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Prospects for the Ukrainian green hydrogen sector

A comparative analysis of the state of hydrogen markets and policies in key countries

PROJECT INFORMATION

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Executive Summary

This study evaluates the export competitiveness of Ukrainian hydrogen exports vis-à-vis key competitors and provides an analysis of key hydrogen demand centres in the EU and emerging infrastructure developments.

On **the supply side**, the study finds that **Morocco** could produce hydrogen at low costs and has existing infrastructural links to the European continent that could potentially be utilised for hydrogen exports. The country could supply green hydrogen to Germany at a cost of 2.01 -4.90 EUR/kgH2 by 2030. Overall, the country holds large potential, in particular to export PtX products. However, many obstacles remain. These include a small projects pipeline, potential water shortages and a coal-fuelled electricity demand growth which could conflict with strict sustainability requirements.

Spain fulfils most of the criteria necessary to export hydrogen to European demand centres – high renewable potential and low production costs, stable political and regulatory environment, and a large project pipeline. By 2030 it could supply green hydrogen to Germany at a cost of 1.61-2.56 EUR/kgH2. However, much of Spain's potential hinges on the successful realisation of a subsea pipeline project connecting it to France.

The United Kingdom emerges as a promising hydrogen producer, benefiting from geological advantages, abundant natural gas resources and substantial offshore wind potential. By 2030, the UK could provide blue hydrogen to Germany at costs ranging from 2.00 -2.34 EUR/kgH2 and 2.93 -3.27 EUR/kgH2 for green hydrogen. However, the prospects for hydrogen exports are heavily contingent on domestic demand projections which are highly uncertain. In addition, the UK currently faces a lack of comprehensive export plans for hydrogen to Europe, as well as insufficient infrastructure.

Norway benefits from existing technology, infrastructure and expertise of the country's oil and gas industry which positions Norway to generate a significant amount of blue hydrogen in the mid-term. Supply costs of blue hydrogen to Germany by 2030 are estimated to be in the range of 1.11-1.96 EUR/kgH2. Supply costs for green hydrogen are significantly higher at 3.29 -4.11 EUR/kgH2. Despite these promising factors, there is discrepancy between potential and signed export contracts and the actual project pipeline, and the government has not yet provided a clear outline of capacity and production goals.

Ukraine, bordering the EU, connected via existing infrastructure and with large renewable and nuclear potential, in principle is well endowed to become a hydrogen supplier to the EU - with potential to deliver green hydrogen to Germany at a cost of 2.3-2.8 EUR/kgH2 by 2030. However, in addition to liberating and demining large parts of its renewable rich territory, it would need to secure reasonable financing costs for its projects, successfully upgrade its gas transportation system and manage to balance domestic needs and export ambitions for green hydrogen. Successful realisation of its potential will thus likely only be possible in the longer term.

Assessing the **demand and infrastructure side**, **the EU** overall, and in particular **Germany** and the wider northwestern European industrial cluster, are likely to become significant importers of hydrogen. The case for imports to Italy and France is less clear cut. **France** actively opposes becoming a hydrogen importer and instead places large bets on its domestic nuclear - and to a lesser extent also renewable - capacity to domestic fulfil demand, while **Italian** hydrogen policy remains in its infancy. However, Italy's state-owned energy companies are forging new ties with potential Northern-African hydrogen producers and aim at turning the country in a transit hub. For the demand side countries under consideration, only Germany seems like a potential importer of Ukrainian hydrogen in the mid-term.

The study concludes that despite its enormous potential for domestic green hydrogen use and exports, Ukraine faces significant obstacles. The prospects of utilising Ukrainian hydrogen potential for exports in the nearer future are unfavourable but could become possible in the medium to longer term.

Inhalt

Introduction

Green hydrogen electrolyzed from renewable energy, and blue hydrogen derived from natural gas with carbon capture, have gained prominence in the debates on the decarbonisation of the energy system and hard-to-abate sectors. It is anticipated that the EU, and Germany in particular, will become major importers of hydrogen in the coming decades, necessitating the development of new trade partnerships with producer countries and facilitating market expansion. Ukraine is considered a potential future supplier of hydrogen to the EU due to its abundance of renewable energy sources, close proximity, and existing infrastructure. The creation of significant hydrogen production capacity has also featured prominently in the vision of Ukraine’s post-war recovery. However, there will be stiff competition from other EU and non-EU countries that also possess similarly favourable conditions, and unlike Ukraine, are not currently facing the significant obstacles caused by the ongoing Russian invasion of the country. Furthermore, there is significant uncertainty surrounding demand and actual import demand in key EU member states. On the one hand, many of the EU's largest economies can strive for self-sufficiency, but on the other hand, future hydrogen demand highly depends on the continuation of energy-intensive industrial manufacturing on the continent.

This study assesses and contrasts the export competitiveness of potential hydrogen exports from Ukraine to the EU with the exports of several key competitors in the EU and its neighbourhood: Morocco, Spain, the United Kingdom, and Norway. The study's primary focus is on pipeline exports and takes multiple qualitative and quantitative criteria into account. These criteria include production and transport prices, existing project pipeline and infrastructure, environmental factors, potential export volumes, and political and regulatory aspects. Moreover, the study looks at the major EU demand centres, Germany, Italy, France as well as the EU as a whole and other regions within it. By assessing their potential import routes and net import potential, this study also evaluates possible EU importers of Ukrainian hydrogen. The study's methodology is based on extensive literature research and the authors’ own analysis.

