The Future of Renewable Hydrogen in the European Union: Market and Geopolitical Implications

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ENVIRONMENT AND NATURAL RESOURCES PROGRAM

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Market and Geopolitical Implications

Alejandro Nuñez-Jimenez
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HARVARD Kennedy School
BELFER CENTER
for Science and International Affairs

REPORT
MARCH 2022

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1 Photo from Unsplash

Executive Summary

As countries around the world pledge to remove nearly all carbon emissions from their economies within the next forty years, the spotlight has moved to the deep decarbonization of all energy sectors. This aggressive push to decarbonize has sparked renewed interest in clean hydrogen—defined as hydrogen produced from water electrolysis with zero-carbon electricity. While hydrogen has been a staple in the energy and chemical industries for decades, renewable hydrogen is now enjoying unprecedented political and business momentum as a versatile and sustainable energy carrier that could be the missing piece in the carbon-free energy puzzle. While success is possible, this transformational effort will require close coordination between policy, technology, capital, and society to avoid falling into the traps and inefficiencies of the past.

This report focuses on the market and geopolitical implications of renewable hydrogen adoption at scale in the European Union (EU) and presents long-term strategies based on three reference scenarios. Each scenario focuses on one key strategic variable: energy independence, cost (optimization), or energy security.

Our analysis shows that only by working together can the EU become a global leader in clean hydrogen innovation and simultaneously contribute to the EU's climate and energy security goals, a more robust economy, and a more integrated union.

What would it require to become hydrogen independent? Where should production be located for cost-competitive supplies? What is the enabling infrastructure that needs to be developed and deployed at scale? How could supply risks be mitigated? Only a thorough analysis of future scenarios can provide policymakers and investors with answers to these key questions, as well as a deep understanding of the associated market and geopolitical implications.

Why renewable hydrogen?

Hydrogen produced from renewable electricity by splitting water has a variety of potential uses, both in mobility and stationary applications. But most importantly, renewable hydrogen has the potential to tackle hard-to-abate emissions in sectors such as iron and steel production, high-temperature industrial heat, aviation, shipping, long-distance road transportation, and heat for buildings. These sectors account for over one-fourth of global carbon dioxide (CO_2) emissions.[1]

While renewable hydrogen's production costs are still higher today than those from fossil fuels, renewable electricity and electrolyzer costs are forecasted to decrease significantly as deployment grows.

Why the European Union?

The EU aims to become carbon neutral by 2050 and sees renewable hydrogen as key to achieving this objective.

In July 2020, the EU published its hydrogen strategy, setting electrolyzer deployment targets to 2030 and outlining the ambition to develop an open and competitive EU hydrogen market. The strategy forecasts that renewable hydrogen will reach maturity and be deployed at scale in all hard-to-decarbonize sectors by 2050, but sets no targets beyond 2030 and provides few details on how the EU could meet this hydrogen demand.

The EU stands at a crossroads. Today, it is no doubt at the forefront of the global hydrogen race. But to maintain its leadership, the EU needs to quickly define and implement a cohesive long-term strategy for developing competitive and secure hydrogen markets.

Our prior work on renewable hydrogen's global geopolitical and market implications[2] shows that while some resource-rich member states, like

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[1] Davis et al. (2018) "Net-zero emissions energy systems," *Science*, 360(6396). https://doi.org/10.1126/science.aas9793

[2] Pflugmann and De Blasio (2020) *Geopolitical and Market Implications of Renewable Hydrogen: New Dependencies in a Low-Carbon Energy World*, Belfer Center for Science and International Affairs, Harvard Kennedy School of Government, March 2020. https://www.belfercenter.org/publication/geopolitical-and-market-implications-renewable-hydrogen-new-dependencies-low-carbon

Spain, can evolve into regional exporters, no member state can become a global export champion. On the other hand, regional partners like Morocco have this potential and could play a significant role in EU hydrogen markets.

As discussed, to shed light on alternative development pathways, this report considers three reference scenarios in which the EU prioritizes one of three strategic variables: energy independence, cost (optimization), or energy security:

- **Hydrogen Independence:** the EU prioritizes energy independence and develops internal, self-sufficient renewable hydrogen markets.
- **Regional Imports:** the EU prioritizes cost optimization by complementing the lowest-cost internal production with imports from neighboring export champions (Morocco and Norway) and renewable-rich countries (Iceland and Egypt).
- **Long-Distance Imports:** the EU prioritizes energy security and cost optimization by combining long-distance imports from export champions (Australia and the United States) with regional imports and internal production.

Each scenario analysis consists of three steps. First, overall renewable hydrogen potentials are calculated for each country (based on renewables, freshwater, and land availability; infrastructure potential; and competing demand for renewable electricity). Second, each country's production cost curves are computed (based on local renewable electricity and electrolyzer costs). Lastly, trade optimizations are carried out (based on production cost curves and transportation costs).

Our study highlights how all three scenarios are viable pathways to meeting the EU's projected renewable hydrogen demand. However, hydrogen independence would only be possible if member states traded significant amounts of hydrogen between them, which would require deploying integrated enabling infrastructure and harmonizing standards and regulations, including certificates of origin.

Furthermore, the analysis of cost-curves shows that renewable hydrogen supplies in the Regional and Long-Distance Imports scenarios are more cost-competitive than in the Hydrogen Independence scenario thanks to significantly lower production costs attainable outside the EU. While member states like Spain and Ireland could develop their full potentials cost-effectively, other states like Denmark would see costs rise as production increases, leading to higher supply costs overall.

As shown in the trade optimization step, while the Regional Imports scenario allows for meeting demand at the lowest cost—even when accounting for the higher transportation costs— member states may rely on a single regional partner to supply a significant fraction of their hydrogen needs. This reliance on a single regional partner would replicate past patterns of energy dependence and security risks.

Supply diversification from long-distance export champions like the United States would be an effective way to increase overall energy security for the EU while maintaining low supply costs.

While all three scenarios are viable pathways to meeting projected EU renewable hydrogen demand, the overall market and geopolitical implications are significantly different in terms of the above key strategic variables and enabling infrastructure investment allocations.

In the end, today's policy choices will determine which scenario will unfold, but policymakers need to evaluate alternative requirements and competing needs carefully. Overall renewable hydrogen adoption at scale in the EU will require policymakers to:

- Lower market risk and remove commercialization barriers to achieve the required economies of scale.
- Define clear policies to stimulate strong growth in renewable energy sources, particularly in member states that could become regional exporters.
- Fund innovation and pilot projects to accelerate progress towards cost-competitive renewable hydrogen technologies.

- Coordinate enabling infrastructure development and deployment across the continent.
- Harmonize standards and regulations, including certificates of origin, to ensure that renewable hydrogen flows seamlessly across borders

Implementation of the Regional Imports or Long-Distance Imports scenarios will also require the definition of:

- Long-term contracts and direct investments to help reduce market risk for producers.
- Transparent regulations and long-term investments in enabling infrastructure to send strong signals to investors in producing nations and trigger production-capacity investments.
- International standards for renewable hydrogen production, transportation, and use.

Renewable hydrogen offers a unique opportunity to accelerate the EU's transition to a low-carbon economy. Still, deployment at scale faces fundamental challenges that neither the private nor public sector can address alone. Only by working together can the EU become a global leader in renewable hydrogen innovation and simultaneously contribute to its climate and energy security goals, a more robust economy, and a more integrated union.

1. Introduction and Literature Review

Since the signing of the landmark Paris Agreement in 2015, the global commitment to decarbonization has grown only stronger. Major economies such as Canada, the European Union, Japan, and the United Kingdom have passed laws requiring net-zero emissions targets to be achieved within the next forty years. Other governments like China and the United States have expressed similar intentions.[3] These decisions have shifted the spotlight to the deep decarbonization of all energy sectors, including those with hard-to-abate emissions, and have thus renewed interest in clean hydrogen.

Hydrogen is a versatile and sustainable energy carrier that has a variety of potential uses, both in mobility and stationary applications. Most importantly, it has the potential to tackle hard-to-abate emissions in sectors such as iron and steel production, high-temperature industrial heat, aviation, shipping, long-distance road transportation, and heat for buildings. These sectors account for over one-fourth of global CO_2 emissions.[4]

While hydrogen has been a staple in the energy and chemical sectors for decades, it is attracting unprecedented attention from policymakers and businesses worldwide. As an example of this extraordinary momentum, in July 2021, McKinsey & Co. estimated that at least 359 large-scale hydrogen projects have been announced globally to date, amounting to 500 billion USD of associated investments through 2030.[5]

These announcements also reflect investors' response to governments' commitments to renewable hydrogen, with half of the world's economies

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[3] Energy and Climate Intelligence Unit (2021) "Net Zero Emissions Race," Net Zero Tracker, accessed 20 September 2021. https://eciu.net/netzerotracker

[4] Davis et al. (2018).

[5] McKinsey and Co. study for Hydrogen Council (2021) "Hydrogen Insights – Executive Summary," July 2021. https://hydrogencouncil.com/wp-content/uploads/2021/07/Hydrogen-Insights-July-2021-Executive-summary.pdf

including green hydrogen in their national plans.[6] In this perspective, the EU is the world's largest economic area to have published a hydrogen strategy that identifies renewable hydrogen as a key priority for achieving its objective of becoming climate neutral by 2050.[7]

Today most hydrogen is produced from fossil fuels through processes that involve significant carbon emissions.[8] Although various carbon-neutral or zero-carbon processes exist, the focus of this report is renewable, or green, hydrogen, which is hydrogen produced by electrolysis (the splitting of water into hydrogen and oxygen) using renewable electricity.

Currently, renewable hydrogen production is several times more expensive than production from fossil fuels.[9] However, technology innovation, cost reductions along value chains, and carbon pricing could help increase its competitiveness.[10] Other key obstacles such as a lack of enabling infrastructure, established markets, and uniform regulations and policies will also need to be addressed.

Today, the EU stands at a crossroads. It is no doubt at the forefront of the global hydrogen race: about 80% of new large-scale hydrogen projects that have been announced are in Europe.[11] And EU member states led the rise in the global deployment of electrolyzers in 2020.[12] But at the same time, the EU needs to quickly define and implement a cohesive long-term strategy to build competitive and secure hydrogen markets and maintain its leadership position.

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[6] World Energy Council (WEC) (2020) *International Hydrogen Strategies: A study commissioned by and in cooperation with the World Energy Council Germany*, September 2020. https://www.weltenergierat.de/wp-content/uploads/2020/10/WEC_H2_Strategies_finalreport.pdf

[7] European Commission (EC) (2020) "A Hydrogen Strategy for a Climate-Neutral Europe," COM(2020) 301 final, 8 July 2020. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52020DC0301

[8] International Energy Agency (IEA) (2019) *The Future of Hydrogen*, June 2019. https://www.iea.org/reports/the-future-of-hydrogen

[9] Ibid.

[10] International Renewable Energy Agency (IRENA) (2020). *Green Hydrogen Cost Reduction*, December 2020. https://www.irena.org/publications/2020/Dec/Green-hydrogen-cost-reduction

[11] Including non-EU countries like the United Kingdom, Switzerland, or Norway, based on Hydrogen Council (2021) "Hydrogen Insights – Executive Summary."

[12] International Energy Agency (IEA) (2020) *World Energy Investment 2020*, May 2020. https://www.iea.org/reports/world-energy-investment-2020

While the EU strategy sets a solid foundation for developing a hydrogen economy, it defines specific targets only up to 2030, leaving the door open to different interpretations on what future hydrogen markets might or should look like post-2030. A fundamental question remains thus unanswered: From where can the EU source competitive and secure renewable hydrogen at scale?

Our prior work on renewable hydrogen's global geopolitical and market implications shows how countries will likely assume specific roles in global renewable hydrogen markets based on their renewable energy and water endowments as well as their infrastructure potential.[13] Recent estimates of global renewable hydrogen potentials[14] and production costs[15] have confirmed our results. As discussed in a previous publication,[16] while some resource-rich member states, like Spain, can become regional exporters, no member state can evolve into a global export champion. However, regional or long-distance partners like Morocco and the United States have this potential. They could thus play a significant role in EU hydrogen markets by providing cost-competitive renewable hydrogen supplies.

Although a rapidly growing body of literature explores technological and economic aspects of large-scale clean hydrogen production[17] and its geopolitical and market implications,[18] a detailed scenario analysis evaluating competitive, secure, and diversified supply options for bridging production gaps for the EU bloc is missing. Several reasons explain this gap in the academic literature. On the one hand, the economics of

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[13] Pflugmann and De Blasio (2020) *Geopolitical and Market Implications of Renewable Hydrogen*.

[14] Heuser et al. (2020) "Worldwide Hydrogen Provision Scheme Based on Renewable Energy," Energy and Fuel Technology Preprints, February 2020, pp. 1–27. https://www.preprints.org/manuscript/202002.0100/v1; Fasihi et al. (2021) "Global Potential of Green Ammonia Based on Hybrid PV-Wind Power Plants," *Applied Energy*, 294(October), p. 116170. https://doi.org/10.1016/j.apenergy.2020.116170

[15] Brändle et al. (2021) "Estimating Long-Term Global Supply Costs for Low-Carbon Hydrogen," *Applied Energy*, 302(20), pp. 117481. https://doi.org/10.1016/j.apenergy.2021.117481

[16] Pflugmann and De Blasio (2020) "The Geopolitics of Renewable Hydrogen in Low-Carbon Energy Markets," *Geopolitics, History, and International Relations*, 12(1), pp. 9–44. https://www.ceeol.com/search/article-detail?id=877414

[17] El-Emam and Özcan (2019) "Comprehensive Review on the Techno-Economics of Sustainable Large-Scale Clean Hydrogen Production," *Journal of Cleaner Production*, 220, pp. 593–609. https://doi.org/10.1016/j.jclepro.2019.01.309

[18] For example, footnote 16 as well as Van de Graaf et al. (2020) "The New Oil? The Geopolitics and International Governance of Hydrogen," *Energy Research and Social Science*, 70(June), p. 101667. https://doi.org/10.1016/j.erss.2020.101667

renewable hydrogen production[19] and its long-term evolution[20] have often been addressed independently from the evaluation of renewable hydrogen's global production potential. The literature has focused on more technological aspects, such as hydrogen network designs.[21] On the other hand, when renewable hydrogen potentials and costs have been assessed for the EU, analyses have disregarded geographical differences,[22] limited trades to European countries[23] or excluded them altogether,[24] or focused only on the short-term.[25] In addition, key variables such as freshwater availability and different infrastructure potentials are often overlooked.

Our report addresses this knowledge gap through the lenses of three reference scenarios to meet renewable hydrogen demand in the EU by 2050. Each scenario prioritizes a key but competing need—energy independence, cost optimization, or energy security—while focusing on a specific supply strategy—internal, regional, or long-distance. By considering renewable hydrogen production and transportation costs, the analyses in this report bridge the gap between qualitative analyses of geopolitical and market implications and scattered quantitative analyses of production potential and cost in the literature. Most importantly, this work contributes to a deeper understanding of the nascent dynamics of a hydrogen economy so that policymakers and investors can better navigate the challenges and opportunities of a low-carbon economy without falling into the traps and inefficiencies of the past.

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[19] Glenk and Reichelstein (2019) "Economics of Converting Renewable Power to Hydrogen," *Nature Energy*. Springer US, 4(3), pp. 216–222. https://doi.org/10.1038/s41560-019-0326-1

[20] See footnote 15.

[21] Baufumé et al. (2013) "GIS-Based Scenario Calculations for a Nationwide German Hydrogen Pipeline Infrastructure," *International Journal of Hydrogen Energy*, 38(10), pp. 3813–3829. https://doi.org/10.1016/j.ijhydene.2012.12.147 and Welder et al. (2018). "Spatio-Temporal Optimization of a Future Energy System for Power-to-Hydrogen Applications in Germany," *Energy*, 158, pp. 1130–1149. https://doi.org/10.1016/j.energy.2018.05.059

[22] Lux and Pfluger (2020) "A Supply Curve of Electricity-Based Hydrogen in a Decarbonized European Energy System in 2050," *Applied Energy*, 269(May), p. 115011. https://doi.org/10.1016/j.apenergy.2020.115011

[23] Blanco et al. (2018) "Potential for Hydrogen and Power-to-Liquid in a Low-Carbon EU Energy System Using Cost Optimization," *Applied Energy*, 232(June), pp. 617–639. https://doi.org/10.1016/j.apenergy.2018.09.216

[24] Kakoulaki et al. (2021) "Green Hydrogen in Europe – A Regional Assessment: Substituting Existing Production with Electrolysis Powered by Renewables," *Energy Conversion and Management*, Vol. 228, Jan. 2021, p. 113649. https://doi.org/10.1016/j.enconman.2020.113649

[25] Andreola et al. (2021) "No-Regret Hydrogen: Charting Early Steps for H_2 Infrastructure in Europe," AFRY Management Consulting for Agora Energiewende. https://www.agora-energiewende.de/en/publications/no-regret-hydrogen/

The remainder of the report is structured as follows: Section 2 analyzes the EU's hydrogen strategy and value chains. Section 3 outlines the three reference scenarios and long-term EU hydrogen demand. Section 4 elucidates the three-step methodology used to investigate the reference scenarios. Section 5 analyzes the viability of each reference scenario. Section 6 addresses cost competitiveness through production cost curves. Section 7 evaluates supply costs, trade flows, and investment needs for each reference scenario and associated sensitivity analyses. Section 8 addresses policy implications. Finally, Section 9 outlines options for future research.

2. Hydrogen in the European Union

This section analyzes EU[26] hydrogen markets and the key aspects of the bloc strategy to 2050.[27]

2.1. Hydrogen Supply and Demand

EU hydrogen demand stands at 7.8 Mt, equivalent to about 11% of global demand.[28] Refining and fertilizers account for 3.9 Mt (50%) and 2.4 Mt (30%), respectively (Figure 1). Consumption for energy and transportation accounts for about 1.2%.[29]

Germany and the Netherlands are the largest consumers of hydrogen, accounting for over a third of EU demand with 1.7 Mt (22%) and 1.3 Mt (17%), respectively. Countries with demands of 0.5 Mt or more include Poland, Spain, Italy, Belgium, and France. The remaining member states collectively account for about 25% of the total demand, with national demands below 0.2 Mt each.

Overall, EU production capacity stands at about 11.3 Mt/yr (Figure 2).[30] Steam methane reforming (SMR)[31] accounts for 77%, while SMR with carbon capture and storage (SMR+CCS) and water electrolysis amount to 0.4% and 0.1%, respectively. The remaining production capacity includes industrial processes, where hydrogen is obtained as a by-product, such as coal coking,[32] and the production of chemicals such as ethylene, styrene, and chlorine.

