's layout and physical line properties covering the 220 kV and 380 kV voltage levels. The dataset includes 530 transmission grid nodes connected by 900 transmission lines. The grid data is completed by transmission expansion projects listed in the network development plan for the scenario calculations (50Hertz Transmission et al., 2020).

Generation Fleet and Demand Data

ELMOD considers detailed modeling of conventional and renewable generation dispatch and storage technologies. All units are calibrated against 2030 data from the Ten-Year Network Development Plan 2020 (TYNDP2020), published by European transmission grid operators (ENTSO-E, 2021). In total, thirteen different conventional generation and storage technologies are distinguished and modeled unit-specific: lignite, oil, nuclear, coal, oil and gas steam, closed-cycle gas turbines, open-cycle gas and oil turbines, waste, run-of-river, reservoir, and pumped storage power plants. Following the national energy strategies in the considered market zones, nuclear and coal-phase outs are assumed. In this work, coal and lignite units are iteratively phased out based on their commissioning year until the targeted reduction level is reached. Gas-fired power plants replace removed coal and lignite units. A total amount of combined gas-fired power generation capacity of approximately 32.6 GW

in Germany in 2030 is assumed (ENTSO-E, 2021). Generation unit additions are assigned to their closest transmission grid nodes observing capacity phase-outs to prevent spatial imbalances in the conventional generation fleet.

In addition to conventional power generation, ELMOD considers variable renewable energy sources (vRES) to satisfy the electricity demands. The renewable generation fleet (vRES) comprises on- and offshore wind, solar, and biomass generation technologies. Renewable expansion is assumed in accordance with the TYNDP2020, resulting in 110 GW of solar electricity generation, 17 GW of offshore wind, and 95 GW of onshore wind power for Germany in 2030 (ENTSO-E, 2021). The nodal renewable generation capacity of the existing fleet is derived from the current plant overview of renewable power generation units published by BNetzA (2022b). Capacities of vRES for neighboring countries are modeled as technology aggregates based on the TYNDP2020 estimations.

Besides the generation fleet, the development of the electricity demand also impacts the future electricity price formation. Hourly electricity demand time series and fuel- and CO₂ prices are also assumed based on the TYNDP2020. The German electricity load included in the market model applied in this work increases by 23% until 2030 compared to the 2020 level, translating to an accumulated electricity demand of approximately 688 TWh (ENTSO-E, 2021).

Scenario Development

The order in which different energy-intensive industries are being decarbonized influences the regional distribution of electrolyzer installations. Therefore detailed knowledge of potential hydrogen demands at specific electricity grid nodes is required for developing scenarios for the future deployment of hydrogen production facilities. Neuwirth et al. (2022) identified in their study eight energy-intensive industry types in Germany and assessed the technical potential of replacing their energy-carrying feedstock with hydrogen. The results of this work provide information on the potential German industry sector's hydrogen demands on a process- and site-specific resolution. Table 1 summarizes aggregated demands and corresponding electrolyzer capacity values taken from their study, along with data on the number of single facilities per sector and the technology readiness level for converting the facility toward hydrogen-based production processes. Based on these characteristics, different scenarios relevant for the model-based investigation of the impact of hydrogen production on the electricity transportation system carried out in this work are created in the following.

Table 1: Key Characteristics of Industry Sectors

Industry Sector	Potential H2 Demand [TWh]	Available Electrolyzer Capacity [MW]	No. of Sites	TRL	Regional Distribution
Refineries	22.6	692	16	8-9	Central
Chemical industry	161.0	4923	30	8-9	Decentral
Paper and printing	30.5	933	162	8-9	Decentral
Non-metallic minerals	8.3	254	46	4-5	Decentral
Mineral Processing	30.7	938	84	4-5	Decentral
Metal Processing	18.0	550	30	4-5	Decentral
Non-ferrous metals	3.7	114	4	4-5	Central
Steel, primary	52.2	1596	8	7-8	Central

The development of scenarios is carried out in four steps as Figures 3-4 illustrate: First, only

industry sectors featuring a high technology readiness level (TRL) are considered for the scenario analysis since only a high technical maturity allows for a short and medium-term implementation of hydrogen based production processes. These sectors have a TRL between 7-9: Refineries, chemical industry, paper and printing, and primary steel.