01

Supply side

Morocco

Introduction

Morocco holds great renewable energy potential and is strategically located at the Strait of Gibraltar, a key chokepoint that connects the Mediterranean Sea to the wider Atlantic Ocean while separating Europe from Africa. Morocco is positioning itself as the gateway to Africa and as a key partner for the EU's decarbonisation goals and could in principle become one of the major suppliers of green hydrogen and its derivatives.

While Morocco's decision-makers realised sooner than regional peers that the transition to renewable energies entails many benefits, the rapid growth in domestic electricity demand provides a significant hurdle for such ambitions as the country struggles to deploy renewable sources fast enough. Large domestic demand for green hydrogen to decarbonise the ammonia and fertiliser industry provides a competing use case for direct hydrogen exports to Europe, while concerns over water availability should also not be underestimated.

National Energy Strategy and Plans

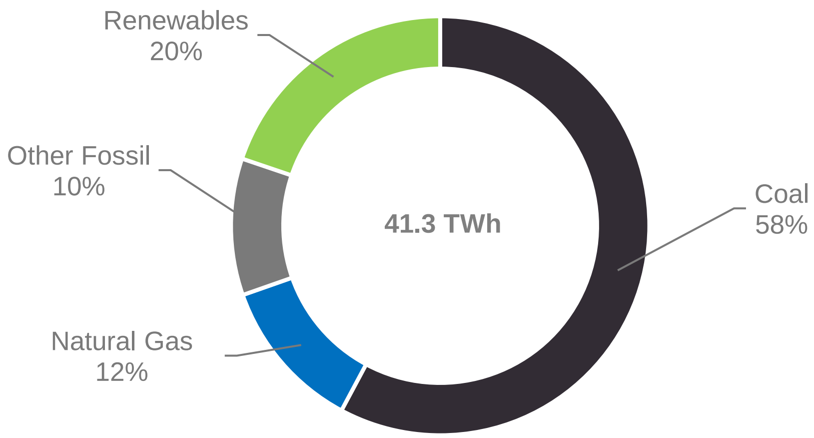
Morocco is the only country in Northern Africa without significant domestic fossil fuel resources. Instead, Morocco has enormous and widely recognized potential for renewable energy, in particular solar and wind. With more than 3000 sunshine hours per year and wind speeds in certain areas reaching an average speed of 10 m/s, the country is in principle well-endowed to supply itself with domestic energy sources many times over. Total technical potential for Solar PV is estimated at 20 000 GW, onshore wind at 6 000 GW and offshore wind at 500 GW.[1]

However, despite these rich endowments and high radiation levels, the country remains heavily dependent on fossil fuels imports to serve its energy needs, in particular oil and coal. In 2021, oil (57%) and coal (32%), dominated the primary energy mix, while all renewable sources combined accounted for only 8% and natural gas for another 3%. A similar situation exists in the electricity sector, where fossil fuels account for 80% of total generation, most of it being coal, which forms 58%. Renewables account for the remaining 20%.[2]

[1] Research Institute for Solar Energy and New Energies (2020)
[2] Ember-Climate (2023); BP (2023)

It is worth pointing out that due to rapidly growing electricity demand (fuelled by population growth and improved electricity access of the population), coal consumption increased more than two-fold between 2010 and 2022, while the share of coal in the electricity mix increased by 15% over the same period.[3]

Figure 1: Electricity Mix in 2021



Source: Ember Climate (2023)

Morocco's decision-makers have begun prioritising the transition to renewable energy sources relatively early on compared to neighbouring countries, starting with the adoption of the 2009 National Energy Strategy, which still remains in place today.[4] The strategy set the goal to install 2 GW of Solar, Wind and Hydro power by 2020. In 2015, in the wake of the 21st UNFCCC Conference, Morocco expanded its plans, outlining that by 2030 the combined installed renewable capacity should reach 52% of installed capacity, 70% in 2040 and 80% in 2050. In order to achieve the 2030 targets, the aim is to add around 10 GW of renewable energy capacities (mostly wind and solar) between 2018 and 2030.[5] However, as of 2022, the country had 1.3 GW Hydro, 1.6 GW Wind and 0.9 GW Solar capacity installed, thereby falling far short of its 2020 goals set out in 2009, putting also the remaining targets into question.

At the same time the country is also trying to diversify its fossil fuel import mix, and in parallel is exploring the possibility of building a floating storage and receiving unit for liquified natural gas and has recently announced a national road map for the development of its domestic natural gas resources.[6]

[3] Ember-Climate (2023)
[4] Ministry for Energy, Mining and Environment (2015)
[5] International Energy Agency (2019)
[6] International Trade Administration (2022)

Hydrogen strategy

The Moroccan hydrogen potential, and in particular its Power-to-X (PtX) potential, was recognized early on, resulting in the publication of a PtX Roadmap for Morocco in 2019.[7] The roadmap concluded that Morocco is a prime candidate to benefit from the upcoming PtX market and estimates that the country could capture a market share of 4% of global demand. The roadmap further outlines necessary steps to achieve these goals, ranging from reducing costs throughout the value chain, building local clusters and establishing the necessary regulatory frameworks.