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[26] Unless otherwise stated, all references to the European Union include the post-Brexit 27 member states.

[27] EC (2020).

[28] Fuel Cell and Hydrogen Observatory (FCHO) (2020) *Hydrogen Molecule Market*, FCHO Reports. https://www.fchobservatory.eu/sites/default/files/reports/Chapter_2_Hydrogen_Molecule_Market_070920.pdf

[29] Energy applications refer to hydrogen combustion in boilers or combined heat and power units. Uses classified as "others" include chemical production, such as methanol and hydrogen peroxide, applications in the food industry, glass manufacturing, automotive, metal welding and cutting, electronics, and research labs.

[30] FCHO (2020).

[31] Methane is the main component of natural gas.

[32] Coal coking is a process used to produce carbon coke, also known as metallurgical coal, a key raw material in steel making. Coal gas is one of the byproducts.

Germany has the largest hydrogen production capacity with 2.4 Mt/yr (21%), followed by the Netherlands with 1.7 Mt/yr (15%) and Poland with 1.4 Mt/yr (12%). Italy, France, Spain, and Belgium have capacities above 0.5 Mt/yr and amount to 27% of the total.

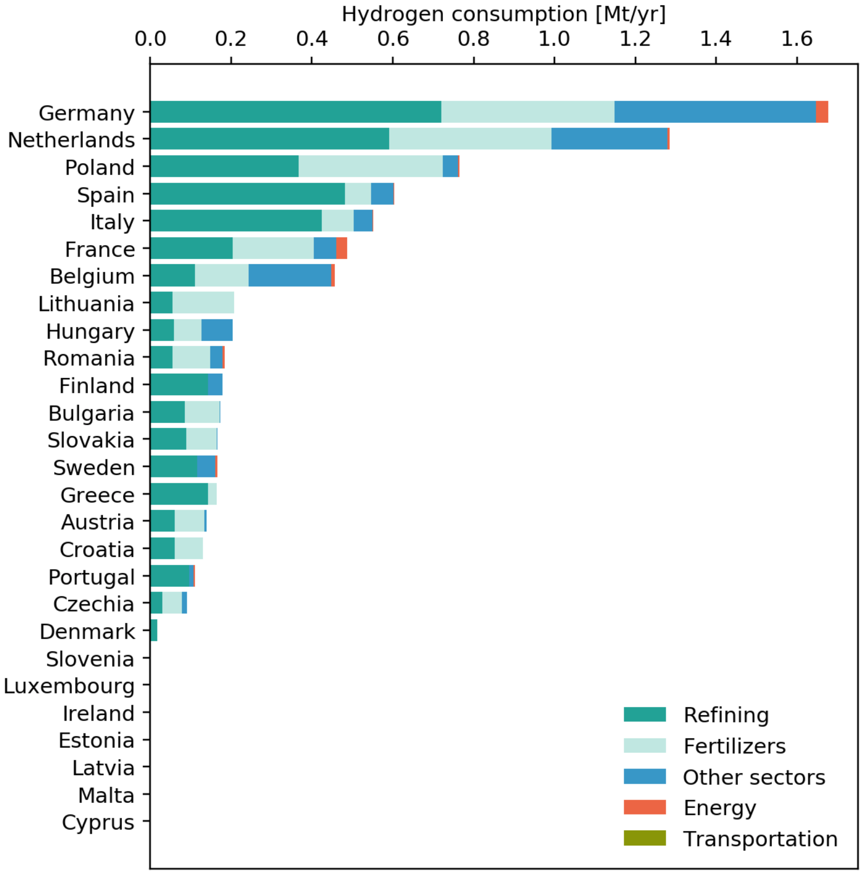

Figure 1. EU hydrogen consumption by country and sector
Source: Authors' elaboration based on FCHO (2020) data

Overall, EU hydrogen demand is mainly met by captive productions—hydrogen produced and used directly within integrated industrial sites owned by a single organization—as the 2020 EU's Fuel Cells and Hydrogen Observatory (FCHO) report highlights.[33] About 88% of the total capacity is captive; merchant facilities that account for the remaining 12% often supply single customers, resulting in small and localized markets. This market structure not only limits hydrogen availability to new players, but it is also responsible for the lack of an integrated infrastructure across the EU—one of the key challenges facing hydrogen deployment at scale.

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[33] FCHO (2020).

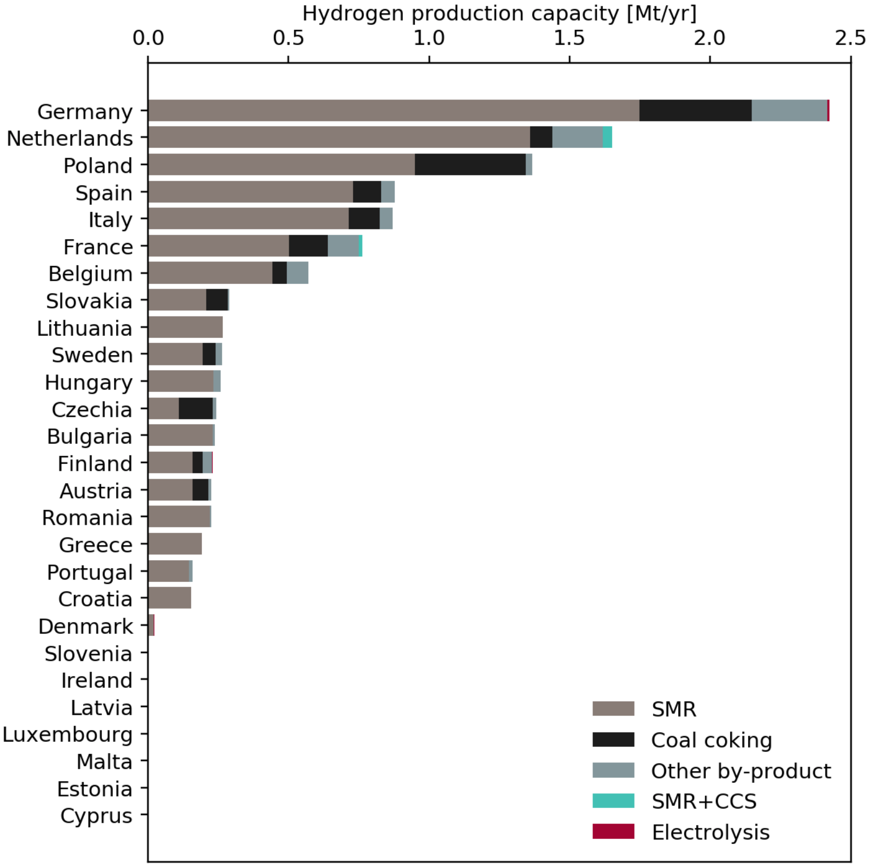

Figure 2. EU hydrogen production capacity by country and technology
Source: Authors' elaboration based on FCHO (2020) data

2.2. **The EU's Hydrogen Strategy**

In July 2020, the European Commission (EC) published the EU's hydrogen strategy,[34] a three-phased plan (2020-24, 2024-30, and 2030-50) that prioritizes renewable hydrogen produced by wind- and solar-powered water electrolysis. The plan acknowledges that other forms of low-carbon hydrogen, such as blue hydrogen (SMR+CCS), could play a role in developing hydrogen markets, but only as an interim solution in the short- to medium-term.

For the first two phases, the strategy defines deployment targets for electrolyzers of 6 GW by 2024 and 40 GW by 2030, which the EC estimates would allow to produce about 10 Mt/yr of hydrogen.[35] The third phase is even more ambitious and aims to deploy renewable hydrogen at scale for all hard-to-abate sectors. Yet the strategy does not set any specific supply target either for internal production or imports, leaving unclear how member states could meet long-term demand.

The EU's strategy incorporates and validates the set of recommendations highlighted in our prior work on the geopolitical and market implications of renewable hydrogen adoption in the EU.[36] The EC's goal to achieve "an open and competitive EU hydrogen market [by 2030], with unhindered cross-border trade and efficient allocation of hydrogen supplies among sectors,"[37] is based on the belief that resource-rich member states should develop their hydrogen industries beyond domestic production needs and become regional exporters supplying renewable-constrained member states.

The strategy also recognizes that renewable hydrogen "offers new opportunities for re-designing Europe's energy partnerships with both neighboring [and] international [-] partners, advancing supply diversification and helping design stable and secure supply chains."[38]
By citing hydrogen supply diversification, the EU strategy builds on our

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[34] EC (2020).

[35] Ibid. Page 6.

[36] Pflugmann and De Blasio (2020) *Geopolitical and Market Implications of Renewable Hydrogen*.

[37] EC (2020). Page 7.

[38] Ibid. Page 19.

assessment of the crucial roles that hydrogen export champions could play in the bloc's energy supply mix.

In summary, while the overall strategy sets a solid foundation for creating an EU hydrogen economy, it only provides specific targets up to 2030, leaving the door open to different interpretations on what the continent's hydrogen markets might or should look like beyond 2030.

But realizing hydrogen's full potential requires careful policy consideration of competing needs and demands. Therefore, it is essential to plan now since the effects of today's policy choices will be felt decades into the future. This is even more true for the development and deployment of the required enabling infrastructure. Hence, synchronizing investments with growth in supply and demand will be key but challenging. This approach will require clear strategies and implementation plans to avoid falling into the traps and inefficiencies of the past.

To address this challenge, this report uses three reference scenarios that target 2050 and prioritize key but competing needs: energy independence, cost (optimization), and energy security.

3. Demand Outlook and Reference Scenarios

3.1. Hydrogen Demand Outlook by 2050

The EU's future energy demand and hydrogen's share remain highly uncertain. Although the EU's strategy does not mandate specific hydrogen consumption levels, it references multiple projections in which energy demand ranges between 5.6 and 11.4 PWh by 2050, together with a hydrogen share of 1% to 23%.[39]

Despite the wide variations in projections, the transition to a low-carbon economy and the need to decarbonize hard-to-abate sectors will significantly increase hydrogen demand across all scenarios. For the following analyses, EU hydrogen demand by 2050 is assumed to be equivalent to 15% of current primary energy consumption or about 76 Mt/yr, in good alignment with recent literature (see Figure 3).[40]

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[39] EU Joint Research Center (JRC) (2019) "Hydrogen Use in EU Decarbonisation Scenarios," EU Science Hub, last update 9 July 2020, accessed 20 September 2021, JRC116452. https://web.archive.org/web/20201214082537/https://ec.europa.eu/jrc/sites/jrcsh/files/final_insights_into_hydrogen_use_public_version.pdf

[40] See also Dos Reis, PC (2021) "Hydrogen Demand: Several Uses but Significant Uncertainty," European University Institute Florence School of Regulation, 18 January 2020. https://fsr.eui.eu/hydrogen-demand-several-uses-but-significant-uncertainty/

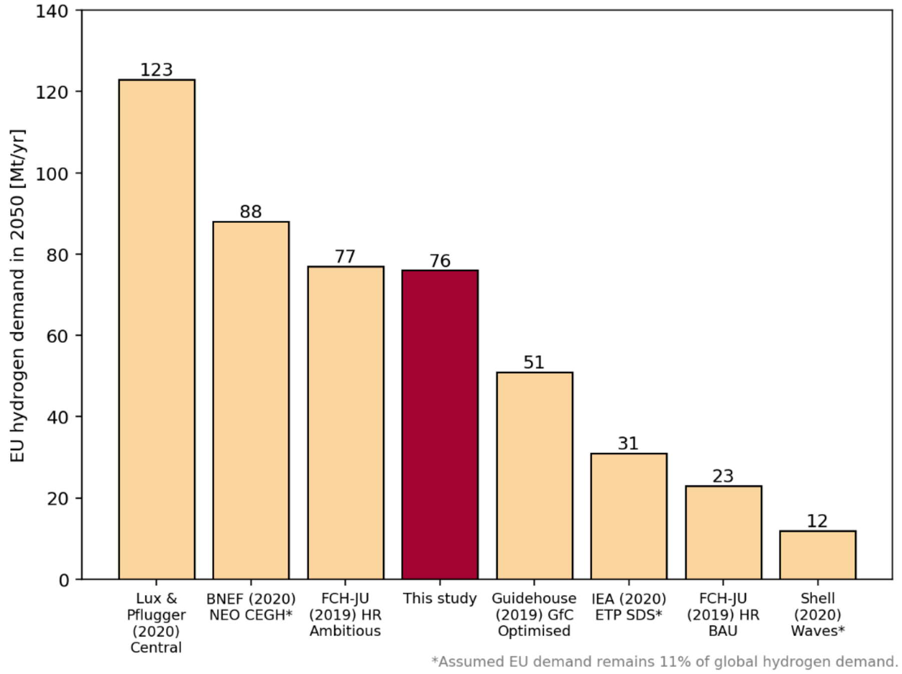

Figure 3. EU hydrogen demand in 2050 in selected scenarios
Source: Authors' elaboration

3.2. **Reference Scenarios**

Ensuring that renewable hydrogen supplies will meet future demand requires the development of a clear long-term strategy. Even if member states were to meet electrolyzer deployment targets for 2030, cumulative renewable hydrogen production would only amount to about 10 Mt/yr.[41] Thus, supply would still need to increase eight-fold by 2050. Hence, a detailed scenario analysis is needed to evaluate competitive, secure, and diversified supply options for bridging this production gap.

To this end, our research analyzes three reference scenarios that focus on internal, regional, or long-distance renewable hydrogen supplies (Table 1). These scenarios allow us to consider the key strategic variables that countries need to take into account when assessing their role in future energy markets: energy independence, cost (optimization), and energy security. Depending on which variable is prioritized, each scenario includes a different set of countries whose renewable hydrogen production could contribute to meeting the overall EU demand.

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[41] As estimated by the European Commission in EC (2020).

- **Hydrogen Independence:** the EU prioritizes energy independence and develops internal, self-sufficient renewable hydrogen markets.
- **Regional Imports:** the EU prioritizes cost optimization by complementing the lowest-cost internal production with imports from neighboring export champions (Morocco and Norway) and renewable-rich countries (Iceland and Egypt).
- **Long-Distance Imports:** the EU prioritizes energy security and cost optimization by combining long-distance imports from export champions (Australia and the United States) with regional imports and internal production.

Table 1. Reference scenarios

Scenario	Priority	Description	Countries
Hydrogen Independence	*Energy Independence*	Demand met with EU internal production only	EU member states
Regional Imports	*Cost Optimization*	EU internal lowest-cost production complemented with imports from regional neighbors	Regional neighbors and EU member states
Long-Distance Imports	*Energy Security*	Long-distance imports complement EU and regional supplies	Long-distance export champions, regional neighbors and EU member states

Building on the results from our previous work on the role countries can play in future renewable hydrogen markets, we selected relevant countries for each scenario (see Table 2).[42] All member states are considered in the hydrogen independence scenario, even if they are renewable-constrained or have low infrastructure potential. Regional partners are renewable-rich countries with high infrastructure potentials that neighbor the EU (i.e., groups 1, 2, and 4, see Table 2).[43] Finally, Australia and the United States are given as examples of global export champions. As discussed, our analysis focuses on renewable hydrogen; however, if we were to include other low-carbon hydrogen supplies—such as blue hydrogen—new

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[42] See Pflugmann and De Blasio (2020) *Geopolitical and Market Implications of Renewable Hydrogen* for a detailed discussion of the country classification.

[43] Countries excluded due to renewable potential constraints (group 3) are Israel, Switzerland, and the United Kingdom. Countries excluded due to low infrastructure potential (group 5) are Algeria, Bosnia and Herzegovina, Georgia, Lebanon, Libya, Russia, Tunisia, and Ukraine. Small states (e.g., Andorra, Liechtenstein, Monaco, San Marino, and the Vatican) and regions with insufficient data available (e.g., Belarus, Moldova, Montenegro, North Macedonia, Palestine, Serbia, and Syria) are also excluded.

potential partners such as Saudi Arabia would emerge, and the role of partners like the United States would need to be reassessed (see textbox *Blue Hydrogen: The Steppingstone*).

Table 2. Country classification
Source: Authors' elaboration based on Pflugmann and De Blasio (2020) *Geopolitical and Market Implications of Renewable Hydrogen*

Group	European Union countries	Regional partners	Long-distance partners
1. Export champions	-	Morocco, Norway	Australia, United States
2. Renewable-rich but water-constrained	Cyprus, Hungary, Malta	Egypt	
3. Renewable-constrained with high infrastructure potential	Austria, Belgium, Czech Republic, Germany, Italy, Luxembourg, Netherlands, Slovenia		
4. Resource-rich with high infrastructure potential	Croatia, Denmark, Estonia, Finland, France, Greece, Ireland, Latvia, Lithuania, Poland, Portugal, Spain, Sweden	Albania, Iceland, Turkey	
5. Resource-rich with low infrastructure potential	Bulgaria, Romania		

Blue Hydrogen: The Steppingstone

Blue hydrogen from natural gas reforming with carbon capture and storage is a promising production route for low-carbon hydrogen. Imports of blue hydrogen from natural gas-rich countries like Russia, Norway, Saudi Arabia, and even the United States could become an alternative to green hydrogen for the EU.

Blue hydrogen production costs are expected to remain lower than those for renewable hydrogen until 2030, but this will depend mainly on the evolution of natural gas prices.[44] For this reason, many believe blue hydrogen could act as a steppingstone in the transition to a low-carbon economy. However, blue hydrogen is not carbon neutral and even though high capture rates can be achieved with existing technologies, the production process would still entail significant greenhouse gas emissions.[45]

Alternatively, the existing natural gas infrastructure could be leveraged to ship natural gas to the EU and produce blue hydrogen onsite, with the option of either sequestering the CO_2 locally or shipping it back to the country of origin.

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[44] See for example: IEA (2019) *The Future of Hydrogen*.

[45] Life-cycle emissions analysis by the Hydrogen Council estimates a wide range between 0.8 and 11.0 kg CO_2eq per kg of hydrogen, while recent research that incorporates methane leaks estimates them between 6.8 and 16.7 kg CO_2eq per kg of hydrogen. See among others: Bauer et al. (2021) "On the Climate Impacts of Blue Hydrogen Production," *Sustainable Energy & Fuels*. https://doi.org/10.1039/D1SE01508G; Hydrogen Council (2021) "Hydrogen Decarbonization Pathways: A Life-Cycle Assessment," January 2021. https://hydrogencouncil.com/wp-content/uploads/2021/01/Hydrogen-Council-Report_Decarbonization-Pathways_Part-1-Lifecycle-Assessment.pdf; Howarth and Jacobson (2021) "How Green Is Blue Hydrogen?" *Energy Science and Engineering*, (July), pp. 1–12. https://doi.org/10.1002/ese3.956

4. **Methodology**

Each scenario analysis consists of three steps: (1) overall renewable hydrogen potentials are calculated for each country (based on renewable, freshwater, and land availability; infrastructure potential; and competing demand for renewable electricity); (2) each country's production cost curves are computed (based on local renewable electricity and electrolyzers costs); and (3) renewable hydrogen trades are optimized to evaluate overall supply costs and investment requirements.