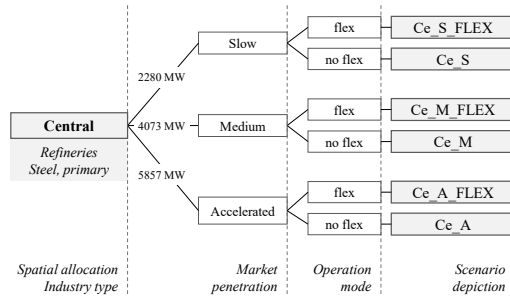


Figure 3: Central Scenario Structure

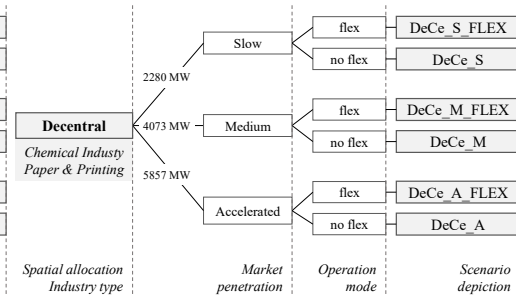


Figure 4: Decentral Scenario Structure

Secondly, the scenarios are created in a way that they distinguish between those industry sectors that feature a rather centralized geographic distribution of single facilities and those more widely distributed throughout Germany measured by the total number of single facility sites in each sector. In this work, all sectors with lower than 20 individual sites are assigned to the *Centralised (Ce)* scenario tree (refineries, primary steel) and those with more than 20 individual sites to the *DeCentralised (DeCe)* scenario tree (chemical industry, paper and printing). The resulting regional distribution of electrolyzer installations is displayed in Figures 5 and 6 for assumed high market penetration levels. In the centralized scenarios, large amounts of electrolyzer capacities are allocated to a comparatively small amount of grid nodes in Western and Northern Germany. In contrast, the decentralized scenario features a more widespread distribution of medium- to small-scale electrolyzer installations at a larger number of electricity grid nodes.

Thirdly, assuming different market penetration levels of electrolyzer installations allows for studying how sensitive transmission system operation is impacted by increasing hydrogen production amounts. The scenarios thus distinguish between *slow*, *medium*, and *accelerated* market penetration of electrolyzer installations translating into total capacity values ranging between 2,280 MW and 5,857 MW of electrical installation power allocated to the transmission grid nodes where the production facilities of the energy-intensive sectors in the different scenarios are located. These values are calculated considering the total expansion target of 10 GW declared by the German parliament for domestic hydrogen production by 2030 to satisfy the hydrogen demand emerging in the mentioned industries but also in further future hydrogen-based technical applications (Federal German Parliament, 2022). The relative site-specific hydrogen demands displayed in Table 1 serve as a scaling parameter to disaggregate the different assumed capacity volumes to the individual electricity grid nodes.

Moreover, the created scenarios differentiate between two operation modes of the electrolyzers: The first operation mode assumes that electrolyzers are not integrated into the congestion management framework (*no flex*), meaning that they are modeled as a pure electricity load during the load flow optimization that cannot be used flexibly for resolving grid bottlenecks. The second operation mode assumes electrolyzer capacity can be redispatched like conventional generators for congestion management tasks (*flex*). Overall, the scenario framework created in this study comprises 12 different scenarios regarding the spatial distribution, market penetration, and operation mode of future electrolyzer installations. Results of the different model runs are then evaluated against a base case in which no electrolyzer installations are considered.