Building on this roadmap and the recommendations of it and of many other studies, Morocco published, as the first African and Arab country, its National Strategy for Green Hydrogen in 2021.[8] The strategy outlines that Morocco plans to produce green hydrogen not only to serve domestic demand, but also to export and to develop its industrial sector around green ammonia and methanol. Furthermore, Morocco requires between EUR 13 and 90 billion of investments between 2020 and 2050 to meet the potential demand by 2050. The strategy further aims to position Morocco as a strategic partner for European countries and their decarbonisation process.

Figure 2: Action Plan of National H2 Green Strategy

Source: PwC (2022)

The implementation of the strategy centres around eight actions (see Figure 2) and follows a detailed plan up to 2050. Green hydrogen exports, local utilization for national industry, particularly phosphates,

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[7] Ministry for Energy, Mining and Environment (2019)

[8] Ministry for Energy, Mining and Environment (2021)

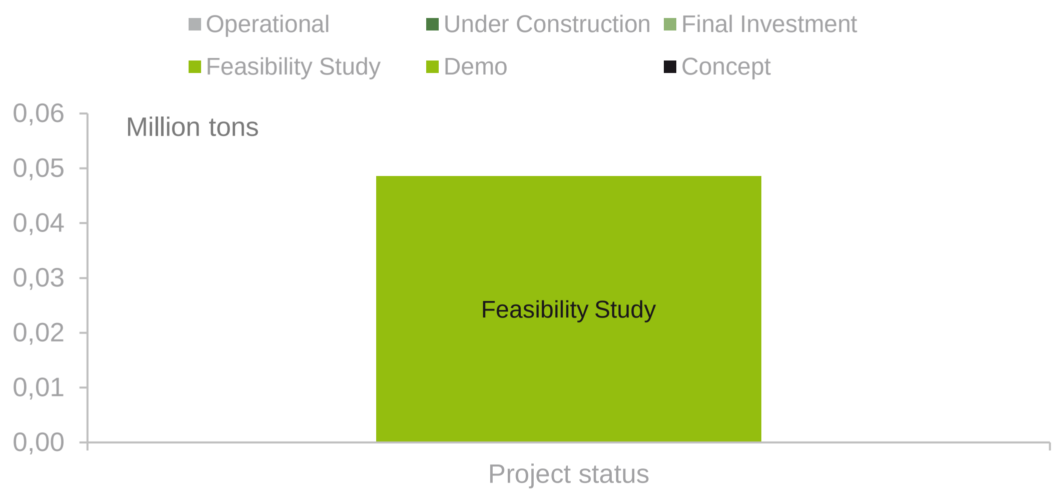
and research of natural hydrogen reserves are the top priority in the short term (2020-2030). Morocco will focus on building hydrogen projects and using green hydrogen as an energy storage vector in the medium term (2030-2040). In the long-term (2040-2050) increased levels of exports and ammonia production are foreseen. The strategy further states that in order to fulfil domestic demand there would be a need of 2.8-5.2 GW of electrolyser capacity installed in 2030, 13.9-23.0 GW in 2040 and 31.4-52.8 GW in 2050.

The key domestic demand sector for green hydrogen in Morocco itself is the decarbonisation of the domestic fertiliser production. The country imports around two million tons of grey ammonia per year, which it subsequently turns into fertilisers for exports. The key player in Morocco is the state-owned company OCP, one of the leading exporters of phosphate rock, phosphoric acid and phosphate fertilizers in the world. The company is responsible for about 20% of the country's total energy consumption and represents approx. 5% of GDP. OCP plans to spend USD 7 billion (EUR 6.6 billion) on a green ammonia plant to avert supply problems following large price swings in ammonia due to tight natural gas markets in recent years. By 2032, the company plans to produce 3 million tons of ammonia from solar and wind produced green hydrogen.[9]

Hydrogen Production Projects and Costs Estimates

Given the country's theoretical renewable potential and the amount of attention the country received regarding its hydrogen potential, the actual project pipeline is relatively meagre. A total of about 49 thousand tons of hydrogen (derivatives) projects are in the pipeline, almost all of it at feasibility study stage.

Figure 3: Hydrogen Projects in Morocco



Source: IEA (2022d)

[9] Reuters (2023a)

Noteworthy is the Morocco-German energy partnership, via which Morocco received a EUR 38 million grant to develop green hydrogen projects, including the construction of a hybrid Solar PV and wind plant with a planned electrolysis capacity of 100 MW, which is expected to become operational by 2025.[10] One key player in the Moroccan renewable project field is the Moroccan Agency for Solar Energy (MASEN). Currently MASEN undertakes a feasibility study for a 10 000 ton per year green hydrogen project financed by German development bank KfW. German Moroccan cooperation in the energy field had stalled as a result of a diplomatic dispute in 2021 over the contested western-Sahara region, resulting in Morocco diversifying its development partners. However, since then, relations normalised.[11]

In July 2021, the HEVO Ammonia Morocco project (183 000 tons of green ammonia planned by 2026) was announced. The project is the largest green hydrogen project (at feasibility study stage) to date and is being developed by Ireland-based hydrogen technology firm Fusion Fuel, which plans to install an 850 m USD ammonia plant. The output could serve about 10% of OCP's current input requirements.[12]