4.1. **Resource Potential Assessment**

Following the methodology developed by Pflugmann and De Blasio (2020),[46] the first step assesses whether renewable hydrogen production potentials for the scenario countries could meet overall EU demand. The analysis considers available renewable energy and freshwater resources, infrastructure potential, and competing demand for renewable electricity.

Available renewable energy resources in each country are calculated based on peer-reviewed databases of renewable electricity potentials.[47,48] Land availability for renewables is derived by deducting protected natural areas and built urban environments for overall surface area. In addition, remote and uneconomic resources are excluded, which aligns with recent literature (See Appendix - Table 5).[49] The equivalent of each country's current primary energy consumption is assumed to be used in other sectors or remain underdeveloped to account for competing renewable electricity demand.[50] The resulting renewable energy potentials are then utilized to calculate renewable hydrogen production potentials—assuming an electrolysis efficiency of 74%, as projected by the International Energy Agency (IEA).[51]

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[46] Pflugmann and De Blasio (2020) *Geopolitical and Market Implications of Renewable Hydrogen*.

[47] Eurek et al. (2017) "An Improved Global Wind Resource Estimate for Integrated Assessment Models," *Energy Economics*, 64(February), pp. 552–567. https://doi.org/10.1016/j.eneco.2016.11.015

[48] Pietzcker et al. (2014) "Using the Sun to Decarbonize the Power Sector: The Economic Potential of Photovoltaics and Concentrating Solar Power," *Applied Energy*, 135(December), pp. 704-720. https://doi.org/10.1016/j.apenergy.2014.08.011

[49] Kakoulaki et al. (2021).

[50] Primary energy data from BP (2020) "Statistical Review of World Energy," accessed 1 December 2020. https://www.bp.com/en/global/corporate/energy-economics/statistical-review-of-world-energy.html

[51] IEA (2019) *The Future of Hydrogen*.

Two factors could further constrain a country's renewable hydrogen potential: freshwater resources and infrastructure availability. Assuming that 9 kg of water is needed per kg of hydrogen produced,[52] water availability is limited to 5% of each country's internal renewable freshwater resources. For reference, the average water withdrawal for industrial use worldwide equals to 13%.[53]

Finally, since no country today has hydrogen infrastructure deployed at scale, in order to assess a country's ability to build and operate future hydrogen production, transportation, and distribution infrastructure, we must rely on the status of its existing infrastructure. Thus our proxy is the overall infrastructure score in the World Economic Forum's 2019 Global Competitiveness Index.[54] Countries with scores below 4 (on a 1-7 scale) are classified as infrastructure constrained.[55]

See Section 5 for a detailed analysis.

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[52] Water consumption based on the chemical reaction in the electrolyzer.

[53] United Nations Food and Agriculture Organization (UN FAO) (2020) AQUASTAT Core Database, Food and Agriculture Organization of the United Nations, accessed 1 December 2020. http://www.fao.org/aquastat/en/databases/maindatabase/

[54] World Economic Forum (WEF) (2019) *World Economic Forum's 2019 Global Competitiveness Report*.

[55] Bulgaria and Romania were not excluded from the analysis because access to European support mechanisms could facilitate the development of hydrogen infrastructure in these EU countries.

4.2. **Production Cost-Competitiveness Analysis**

The second step requires calculating hydrogen production costs for every country and evaluating the cost competitiveness of each reference scenario.

Production costs are computed as the levelized cost of hydrogen (LCOH) over the lifetime of electrolysis plants.[56] Economic and financial parameters, including a discount rate of 8%, are based on long-term technology cost projections by the IEA and the International Renewable Energy Agency (IRENA) (see Table 3).[57] Production costs for all renewable energy resources are then compiled into cost curves.

Table 3. Economic parameters for estimating renewable hydrogen production costs

Parameter	Units	PV	Onshore wind	Offshore wind	Electrolyzer
Investment costs (CAPEX)	[USD/kW]	407	1,273	1,720	450
Operation and maintenance costs (OPEX)	[% CAPEX per year]	2.5%	2.9%	2.5%	1.5%
Lifetime	[years]	25	25	25	20
Electrical efficiency	[%]*	-	-	-	74%

*Based on hydrogen's lower heating value (LHV).

See Section 6 for cost-competitiveness evaluations for each scenario.

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[56] See 10.2 in the Appendix.

[57] See 10.1 in the Appendix.

4.3. **Hydrogen Trade Optimization**

The methodology's third step consists of a hydrogen trade optimization to evaluate overall supply costs and investment requirements for each reference scenario.

To this end, we developed MIGHTY (Model for International Green Hydrogen Trade), which optimizes renewable hydrogen trades between countries by minimizing supply costs—defined as the sum of production and transportation costs.[58]

From an infrastructure perspective, hydrogen's low volumetric energy density and liquefaction temperatures of around -253°C (-423°F) make transportation a key variable. To address this, MIGHTY considers three different alternatives:

1. **Hydrogen Gas Pipelines**, in which hydrogen is dispatched as a compressed gas.
2. **Liquefied Hydrogen Shipping**, in which hydrogen is liquefied at export terminals, shipped, and finally regasified at import terminals.
3. **Ammonia Shipping**, in which hydrogen is used to produce ammonia, which is shipped and then converted back into hydrogen at the destination.

All continental member states are assumed to deliver hydrogen by pipeline instead of shipping because costs are lower for distances under 1,000 to 2,000 km (see Figures 4 and 5). In contrast, North African countries, island states, and long-distance partners are assumed to ship either hydrogen or ammonia to the EU.[59]

Ammonia, which contains 17.65% hydrogen by weight, is a staple in the energy sector and is mainly used to produce fertilizers and other chemicals. Ammonia is considered an alternative to liquefied hydrogen transportation thanks to its higher volumetric energy density and easier

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[58] See 10.3 in the Appendix for a model overview.

[59] See 10.4 in the Appendix.

liquefaction at -33°C (-28°F), resulting in lower transportation costs (see Figure 5). Furthermore, it can leverage existing technologies and infrastructure.[60]

Economic parameters for transportation costs assume the deployment of new infrastructure and are in line with the IEA and recent literature.[61]

MIGHTY was explicitly designed to provide more precise evaluations of transportation costs than other mathematical models, thanks to two key features. First, enabling infrastructure needs are calculated as a function of traded volumes and distances, which significantly impact overall costs both for pipelines and ships (see Figures 4 and 5). Second, minimum volume considerations prevent mathematically correct but uneconomical routes from being part of the model's solution.[62]

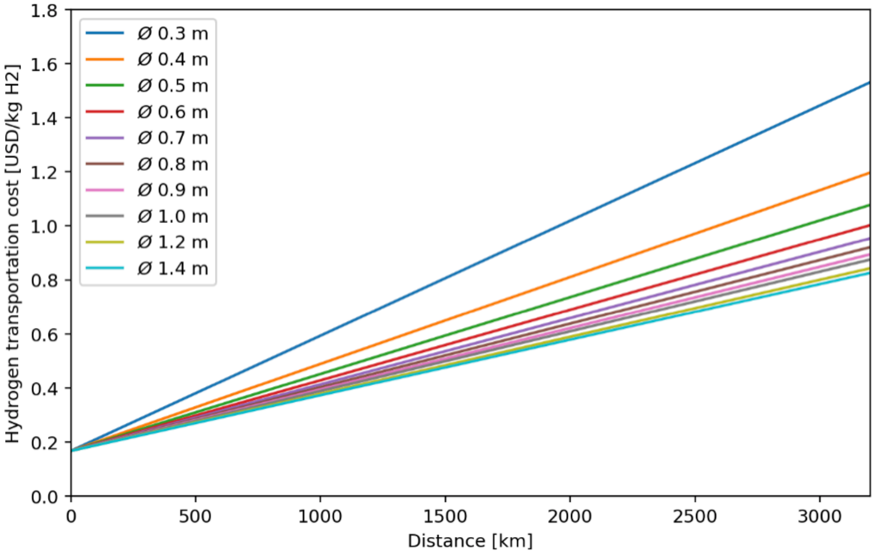

Figure 4. Hydrogen transportation costs by pipeline
Source: Authors' analysis

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[60] Global ammonia trade, including transoceanic routes, is expected to have reached 19 Mt/yr in 2021 according to Argus Media (2021).

[61] See 10.1 in the Appendix.

[62] Minimum trade flows set at 100 kt/yr for long-distance importers, 10 kt/yr for regional importers, and 1 kt/yr for internal EU trade.

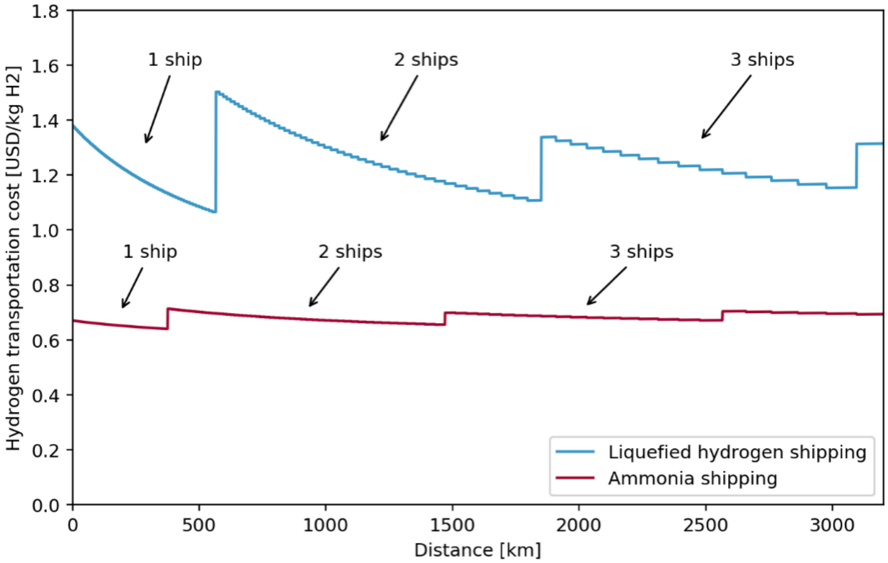

Figure 5. Hydrogen transportation costs by ship
Source: Authors' analysis for shipping 1 Mt/yr from North Africa to the EU

See Section 7 for the analysis of hydrogen trade in each reference scenario.

5. **Renewable Hydrogen Potential**

This section analyzes renewable hydrogen potentials for each country to assess the viability of each reference scenario.

5.1. **Renewable Hydrogen Potentials in the EU and Trade Partners**

In line with our previous research (see Table 2),[63] the detailed quantitative analysis of renewable hydrogen potentials for each country shows that only a small number of member states could become regional exporters (group 4 in Table 2), and that no member state has the potential to develop into an export champion. All EU member states have moderate or low potentials (see Figure 6). Central European countries such as Germany and the Netherlands have the lowest, while countries in the EU's periphery such as Spain, Portugal, Ireland, and the Baltic States[64] have the largest, ranging from 4 to 22 Mt/yr.

In contrast, neighboring countries like Morocco and Norway and long-distance partners like Australia and the United States all have the potential to emerge as global export champions. Morocco dominates with more than 161 Mt/yr among regional partners, followed by Norway and Iceland with about 16 Mt/yr each. Turkey and Albania's potentials are significantly limited by the low cost-competitiveness of their renewable energy resources. Finally, potentials for Australia and the United States are orders of magnitude larger than any other country considered, with 2,733 Mt/yr and 1,810 Mt/yr, respectively.

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[63] See Pflugmann and De Blasio (2020) *Geopolitical and Market Implications of Renewable Hydrogen* for a detailed discussion of the country classification.

[64] Estonia, Latvia, and Lithuania.

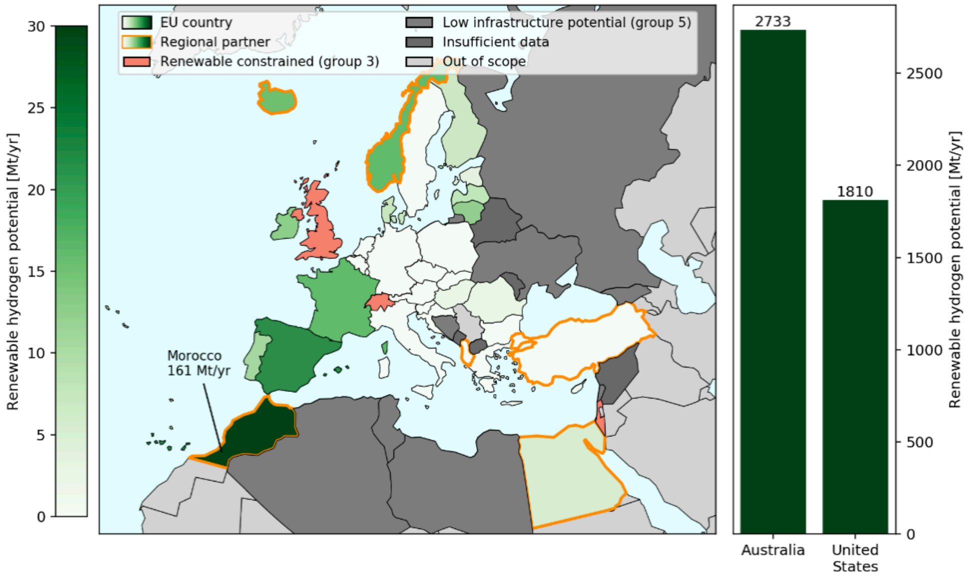

Figure 6. Renewable hydrogen potentials by 2050
Source: Authors' analysis

Our analysis reveals that fifteen member states would not be able to meet internal future hydrogen demands.[65] Countries like Germany, the Netherlands, and Italy are constrained by low renewable energy resources and/or land availability, as well as intense competition for renewable electricity in other sectors. Only a few EU countries—Portugal, Spain, and France in the south, Ireland in the northwest, Finland and the Baltic States in the northeast—have potentials that could fulfill internal demand and allow them to emerge as regional exporters. These uneven renewable hydrogen potentials across the EU highlight, once more, the key role cross-border cooperation and infrastructure planning will play in enabling fully functioning hydrogen markets in all reference scenarios.

Finally, the large production potentials in regional and long-distance partners greatly exceed future EU hydrogen demand making both the Regional and Long-Distance Import scenarios viable. As for the Hydrogen Independence scenario, overall viability depends on whether excess production by EU regional exporters can fill the gap of the more than half of member states who cannot meet internal demand.

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[65] Austria, Belgium, Bulgaria, Croatia, Czechia, Germany, Greece, Italy, Luxembourg, Malta, the Netherlands, Poland, Slovakia, Slovenia, and Sweden.

5.2. **Hydrogen Independence Scenario**

The EU's combined renewable hydrogen production potential of 106 Mt/yr is higher than the projected demand of 76 Mt/yr (see Figure 7), confirming the viability of the Hydrogen Independence scenario. At the same time, our analysis shows that in order for this scenario to materialize, key requirements must be met:

- At least two-thirds of the EU demand (48 Mt/yr) must be fulfilled from production by member states who have the potential to evolve into regional exporters.[66]
- As much as one-third of total demand (up to 28 Mt/yr) must be met by each country's self-consumption.

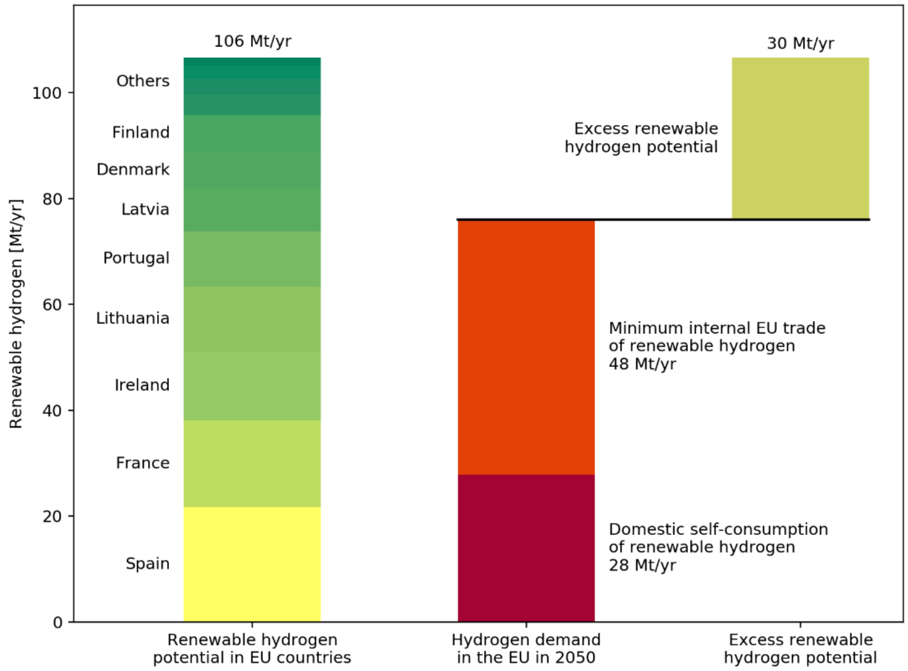

Figure 7. EU 2050 renewable hydrogen market outlook
Source: Authors' analysis

The excess production potential of 30 Mt/yr has significant market implications because EU regional exporters could produce much more hydrogen than is required to fill the EU overall demand gap. Therefore, member states could import renewable hydrogen from regional exporters

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[66] This number takes into consideration only renewable hydrogen potentials, without any cost optimization considerations. As discussed later in the paper, also taking into consideration a cost optimization, the needed trades between member states would need to account for almost 70% (or 52 Mt/yr).

when it is cheaper to import than to internally produce. While the excess production potential could significantly impact EU overall supply costs, this outcome would require fully functioning transnational markets and infrastructure deployment at scale.

As the above analysis has shown, hydrogen trade will play a critical role in future EU hydrogen markets. Our results underscore the need for an integrated policy strategy that supports the design and deployment of functioning markets and the deployment of an enabling infrastructure that connects supply and demand centers across the continent.