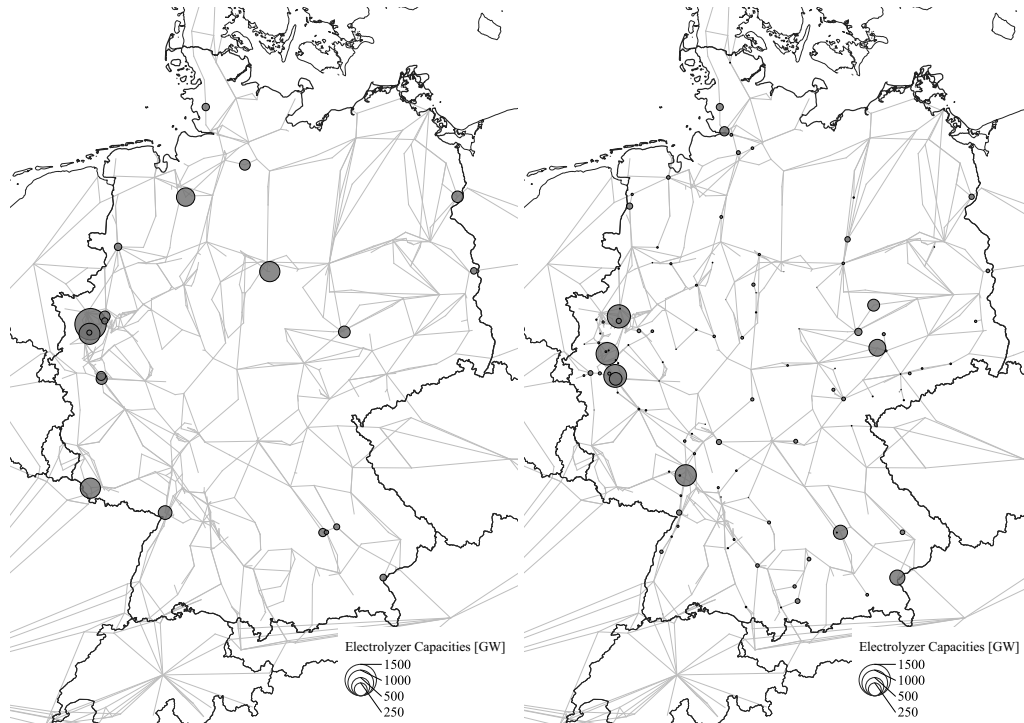


Figure 5: Distribution of Electrolyzer Capacities in the Central Scenario (Accelerated Penetration) **Figure 6: Distribution of Electrolyzer Capacities in the Decentral Scenario (Accelerated Penetration)**

5. RESULTS

5.1 Aggregated Results on a Market Zone Level

The following presents model-endogenous results on congestion management volumes differentiated by the types of remedial actions that can be utilized for congestion management, i.e., redispatch of conventional generators, redispatch of electrolyzers, and curtailment of renewable energies aggregated to a market zone level for Germany, before being discussed in greater spatial detail. Individual congestion management volumes resulting in the different model runs are compared against a benchmark base case, in which no electrolyzers are considered. This procedure allows the evaluation of each scenario's impact on the electricity transmission system.

Figure 7 displays model outputs on congestion management for the scenarios where the electrolyzers cannot be utilized to resolve grid bottlenecks. In the base case, the total congestion management volume in Germany amounts to 63 TWh.¹ In the scenarios where electrolyzers are installed in the chemical industry, and paper and printing facilities (decentral distribution), the congestion management volumes increase steadily above the base case results, respectively, with increasing penetration levels of electrolyzers. In contrast, observed congestion management volumes in the centralized scenarios (refineries, primary steel) are consistently below the base case results. A decrease in curtailment rates can be observed in those model runs, indicating fewer congested transmission lines. As a consequence, also positive redispatch volumes decrease. In summary, reduced curtailment rates of renewable energies exert the most significant reduction of congestion manage-

¹This is roughly three times the amount that the electricity system regulator in Germany recorded during the year 2020.