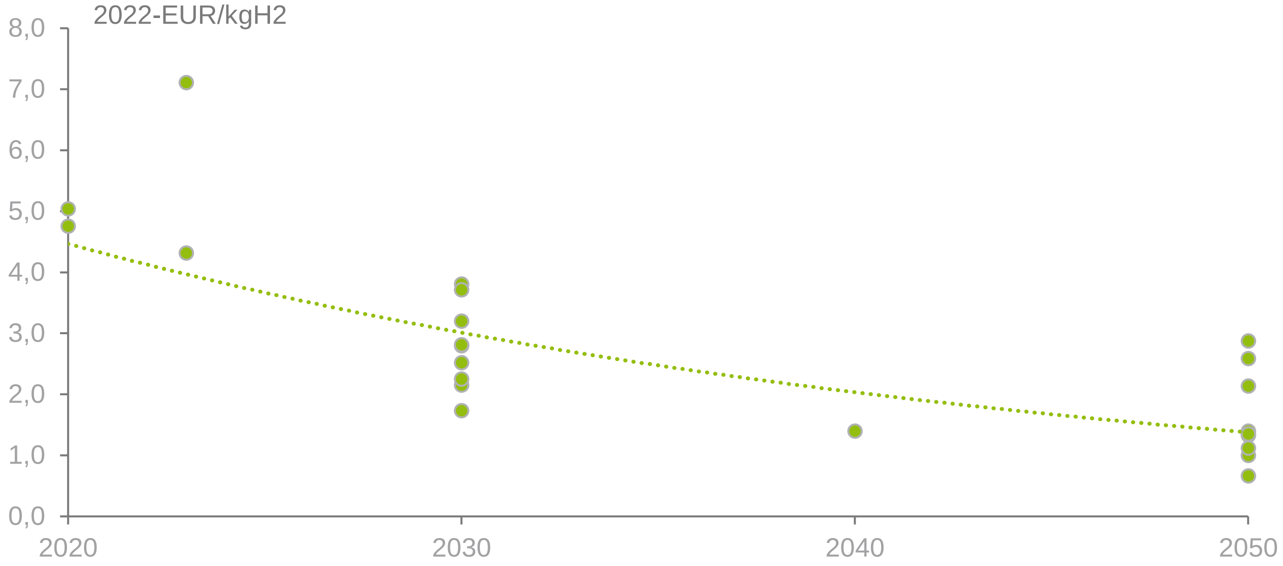
In 2022, Morocco also signed a Memorandum of Understanding on the establishment of a Green Partnership with the EU that focuses on energy efficiency and renewable energy, including green hydrogen.[13]

Morocco's high renewable potential would allow it to produce hydrogen at favourable costs, especially if good financing conditions are secured. The graph below shows the estimated costs of producing green hydrogen at various points in time based on estimates gathered from various publications and forecasts, while the dashed line represents a logarithmic trendline that encapsulates these projects.

Production costs in 2030 could range between 1.7 and 3.8 EUR/kgH2 and 0.7 and 2.9 EUR/kgH2 in 2050. The large differences in cost estimates stem from different renewables sources with varying capacity factors (e.g.: onshore wind, solar PV) used in the modelling as well as different interest rates and cost estimates for electrolysers in the future.

[10] Energy News (2022)
[11] Euractiv (2022)
[12] Fusion Fuel (2021)
[13] Ministry of Foreign Affairs, African Cooperation and Moroccan Expatriates – Kingdom of Morocco (2022)

Figure 4: Cost Estimates for Green Hydrogen Production in Morocco



Sources: Deloitte (2023), Aurora Energy Research (2023), Guidehouse (2022b), International Renewable Energy Agency (2022b), Statista (2021a), Adelphi (2020), Frauenhofer ISI (2019)

Potential for Export and Transport Corridors

Morocco has ample space and renewable endowments to produce hydrogen at scale. However, the country also has domestic applications that could utilise hydrogen production. Even after satisfying domestic demand, Moroccan decision-makers are confident that the country can produce excess quantities for exports from 2030 onwards. The Moroccan Hydrogen Roadmap gives detailed estimates on domestic demand and export potential of green hydrogen which are roughly in line with estimates of other sources and studies. The table below is based on multiple sources and gives ranges for estimates of annual green hydrogen demand and export potential.

