[*INFRASTRUCTURE DIVERSIFICATION - THE CASE OF HYDROGEN PIPELINE IMPORTS TO EUROPE*]

[Silvian Radke, Brandenburg University of Technology, silvian.radke@b-tu.de]
[Felix Müsgens, Brandenburg University of Technology, felix.muesgensb-tu.de]

Overview

In line with the RePowerEU plan, several studies forecast a strong growth of hydrogen consumption in Europe. Based on European Union's decarbonisation plan we assume this hydrogen demand to be served with green hydrogen. Thus we always mean green hydrogen when we refer to hydrogen and green ammonia when referring to ammonia. Starting from 2030, half of this demand is expected to be met through imports. Suppliers therefore play an important role in supply securityEnergy carriers are typically imported via ships or pipelines, each with distinct advantages depending on distance and reliability. Pipelines offer a cost advantage over shorter distances, whereas transportation by ship becomes more economical over longer distances. Reliability also varies between the two: while liquid markets for energy carriers transported by ship provide flexibility to respond to supply disruptions, pipelines lack this ability to switch to alternative suppliers in case of failure. Consequently, pipelines tend to be more cost-effective, but ship-based supply chains can offer greater reliability.

Diversification is a well-established strategy to manage uncertainty. In the context of energy supply, it is often emphasized in the transition to renewable energy sources, as well as in managing uncertainty in fossil fuel supply chains. While future energy supply chains are frequently analysed in terms of costs, technical feasibility, and the environmental sustainability of renewable energy sources, the uncertainty surrounding energy supply is less commonly addressed. In energy economics, diversification is typically discussed across different fossil energy carriers but rarely within a single renewable energy carrier.

Most existing studies that address supply chain uncertainty focus on robust optimization of energy systems. However, there is a gap in fundamental research on the costs and benefits of diversifying renewable energy carriers. This work aims to explore the impact of diversification within the supply chain of a single energy carrier on social welfare.

Methods

We develop a stochastic model that incorporates uncertainty and supply chain security, applied to the analysis of Europe's green hydrogen supply in 2030. In this context, "hydrogen" refers to green hydrogen, and "ammonia" refers to green ammonia. The model is a two-stage stochastic optimization framework, consisting of pipeline-based and ship-based supply chains. The first stage represents the investment decision (in pipelines or import terminals) while the second stage represents dispatch optimization for different uncertainty realisations. The model includes demand and supply nodes. Each demand node has associated hydrogen demand and demand response characteristics. Supply nodes are parametrized either as suppliers of gaseous hydrogen via pipeline or as supplier of a liquid hydrogen carrier via ships, assuming a global market for green ammonia. Supplier nodes differ in variable supply costs and fixed investment costs. The nodes are connected via edges, representing pipelines or ship routes, each characterized by transfer capacity, variable transport costs (including conversion and re-conversion) and availability. We assume varying levels of uncertainty within the supply chain. Ship-based connections to demand nodes are considered certain, with a zero probability of outages, while pipelines have a probability for outages.

The objective is to optimize social welfare across different scenarios, capturing the costs and benefits of supply chain diversification and infrastructure redundancy. Economic welfare is defined as sum of consumer and producer rents. The optimisation problem is formulated as a cost minimisation problem where production costs and welfare loss from reduced demand due to positive prices are minimised and deducted from gross welfare at latent demand (demand at a price of zero). We compare two different strategies to handle uncertainty. First, an uncertainty ignoring strategy in which import capacities are only established to the cheapest possible option ('naïve scenario'). And in contrast the stochastic optimal in which uncertainties (probabilities for supply interruptions) are considered. The additional welfare between the uncertainty ignoring strategy and the stochastic optimal is attributed to the benefits of

diversification of the supply chain and excess capacities to supply nodes. We explore these effects using both a simplified three-node model as well as an empirical model.
The empirical model covers the member states of the European Union (EU) which are aggregated into six demand regions, based on the European Hydrogen Backbone Initiative. Suppliers are either neighbouring natural gas suppliers based on existing connections (but excluding Russia) or an assumed global market for liquid ammonia.
Our analysis examines the additional welfare under varying scenarios, considering different outage probabilities and supply cost variations. This enables to cover the uncertainty in determining the probabilities for supply interruptions as well as generation and conversion or reconversion costs. This approach captures uncertainties related to supply disruptions, as well as generation, conversion, and reconversion costs. Although the study focuses on green hydrogen imports to Europe in 2030, the developed model and methodology can also be applied to historical events, such as the 2022 European gas price crisis, or to analyse future supply chain diversification potentials.

Results

We calculate the social welfare for Europe in different scenarios to investigate the influence of different reliability levels as well as different developments of generation costs. One plausible scenario investigates hydrogen and ammonia import capacities to the European Union.

Our study demonstrated that import terminals for liquid hydrogen carriers are part of the optimal solution. Even demand nodes with strong pipeline connections to supply nodes invest in terminal capacities to mitigate the risk of supply interruptions. The extent of these backup capacities depends the strength of interconnections within the European demand nodes and also the demand response and cost differences between the different uncertain supply options.

Furthermore, our results indicate that, under uncertainty, the import capacities include backup capacities to address potential supply interruption. In the optimal solution, import capacities are approximately 50 % higher compared to the ‘naïve scenario’. Moreover, optimal import capacities exceed the total latent hydrogen demand by nearly 20 %, while the ‘naïve scenario’ only provides import capacities for 80 % of the latent demand.

The additional welfare generated by the stochastic optimal compared to the ‘naïve’ strategy is approximately 10 % in total welfare. Around half of this is attributed to diversification and around 10 % stemming from backup capacities, and the remainder arising from cross effects.

Conclusions

If a low-cost supplier has the potential to cover a significant share of the demand, an optimal stochastic solution mitigates the risk of supply disruptions by incorporating additional capacity. In case of green energy carriers, liquid hydrogen derivates like green ammonia or liquid hydrogen can serve as backup options, complementing gaseous hydrogen from MENA pipelines. The option to ignore uncertainty and “put all eggs in the same basket” has not only proven a risk after the Russian invasion in Ukraine but will thus also be an economically inefficient solution for such a future system of green energy carriers. If the objective is a resilient energy system that provides secure energy supply, expensive but reliable supply options are part of the optimal mix.

However, our results are only transferable to a limited extent. Our model reacts to a limited supply by increasing the price and thereby reducing the met demand. In the gas price crisis for example, prices became subject of political interventions (e.g. maximum prices for gas and power to private and commercial consumers) that influence the demand reaction.