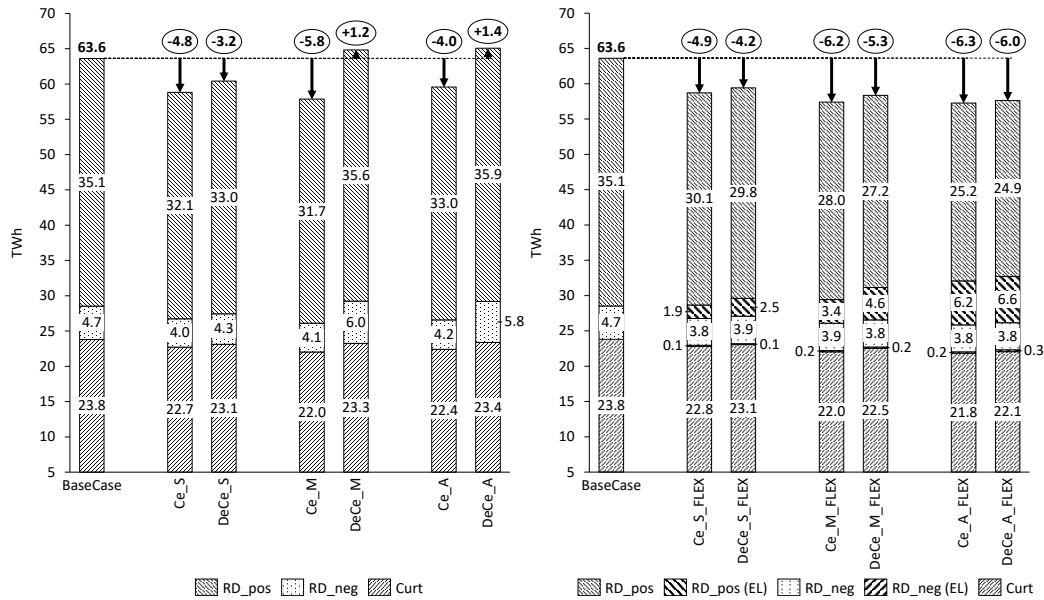


Figure 7: Total Volume of Congestion Management Measures; No Flexibility of Electrolyzers **Figure 8: Total Volume of Congestion Management Measures; Flexibility of Electrolyzers**

ment requirements when electrolyzer capacities are placed near refineries and steel production facilities.

