Global hydrogen trade: Analyzing market equilibrium in a future oligopolistic Cournot market

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Overview

Due to global ambitions to reduce greenhouse gas emissions, a market for green hydrogen and hydrogen-based derivatives produced from renewable electricity is currently in the start-up phase. This future green energy commodity market differs from fossil fuel markets by the following factors: First, the production potential for renewable energies is spread worldwide instead of concentrated resources in a few countries. Second, due to the seasonally varying profile of renewable energies, the production of green energy commodities is time-variant instead of constant. Third, transport and storage costs are considerably higher for hydrogen than for natural gas. There are no examples of real green energy commodity markets yet, so it is unclear how these markets will develop.

The existing literature already provides several analyses on the supply side of green energy commodities by quantifying the production and transportation costs of hydrogen and hydrogen derivatives (e.g. Moritz et al., 2023 and Hampp et al., 2023). However, to derive a conclusion about future green energy commodity markets, aspects of energy commodity markets should be considered: To identify prices and trade flows, the equilibrium of supply and demand in a global market should be taken into account. As green hydrogen and hydrogen-based derivatives are produced with the same renewable energy potential, the demand for these commodities should be supplied in a combined market. As high investments and low demand elasticity characterize energy commodity markets, market actors can potentially exert market power (Gabriel, 2013). Therefore, the strategic behavior of market actors should also be considered. To react to potentially high prices, the demand elasticity of importing regions should be incorporated. Finally, due to the seasonally varying profile of renewable energies, the seasonal dependency of supply quantities and storage capacities to balance this seasonal dependency should be modeled. To cover these aspects, a market model for green energy commodities is necessary.

Therefore, we propose an equilibrium model that includes hydrogen and hydrogen derivative producers, traders, commodity converters, and storage operators as separate actors to provide an elastic green commodity consumer demand. We analyze potential green commodity trade flows between world regions and green commodity prices in different world regions. We calculate different scenarios regarding strategic behavior, demand, and supply.

Methods

We propose a Mixed Complementarity Problem (MCP) model for modeling the global green energy commodity market. The model represents a global market with several profit-maximizing market actors. The model is spatially structured in 117 exporting countries and 22 importing regions. In each exporting region, there is a producer and exporter. The exporter can buy the produced commodities from the producer and sell them to any importing region. Apart from the production cost, the exporter also needs to pay transport costs for pipeline or shipping transport.

In each importing region, converters and storage operators for each commodity are additional market actors. The converter can buy commodities from exporters, convert them to another commodity, and sell them to the importing region or the storage operator. The storage operator can buy commodities from exporters or converters and sell them to the importing region or converter. The consumers in importing regions are no profit-maximizing market actors but have an elastic demand, which is supplied in the market equilibrium condition.

To model strategic behavior, we choose the Cournot model approach. A Cournot model is an economic model for oligopoly competition, where firms compete based on quantities. We decided to choose the Cournot model based on the findings of Truby (2012). He compares different competitive and non-competitive models to reproduce real market equilibria in the international market for metallurgical coals. His results show that Cournot models reproduce trade flows and prices accurately for mid-range elasticities. Additionally, Barner (2024) derives insights on strategic behavior in a green energy commodity market with a Cournot model proving the approach's applicability. For the proposed model in this study, this means that exporters can strategically withhold quantities from selling to converters, storage operators, or importing regions. The strategic behavior is modeled via a conjectural variation stating how each exporter expects its rivals to adjust their output in response to its own changes. By changing the conjectural variation, we can vary the strategic behavior in different scenarios.

We conduct a pre-optimization in another cost-minimizing optimization model to derive detailed production and transport costs for the model. The model determines optimal capacities and operation of production systems in each exporting country using hourly renewable energy profiles to achieve minimal production costs covering an inelastic demand of hydrogen or hydrogen-based derivatives. The results and methods are explained in detail in the documentation of the EWI Global PtX cost tool (EWI, 2024). Hydrogen and hydrogen-based derivatives can be transported via pipeline or ship and increase with distances between the exporting country and the importing region. The transportation cost includes domestic transportation via pipeline, liquefaction, regasification, and shipping and pipeline transport from the exporting country to the importing region. The transportation cost data is calculated in three scenarios for shipping cost and three scenarios for pipeline cost. With multiple cost scenarios and 12-time steps per year, the supply and transport side is quantified in detail.

To derive a well-founded conclusion on future green energy commodity markets, we analyze 48 scenarios. Each scenario combines scenario configurations of production costs, transport costs, demand, supply potential, and strategic behavior. For the production costs, we define the configurations "baseline" and "optimistic". For transportation costs, we propose the three configurations "pipeline beneficial", "neutral" and "shipping beneficial" based on combinations of the pipeline and shipping cost scenarios. We base our demand scenarios on the World Energy Outlook for the year 2050 and choose the configurations "low carbon" and "net-zero" (IEA, 2023). For supply potential and strategic behavior, we define both "low" and "high" scenarios. With these scenario configurations, we examine the influence of multiple parameters and thus deliver a comprehensive analysis of future green energy commodity markets.

Results

Preliminary results confirm our hypothesis of regional pipeline-based hydrogen markets and global hydrogen-based derivatives markets. Eight scenarios were analyzed in a preliminary model run, including varying demand, supply potential, and strategic behavior. Production and transport cost scenarios have been assumed to be "baseline" and "neutral" for each scenario. Each scenario was investigated in four steps per year, and market actors were restricted to fully-integrated exporters and storage operators. The preliminary results show a high share of pipeline supply in all importing regions, with twelve importing regions having 100 percent pipeline supply in all eight scenarios. The lowest pipeline share recorded is around 70 percent in South Korea. Preliminary results for methanol show a greater variety of pipeline and shipping supplies in different importing regions, showing a mixture of regional and global imports. Based on the observed preliminary results, our hypothesis can be initially confirmed. However, including more scenarios, especially the transport cost scenarios, might considerably influence the results. We will continue our research as proposed in the methods section.