In summary, all three reference scenarios are viable alternatives to meet overall demand. However, realizing the EU's full hydrogen potential will require careful policy consideration of competing needs. While market economics must be the driving force behind production and demand decisions, regulatory incentives will play a pivotal role in designing and deploying enabling infrastructure at scale. It is essential to plan for the future now since the effects of policy choices made today will be felt decades in the future.

6. Renewable Hydrogen Cost Curves

In this section, we analyze renewable hydrogen cost curves to assess the relative competitiveness of the three reference scenarios.

In general, cost curves are graphs of production costs as a function of total quantities produced. In free-market economies, stakeholders optimize production by minimizing costs associated with each level of production.

In order to highlight key cost-competitiveness factors between reference scenarios, production costs in each curve are also represented as a function of renewable electricity, electrolysis, and operating costs.

6.1. Cost Curves in the Hydrogen Independence Scenario

EU renewable hydrogen cost curves elucidate the competitiveness of both the Hydrogen Independence scenario and overall EU hydrogen production in the scenarios that include imports. Depending on how much hydrogen can be produced internally at a competitive price, EU production will supply a larger or smaller share of total demand compared to imports.

Renewable hydrogen cost curves for the member states that have the potential to become regional exporters[67] show significant differences in production costs between EU countries (see Figure 8), ranging from 2.7 to 4.4 USD/kg. Ireland, Cyprus, and Portugal have the most competitive potentials with production costs below 3 USD/kg thanks to wind energy resources with high capacity factors.[68] On the other hand, Romania and Hungary have the least competitive potentials due to solar energy with low capacity factors that lead to production costs of over 4 USD/kg.

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[67] Member states in which production potential exceeds projected internal demand of hydrogen.

[68] Wind power typically allows for higher electrolyzer loads thanks to its higher capacity factors. As reported by the International Renewable Energy Agency (IRENA) (2021) *Renewable Power Generation Costs in 2020*, onshore wind has an average capacity factor of 36%, compared to only 16% for solar. Thus, renewable hydrogen potentials tied to wind energy yield lower electrolysis costs.

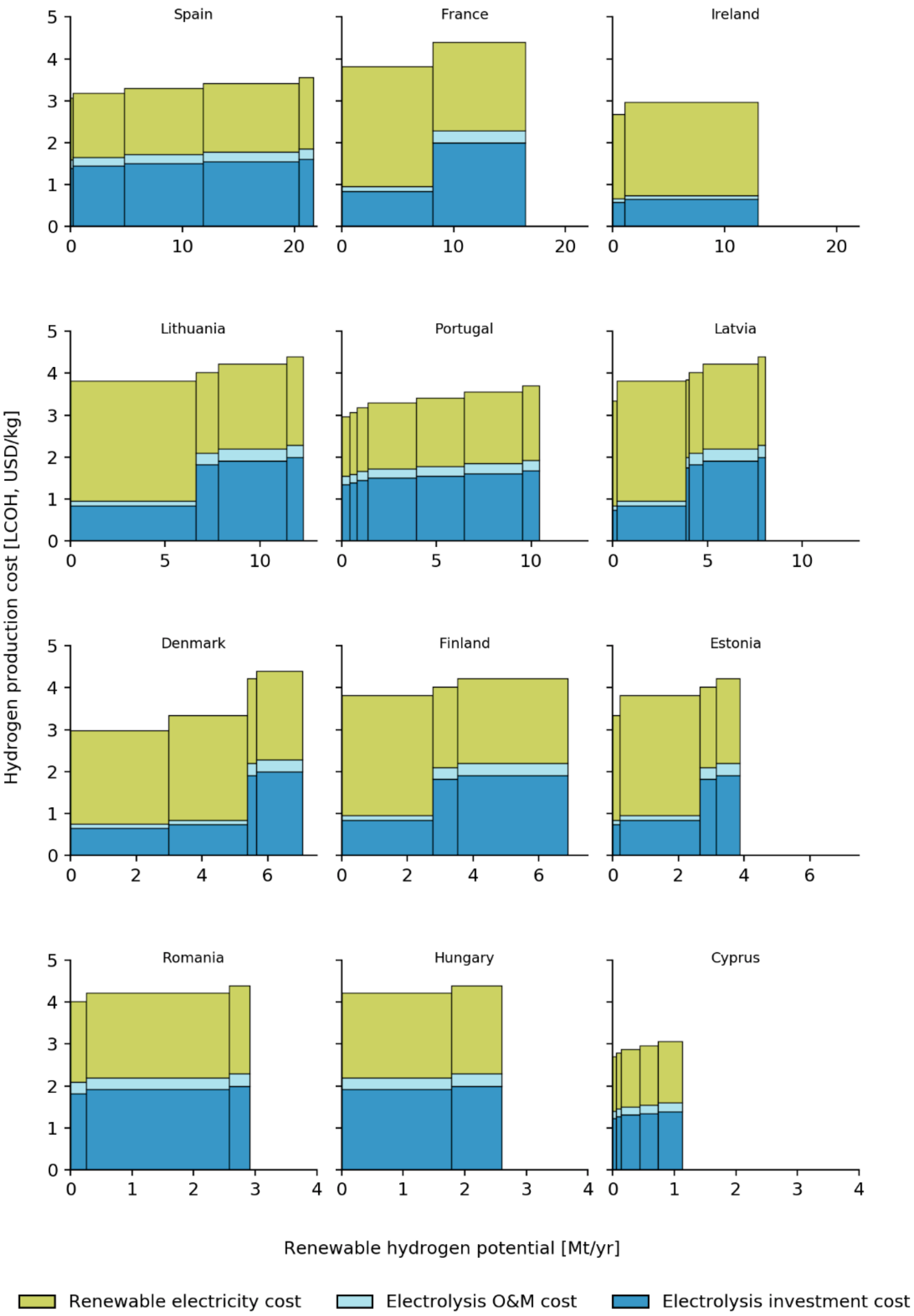

Figure 8. Renewable hydrogen cost curves in selected EU countries
Source: Authors' analysis

Low and flat renewable hydrogen cost curves highlight how countries can remain cost-competitive as they ramp up overall production. For example, Ireland and Spain could produce nearly 13 and 22 Mt/yr with costs between 2.7-3.0 USD/kg and 3.1-3.6 USD/kg respectively. In contrast, countries with steep cost curves like Denmark will experience rising costs as they scale up production. For example, growing Danish renewable hydrogen production from 2 to 6 Mt/yr would increase costs from 3.0 to 4.3 USD/kg. In other words, countries with low and flat cost curves like Ireland and Spain would be able to develop their full production potentials with competitive pricing. In contrast, those with steep curves might be able to leverage only a fraction of their production potential before costs become uncompetitive compared to production costs in other countries.

The different production cost-competitiveness among member states highlights how an efficient market design and trade could significantly reduce supply costs. Ideally, the lowest-cost hydrogen could be made available to countries that would otherwise need to develop uncompetitive internal resources. While this consideration is valid for all reference scenarios, it is particularly relevant for the Hydrogen Independence scenario, as Figure 9 elucidates.

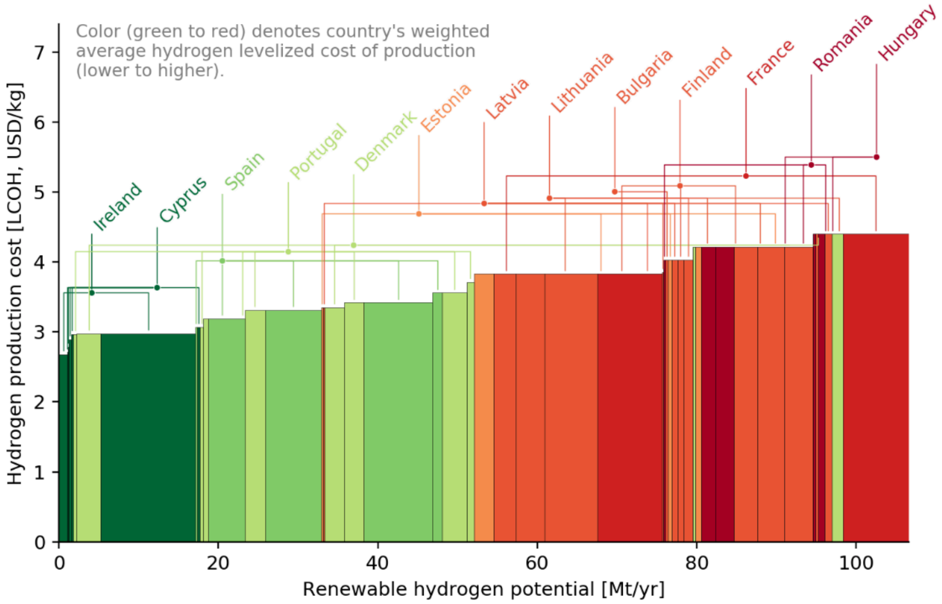

Figure 9. EU-wide renewable hydrogen cost curve
Source: Authors' analysis

Without fully integrated markets, countries like Romania and Hungary would have to meet demand with internal production costs of above 4 USD/kg instead of being able to leverage EU average costs of 3.5 USD/kg.[69]

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[69] Minimum weighted average production cost. Transportation costs excluded.

The creation of efficient EU hydrogen markets will also require the deployment of a fully integrated infrastructure across the continent - with corresponding transportation costs (see Section 7). Hence there will be a breakeven point at which local resources, even if costlier to produce, become more attractive than imports from other member states, thanks to their proximity to demand. In this way, the extent to which trades between member states could enhance the competitiveness of the Hydrogen Independence scenario will be a function not only of production costs but also of transportation costs.

Overall, the Hydrogen Independence scenario prioritizes energy independence considerations at the expense of higher supply costs, as discussed in the following sections.

6.2. **Cost Curves in the Regional and Long-Distance Reference Scenarios**

In line with the Hydrogen Independence scenario, cost curves for regional and long-distance partners reveal a wide range of production costs (see Figure 10)—from 2.5 to 4.4 USD/kg, but with much larger production potentials at costs below 3 USD/kg. Only Australia has a significant share of its overall potential (13%) above 4 USD/kg. Despite similar production cost ranges, regional and long-distance partners have significantly larger competitive renewable hydrogen potentials than EU countries.

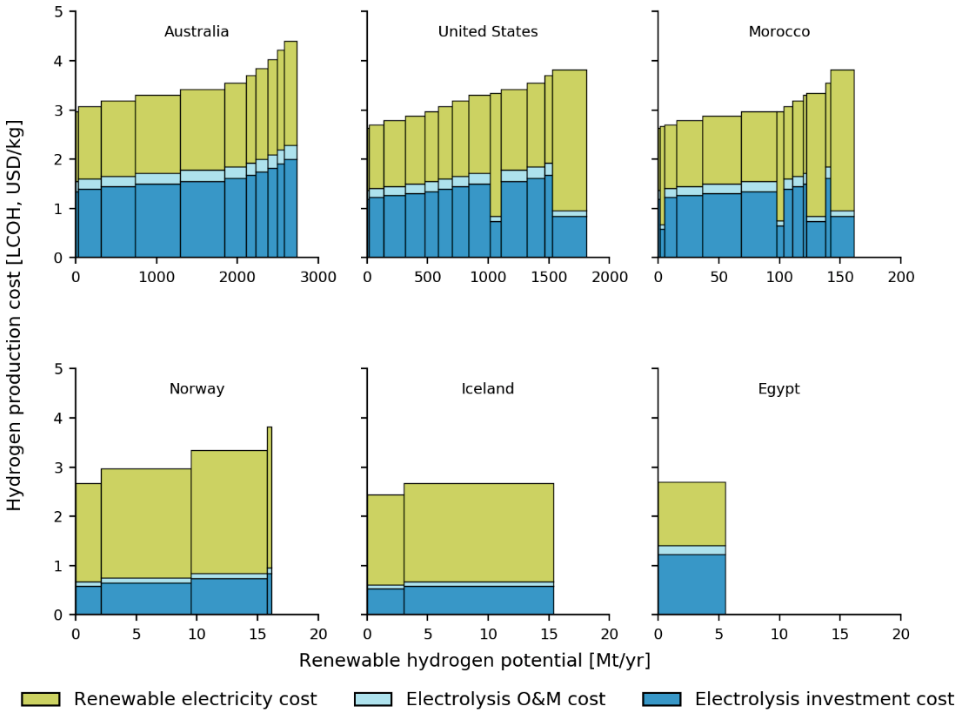

Figure 10. Renewable hydrogen cost curves in regional and long-distance partners
Source: Authors' analysis

Morocco, for example, could ramp up production up to 68 Mt/yr at costs below 3 USD/kg. On the other hand, countries with steeper cost curves, which theoretically could limit their ability to produce cost-competitively, have such large production potentials that they will still be able to supply significant amounts of renewable hydrogen at lower costs. For example, the United States could scale up production to over 587 Mt/yr with costs below 3 USD/kg despite a steeper curve than Egypt, which could only supply around 5 Mt/yr.[70]

Export champions like the United States and Morocco can also count on diversified renewable energy sources, making them more resilient to disruptions. However, countries with smaller potentials tend to rely on a single renewable energy source: wind in Norway and Iceland, solar in Egypt.[71]

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[70] Egypt's renewable hydrogen potential is severely limited by the availability of internal renewable freshwater resources—around 5.6 Mt/yr.

[71] Production costs of renewable hydrogen from wind energy are characterized by a higher share of renewable electricity costs and a lower share of electrolyzer investment costs due to higher investment cost and capacity factors of wind farms than solar PV plants.

Overall, renewable hydrogen imports could meet demand at lower production costs than internal EU production alone. Regional partners could meet EU demand at an average cost of 2.8 USD/kg and long-distance partners at 2.7 USD/kg.[72] However, transportation costs for shipping hydrogen to the EU over long distances will be high (see Section 7).

In summary, the Regional and Long-Distance scenarios are more competitive than the Hydrogen Independence scenario, thanks to lower production costs even when taking into consideration higher transportation costs, as discussed in the following section.

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[72] Minimum weighted average production cost. Transportation costs excluded.

7. Renewable Hydrogen Markets

This section assesses future hydrogen markets based on supply costs (production plus transportation costs), trade flows, and investment needs for each reference scenario.

The MIGHTY model considers future EU demand, renewable hydrogen potential, cost curves, and transportation costs to optimize hydrogen trades between countries in each scenario. As discussed, hydrogen's preferred transportation option is still unclear. Hence, the model considers two transportation alternatives for each of the reference scenarios (Hydrogen Independence [HI], Regional Imports [RI], and Long-Distance Imports [LDI]) (see Table 4):

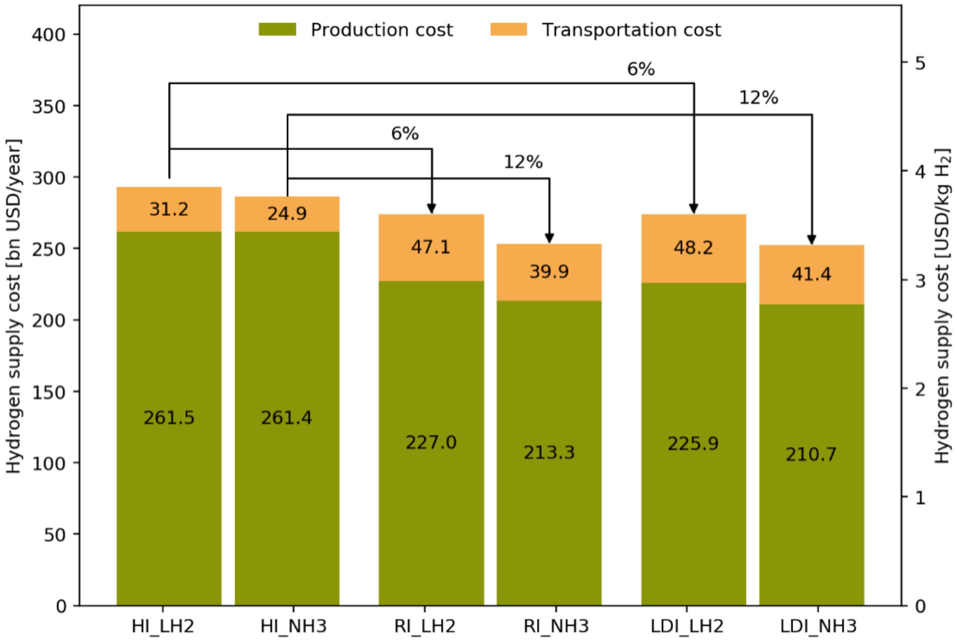
1. **Hydrogen gas pipelines plus liquefied hydrogen shipping (LH2).** Hydrogen is dispatched as a compressed gas between continental countries and as liquefied hydrogen by sea.
2. **Hydrogen gas pipelines plus ammonia shipping (NH3).** Hydrogen is dispatched as compressed gas between continental countries and as ammonia by sea before being reconverted to hydrogen on arrival.

Table 4. Summary of simulated scenarios

Hydrogen transportation options	Hydrogen Independence (HI)	Regional Imports (RI)	Long-Distance Imports (LDI)
Pipelines and liquefied hydrogen shipping (LH2)	HI_LH2	RI_LH2	LDI_LH2
Pipelines and ammonia shipping (NH3)	HI_NH3	RI_NH3	LDI_NH3

7.1. **Hydrogen Supply Costs**

Our analysis shows how meeting EU renewable hydrogen demand would cost between 253 billion and 293 billion USD per year (see Figure 11).



Scenario labels: HI: Hydrogen Independence, RI: Regional Imports, LDI: Long-Distance Imports.
Transportation scenario labels: LH2: hydrogen gas pipelines and liquefied hydrogen shipping, NH3: hydrogen gas pipelines and ammonia shipping.

Figure 11. EU hydrogen supply costs
Source: Authors' analysis

Overall, scenarios where hydrogen is shipped as ammonia result in lower supply costs, thanks to both lower transportation costs (shipping ammonia is significantly less costly than shipping liquefied hydrogen) and higher volumes from producers with lower costs than those in EU countries.

Renewable hydrogen imports from outside the EU could lower overall supply costs between 6% and 12%, even when higher transportation costs are accounted for. Long-distance partners, however, provide no additional cost optimization opportunities because the higher transportation costs increasingly offset lower production costs.

Hence, if cost considerations are prioritized, the Regional Imports scenario is the optimal route for meeting future renewable hydrogen demand in the EU at the lowest cost possible.

7.2. Renewable Hydrogen Trade Flows

International trade of renewable hydrogen plays a significant role in all reference scenarios. Based on our analysis, trade between countries would cover between almost 70% and 86% of EU overall demand. To elucidate the associated market dynamics, we developed flow diagrams for each reference scenario, connecting supply with demand.