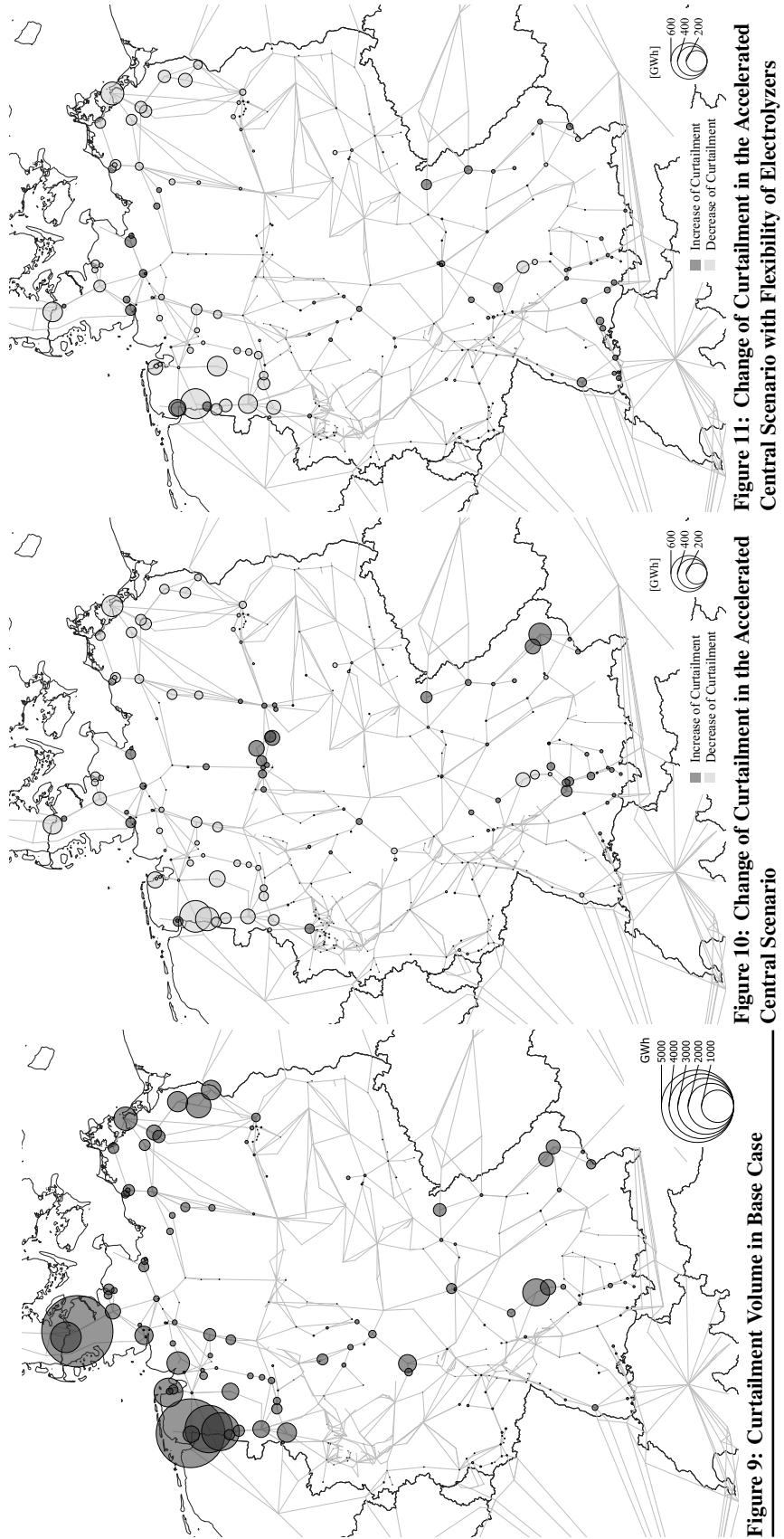
Results in scenarios where a flexible operation of electrolyzers for congestion management is assumed behave differently (see Figure 8). Here, the total congestion management volume decreases proportionally to the market penetration of electrolyzer installations, independently of the spatial allocation of electrolyzer capacities. In addition, the difference in the aggregated redispatch volume between the scenarios differing in the spatial allocation of electrolyzers, i.e., centralized vs. decentralized, varies only by a small margin. This result means electrolyzers can contribute significantly to congestion relief by providing a dispatchable load capacity. In all scenarios, redispatch measures of electrolyzers increasingly replace redispatch measures provided by conventional power stations. Overall, a reduction of curtailment volume can be observed in all flexibility scenarios, indicating that if electrolyzers are allocated also to chemical industry facilities and paper production and printing sites, they can significantly contribute to the management of grid congestions, but only if they are included in congestion management practices.

5.2 Results on a Regional Level

Effects on Curtailment in the Centralized Scenarios

Aggregated results provide meaningful insights into the general impact of hydrogen production on the electricity transmission system. The following presents the observed market interactions on a detailed nodal level. Moreover, the presented results are limited to the changes present in the curtailment rates, as renewable curtailment seems to exert the most decisive impact on the total congestion management requirements. Moreover, displayed values are limited to the model runs with accelerated market penetration levels of electrolyzer capacities since results are most pronounced in those model runs.

If electrolyzer capacities are allocated at refineries and facilities for primary steel production, significant amounts are installed at electricity nodes in the North of Germany. As illustrated in Figure



9, in the base case runs largest curtailment rates can be observed in the North-West and North-East of Germany. The distribution of electrolyzer capacities coincides very well with those regions facing large curtailment volumes. Large expansion quantities of wind power in North Germany until 2030 are not effectively integrated into the transmission grid due to limited line capacities, despite the assumed grid expansion and reinforcement measures. As a result of this imbalance, in both centralized scenarios, electrolyzer operation decreases curtailment rates, especially in North-West Germany, even when operated purely market-based. Furthermore, offshore wind installations in the Dutch North Sea create additional stress on the German electricity grid in North-West Germany. Also offshore wind integration benefits from the electrolyzer installations assumed (see changes in curtailment rates displayed in Figure 10 and Figure 11).

