Investments in coupled energy sectors and market pricing

(3) Sektorkopplung und Flexibilität

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Motivation and central research question

The low-carbon transition of the energy system is important to reach the goal of climate neutrality in Europe until the year 2050, as decided in the European Green Deal (European Commission, 2019). With increasing levels of renewable electricity generation, the concept of sector coupling is gaining more and more attention in energy-economic research and policy discussions (Bundesministerium für Umwelt, Naturschutz und nukleare Sicherheit (BMU), 2016; Bundesministerium für Wirtschaft und Energie (BMWi), 2020; Deutsche Energie-Agentur GmbH (dena), 2018; Deutsche Energie-Agentur GmbH (dena), 2021; Ramsebner, Haas, Ajanovic, & Wietschel, 2021). The complete decarbonization of the power sector will lead to renewable electricity substituting fossil energy carriers in the heat and mobility sectors, either directly or as input to produce sustainable synthetic fuels like hydrogen. These green energy carriers are broadly promoted to decarbonize especially emission-intensive industry applications, certain types of mobility, and backup power generation which cannot be electrified easily (IEA, 2021). The production of green hydrogen via electrolysis with renewable electricity is the only viable long-term solution as a basis for further hydrogen-based energy carriers (Bukold, Huneke, & Claußner, 2020), which will lead to a world in which electricity and hydrogen markets will be linked by electrolysis and re-electrification (Ramsebner et al., 2021). To gain a better understanding of the impacts of market pricing for coupled energy sectors, we develop a multi-level sector-coupling market model covering different market designs, i.e., different bidding zone configurations (one or two bidding zones per energy carrier) and different time characteristics for the energy products (e.g., hourly or daily trading). As far as we know, this is the first approach to implement a multi-level sector-coupling model with different time characteristics of energy products, which is especially interesting in the consideration of the developing hydrogen markets.

Methodology

The mathematical model is a three-level optimization problem. The investment in transport infrastructure is determined on the first level by the regulated transmission system operators to maximize overall cross-sector social welfare, using exogenously given network structures and respective trade parameters between the bidding zones in our application. On the second level, private firms choose investment in conversion, generation, and storage capacities anticipating their revenues from subsequent spot-market operations within their bidding zones. On the third level, the transmission system operators choose congestion management measures to minimize overall cross-sector costs for the implementation of the market outcomes under the constraint of the final demand results from the spot market and the transmission capacity limits determined on the first level. In order to render the model feasible, investment in backup capacity is possible to meet the final demand within each bidding zone. In our model, we distinguish between sector-specific generation and sector-coupling technologies that differ in the fact that the input factor price for sector-coupling technologies is endogenously calculated within the modeling of the coupled sectors, while the input factor price for sector-specific generation technologies is exogenously given by fixed input prices. This is due to the fact that the sectors from which sector-specific technologies obtain their input factors are not endogenously included in the modeling. In addition, storage assets are considered to increase flexibility options within the optimization. Egerer et al. (2022) show that specific conditions must be fulfilled to ensure uniqueness of equilibrium in such models of coupled markets for different energy sectors. The fact that on the one hand storage and therefore temporal flexibility is possible (Grübel et al., 2020) and on the other hand different durations of the trading periods are assumed, contribute to the property that for this model uniqueness cannot be guaranteed without imposing additional nonstandard assumptions. Further research could develop such uniqueness conditions to tackle the challenge of multiplicities, giving implications for suitable market rules to guarantee a unique solution. Besides multiplicities on the second level, another challenge arises from considering storage assets and the thereby gained time flexibility within the congestion management on the third level of the model. We propose the following modeling approach. To ensure the storage operators’ marginal rents to cover investment costs, we fix the storage operations in the third level to the solution of the second level to secure those margins but include the surplus capacities of the storage assets into the third-level modeling to use those capacities for congestion management operations. Finally, the sector-coupling model is applied in a case study to discuss the design of future coupled hydrogen and electricity markets using two bidding zones per energy carrier as status quo for our analysis. We consider all possible combinations of the bidding zone configurations (1:1; 1:2; 2:1; 2:2) and combine these configurations in a green field approach with only new investments in generation, sector-coupling, and storage assets and no existing capacities. The temporal setting follows the standard energy market design of electricity and gas markets. As it is the case in Germany, electricity is traded on the spot market mostly on an hourly basis, so the traded product in the electricity sector is a one-hour product. As a German and especially global hydrogen market is currently developing (Bundesministerium für Wirtschaft und Energie (BMWi), 2020), the duration of the trading period and thus the standard product traded on the future hydrogen spot market has not yet been generally fixed. Therefore, four different possibilities for the hydrogen market are considered in this paper: A twenty-four-hour product (365 trading periods per year), a twelve-hour product (730 trading periods per year), an eight-hour product (1095 trading periods per year), and a one-hour product (8760 trading periods per year). As input data, we use existing data for RES availability of European countries. The inverse demand functions are calculated by reference demand time series referred to the year 2030. Here, the electricity demand is scaled according to existing demand time series, while for hydrogen, based on a predicted yearly demand, daily variation with peak and off-peak times is used to depict future hydrogen-consuming industry behavior.

Results and conclusions

We consider investments in solar and wind generators as well as battery and compressed hydrogen storage assets. As sector-coupling technologies, electrolysis and hydrogen turbines can be used to convert the underlying energy carriers in times of profitable price divergences in the markets. The results show investments dominated by wind generators as availability factors during the year are more beneficial compared to solar availabilities and no technical investment limits are considered in this theoretical case. As the circular efficiency of hydrogen generation by electrolysis, storing, and re-electrification with hydrogen turbines is very low compared to direct electricity generation, only an exogenously given “Dunkelflaute” in the RES availability time series leads to investments in hydrogen turbines to cover electricity demand within these periods. A longer duration of the trading period of hydrogen leads to increasing flexibility options in the market, thus reducing investments in storage capacities to balance supply and demand within the trading period.

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