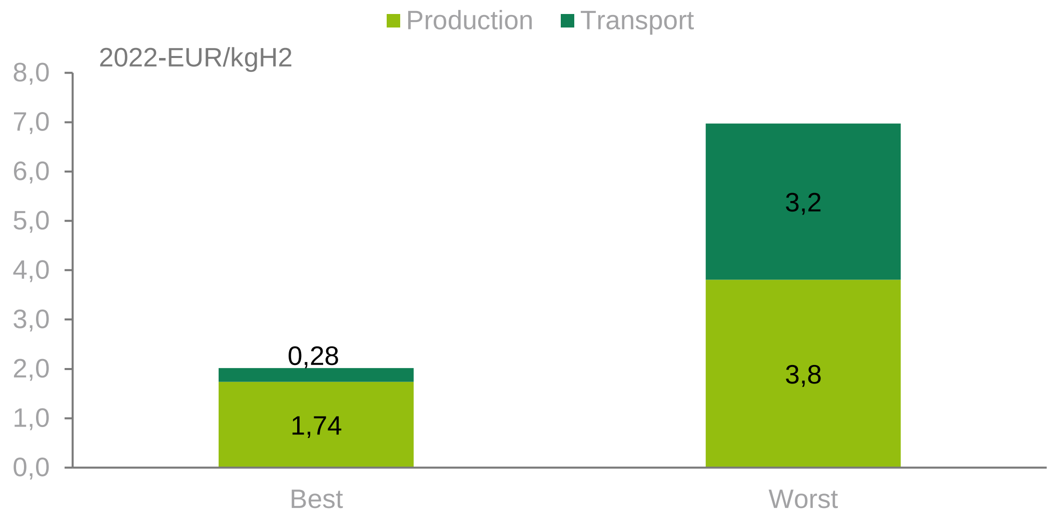
Table 1: Potential for Export and Transport Corridors, in Million Tons of H2

Million Tons of H2	2030	2040	2050
Supply Potential	0.4 - 0.9	1.4 - 6.9	3.5 - 9.2
Demand Potential	0.1 - 0.3	0.7 - 4.0	1.2 - 2.3
Export Potential	0.3 - 0.7	0.7 - 6.0	2.3 - 6.9

Source: Eurostat 2018

As highlighted in Table 1, Morocco could have excess green hydrogen production capacity. The net supply of green hydrogen could reach up to 6 million tons in 2040 and up to 7 million tons in 2050. Morocco could therefore potentially export significant amounts of hydrogen at competitive prices, although there is a significant degree of uncertainty attached to all estimates as can be seen in Figure 5 below, which plots the best and worst estimates for production and transport costs to Germany in 2030.[14]

Figure 5: Best- and Worst-Case Projections for Costs to Export Green Hydrogen from Morocco to Germany 2030



Source: EWI (2021), Wuppertalinstitut (2020), Adelphi (2019)

While the above factors form a solid basis for being a prospective hydrogen exporter to the EU, other factors complicate the outlook. The most challenging factor for Morocco likely will be the rather strict EU regulations on what can be considered as green hydrogen, which has been set out in the Delegated Acts of the European Commission.[15] The regulation, that also applies to imports, sets strict criteria for additionality and temporal and spatial correlation of hydrogen production with renewable electricity generation. Given the high, and still rising share of coal in Morocco's electricity mix, there are well founded concerns that hydrogen production from renewables could conflict with the country's domestic decarbonisation goals. If existing renewable capacities were to be dedicated to hydrogen and PtX production, fossil fuels will have to serve the domestic electricity needs even more than is already the case.

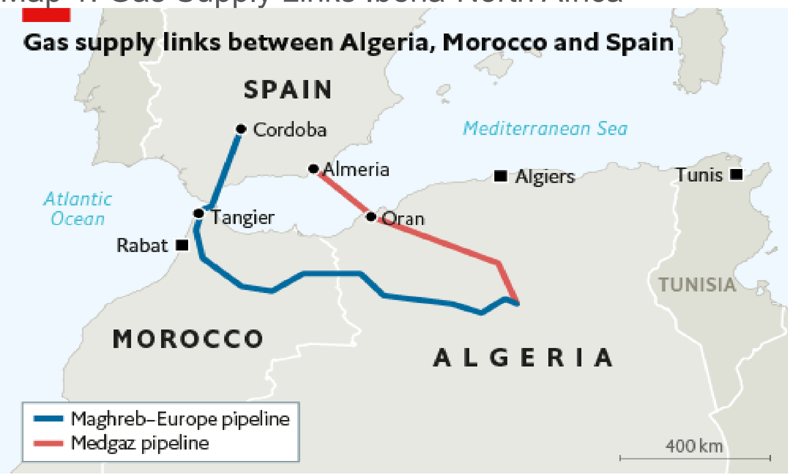
[14] The high difference in the transportation cost stems from the lower estimate assuming a cheaper retrofitting of existing pipelines, while the higher estimate stems from the costs required to construct a new pipeline.
[15] Hydrogen Insight (2023)

To avoid this, the EU Delegated Acts implement the so-called additionality criteria. More specifically, the regulation requires that renewable plants used for electrolysis must be not older than 36 months. Additionally, to make use of the benefits of higher capacity factors to reduce costs, grid electricity can be used for the electrolyser, but the hydrogen production must match renewable electricity generation in the same bidding zone on a monthly basis until 2030 and afterwards on an hourly basis.

These strict requirements aim to prevent that the increased electricity demand from electrolysis results in higher emissions elsewhere and will require a certain certification system that ensures imported gases fulfil these criteria. While this will likely prevent additional fossil fuel usage in Morocco as a result of green hydrogen production earmarked for exports to the EU, it will likely also provide a large stumbling block to any short-term exports from the country to the EU.

