GERMANY'S HYDROGEN IMPORT PATHWAYS: BALANCING COSTS AND SUSTAINABILITY

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Overview

Hydrogen could play a pievotal role in the development of low-carbon emission energy systems. During its utilization, hydrogen is emissions-free and it offers the potential to store electricity generated from renewable sources, facilitate its transportation, and enable usage independent of time and the electricity grid. However, the extent to which hydrogen will be integrated into energy systems remains uncertain, particularly due to questions surrounding the future cost trajectories of hydrogen production and deployment. These uncertainties are already impacting ongoing developments and investments within the hydrogen sector.

Germany, characterized by its high energy demand and limited domestic hydrogen production capacities, faces critical decisions regarding the spatial distribution and scale of hydrogen deployment across various sectors and regions. Thus, affordable hydrogen imports are essential for its adoption in an economy that seeks to balance energy requirements with environmental commitments.

Current studies, such as those by Seeger et al. (2024), Moritz et al. (2023), IEA (2024), and IRENA (2022) provide detailed cost assessments that incorporate uncertainty parameters, offering insights into the economic viability of hydrogen projects. Additionally, research has examined the environmental impacts of specific stages within hydrogen supply chains such as Wei et al. (2024), Hajjiaji et al. (2013), Shaya & Glöser-Chahoud (2024) and Kanz et al. (2021). Some also integrate different transportation options such as Kockel et al. (2024) and Alghool et al. (2024). However, modeling approaches often evaluate costs and environmental impacts separately. This compartmentalized analysis may lead to suboptimal decisions, as it overlooks potential synergies and conflicts between economic and environmental objectives. There is a notable gap in analyses that simultaneously consider comprehensive greenhouse gas emissions and cost evaluations, particularly concerning technical uncertainties and the scenarios upon which cost and environmental parameters depend. Addressing this gap is crucial for developing strategies that optimize both economic efficiency and environmental sustainability. Therefore, our research aims to address the following question: How do uncertain cost and environmental parameters influence the potential allocation of hydrogen production and import pathways for Germany?

Methods

Building upon the methodologies developed in previous research (Kockel et al., 2024; Seeger et al., 2024), we employ an integrated simulation and optimization modeling framework to evaluate diverse hydrogen production and transport pathways. This framework includes the generation of hydrogen using electrolyzers powered by photovoltaic or wind energy, as well as the production of blue hydrogen through steam methane reforming and carbon capture and storage. For extended transportation distances, economically viable options include the liquefaction of hydrogen or its conversion into derivatives. However, significant uncertainties are associated with these costs, as some technologies remain underdeveloped and the expenses of energy-intensive (re-)conversion processes are subject to volatile energy prices (Ortiz Cebolla et al., 2022). Consequently, we assess various transportation methods for hydrogen, including gaseous form via pipelines, and shipping in the forms of liquid hydrogen, ammonia, methanol, and LOHC. Each transportation method's conversion and reconversion steps for different hydrogen forms, derivatives, or carriers are also considered.

The simulation model integrates comprehensive data on the costs and environmental impacts of various hydrogen production and transport options, enabling simultaneous analysis of environmental impacts and associated costs under consistent uncertainty parameters and scenario assumptions. To capture the evolving environmental impacts in future years, a prospective Life Cycle Assessment (LCA) is employed. Cost development is modeled based on learning curves, reflecting the anticipated reductions in costs with increased deployment and technological advancements.

Based on the primary drivers for environmental and cost parameters, we conduct a Monte Carlo simulation to incorporate uncertainty, quantifying the variability in input data and generating uncertainty distributions. These uncertainty distributions are subsequently utilized in a global optimization model designed to allocate hydrogen production and import pathways optimally across different scenarios. Additionally, the model incorporates future scenarios involving capacity expansion and demand projections, enabling the assessment of how uncertainties in cost and environmental parameters influence optimal hydrogen allocation strategies.

Results

Preliminary analyses reveal variations in both the cost and environmental impacts of different hydrogen production and transportation methods. For example, hydrogen production using photovoltaic (PV) energy is currently more cost-effective compared to production using wind energy. However, the PV-based hydrogen generation exhibits higher environmental impacts than its wind-powered counterpart. In future scenarios, the environmental impacts associated with PV-based hydrogen production are projected to decrease substantially. Figure 1 illustrates exemplarily this relationship, showing the Global Warming Potential (GWP) and Levelized Cost of Electricity (LCOE) for electricity generated by wind and PV energy at different points in time (Today, 2030, and 2045). with each data point representing a specific region in the world.

