RENEWABLE HYDROGEN TRADE DYNAMICS IN THE EUROPEAN UNION: A GAME-THEORETIC MODELLING APPROACH

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Overview

Renewable hydrogen is increasingly recognized as a critical energy carrier in global efforts to mitigate climate change. Its potential to decarbonize hard-to-abate sectors such as industry and heavy transport has garnered significant attention, especially as nations strive to meet their net-zero targets. International trade is anticipated to play an important role in addressing the growing demand for hydrogen in resource-constrained countries in Europe. Countries such as Germany and the Netherlands are actively negotiating bilateral trade agreements with resource-abundant regions to secure low-cost renewable hydrogen supplies.

While numerous studies have assessed the techno-economic feasibility of global hydrogen trade, they predominantly adopt cost-minimization within siloed planning approaches. Such methods often assume that hydrogen producers act as price-takers, neglecting the strategic interactions that can shape market dynamics and influence hydrogen prices in importing regions. This study addresses this gap by employing game-theoretical modeling to capture the strategic behavior of producers and consumers in international hydrogen markets. By integrating concepts from equilibrium modeling, this work provides a new perspective on the interplay between supply and demand in shaping hydrogen trade flows, with a particular focus on exports to the European Union (EU).

Methods

We developed a novel modeling framework to simulate game-theoretic market equilibria in international hydrogen trade, incorporating stepwise supply and demand curves to capture the strategic behavior of hydrogen producers. The framework is based on a Stackelberg game, where hydrogen producers, acting as leaders, maximize their surplus in the upper-level problem, while the lower-level problem models the maximization of social welfare within the market.

For a single producer, the lower-level problem is reformulated using the Karush-Kuhn-Tucker (KKT) conditions, transforming the model into a Mathematical Program with Equilibrium Constraints (MPEC). To extend the framework to multiple producers, individual MPECs for each producer are combined to form an Equilibrium Problem with Equilibrium Constraints (EPEC). The stationarity conditions of the MPECs are then derived and solved simultaneously to achieve Nash equilibrium in the EPEC model.

Consumers are also modeled strategically by imposing constraints that ensure a minimum level of domestic production and a maximum allowable import volume from any single supplier. This approach enables the analysis of complex interactions between producers and consumers, providing insights into the dynamics of international hydrogen trade.

Results

Preliminary results indicate that the EU would predominantly rely on imports from North Africa to meet its renewable hydrogen demand, driven by North Africa's abundant low-cost resources and geographical proximity. However, this reliance raises energy security concerns within the EU. To mitigate these risks, the EU is likely to implement strategic policies aimed at stimulating domestic hydrogen production and diversifying import sources. Such measures are projected to enable low-cost EU producers, such as Spain, Portugal and Ireland, to supply approximately 70% of the region's renewable hydrogen demand. Regarding imports, the model suggests that the EU is likely to source most of its hydrogen via pipelines from North Africa, followed by offshore renewable hydrogen production in Norway. Smaller volumes of hydrogen would be imported from Chile, transported as ammonia to serve as a hydrogen carrier. EU renewable hydrogen trade flows for the year 2050 are depicted in Figure 1. It is important to note that these findings are preliminary and ongoing model refinements will provide deeper insights into equilibrium demand, prices, and trade flows.

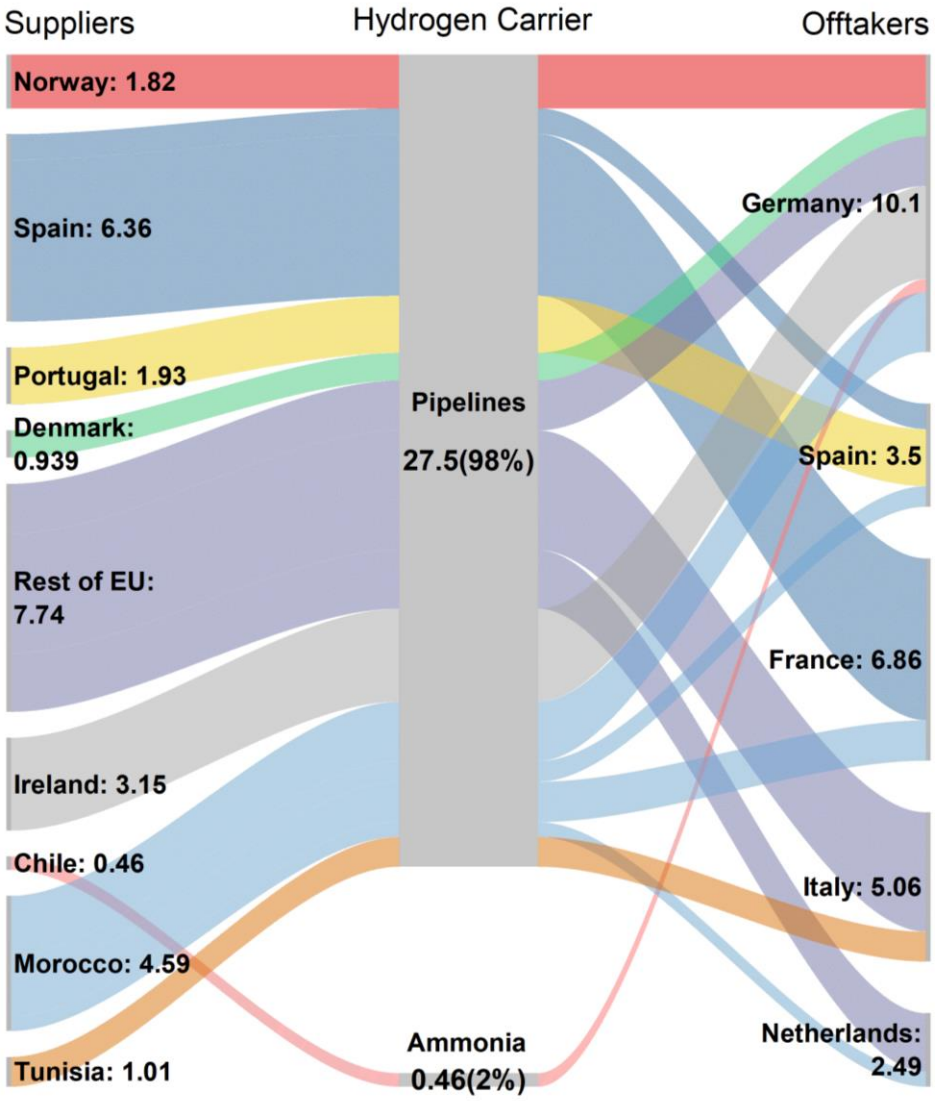

Figure 1: Model results showing renewable hydrogen trade flows in EU for 2050 (in Mt).

Conclusions

Renewable hydrogen trade into the EU has been extensively investigated in the literature, driven by the EU's ambitious decarbonization goals and limited renewable energy resources. However, most studies analyze international hydrogen trade using cost-minimization approaches that fail to capture the strategic behavior of hydrogen producers and consumers. To address this limitation, this study introduces a novel modeling framework based on game theory to examine the dynamics of renewable hydrogen trade in the EU. By capturing the strategic interactions between market players, our research provides valuable quantitative insights into hydrogen market development and informs strategies to balance energy security, economic competitiveness and sustainability in this emerging market.

References

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