Regarding transport infrastructure and potential export routes, Morocco has several options. On the one hand, Morocco is linked to Spain via the Maghreb-Europe pipeline which used to transport natural gas from Algeria via Tangier in Morocco to Cordoba in Spain. However, since the diplomatic fallout over the status of the Western Sahara between Algeria and Morocco, the gas flows from Algeria via this pipeline stopped.[16] Instead, Spain now supplies Morocco with natural gas sourced from international markets which boosted Spanish Moroccan diplomatic relations. [17] Whether this pipeline could be repurposed to carry hydrogen or whether a new pipeline would need to be built remains unclear. Via the planned Spanish hydrogen pipeline system (H2 Med pipeline via France) Moroccan hydrogen could reach Northwest European markets.

Map 1: Gas Supply Links Iberia-North Africa



Source: The Economist Intelligence Unit (2022)

[16] The Pipeline Technology Journal (2023)
[17] Morocco World News (2023)

Another long-term project worth mentioning is a natural gas pipeline which should connect Nigeria to Morocco. If it were to be constructed in a way that would allow easily switching to hydrogen at a later point, this could potentially become a broad Africa-Europe hydrogen export corridor with Morocco as a gateway keeper. Prospects for the success of this pipeline however remain highly uncertain.[18]

On the other hand, Morocco also has a favourable geographical location as the country is positioned at the Strait of Gibraltar linking Europe, Africa, and the Middle East. Moreover, Morocco has a well-developed port infrastructure, which is already handling large quantities of ammonia – a hydrogen derivate. An alternative export vector thus could be maritime trade with PtX products like ammonia and methanol. The port of Hamburg and the Moroccan port of Tangier signed a partnership agreement in 2020 to boost cooperation, also for the import of green hydrogen.[19] However, connecting the best sites for hydrogen production in the south of the country with the port infrastructure might also require investments into logistics and possibly new ports itself.[20] How much of exports would ultimately be available to Germany is unclear and cannot be estimated credibly as much depends on how the markets develop, e.g., who locks in exports via long term contracts. If Morocco were to export via pipeline and the Iberian corridor, its exports would be destined for the Northwest European industrial demand centres like Germany, Netherlands, and Belgium. If Morocco were to export PtX products via ship, it would be more flexible in regard to potential customers compared to pipeline transport.

Other Factors

As Morocco is not member of the European Union, concerns regarding security of supply and poor environmental and labour standards could potentially arise; Morocco is generally considered to be a closed autocracy, with concerns regarding environmental and social aspects.[21] Other issues that may arise include potential water availability concerns. Morocco is considered to be among the countries with the highest water stress level worldwide.[22] Massive desalination plants will be required to allow for large scale hydrogen production. And while they would increase the levelized cost of hydrogen only marginally, the initial CAPEX for the plants would still be significant. Moreover, desalination plants require large amounts of electricity which would again have to be sourced from renewables to avoid increased fossil fuel usage and ensure zero emission hydrogen production across the value chain.

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[18] Africa News (2022); Brookings (2022)
[19] Afrik 21 (2021)
[20] PwC (2022)
[21] V-Dem Institute (2023)
[22] World Resource Institute (2015)

Conclusion

Overall, Morocco can produce hydrogen at significantly lower costs than most countries globally. The country holds large potential, in particular to export PtX products and decarbonise its fertiliser industry which could otherwise be negatively affected by the adoption of carbon borders in the EU and high volatility in gas markets.

However, many hurdles to export green hydrogen to the EU and Germany remain. The combination of rapid electricity demand growth, enabled by increased usage of coal, and strict requirements for additionality, are the biggest challenges. Decarbonising the domestic grid and serving rising demand with renewables alone already proves to be a very challenging task, as can be seen by the failure to meet the country's set 2020 goals. Additionally, increasing electricity demand by aiming to produce large quantities of green hydrogen via electrolysis, and only using new earmarked renewable capacity for it, will prove even harder and require even quicker and larger expansion of renewable capacity in the country.

Spain

Introduction

Spain is due to become one of the key players in the European hydrogen market. Endowed with significant renewable energy potential and given its relative proximity to key demand centres in Europe, the country could produce significant excess quantities of green hydrogen from renewable-generated electricity from 2030 onwards and, under the right conditions, become a primary supplier of green hydrogen to key demand centres in the EU like Germany. If all the currently announced projects were to be realised, Spain would be home to the largest installed capacity of electrolysers in Europe by 2030. However, there are also potential future challenges that Spain's hydrogen ambitions face. Much will depend on the successful physical integration of the country into European energy markets to deliver hydrogen to demand centres, but also on other issues such as actually securing final investment decisions on hydrogen production projects, potentially competing domestic industrial decarbonisation plans, and sustainability concerns.