7.2.1. Hydrogen Independence Scenario

In the Hydrogen Independence scenario, renewable hydrogen trades between member states would account for almost 70% of demand, while the remainder would be self-consumption. Almost all hydrogen would be dispatched by pipeline, resulting in similar trade flows between countries regardless of the sea shipping choice (see Figures 12 and 13).

In this scenario, two regions—the Iberian Peninsula and the Baltic States—and two member states—Ireland and Denmark—would supply nearly nine out of ten kilograms of renewable hydrogen traded within the EU. The Iberian Peninsula would become the largest export region, with Spain and Portugal dispatching around 23 Mt/yr of renewable hydrogen to Italy, France, Germany, and Belgium. In the east, the Baltic States would supply nearly 11 Mt/yr of renewable hydrogen to other member states, with Denmark supplying about 5 Mt/yr mainly to the Netherlands and Germany. Only Ireland would deliver by ship about 12 Mt/yr to the continent.

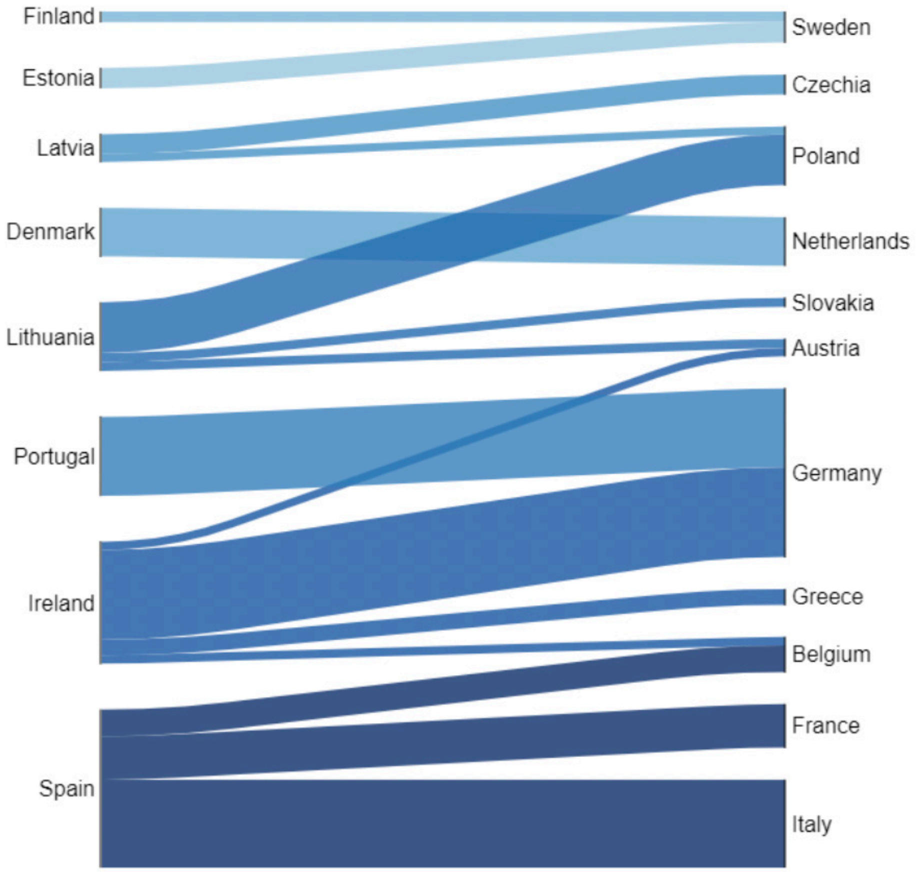


Figure 12. Renewable hydrogen trade flows in the HI_LH2 scenario
Source: Authors' analysis. Hydrogen flows from exporters (left) to importers (right). Connection width is proportional to hydrogen mass flow. Hydrogen flows below 0.5 Mt/yr are not depicted for clarity

Large hydrogen flows from the EU's edge to central Europe again highlight the need for integrated hydrogen infrastructure and markets. In this scenario, hydrogen pipelines running from the Iberian Peninsula and the Baltic States would connect to the Netherlands, Denmark, Belgium, and Germany,[73] in addition to shipping terminals connecting insular countries to the continent.

An integrated hydrogen transportation infrastructure will thus be essential for the EU to reach hydrogen independence and optimal allocation of hydrogen production, a goal which can only be achieved at higher overall supply costs.

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[73] Recent developments already point in this direction. The Dutch government has already commissioned studies on retrofitting 1,200 km of existing natural gas pipelines for transporting hydrogen by 2027 that would connect Germany, the Netherlands, and Belgium, as reported in Brooks (2021).

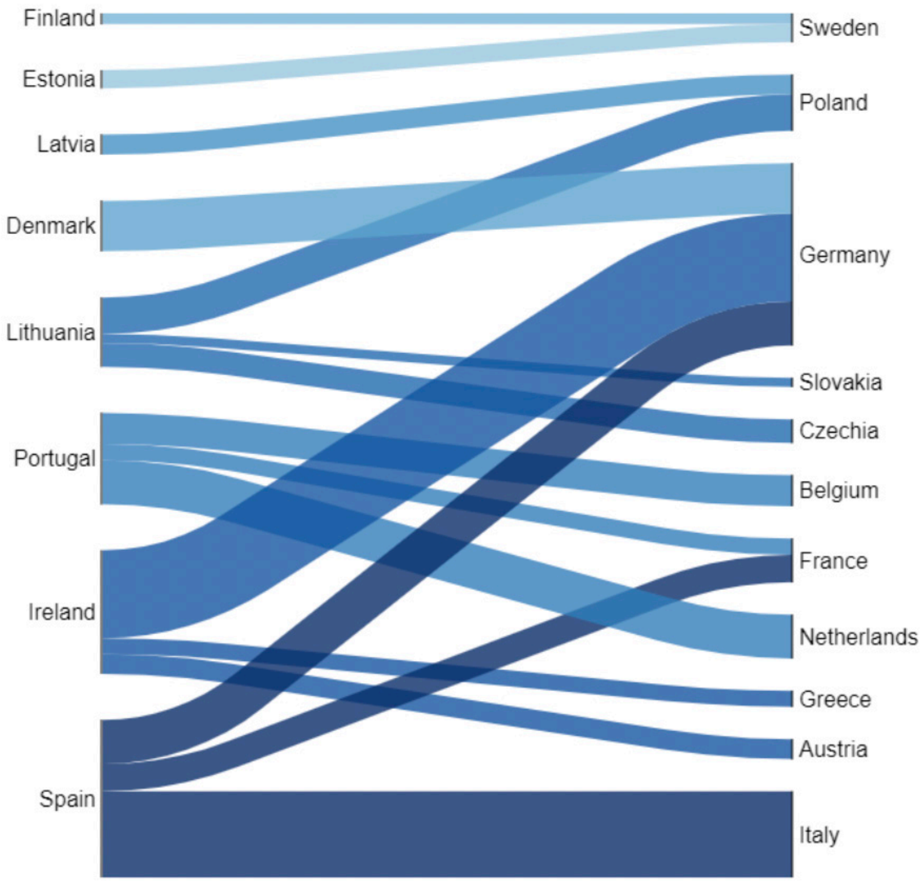

Figure 13. Renewable hydrogen trade flows in the HI_NH3 scenario
Source: Authors' analysis. Hydrogen flows from exporters (left) to importers (right). Connection width is proportional to hydrogen mass flow. Hydrogen flows below 0.5 Mt/yr are not depicted for clarity

7.2.2. **Regional Imports Scenario**

When considering imports from regional partners, overall supply costs decrease between 6% and 12%. In part this is because lower-cost internal trade between member states and imports from regional partners account for up to 86% of EU overall demand.

Shipped hydrogen represents a more significant fraction of demand here than it does in the Hydrogen Independence scenario, and trade flows change considerably depending on the shipping choice (see Figures 14 and 15). The lower transportation costs associated with ammonia shipping increase imports from regional partners to 63 Mt/yr, while the costlier shipping of liquefied hydrogen limits imports to 47 Mt/yr.

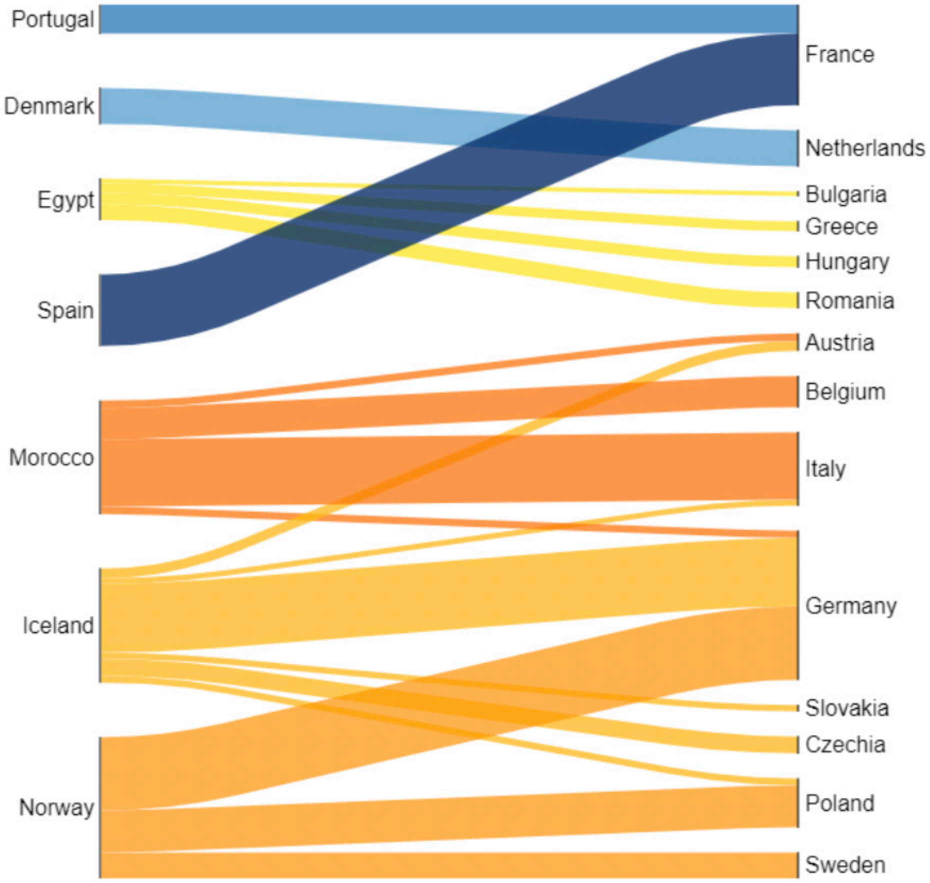

Figure 14. Renewable hydrogen trade flows in the RI_LH2 scenario
Source: Authors' analysis. Hydrogen flows from exporters (left) to importers (right). Connection width is proportional to hydrogen mass flow. Hydrogen flows below 0.5 Mt/yr are not depicted for clarity

From a country-level supply perspective, trade fluxes shift from North European to North African countries depending on the hydrogen carrier used for shipping (see Figures 14 and 15). In the case of liquefied hydrogen shipping, Norway and Iceland would become the leading suppliers with about 29 Mt/yr compared to around 19 Mt/yr for Morocco and Egypt. Regarding ammonia shipping, however, Morocco becomes the lead supplier with over 32 Mt/yr, while Norway and Iceland contribute about 25 Mt/yr. Egypt continues to supply about 5 Mt/yr since freshwater availability constraints limit its ability to increase market share.

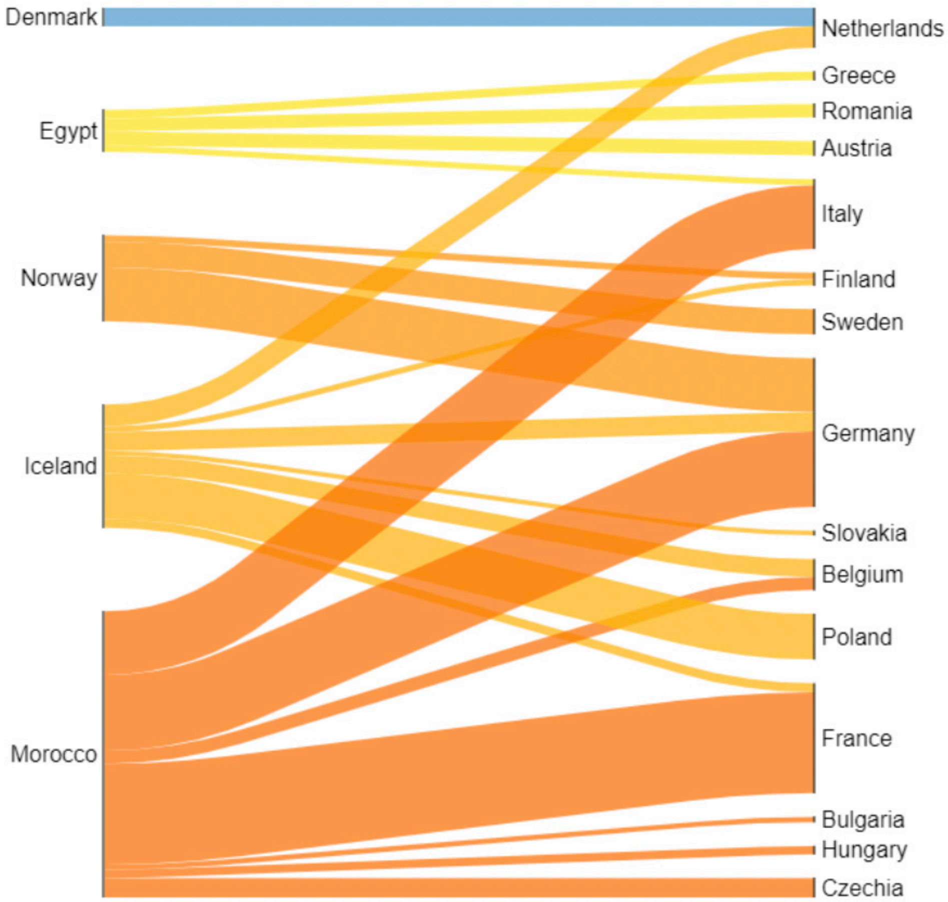

Figure 15. Renewable hydrogen trade flows in the RI_NH3 scenario
Source: Authors' analysis. Hydrogen flows from exporters (left) to importers (right). Connection width is proportional to hydrogen mass flow. Hydrogen flows below 0.5 Mt/yr are not depicted for clarity

Furthermore, in the case of ammonia shipping, imports from non-EU countries cover 83% of overall demand at much lower supply costs. At the same time, this extensive import dependency raises significant energy security issues. For reference, the EU's energy dependency on coal and natural gas today equals 63% and 89.5%, respectively.[74]

In the case of liquefied hydrogen shipping, North European and North African partners would contribute equally to EU demand. However, for ammonia shipping, Morocco alone would supply nearly 43% of EU demand. The EU could diversify supply sources by leveraging long-distance imports from global export champions, like Australia and the United States, in order to address these energy security concerns.

7.2.3. **Long-Distance Imports Scenario**

Our analysis shows that adding long-distance partners would increase the share of EU demand supplied by trades between EU countries and regional and long-distance partners up to 86%. Long-distance imports, however, would only play a meaningful role if competitive shipping costs were available (see Figures 16 and 17). Long-distance imports are largely uncompetitive with liquefied hydrogen shipping and amount to about 0.1 Mt/yr, while they increase to 17 Mt/yr with ammonia shipping.

In the latter case, the United States could become the largest supplier of renewable hydrogen to the EU with 17 Mt/yr. Despite Australia's vast potential and highly competitive production costs, their imports cannot enter the supply mix due to the high transportation costs.

Compared to the Regional Imports scenario, in this scenario imports from North America would flow to France, Germany, the Netherlands, and Belgium, while Moroccan imports would be reduced by half. Other regional exporters to the EU like Norway, Iceland, or Egypt would remain unaffected by incorporating long-distance partners and would supply similar amounts of renewable hydrogen as they do in the Regional Imports scenario.

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[74] Based on Eurostat data for coal and natural gas supply in 2019. Eurostat (2020) 'Coal production and consumption statistics', last edited 3 August 2021, accessed 20 September 2021. https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Coal_production_and_consumption_statistics and Eurostat (2020) 'Natural gas supply statistics', last edited on 20 July 2021, accessed 20 September 2021. https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Natural_gas_supply_statistics

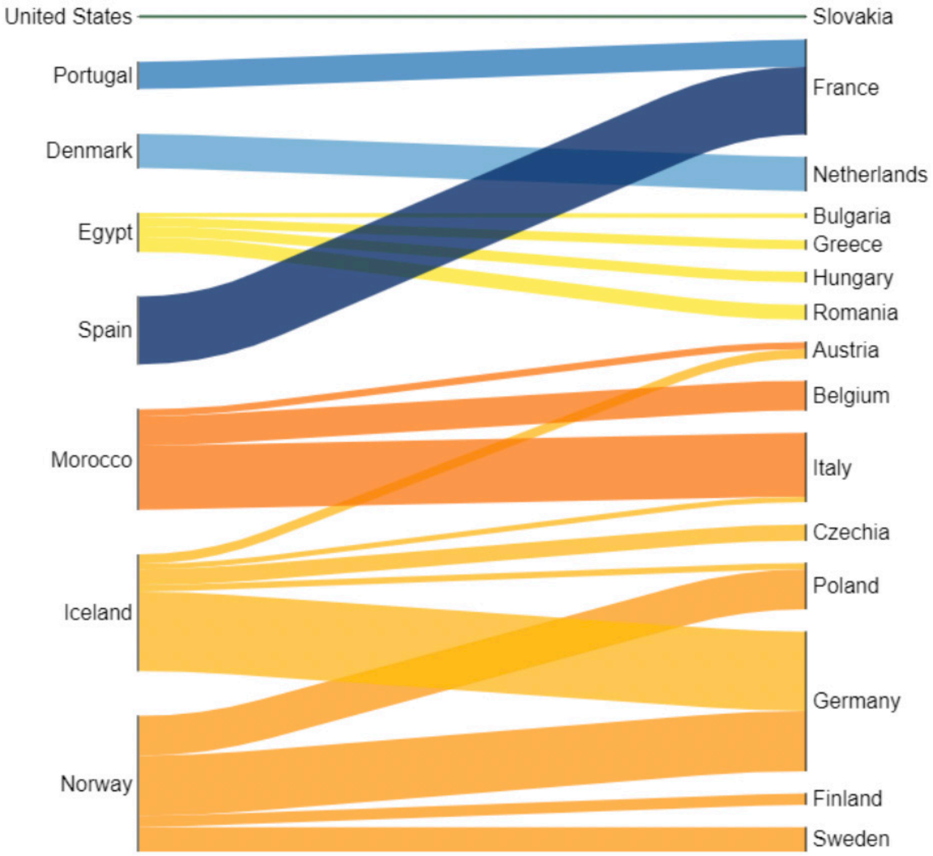

Figure 16. Renewable hydrogen trade flows in the LDI_LH2 scenario
Source: Authors' analysis. Hydrogen flows from exporters (left) to importers (right). Connection width is proportional to hydrogen mass flow. Hydrogen flows below 0.5 Mt/yr are not depicted for clarity, except for the United States

Long-distance imports would not lower the EU's overall supply costs or the bloc's dependence on external imports, which would account for between 63% and 83% of demand. Still, long-distance imports could have significant implications from a security of supply perspective. The emergence of the United States as the largest exporter of renewable hydrogen to the EU would limit imports from any single trade partner to about 22% of overall demand. Therefore, diversification would be an effective strategy to reduce supply security risks without increasing overall supply costs.[75]

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[75] By gaining access to low-cost renewable hydrogen potentials in global export champions, production costs decrease in the LDI_NH3 scenario compared to RI_NH3. However, due to the longer shipping distances, transportation costs increase and offset the cost advantage of the long-distance imports.