Nonetheless, some single electricity grid nodes experience also increases in curtailment rates, particularly in the South of Germany, if electrolyzers are not considered in congestion management practices. This result indicates that additional electrical loads from electrolyzer operation exerts additional stress on transmission lines around the installations in some regions. As a result of additional grid bottlenecks, the integration of electricity generation from renewable-based generation units is affected. This effect, however, can be counterbalanced, if electrolyzers are also dispatched for congestion management. Over all, a flexible operation of green hydrogen production units yields a significant reduction in congestion management measures to resolve bottlenecks, especially at transmission grid nodes experiencing high curtailment volumes.

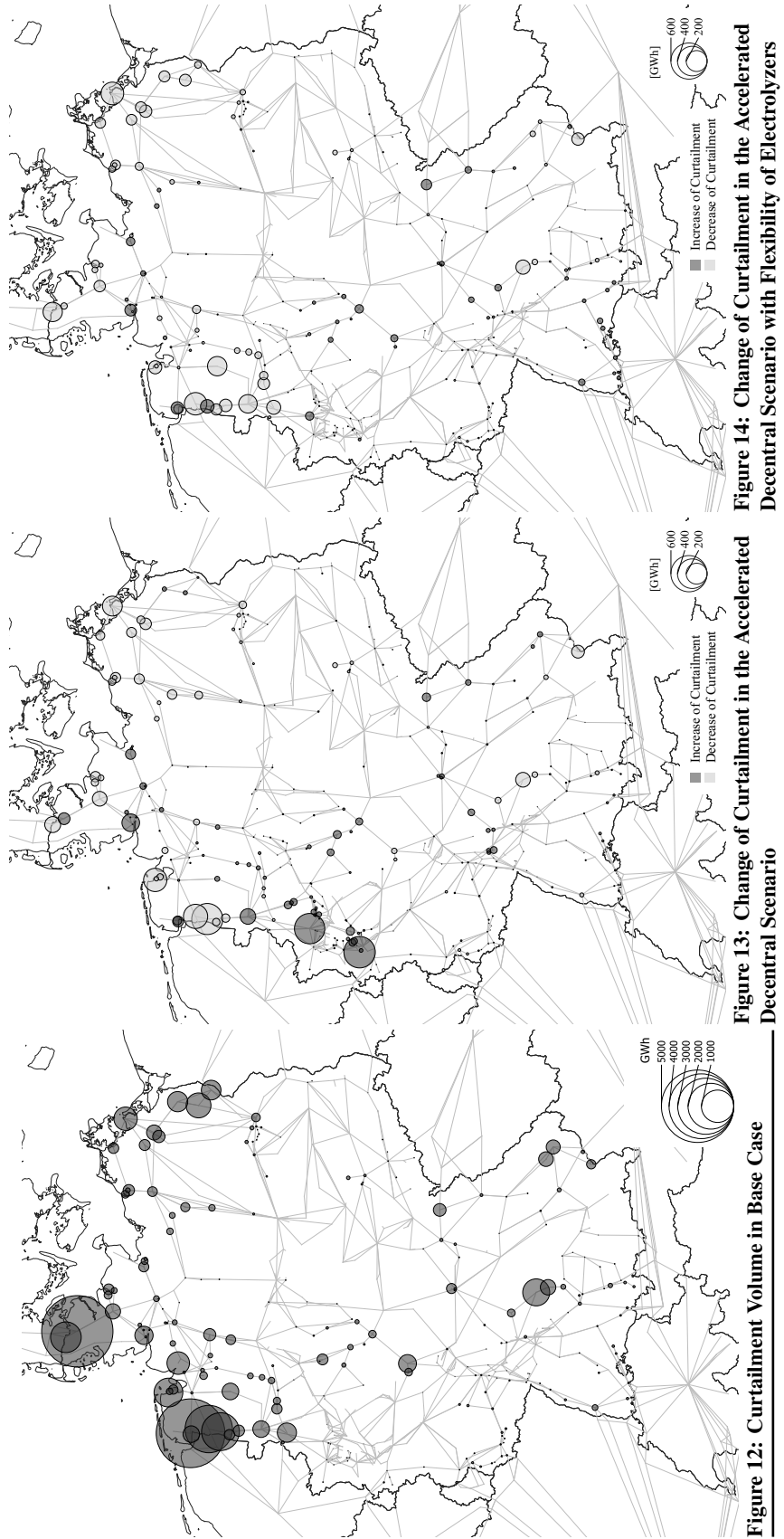
Effects on Curtailment in the Decentralized Scenarios