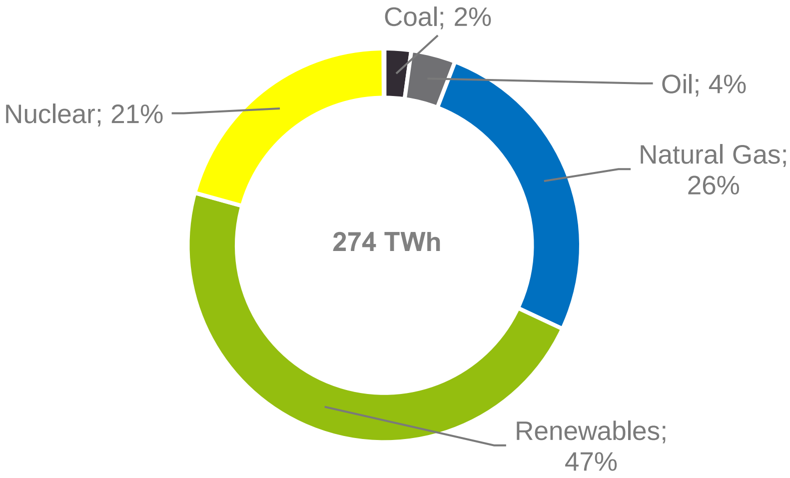
National Energy Strategy and Plans

Spanish climate neutrality goals - 100% renewable electricity and a 97% share of renewables in the energy mix by 2050 - are the foundation of the current Spanish framework for energy and climate policy, as set in the countries Long-term Decarbonisation Strategy until 2050 and the Law on Climate Change and Energy transition.[23] As an intermediary target, the National Energy and Climate Plan indicates that renewable electricity generation is envisaged to make up for 74% of the electricity mix in 2030.[24] The rapid deployment of renewable energy, in particular solar and wind energy, but also strong increases in energy efficiency and electrification, as well as the use of renewable hydrogen, are the country's focus.

Despite progress in the deployment of renewable sources for electricity generation, Spain's energy mix is still dominated by fossil fuels, with oil and natural gas accounting for 42% and 26% of total energy supply in 2021, respectively. Nuclear power makes up for another 13% while wind, solar and hydro combined only account for 10% of the energy mix.[25]

Electricity generation is more diversified, with natural gas (26%) and nuclear (22%) together serving almost half of the bulk of electricity consumption in 2021, while 47% of electricity was generated by renewables, the bulk of it wind (22%) and hydro (12%). However, Spain is planning to not only phase out nuclear power and remaining coal power plants by 2035, but it also has very ambitious plans for the roll-out of renewables.[26]

Figure 6: Electricity Mix in 2021



Source: IEA (2022b)

[23] Ministry for Ecological Transition and the Demographic Challenge (2020a); State Agency Official State Gazette (2021)
[24] Ministry for Ecological Transition and the Demographic Challenge (2020b)
[25] International Energy Agency (2022b)
[26] International Energy Agency (2022b)

The renewable deployment targets of the government are to install an additional 22 GW of wind, 30 GW of solar PV, 5 GW of Concentrated Solar Power (CSP), 3.5 GW of pumped storage, and 0.8 GW of biomass between 2020 and 2030.[27] Since 2019, Spain already increased its RES deployment significantly. In 2022 Spain had 20.5 GW of Solar and 29.3 GW of Wind capacity installed.[28]

As a result, if all plans were to be implemented successfully, the Spanish energy system would undergo a rapid transformation in the coming years and decades, moving rapidly towards decarbonisation.

Hydrogen Strategy

In Spain, the idea of green hydrogen as an alternative energy carrier has been met with great enthusiasm and resulted in the publication of the Spanish Hydrogen Strategy in 2020, becoming one of the first countries globally with a dedicated green hydrogen strategy.[29] The roadmap makes clear which industries have potential for hydrogen deployment as well as the environmental, economic, and societal benefits of hydrogen. It offers a vision for 2030 and 2050 and sets the rather modest goal of installing 4 GW of electrolysers by 2030, and no target for 2050. The strategy also foresees EUR 8.9 billion in investments for green hydrogen production projects. The lack of meaningful domestic gas reserves makes it clear that Spain will focus on green hydrogen production produced via electrolysis.

At the time of publication of the strategy, the focus and priorities of the government revolved around green hydrogen as a tool to decarbonise and develop industry as well as to serve the diversification of the economy and the energy mix. The strategy therefore focuses on primarily on domestic aspects, possible industrial use cases, applications in the transport sector, as well as the development of regional hydrogen clusters.

Spain is already a large consumer of hydrogen. The hydrogen strategy indicates a consumption of 500,000 tons of grey hydrogen per year, mainly used as industrial feedstock for its large refining and fertiliser sector. Hydrogen is also seen as a way to reindustrialise certain regions and bring about higher value-added industries and jobs. In accordance with the 2030 goals outlined in the strategy, hydrogen should account for at least 25% of energy consumed in Spain's industrial sectors. The strategy does not give an estimate of what this target would translate to in absolute numbers, but key industries that could use green hydrogen have already been pushing for its ramp up, especially the steel, fertilisers, chemical and petrochemical sectors. For example, Spain's large oil refining sector (Repsol, BP, Cepsa) is an early mover and announced plans to decarbonise all their consumption by 2030, while metal giant

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[27] Enerdata (2023)
[28] International Renewable Energy Agency (2023)
[29] Ministry for Ecological Transition and the Demographic Challenge (2020a)

ArcelorMittal signed an agreement with the Spanish government for funding support to build a 2.3 million tons green hydrogen direct reduced iron (DRI) plant.[30]