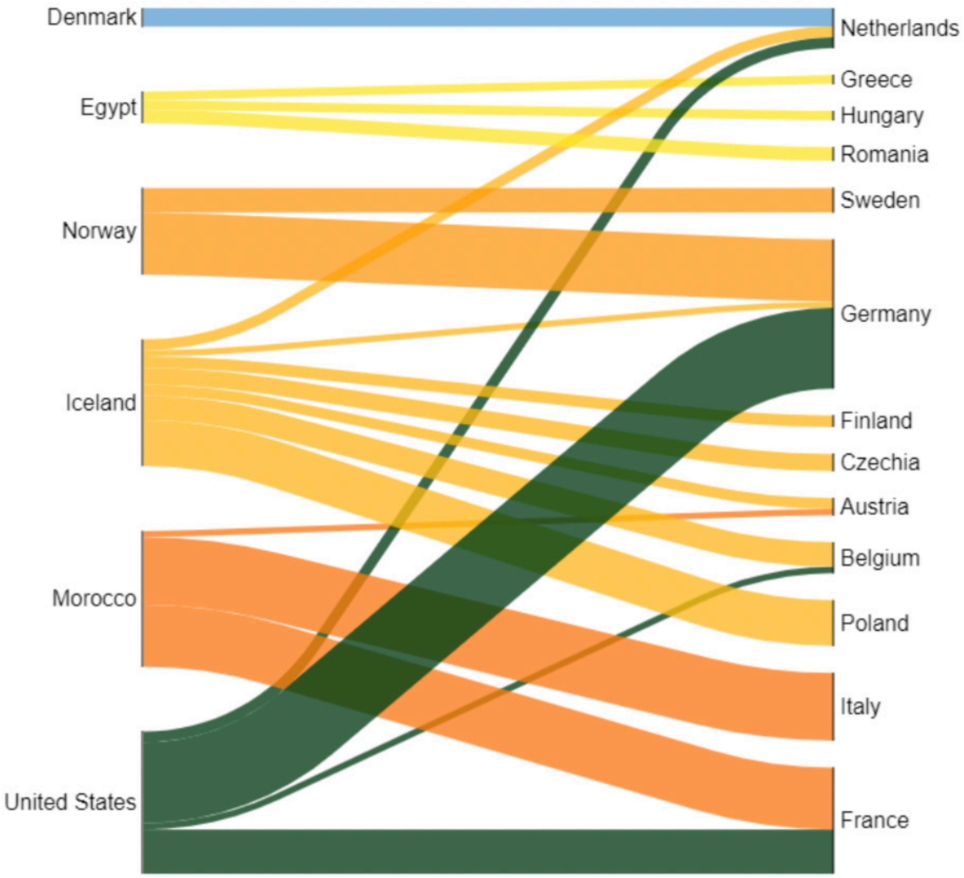
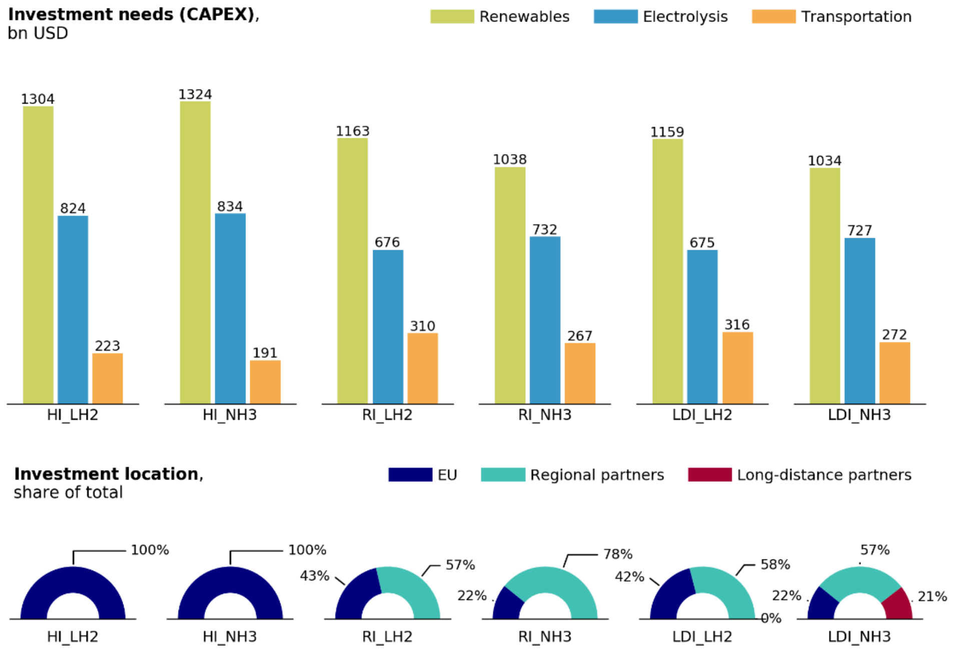


Figure 17. Renewable hydrogen trade flows in the LDI_NH3 scenario
Source: Authors' analysis. Hydrogen flows from exporters (left) to importers (right). Connection width is proportional to hydrogen mass flow. Hydrogen flows below 0.5 Mt/yr are not depicted for clarity

7.3. **Investment Requirements**

Investments between 2 trillion and 2.4 trillion USD in renewables, electrolysis, and enabling infrastructure would be needed to meet future EU renewable hydrogen demand. Hydrogen imports could lower total investment needs by 9% to 13%, but they would also change the physical allocation with significant market consequences (see Figure 18).



Scenario labels: HI: Hydrogen Independence, RI: Regional Imports, LDI: Long-Distance Imports. Transportation scenario labels: LH2: hydrogen gas pipelines and liquefied hydrogen shipping, NH3: hydrogen gas pipelines and ammonia shipping.

Figure 18. Investment allocation by scenario
Source: Authors' analysis

In all scenarios, investments in renewables and electrolysis account for more than 80% of overall CAPEX, reaching 90% in the Hydrogen Independence case. Investments in renewables are lower in the Regional and Long-Distance Imports scenarios for two reasons. Countries like Morocco and the United States can rely on solar power, while key EU producers like Ireland, Denmark, and the Baltic States would need to deploy costlier wind power because they lack competitive solar resources. In addition, higher capacity factors for renewable energy resources in regional and long-distance partners would reduce overall investment needs.

As expected, import scenarios require about 40% more investments in transportation infrastructure than the Hydrogen Independence scenario because of the need to deploy import and export shipping terminals to complement hydrogen pipeline networks in the EU.

The Regional and Long-Distance Imports scenarios allocate 57% to 78% of overall investments outside the EU. While this could encourage participation from a broader group of investors, it reduces the EU's ability to control project development and introduces additional risk to a successful strategy implementation.

7.4. **Sensitivity Analysis**

Since underlying assumptions and estimations may vary over time due to multiple external factors, it is crucial to conduct sensitivity analyses on key variables and evaluate possible impacts on overall results. For example, in the past, technological cost reductions have been faster than anticipated in some cases, like with solar photovoltaics,[76] and slower in other cases.[77]

As discussed, the MIGHTY model identifies key trade partners for meeting EU hydrogen demands at the lowest possible cost. Hence, renewable hydrogen production and transportation costs, a function of investment costs,[78] are key drivers in the reference scenarios' results. Consequently, a ±50% sensitivity analysis on investment costs for renewable energy, electrolyzers, pipelines, and hydrogen shipping is carried out.[79] In addition, a ±50% sensitivity to the cost of capital, represented by the overall discount rate, is also carried out.

The sensitivity analyses show that while overall supply costs change significantly, the impact on the reference scenario rankings is negligible. The overall implications and considerations remain the same, because all

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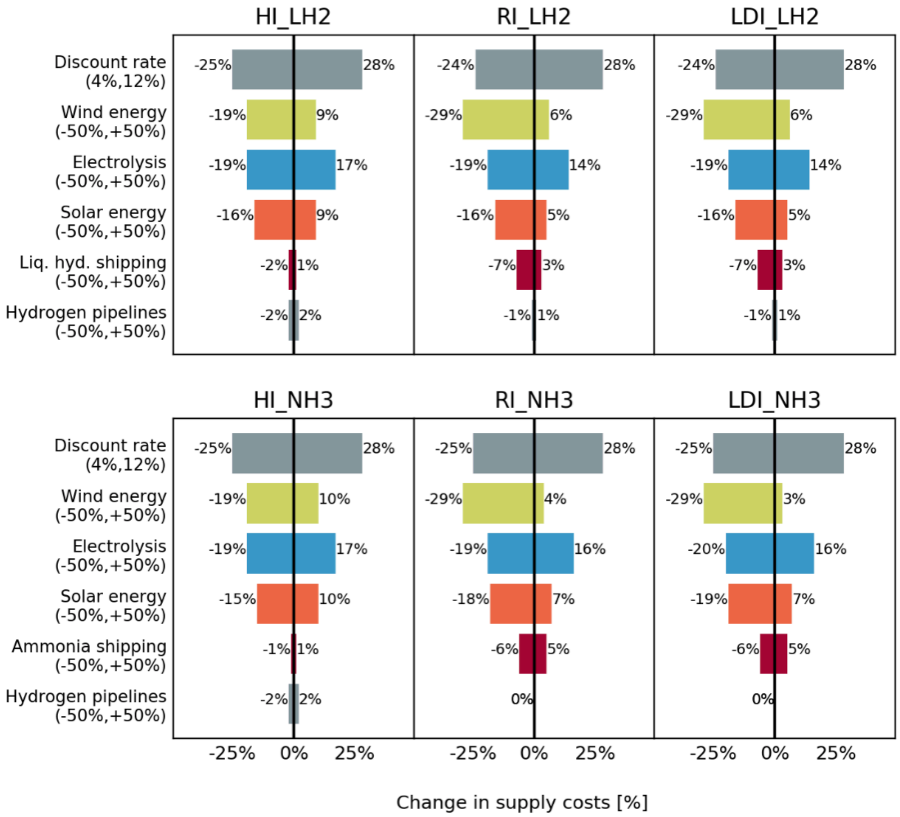
[76] For example, see Creutzig et al. (2017) "The Underestimated Potential of Solar Energy to Mitigate Climate Change," *Nature Energy*, 2(9). https://doi.org/10.1038/nenergy.2017.140

[77] For example, see Lilliestam et al. (2017) "Empirically Observed Learning Rates for Concentrating Solar Power and Their Responses to Regime Change," *Nature Energy*, 2(7), 17094. https://doi.org/10.1038/nenergy.2017.94

[78] Other production routes, such as blue hydrogen from natural gas with carbon capture, have much higher operational costs than renewable hydrogen that also influence production and transportation costs. See for example IEA (2019) *The Future of Hydrogen*.

[79] See specific values 10.5 in the Appendix.

the scenarios are affected consistently by the sensitivity analyses (see Figure 19). For example, if electrolyzers were 50% cheaper than in the reference case, supply costs would decrease about 20% across all scenarios.



Scenario labels: HI: Hydrogen Independence, RI: Regional Imports, LDI: Long-Distance Imports.
Transportation scenario labels: LH2: hydrogen gas pipelines and liquefied hydrogen shipping, NH3: hydrogen gas pipelines and ammonia shipping.

Figure 19. Sensitivity analyses
Source: Authors' analysis

Across all the scenarios, the cost of capital is the variable with the highest impact on overall supply costs, followed by renewable energy and electrolyzer investment costs. The sensitivity analysis shows how a 4% discount rate (50% lower than the base case) would reduce supply costs to between 2.5 and 2.9 USD/kg, from 3.3 to 3.9 USD/kg (see Figure 11). This trend highlights how policy measures aimed at reducing the cost of capital could be particularly effective in increasing competitiveness and driving adoption at scale.

The sensitivity analysis on renewable energy and electrolyzer investment costs also reveals a potential switch effect: costlier solar (or wind) energy with respect to the base case would drive producers to switch to wind (or solar), thus capping increments in overall supply costs.[80] In other words, costlier-than-anticipated renewables and electrolyzers would increase hydrogen supply costs less than expected (see Figure 19). Scenarios with higher renewable energy potentials are more sensitive to this effect because producers have more opportunities to switch to more competitive wind or solar energy. This is a significant additional benefit of including regional and long-distance partners in the EU's supply mix.

Finally, changes in transportation costs with respect to the base case have only minor impacts on overall supply costs (see Figure 19). At the same time, cheaper-than-expected shipping could result in more considerable reductions in overall supply costs than cheaper-than-expected pipelines because shipping would allow for more imports at lower production costs. On the other hand, if transportation costs were to be more expensive, the EU could limit the impact by reducing trade and developing its domestic resources. Both considerations can only be elucidated thanks to the MIGHTY model, which optimizes overall supply costs based on production potentials and transportation costs.

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[80] The switch effect is also present for costlier wind energy than anticipated and if electrolyzer investment costs turn out to be higher than in the reference assumption. As discussed before, electrolysis investment costs typically represent a larger fraction of hydrogen production costs when electrolyzers are powered by solar energy because of lower capacity factors than for wind farms. Therefore, higher electrolyzer investment costs would impact production costs of producers using solar energy more than of those relying on wind energy. For this reason, the switch effect will incentivize producers to produce less with solar energy and more with wind energy.

8. **Policy Implications**

Attaining competitive and secure supplies of renewable hydrogen is becoming a key policy priority in efforts to accelerate the worldwide transition to low-carbon economies. Unconstrained by legacy infrastructure, hydrogen offers policymakers, investors, and other stakeholders the opportunity to design and deploy new and efficient energy systems. Harnessing hydrogen's full potential will require assessing the associated economic, environmental, and geopolitical implications, identifying strategies to address them, and defining implementation plans. Today no major hydrogen pipeline networks exist, and no liquefied hydrogen ships are in commercial operation, which could have a significant impact on the needed investments in supply and demand.

To better understand these dynamics, we developed three long-term scenarios focused on the strategic variables of energy independence, cost (optimization), and energy security. The considerations outlined in the previous sections make it clear that only by working together can the EU become a global leader in renewable hydrogen innovation and simultaneously contribute to the EU's climate and energy security goals, a more robust economy, and a more integrated union. This transformational effort will require close coordination between policy, technology, capital, and society and for EU countries to unite behind a shared long-term vision.[81]

Overall a successful transition will require:

- Clear regulations and standards for renewable hydrogen production, transportation, and certification[82,83] that enable cross-border trade at scale. Member states should also revisit their internal regulatory frameworks to harmonize and streamline them.

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[81] De Blasio, N, Nuñez-Jimenez, A (2020) "Will Renewable Hydrogen Help Unite Europe?" Agenda Pública – El País, 10 November 2020. https://www.belfercenter.org/publication/will-renewable-hydrogen-help-unite-europe

[82] De Blasio, N, Hua, C (2021) "The Role of Blockchain in Green Hydrogen Value Chains," Policy Brief, November 2021. https://www.belfercenter.org/publication/role-blockchain-green-hydrogen-value-chains

[83] Velazquez A, Dodds, PE (2020) "Green Hydrogen Characterisation Initiatives: Definitions, Standards, Guarantees of Origin, and Challenges," *Energy Policy*, 138(August 2019), p. 111300. https://doi.org/10.1016/j.enpol.2020.111300

- Policies to lower market risk, address commercialization barriers, and achieve the required economies of scale. Examples include renewable hydrogen standards requiring stakeholders to source part of the traded hydrogen from renewable sources and mandating the labelling of CO_2 intensities of products, thus spurring the emergence of green premiums.[84]
- Funding innovation and pilot projects to help reach the tipping point at which renewable hydrogen technologies become cost competitive. For example, the EU could borrow the idea of the "Energy Earthshots Initiative" from the United States Department of Energy[85] and fund initiatives aimed at establishing ambitious cost-reduction targets with clear timelines and regular funding reviews.

In the remainder of this section, we outline key policy and market options for each reference scenario.

Hydrogen Independence

The EU prioritizes energy independence and develops internal, self-sufficient renewable hydrogen markets. Overall, hydrogen demand can be met with internal production but at higher costs.

Our analysis shows that hydrogen self-sufficiency is achievable. Still, success requires designing and deploying efficient and integrated hydrogen markets to enable cross-border trade between member states. Policymakers will need to define strategies to support the deployment, sharing, and operation of highly integrated infrastructure networks across the continent and, in parallel, stimulate strong growth in renewable electricity generation.

Integrated hydrogen markets will allow member states to rely on the most competitive resources available instead of more expensive domestic production. Achieving this goal will require close coordination and investment planning with member states that have the potential to become regional exporters, such as Spain, Portugal, Ireland, Denmark, and the Baltic States.

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[84] European Commission (EC) (2021) proposal to amend the EU Renewable Energy Directive.

[85] In June 2021, the United States Department of Energy announced the first Energy Earthshot aimed at reducing the cost of clean hydrogen by 80% to 1 USD/kg in one decade. United States Department of Energy (US DOE) 2021, "Secretary Granholm Launches Hydrogen Energy Earthshot to Accelerate Breakthroughs Toward a Net-Zero Economy," US DOE articles, 7 June 2021. https://www.energy.gov/articles/secretary-granholm-launches-hydrogen-energy-earthshot-accelerate-breakthroughs-toward-net

From a security of supply perspective, although long-term demand would be met by internal production, continent-wide periods of low renewables production and high energy demand could still disrupt supplies. A strategic allocation of production and storage facilities across the continent would help increase overall supply security.

