DECARBONIZING THE INDUSTRY SECTOR AND ITS EFFECT ON ELECTRICITY TRANSMISSION GRID OPERATION – IMPLICATIONS FROM A MODEL BASED ANALYSIS FOR GERMANY

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Overview

With the latest federal election in Germany in late 2021, the newly formed government decided even to accelerate the deployment of renewable energies and increase the targeted renewable amounts aiming at renewable penetration levels up to 80% of the total electricity demand until the year 2030. 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 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 with a particular focus on how different decarbonization orders of specific industries impact individual grid bottlenecks and the efficiency of congestion management.

Methods

To investigate the impact of electrolyzer operation on the operation of transmission grids, the application of a fundamental electricity market model and scenario-based research is proposed. A scenario framework is created, representing a set of future electrolyzer infrastructures differing in the geographic distribution based on the decarbonization order of specific energy-intensive industries and the level of integration into congestion management practices. Especially the technology readiness level of industrial processes to utilize hydrogen effectively was taken into account for electrolyzer site selection. A linear transmission grid model for the German electricity transportation system, encompassing more than 500 grid nodes, is exploited to study interactions between hydrogen production and transmission grid operation in the target year 2030. The optimisation model comprises two stages: Wholesale electricity market clearing and grid operation optimisation. During the first stage, the cost-minimising power generation dispatch in the European electricity market at a market-zone level is determined in an hourly resolution for 8760 hours of a year to serve the market's demands. The operation of electrolyzer capacities is a direct model-endogenous result. The cost-minimising optimisation yields a dispatch schedule of electrolyzers in which hydrogen is produced during low price hours. In addition to specific technology dispatch, storage, and trade constraints, a pre-defined amount of total hydrogen production is enforced by the model for a year, assuming sufficient storage and transportation infrastructures. Both the hourly operation of the conventional and renewable generation and storage fleet and the operation levels of the electrolyzer capacities serve as input for the grid optimisation model. While the geographic distribution is not impacting the market-clearing dispatch at a market-zone level, it has a decisive impact on the operation of transmission grids. During the second stage, the grid model optimises the application of different congestion management measures, comprising the redispatch of domestic plants, the redispatch of hydrogen capacities, cross-border remedial actions, renewable curtailment, and demand-side applications to resolve grid bottlenecks resulting from the market-clearing dispatch in a cost-minimising way. In addition to the differences in the geographic distribution of electrolyzer capacities, two different operation modes are considered in the scenario framework, a flexible and non-flexible operation. A flexible operation allows for the active participation of electrolyzers in congestion management through load-shifting. During the non-flexible operation scenarios, the electrolyzers' imputed loads that are endogenously modeled during market-clearing cannot be adjusted to manage grid congestions. Like the market-clearing model, the optimisation of remedial actions is carried out in an hourly resolution for 8760 hours of a year but applying a rolling horizon modeling approach to handle the higher complexity due to the higher granularity of grid representation. The modeled remedial action and congestion volumes then serve as comparative benchmark indicators to evaluate different hydrogen infrastructures differing in the decarbonization order of energy industries and operation modes.

Results

Initial results of this research indicate that the operation of electrolyzer capacities, in general, affects the operation of the transmission system, significantly exerting a strong impact on congestion management results. But the geographic distribution of electrolyzer capacities assumed in the different scenarios heavily influences these results. Energy-intensive industries are distributed differently throughout Germany. For example, the large pulp and paper production and mineral processing facilities feature a more spatially widespread distribution than refineries, basic chemicals, and metal production facilities. As a result, the operation of electrolyzers impacts grid congestions differently. The spatially widespread deployment of electrolyzer capacities translates into lower congestion management volumes and thus integration costs. Therefore, the order in which those industries decarbonize significantly impacts the system integration of increasing electrolyzer capacities. Moreover, the participation of electrolyzer capacities in grid management, i.e. through load-shifting of electrolyzer capacities, can substantially counteract additional grid congestions resulting from hydrogen production, reducing total congestion management volumes and costs while preserving total hydrogen production levels. However, installing electrolyzers more centralized at fewer locations still increases required congestion management actions regardless of operation mode.

Conclusions

Integrating large amounts of electrolyzers into energy systems poses particular challenges for electricity transmission system operators, as this research indicates. The deployment of those technologies for decarbonizing energy-intensive industries must thus be thoroughly considered in 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, particularly for decarbonizing industries that feature a relatively centralized geographic distribution. The results of this research thus emphasize the importance of designing congestion management frameworks that enable the owners of those technologies to participate in the management of electricity grids. While Germany's congestion management was traditionally organized and deployed directly through the transmission system operators, the newest European regulatory reforms require market-based forms for congestion management practices. Considering these developments, designing future congestion management systems increases complexity since providing redispatch capacity through electrolyzers typically involves some opportunity cost for electrolyzer owners, and corresponding frameworks must consider it to provide sufficient incentives.