When electrolyzer capacities are assigned to the chemical industry and paper and printing facilities (decentralized scenario), they share greater proximity with the electricity load centers in West and South Germany. The impact of hydrogen production on electricity transmission grid operation is most prominent in those regions as Figure 13 and 14 show. While electricity grid nodes in North Germany experience large reductions in curtailment volumes, at two grid nodes in West Germany, curtailment amounts increase significantly in the scenarios without electrolyzers considered for congestion management. Additional electricity loads resulting from hydrogen production at those nodes put additional stress on the grid in West Germany, creating additional bottlenecks at the critical north-to-south corridor for integrating large amounts of renewable feed-in in North Germany and transporting the renewable supply toward the load centers in the South. Likely reducing renewable feed-in in those regions has a greater total effect on renewable integration, enabling a more efficient congestion management.

However, when electrolyzers are operated more flexibly and are used for congestion management, additional electricity grid bottlenecks resulting from hydrogen production can be avoided. A more flexible dispatch of electrolyzers also impacts single electricity grid nodes without electrolyzer capacity installations. That is illustrated by reduced curtailment amounts in the scenarios with a flexible operation mode. Most notable decreases in renewable energy curtailment can be observed in North-East and North-West Germany, which feature high amounts of renewable power plant units.

6. DISCUSSION AND CONCLUSION

This research investigates the effects of electrolyzer operation on the German transmission grid system differing in different electrolyzer deployment strategies. A particular focus is put on how decarbonizing different sectors of energy-intensive industries affects the management of future electricity grids.



More general results of this work indicate that integrating increasing amounts of electrolyzer capacities in the German electricity system poses particular challenges for transmission system operators.

Renewable energy integration can benefit from electrolyzer operation depending on the geographic distribution of electrolyzer installations. Conclusively, hydrogen production can positively impact integrating renewable feed-in if electrolyzers are operated near electricity grid nodes experiencing high curtailment volumes. Refineries and primary steel production facilities with a high technology readiness level for hydrogen-based production processes share greater proximity within regions in the North-West of Germany, characterized by a strongly loaded electricity transmission grid during times of wind generation. Total congestion management volumes can be reduced even if electrolyzers are operated purely market-based compared to an electricity system without electrolyzer installations assumed. However, if electrolyzers are installed at chemical industry facilities and the paper and printing industry sites distributed more widely throughout Germany, electrolyzer operation additionally stresses electricity transmission lines, increasing total congestion management volumes and costs.

Moreover, the operation mode of electrolyzer installations, i.e., purely market-based or integrated into congestion management practices, exerts a substantial impact on resulting congestion management volumes. Results of this research indicate increasing requirements of congestion management in the scenarios where electrolyzer capacities are allocated to the chemical industry and the paper and printing facilities, and their operation is not capable of swift dispatch or redispatch. However, in all scenarios in which a flexible operation of electrolyzer capacities is assumed, total congestion management volumes decrease parallel to increasing electrolyzer market penetration rates.

The findings of this work emphasize the importance of thoroughly considering flexibility sources from hydrogen production resulting from decarbonizing German energy-intensive industries when designing future congestion management frameworks. Integrating electrolyzer capacities into congestion management practices is essential for mitigating additional congestion management requirements induced by domestic green hydrogen producers, especially if industries feature a relatively decentralized geographic distribution in Germany. Future congestion management frameworks must enable the owners of those technologies to participate in the management of electricity grids. While Germany's congestion management has been traditionally organized and deployed directly through the transmission system operators, the newest European regulatory reforms require market-based forms for congestion management practices. In this context, future congestion management systems increase in complexity since providing redispatch capacity through hydrogen producers typically involves some opportunity cost for electrolyzer owners, and corresponding frameworks must consider it to provide sufficient incentives. Future research should thus investigate potential design options for future congestion management frameworks and incentive mechanisms for electrolyzer owners to participate in competitive forms for providing transmission system operators with sufficient amounts of regional flexibility sources for congestion management.

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