Finally, hydrogen self-sufficiency and large-scale internal trade would trigger profound shifts in the political relations and alliances between member states. In particular, large flows of hydrogen from the Baltic States, Portugal, and Spain to central Europe would strengthen the economic and social cohesion of the Union, while at the same time transforming relationships with current energy providers like Russia.

Regional Imports

The EU prioritizes cost optimization by complementing the lowest-cost internal production with imports from neighboring countries. Regional imports would optimize overall supply costs but also reproduce energy dependence patterns of the past.

Overall supply costs can be optimized by complementing the lowest-cost internal production with imports from resource-rich neighboring countries. The feasibility of this scenario relies on the ability of exporters to develop hydrogen potentials at scale. On the one hand, this will require the EU to set policies that promote long-term contracts and direct investments in producing nations to help reduce market risk. On the other hand, producers will need to define strategies that trigger infrastructure investments and align with the EU on domestic regulations and standards for renewable hydrogen production, transportation, and certification, paving the way for a dominating position in future markets.

The price to pay for cheaper hydrogen supplies will be the possibility of reproducing past energy dependence patterns and security of supply risks. In this scenario, the EU would remain as dependent on hydrogen imports from Morocco as it is today on gas imports from Russia. While shifting the geopolitical center of gravity from East to South would have major implications, it would do little to enhance the Union's strategic autonomy on energy.

To manage some of these risks without sacrificing the cost advantage, the EU could ensure uninterrupted supplies by extending strategic energy reserve requirements to hydrogen.[86] A longer-term solution would require diversification of regional imports, for example by unlocking, through technical assistance and direct investments, large potentials in nearby countries like Algeria and Egypt that are constrained by energy infrastructure and freshwater availabilities.

Long-Distance Imports

The EU prioritizes energy security and cost optimization by combining long-distance imports from export champions like the United States with regional imports and internal production.

Adding imports from long-distance partners to its hydrogen mix would allow the EU to maintain low overall supply costs while addressing some of the security risks inherent in depending on imports from very few neighbors.

This strategy hinges on the emergence of truly global markets and requires the concerted effort of multiple players. To this end, the EU should promote the adoption of clear international regulations and standards on renewable hydrogen production, transportation, and certification. A new international forum, acting as a coordinating body, could eventually lead to the creation of agencies responsible for developing these standards and working with national regulatory bodies to facilitate implementation.

From a security of supply perspective, the emergence of global markets, standards, and certificates of origin would allow member states to develop a diversified import mix. More global and less regionalized hydrogen trade flows would also reconfigure the geopolitical balance between suppliers and consumers by making it easier to switch providers, thus ending the influence of dominant suppliers. At the same time, the role of strategic reserves would be even more relevant for weathering short-term supply disruptions.

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86 European directives require EU countries to maintain reserves of at least 90 days of imports or 61 days of inland consumption, whichever is greater, of crude oil and/or petroleum products. European Commission (EC) (2009) “Council Directive 2009/119/EC of 14 September 2009.”

9. **Options for Further Analysis**

Beyond the direct scope of our analysis, we have identified several adjacent research topics in need of further academic analysis. Potential areas include but are not limited to:

1. Applying our analytical framework to other regions of the world, allowing decision-makers to assess better supply scenarios based on the key strategic variables of energy independence, cost (optimization), and security of supply.
2. Examining other production technology pathways and overall value chains to shed light on synergies that could accelerate low-carbon hydrogen adoption and to address questions such as: Which low-carbon hydrogen production mix suits which countries? How could technology competition change the role countries play in future hydrogen markets?
3. Assessing pathways to accelerate hydrogen adoption at scale in selected applications.

10. **Appendix**

This appendix collects input parameters; assumptions used throughout this report; and methodological notes on hydrogen production estimates, transportation costs, and optimization of trade flows.

10.1. **Input Parameters and Assumptions**

10.1.1. **General Inputs and Assumptions**

General inputs and assumptions apply to all calculations and variables. In the cases of hydrogen lower heating value and ammonia hydrogen content by weight, assumptions were based on available scientific estimates and composition. Capital cost and technology readiness are assumed constant across regions for simplicity and coherence, and to facilitate hydrogen production competitiveness analyses. While for globally manufactured technologies like solar photovoltaic modules, differences between countries are likely to be minor and primarily related to soft costs (e.g., labor, permitting fees, and others), cost of capital is likely to be significantly different between countries.[87] As discussed, the high sensitivity of production costs to variations in the cost of capital offers a promising path for future analyses.

- Hydrogen lower heating value (LHV): 33.333 kWh/kg H_2
- Ammonia's hydrogen content by weight: 5.667 kg NH_3/kg H_2
- Discount rate: 8%, based on IEA assumptions[88]

Another set of general assumptions was employed to determine renewable electricity generation's economic potential in countries included in the analyses (see Table 5). These assumptions consider solar and wind energy resources with low capacity factors and in remote locations as uneconomic and thus unlikely to be developed, reducing a country's economic potential. Specific thresholds for each technology (e.g., capacity factor and

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[87] Egli et al. (2019) "Bias in Energy System Models with Uniform Cost of Capital Assumption," *Nature Communications*, 10, 4588. https://doi.org/10.1038/s41467-019-12468-z

[88] IEA (2019) *The Future of Hydrogen*.

distance values) were determined based on the granularity of the data sources.

Table 5. Assumptions for economic renewable electricity generation potentials

Variable	Economic viability assumptions	Data source
Solar energy	Resources with a capacity factor higher than 11% (equivalent to 1,000 full load hours) and less than 100 km from towns are economically viable.	Pietzcker et al. (2014)
Onshore wind energy	Resources with a capacity factor higher than 26% (equivalent to 2,278 full load hours) and less than 160 km from towns are economically viable.	Eurek et al. (2017)
Offshore wind energy	Resources with a capacity factor higher than 26% (equivalent to 2,278 full load hours), less than 20 nautical miles (approximately 37 km) from the coast, and sea depths less than 30 meters are economically viable.	Eurek et al. (2017)

10.1.2. Renewable Technologies Input Parameters

The IEA's World Energy Outlook 2020 projects renewable energy technology costs up to 2040.[89] To project costs to 2050, IEA's outlook was combined with cumulated installed capacity scenarios by the International Renewable Energy Agency (IRENA)[90] and cost reductions estimated using experience curves (see Table 6).

Table 6. Renewable energy technology economic inputs

	PV	Onshore wind	Offshore wind
Global cumulated installed capacity[91]	2040: 5,982 GW 2050: 10,651 GW	2040: 4,195 GW 2050: 6,693 GW	2040: 552 GW 2050: 1,143 GW
Learning rate[92]	20%	15%	15%
Investment cost[93]	2040: 490 USD/kW 2050: 407 USD/kW	2040: 1,420 USD/kW 2050: 1,273 USD/kW	2040: 2,040 USD/kW 2050: 1,720 USD/kW
Operation and maintenance costs[94]	2.5% CAPEX	2.9% CAPEX	2.5% CAPEX
Lifetime[95]	25 years	25 years	25 years

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[89] IEA (2020) *World Energy Outlook 2020*, https://www.iea.org/reports/world-energy-outlook-2020

[90] IRENA (2020) Global Renewables Outlook: Energy Transformation 2050, April 2020. https://irena.org/publications/2020/Apr/Global-Renewables-Outlook-2020

[91] Data from cumulative capacity additions in IRENA (2020).

[92] Based on learning rates review in Brändle et al. (2021).

[93] Investment cost in 2040 based on Stated Policy Scenario for Europe in IEA (2020).

[94] Estimated from capital costs, operation and maintenance costs, and capacity factors for Europe 2040 in the Stated Policies Scenario in IEA (2020).

[95] Based on IEA (2019).

10.1.3. Electrolysis Input Parameters

Input parameters for water electrolysis are based on long-term projections for polymer electrolyte membrane (PEM) electrolyzers by the IEA (see Table 7).[96] While PEM electrolyzers are costlier than alkaline electrolyzers and less efficient than solid oxide electrolyzers, their greater flexibility to operate efficiently with variable power sources and more robust learning effects could make them the most competitive in the short to medium term.[97] For these reasons, electrolysis input parameters were chosen based on PEM electrolyzers.

Table 7. Electrolysis input parameters (based on IEA [2019] *The Future of Hydrogen*)

	Electrolyzer
Investment cost	450 USD/kW
Operation and maintenance costs	1.5% CAPEX
Efficiency	74% LHV
Lifetime	20 years
Water consumption	9 kg water/kg H_2

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[96] IEA (2019) *The Future of Hydrogen*.

[97] Böhm et al. (2020) "Projecting Cost Development for Future Large-Scale Power-to-Gas Implementations by Scaling Effects," *Applied Energy*, 264(March), pp. 114780. https://doi.org/10.1016/j.apenergy.2020.114780

10.1.4. Hydrogen Transportation Input Parameters

The future evolution of hydrogen transportation remains highly uncertain. Currently, no infrastructure exists for hydrogen transportation over long distances at scale, whether as compressed gas in pipelines, liquefied in ships, or contained in other molecules like ammonia shipping.

Although there are about 3,000,000 kilometers of natural gas pipelines worldwide, only 5,000 km of hydrogen pipelines exist, most of which are part of chemical facilities or refineries.[98] Pipelines transporting pure hydrogen may require different materials than those transporting natural gas.[99] Compressors, valves, and sensors also need to be adapted or explicitly built for pure hydrogen. While significant investments in new and repurposed pipelines would be required, the technologies to manufacture hydrogen pipelines, compressors, and equipment exist.

In contrast, there is no commercial liquefied hydrogen shipping infrastructure anywhere in the world, and deployment at scale by 2050 will require significant investments. Today, only one liquefied hydrogen vessel[100] and one import terminal[101] exist as part of a demonstration project by Japanese group Kawasaki Heavy Industries. While hydrogen liquefaction and evaporation technologies are well known, they have been built only on a small scale. Therefore, the technologies required to establish liquefied hydrogen shipping routes at scale are relatively immature and require significant innovation and development efforts.

On the other hand, ammonia shipping is an established technology with long-distance commercial routes connecting producers and importers.

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[98] IEA (2019) *The Future of Hydrogen.*

[99] Melaina et al. (2013) "Blending Hydrogen into Natural Gas Pipeline Networks: A Review of Key Issues," National Renewable Energy Laboratory, NREL TP-5600-51995. https://www.nrel.gov/docs/fy13osti/51995.pdf

[100] Kawasaki Heavy Industries (2019) "World's First Liquefied Hydrogen Carrier SUISO FRONTIER Launches Building an International Hydrogen Energy Supply Chain Aimed at Carbon-Free Society," Kawasaki Newsroom, 11 December 2019, accessed 20 September 2021. https://global.kawasaki.com/en/corp/newsroom/news/detail/?f=20191211_3487

[101] Kawasaki Heavy Industries (2020) "Kawasaki Completes World's First Liquefied Hydrogen Receiving Terminal Kobe LH2 Terminal (Hy touch Kobe)," Kawasaki Newsroom, 3 December 2020. https://global.kawasaki.com/en/corp/newsroom/news/detail/?f=20201203_2378

Global trade of ammonia accounted for 19 Mt in 2021,[102] which is significantly smaller than what future hydrogen markets would require.[103] At the same time, ammonia is highly toxic and might require reconversion to hydrogen.

For these reasons, investment projections to 2050 were developed combining IEA estimates and a cost evolution scenario based on current technology maturity and commercial availability for each hydrogen transportation method (see Table 8).

Table 8. Investment cost evolution scenarios for hydrogen transportation technologies
Source: Authors' analysis

Investment cost variable	2020	2050	Cost evolution scenario
Pipeline [USD/m] (D = pipe diameter [m])	$4,000 \bullet D^2+$ $598.6 \bullet D+329$	$3,200 \bullet D^2+$ $478.9 \bullet D+263.2$	20% cost reduction
Liquefied hydrogen ship [bn USD per ship]	0.412	0.206	50% cost reduction
Liquefied hydrogen export terminal [bn USD/Mt H_2]	90.909	45.455	
Liquefied hydrogen import terminal [bn USD/Mt H_2]	90.141	45.071	
Hydrogen liquefaction [bn USD/(Mt H_2/yr)]	5.385	2.693	
Liquid hydrogen evaporation [bn USD/(Mt H_2/yr)]	0.016	0.008	
Ammonia ship [bn USD per ship]	0.085	0.060	30% cost reduction
Ammonia export terminal [bn USD/Mt NH_3]	1.994	1.396	
Ammonia import terminal [bn USD/Mt NH_3]	1.711	1.198	
Ammonia conversion [bn USD/(Mt H_2/yr)]	2.984	2.089	
Ammonia reconversion [bn USD/(Mt NH_3/yr)]	0.307	0.215	

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[102] Argus Media (2020) "Global Ammonia Trade to Recover in 2021," Argus Media News, 11 November 2020, accessed 20 September 2021. https://www.argusmedia.com/en/news/2158915-global-ammonia-trade-to-recover-in-2021

[103] IEA foresees 75 Mt of demand for low-carbon hydrogen in 2040 in the Sustainable Development Scenario in IEA (2020), while consultancy firm BloombergNEF includes a scenario with 801 Mt demand for green hydrogen in BloombergNEF (BNEF) (2020) "New Energy Outlook 2020," October 2020. https://about.bnef.com/new-energy-outlook-2020/

Figure 20 offers a schematic representation of renewable hydrogen production and transportation by pipeline. Our analysis computed the length of pipelines by considering the distance between the countries' centers; following a conservative approach, pipelines were assumed to be newly built (see Table 9).

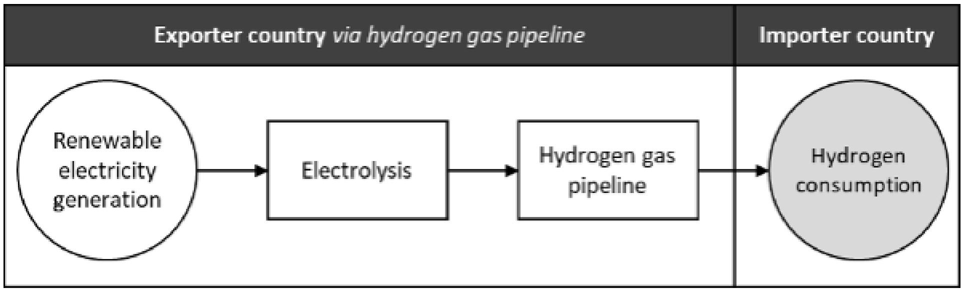

Figure 20. Schematic representation of hydrogen shipping by pipeline

Different sources estimate that retrofitting existing natural gas pipelines for transporting hydrogen could reduce investment costs significantly.[104] However, routes connecting renewable hydrogen production and consumption centers are likely to differ from existing natural gas networks. Therefore, future hydrogen pipelines will be unable to rely entirely on retrofitted natural gas infrastructure. Given the difficulty of assessing which shares of existing infrastructure could be retrofitted, input parameters are based on new pipeline construction.

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[104] Estimates vary widely with cost reductions ranging between 20% and over 70%. For example, see Cerniauskas et al. (2020) "Options of Natural Gas Pipeline Reassignment for Hydrogen: Cost Assessment for a Germany Case Study," *International Journal of Hydrogen Energy*, 45(21), pp. 12095–12107. https://doi.org/10.1016/j.ijhydene.2020.02.121; Wang et al. (2020) "European Hydrogen Backbone," Guidehouse for Enagás, Energinet, Fluxys Belgium, Gasunie, GRTgaz, NET4GAS, OGE, ONTRAS, Snam, Swedegas, Teréga, July 2020. https://guidehouse.com/-/media/www/site/downloads/energy/2020/gh_european-hydrogen-backbone_report.pdf ; or Tezel and Hensgens (2021) "HyWay 27," strategy&, PwC for Gasunie, June 2021. https://www.gasunie.nl/en/news/gasunie-decision-on-hydrogen-infrastructure-is-milestone-for-energy-transition/

Table 9. Hydrogen pipeline input parameters

	Value	Unit	Source	Notes
Investment cost	3,200•D^2+ 478.9•D+ 263.2	[USD/m]	(IEA 2019)	D = pipe diameter in meters. Includes the cost of compressors.
Operation and maintenance cost	4.0%	[% CAPEX]	(Reuß et al. 2017)	
Operational lifetime	40	[years]	(IEA 2019)	
Gas density	7.9	[kg/m^3]	(IEA 2019)	Assumed pressure of 100 bars.
Velocity	15.0	[m/s]	(IEA 2019)	
Average utilization	75.0%	[% max flow]	(IEA 2019)	
Storage	70	[days]	Assumption based on 20% of annual flow (BNEF 2020)	Assumed storage in salt caverns.
Storage investment cost	8.0	[USD/kg H_2]	(Samsatli et al. 2016)	Reported costs for Warmingham salt cavern.
Storage operation and maintenance cost	2.0%	[% storage CAPEX]	(Samsatli et al. 2016)	Assumed use of salt caverns.
Storage operational lifetime	30	[years]	(Reuß et al. 2017)	Assumed use of salt caverns.

Hydrogen transportation by liquefied hydrogen shipping requires additional infrastructure for liquefaction, export and import terminals, vessels connecting countries, and regasification, as shown in Figure 21.

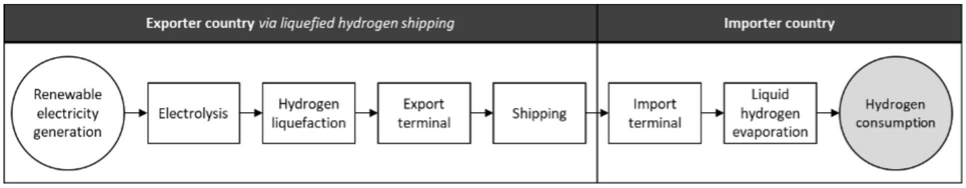

Figure 21. Schematic representation of hydrogen shipping

It is assumed that ships are fueled by hydrogen boil-off on the outgoing leg and retain part of their cargo for the return leg. Shipping fleets serve specific trade routes between exporter and importer countries, so the number of ships in one fleet depends on distances and traded volumes. However, the sizes of liquefaction, export and import terminals, and liquid hydrogen evaporation infrastructures depend on the overall volumes each country exports or imports.[105] Overall, shipping costs depend on traveled distance, transported volumes per year, and renewable electricity and hydrogen costs. Input parameters for hydrogen liquefaction are shown in Table 10, for export terminals in Table 11, for ships in Table 12, for import terminals in Table 13, and for liquid hydrogen evaporation in Table 14.