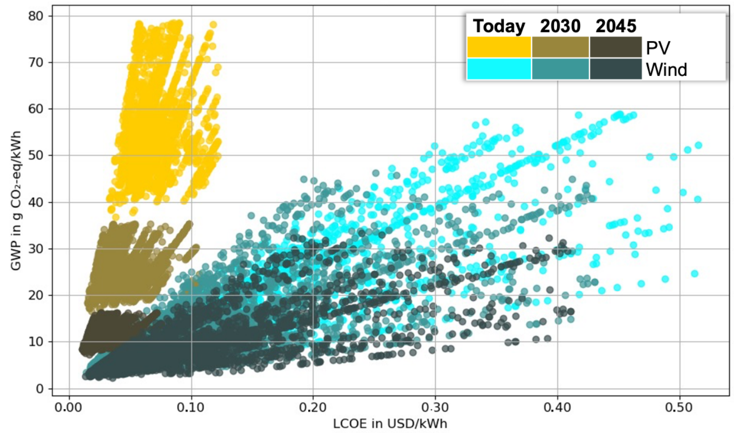

Figure 1: *GWP LCOE for electricity produced by PV and wind energy across three time horizons and different areas*

Conclusions

Our developed integrated simulation and optimization framework can highlight the uncertainties and trade-offs between cost and environmental impacts in hydrogen deployment. By simultaneously assessing greenhouse gas emissions and economic factors, the methodology clarifies where uncertainties lie and how they influence decision-making. The results identify which hydrogen production and transport pathways offer the best balance of cost-effectiveness and environmental sustainability, providing valuable guidance for selecting suitable hydrogen types for import to Germany. This enhanced understanding supports more informed energy policies and investment decisions, fostering the development of a resilient and low-carbon energy infrastructure in Germany.

References

Alghool, D., Haouari, M., & Trucco, P. (2024). It is not the same green: A comparative LCA study of green hydrogen supply network pathways. *International Journal of Hydrogen Energy*. https://doi.org/10.1016/j.ijhydene.2024.06.346

Hajjaji, N., Pons, M.-N., Renaudin, V., & Houas, A. (2013). Comparative life cycle assessment of eight alternatives for hydrogen production from renewable and fossil feedstock. *Journal of Cleaner Production*, *44*, 177-189. https://doi.org/10.1016/j.jclepro.2012.11.043

IEA. (2024). *Global Hydrogen Review 2024*.

IRENA. (2022). *Global hydrogen trade to meet the 1.5°C climate goal: Part III – Green hydrogen cost and potential*. International Renewable Energy Agency.

Kanz, O., Bittkau, K., Ding, K., Rau, U., & Reinders, A. (2021). Review and Harmonization of the Life-Cycle Global Warming Impact of PV-Powered Hydrogen Production by Electrolysis. *Frontiers in Electronics*, *2*. https://doi.org/10.3389/felec.2021.711103

Kockel, C., Kulawik, J., Wohlleben, D., & Praktiknjo, A. (2024). Which Way to Choose? A Generic Modular Life Cycle Assessment for Hydrogen Production and Import Pathways to Germany. *The Energy Journal*. https://doi.org/10.5547/01956574.45.SI1.ckoc

Moritz, M., Schönfisch, M., & Schulte, S. (2023). Estimating global production and supply costs for green hydrogen and hydrogen-based green energy commodities. *International Journal of Hydrogen Energy*, *48*(25), 9139-9154. https://doi.org/10.1016/j.ijhydene.2022.12.046

Ortiz Cebolla, R., Dolci, F., & Weidner, E. (2022). Assessment of Hydrogen Delivery Options: Feasibility of Transport of Green Hydrogen within Europe. *Joint Research Centre, European Commission*.

Seeger, K., Genovese, M., Schlüter, A., Kockel, C., Corigliano, O., Canales, E. D., Fragiacomo, P., & Praktiknjo, A. (2024). Evaluating Supply Scenarios for Hydrogen and Green Fuels from Canada, Chile, and Algeria to Germany via a Techno-Economic Assessment. *USAEE Working Paper*, *24-631*.

Shaya, N., & Glöser-Chahoud, S. (2024). A Review of Life Cycle Assessment (LCA) Studies for Hydrogen Production Technologies through Water Electrolysis: Recent Advances. *Energies*, *17*(16). https://doi.org/10.3390/en17163968

Wei, S., Sacchi, R., Tukker, A., Suh, S., & Steubing, B. (2024). Future environmental impacts of global hydrogen production. *Energy & Environmental Science*, *17*(6), 2157-2172. https://doi.org/10.1039/d3ee03875k