Table 10. Hydrogen liquefaction input parameters

	Value	Unit	Source	Notes
Investment cost	2.693	[bn USD/(Mt H_2/yr)]	(IEA 2019)	
Operation and maintenance costs	4.0%	[% CAPEX]	(IEA 2019)	
Electricity demand	6.1	[kWh/kg H_2]	(IEA 2019)	
Operational lifetime	30	[years]	(IEA 2019)	
Availability	7,884	[hours per year]	(IEA 2019)	Equivalent to 90% availability.

Table 11. Liquefied hydrogen export terminal input parameters

	Value	Unit	Source	Notes
Investment cost	45.455	[bn USD/Mt H_2]	(IEA, 2019)	
Operation and maintenance costs	4.0%	[% CAPEX]	(IEA, 2019)	
Electricity demand	0.61	[kWh/kg H_2]	(IEA, 2019)	
Storage	3	[days]	(Mizuno et al. 2016)	
Boil-off rate	0.1%	[% capacity per day]	(IEA, 2019)	
Operational lifetime	30	[years]	(IEA, 2019)	
Availability	7,884	[hours per year]	(IEA, 2019)	Equivalent to 90% availability.

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[105] Detailed engineering design of shipping infrastructure would require a more in-depth consideration of factors such as economies of scale, overcapacity and/or storage required to supply the desired amount of hydrogen with operational hours limited by intermittent renewable energy resources, and overproduction to account for hydrogen losses along the supply route.

Table 12. Liquefied hydrogen ship input parameters

	Value	Unit	Source	Notes
Ship capacity	0.011	[Mt H_2]	(IEA, 2019)	
Investment cost	0.206	[bn USD per ship]	(IEA, 2019)	
Operation and maintenance costs	4.0%	[% CAPEX]	(IEA, 2019)	
Boil-off rate	0.2%	[% capacity per day]	(IEA, 2019)	
Fuel consumption	12.396	[kg H_2/km]	(IEA, 2019)	Assumes electric propulsion using a hydrogen fuel cell.
Speed	30.0	[km/h]	(IEA, 2019)	
Load/unload time	24	[hours per trip-leg]	Assumption	
Availability	7,884	[hours per year]	(IEA, 2019)	Equivalent to 90% availability.
Lifetime	30	[years]	(IEA, 2019)	

Table 13. Liquefied hydrogen import terminal input parameters

	Value	Unit	Source	Notes
Investment cost	45.071	[bn USD/Mt H_2]	(IEA, 2019)	
Operation and maintenance costs	4.0%	[% CAPEX]	(IEA, 2019)	
Electricity demand	0.2	[kWh/kg H_2]	(IEA, 2019)	
Storage	20	[days]	(Mizuno et al. 2016)	
Boil-off rate	0.1%	[% capacity per day]	(IEA, 2019)	
Operational lifetime	30	[years]	(IEA, 2019)	
Availability	7,884	[hours per year]	(IEA, 2019)	Equivalent to 90% availability.

Table 14. Liquid hydrogen evaporation input parameters

	Value	Unit	Source	Notes
Investment cost	0.008	[bn USD/(Mt H_2/yr)]	(Reuß et al. 2017)	
Operation and maintenance costs	3.0%	[% CAPEX]	(Reuß et al. 2017)	
Electricity demand	0.6	[kWh/kg H_2]	(Reuß et al. 2017)	
Operational lifetime	10	[years]	(Reuß et al. 2017)	
Availability	7,884	[hours per year]	Assumption	Equivalent to 90% availability.

Shipping hydrogen as ammonia requires a different infrastructure: renewable hydrogen is converted into ammonia, which is shipped and then reconverted to hydrogen (see Figure 22).

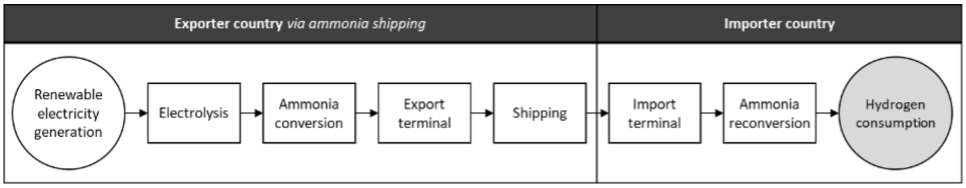

Figure 22. Schematic representation of ammonia shipping

For coherence across scenarios, it was assumed that all ammonia was converted back into hydrogen. All vessels were assumed to run on ammonia. Ammonia and electricity costs depend on the renewable electricity and hydrogen production costs in producing countries, while heat costs are assumed to average 0.05 USD/kWh. Input parameters can be found in Table 15 for ammonia conversion, Table 16 for an export terminal, Table 17 for ammonia shipping, Table 18 for an import terminal, and Table 19 for ammonia reconversion.

Table 15. Ammonia conversion input parameters

	Value	Unit	Source	Notes
Investment cost	2.089	[bn USD/(Mt H_2/yr)]	(Ikäheimo et al. 2018)	Includes air separation unit and synthesis process.
Operation and maintenance costs	2.0%	[% CAPEX]	(Ikäheimo et al. 2018)	
Electricity demand	3.627	[kWh/kg H_2]	(Ikäheimo et al. 2018)	
Operational lifetime	30	[years]	(IEA 2019)	
Availability	7,884	[hours per year]	(IEA 2019)	Equivalent to 90% availability.

Table 16. Ammonia export terminal input parameters

	Value	Unit	Source	Notes
Investment cost	1.396	[bn USD/Mt NH_3]	(IEA 2019)	
Operation and maintenance costs	4.0%	[% CAPEX]	(IEA 2019)	
Electricity demand	0.005	[kWh/kg H_2]	(IEA 2019)	
Storage	3	[days]	(Mizuno et al. 2016)	
Boil-off rate	0%	[% capacity per day]	(IEA 2019)	
Operational lifetime	30	[years]	(IEA 2019)	
Availability	7,884	[hours per year]	(IEA 2019)	Equivalent to 90% availability.

Table 17. Ammonia shipping input parameters

	Value	Unit	Source	Notes
Ship capacity	0.053	[Mt NH_3]	(IEA 2019)	
Investment cost	0.060	[bn USD per ship]	(IEA 2019)	
Operation and maintenance costs	4.0%	[% CAPEX]	(IEA 2019)	
Boil-off rate	0.04%	[% capacity per day]	(Kim et al. 2020)	
Fuel consumption	94.575	[kg NH_3/km]	(Kim et al. 2020)	Assumes electric propulsion using an ammonia fuel cell.
Speed	30.0	[km/h]	(IEA 2019)	
Load/unload time	24	[hours per trip-leg]	Assumption	
Availability	7,884	[hours per year]	(IEA 2019)	Equivalent to 90% availability.
Lifetime	30	[years]	(IEA 2019)	

Table 18. Ammonia import terminal input parameters

	Value	Unit	Source	Notes
Investment cost	1.198	[bn USD/Mt NH_3]	(IEA 2019)	
Operation and maintenance costs	4.0%	[% CAPEX]	(IEA 2019)	
Electricity demand	0.02	[kWh/kg NH_3]	(IEA 2019)	
Storage	20	[days]	(Mizuno et al. 2016)	
Boil-off rate	0%	[% capacity per day]	(IEA 2019)	
Operational lifetime	30	[years]	(IEA 2019)	
Availability	7,884	[hours per year]	(IEA 2019)	Equivalent to 90% availability.

Table 19. Ammonia reconversion input parameters*

	Value	Unit	Source	Notes
Investment cost	0.215	[bn USD/(Mt NH_3/yr)]	(IEA 2019)	
Operation and maintenance costs	4.0%	[% CAPEX]	(IEA 2019)	
Electricity demand	1.5	[kWh/kg H_2]	(IEA 2019)	
Heat demand	9.7	[kWh/kg H_2]	(IEA 2019)	
Operational lifetime	30	[years]	(IEA 2019)	
Availability	7,884	[hours per year]	(IEA 2019)	Equivalent to 90% availability.

*Hydrogen recovery rate assumed 100% and heat costs assumed 0.05 USD/kWh of heat.

10.2. **Renewable Hydrogen Production Cost Model**

Renewable hydrogen production costs are estimated using a levelized hydrogen (LCOH) cost, which considers all costs and expected hydrogen production over an electrolysis plant's lifetime.

First, the levelization factor for hydrogen production L_{H2} is computed, which represents the hours that the electrolysis plant operates during its lifetime T_H discounted over time with rate d. Co-located renewable electricity, with the same power rating as the electrolyzer, determines the number of full load hours FLH_{RE} the plant operates at, which is dependent on each country's wind and solar resources (see Equation 1).

Equation 1. Levelization factor for hydrogen production

$$L_H[h] = \sum_{y \in T_H} \frac{FLH_{RE}[h]}{(1 + d[\%])^y}$$

Second, capital expenditures $CAPEX_H$ were estimated by calculating the investment cost of the electrolysis plant I_H for each kilogram of hydrogen produced during the plant's lifetime, which is dependent on the levelization factor for hydrogen production L_H, the electrolyzer efficiency μ_H, and hydrogen's lower heating value LHV_H (see Equation 2).

Equation 2. Capital expenditures of electrolysis plant

$$CAPEX_H \left[\frac{USD}{kg}\right] = \frac{LHV_H \left[\frac{kWh_H}{kg}\right]}{\mu_H \left[\frac{kWh_H}{kWh_e}\right] \cdot L_H[h]} \cdot I_H \left[\frac{USD}{kW_e}\right]$$

Third, operational expenditures $OPEX_H$ per kilogram of hydrogen produced were computed by estimating operation and maintenance cost $O\&M_H$ as a function of investment cost I_H, discount rate d, the levelization factor for hydrogen production L_H, the electrolyzer efficiency μ_H, and hydrogen's lower heating value LHV_H (see Equation 3).

Equation 3. Operational expenditures of electrolysis plant

$$OPEX_H\left[\frac{USD}{kg}\right]=\frac{LHV_H\left[\frac{kWh_H}{kg}\right]}{\mu_H\left[\frac{kWh_H}{kWh_e}\right]\cdot L_H[h]}\cdot\sum_{y\in T_H}\left(\frac{O\&M_H[\%]\cdot I_H\left[\frac{USD}{kW_e}\right]}{(1+d[\%])^y}\right)$$

Finally, the cost of renewable electricity was estimated using the levelized cost of electricity $LCOE_{RE}$ of the wind or solar energy resource co-located with the electrolysis plant, which depends on the investment cost of the renewable electricity plant I_{RE}, operation and maintenance cost $O\&M_{RE}$, operational lifetime T_{RE}, full load hours per year FLH_{RE}, and discount rate d (see Equation 4).

Equation 4. Levelized cost of renewable electricity

$$LCOE_{RE}\left[\frac{USD}{kWh_e}\right]=\frac{I_{RE}\left[\frac{USD}{kW_e}\right]+\Sigma_{y\in T_{RE}}\left(\frac{O\&M_{RE}[\%]\cdot I_{RE}\left[\frac{USD}{kW_e}\right]}{(1+d[\%])^y}\right)}{\Sigma_{y\in T_{RE}}\frac{FLH_{RE}[h]}{(1+d[\%])^y}}$$

With capital and operational expenditures as well as electricity costs, the production costs of renewable hydrogen were estimated for each country's resources following Equation 5, where the electrolyzer efficiency μ_H and hydrogen's lower heating value LHV_H are used to estimate renewable electricity costs per kilogram of hydrogen produced.

Equation 5. Levelized cost of hydrogen production

$$LCOH\left[\frac{USD}{kg}\right]=CAPEX_H\left[\frac{USD}{kg}\right]+OPEX_H\left[\frac{USD}{kg}\right]+LCOE_{RE}\left[\frac{USD}{kWh_e}\right]\cdot\frac{LHV_H\left[\frac{kWh_h}{kg}\right]}{\mu_H\left[\frac{kWh_h}{kWh_e}\right]}$$

10.3. **MIGHTY Model Overview**

The Model for International Green Hydrogen Trade (MIGHTY) was developed to investigate hydrogen trades. MIGHTY is a mixed-integer linear programming (MILP) optimization model that identifies combinations of renewable hydrogen production and consumption within one country (i.e., domestic self-consumption) and international imports that minimize annual supply costs to meet demand either for one country or a group of countries (e.g., the European Union).

MIGHTY scenarios are based on demand scenarios, production, and transportation costs (see Section 10.1.4). Each producing country has an associated production cost curve and is assigned a mode of hydrogen transportation (see Section 10.4). Using these inputs, MIGHTY finds a solution that meets all selected consumer countries' hydrogen demand at the lowest supply costs possible.

A set of constraints ensures that MIGHTY searches for viable solutions:

- a demand constraint ensures that hydrogen supply meets all consumer countries' hydrogen demand;
- a supply constraint guarantees that producer countries do not produce more hydrogen than their renewable hydrogen potentials;
- a transportation constraint makes sure that MIGHTY solutions employ hydrogen gas pipelines by default, except for countries that need to use shipping routes (see Section 10.4);
- to avoid mathematically correct but unrealistically small hydrogen trades, another constraint requires minimum exports of 10^6, 10^9, and 10^{12} kg per year between European, regional, and long-distance producers, respectively.

Finally, MIGHTY determines pipeline diameters, the number of ships, and the scale of export and import terminals (and associated liquefaction or ammonia conversion and reconversion infrastructure), all of which depend on international hydrogen flows between countries. The model uses a set of discrete pipeline diameter sizes based on Reuß et al. (2019)[106] and a discrete number of vessels serving each shipping route that depends on how much hydrogen flows between the producing and consuming countries and their distance.

This report used the version v0.1.0 of MIGHTY formulated in Python using Pyomo and solved with Gurobi under an academic license.

10.4. **Hydrogen Transportation Mode**

All continental countries are assumed to have access to hydrogen pipelines. In contrast, countries in the north of Africa (Morocco, Egypt), island states (Iceland, Ireland, Malta, Cyprus), and long-distance exporters (Australia, the United States) are assumed to ship their hydrogen to the EU (see Figure 23). Distances between countries are computed based on their geographical centers.

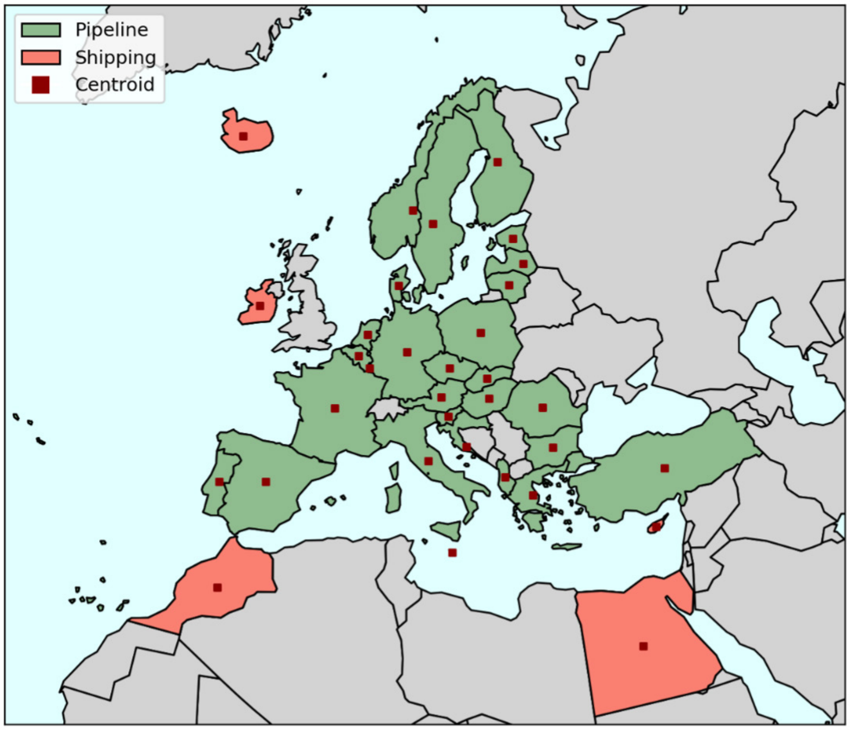

Figure 23. Hydrogen transport mode and centroid per country
Source: authors' analysis

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[106] Reuß et al. (2019) "Modeling Hydrogen Networks for Future Energy Systems: A Comparison of Linear and Nonlinear Approaches," *International Journal of Hydrogen Energy*, 44(60), pp. 32136-32150. https://doi.org/10.1016/j.ijhydene.2019.10.080

10.5. **Sensitivity Analysis Inputs**

For the sensitivity analysis, all three scenarios were simulated under 16 different combinations of input parameters in which key economic parameters were increased or reduced by 50% (see Table 20). Renewable electricity resources have been extensively studied in the past and therefore there is abundant data about their availability in different countries. Thus, the main uncertainties around future renewable hydrogen production costs arise from the evolution of technology costs rather than resource potentials, which warrants the focus on capital costs (represented by a discount rate) and investment costs in the sensitivity analysis.

Table 20. Sensitivity analysis inputs

Variable	Lower value	Reference	Higher value
Discount rate [%]	4%	8%	12%
Solar investment cost [USD/kW]	204	407	611
Onshore wind investment cost [USD/kW]	637	1,273	1,910
Offshore wind investment cost [USD/kW]	860	1,720	2,580
Electrolyzer investment cost [USD/kW]	225	450	675
Pipeline investment cost [USD/m] (D = pipe diameter [m])	$1{,}600 \bullet D^2 + 239.45 \bullet D + 131.6$	$3{,}200 \bullet D^2 + 478.9 \bullet D + 263.2$	$4{,}800 \bullet D^2 + 718.35 \bullet D + 394.8$
Liquefied hydrogen			
Ship [bn USD per ship]	0.103	0.206	0.309
Liquefaction [bn USD/(Mt H_2/yr)]	1.347	2.693	4.040
Export terminal [bn USD/Mt H_2]	22.728	45.455	68.183
Import terminal [bn USD/Mt H_2]	22.536	45.071	67.607
Liquid hydrogen evaporation [bn USD/(Mt H_2/yr)]	0.004	0.008	0.012
Ammonia			
Ship [bn USD per ship]	0.030	0.060	0.090
Synthesis [bn USD/(Mt H_2/yr)]	1.045	2.089	3.134
Export terminal [bn USD/Mt NH_3]	0.698	1.396	2.094
Import terminal [bn USD/Mt NH_3]	0.599	1.198	1.797
Reconversion [bn USD/(Mt NH_3/yr)]	0.108	0.215	0.323

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