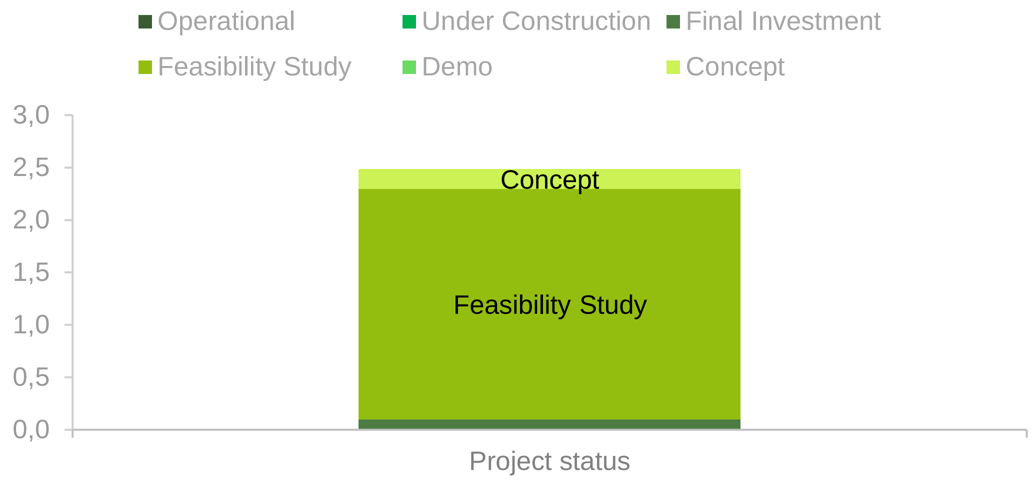
Spain has adapted its hydrogen policy after the Russian invasion of Ukraine in 2022 and the ambitious REPowerEU plans to phase out Russian gas. The country now incorporates a stronger external dimension and energy security aspects in its policy. Spain also strives to become a key transit country and exporter of hydrogen. It therefore fosters the development of a European hydrogen market and intensifies its actions to fulfil its longstanding goal of better physical integration into European energy markets.[31]

Hydrogen Production Projects and Costs Estimates

Spain is expected to become one of the key players in the green hydrogen market in Europe with a wide range of projects in the pipeline, though mostly at the feasibility study stage. Noteworthy is the HYDeal project, which aims to start production in 2027 with a total installed capacity of 7.4 GW of electrolysers by 2030 - almost twice as much electrolyser capacity as was envisaged in the country's hydrogen strategy. The main offtakers of the HyDeal project are ArcelorMittal and Grupo Fertiberia which plan to purchase 6.6 million tons of renewable hydrogen over 20 years[32] (330,000 tons per year) dedicated to the production of green steel and fertilizers. HyDeal is at the core of the HyDeal Ambition project, one of the world's largest integrated renewable and hydrogen hub projects. The project hopes to produce 3.6 million tons of green hydrogen in Europe by 2030.[33] In total, the projects in the database amount to about 2.5 million tons of production.

30 ArcelorMittal (2022a)
31 Escribano G. & Urbasos I. (2023)
32 ArcelorMittal (2023b)
33 HyDeal Ambition (n.d.)

Figure 7: Hydrogen Projects in Spain

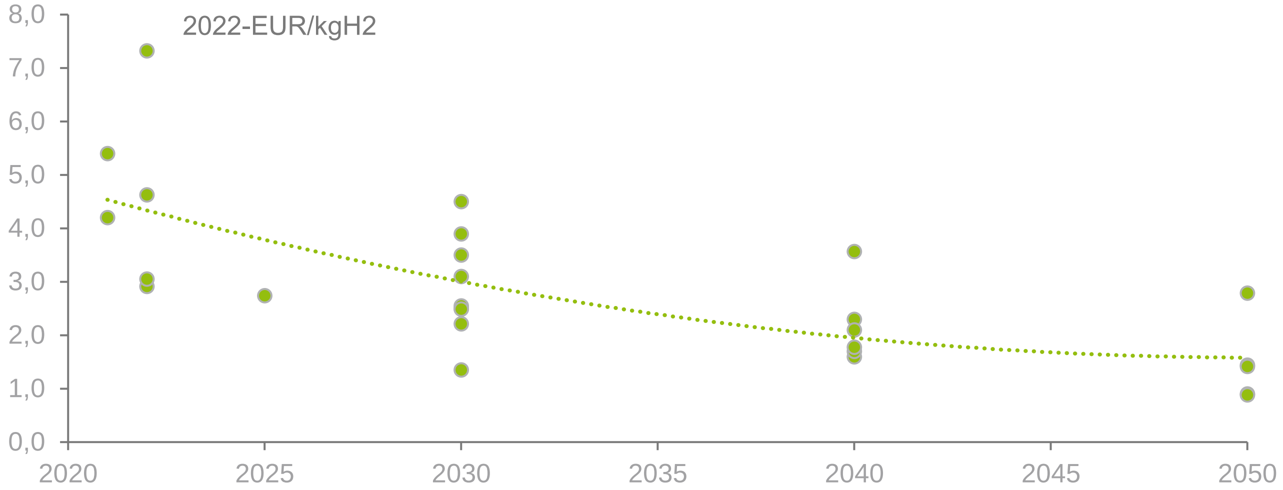


Source: IEA (2022d)

The geographical location of Spain brings with it significant benefits for the prospects of producing green hydrogen at favourable costs using its abundant domestic wind and solar resources and high radiation levels.

The graph below shows the estimated costs of producing green hydrogen at various points in time based on estimates gathered from various publications and forecasts. Production cost estimates for 2021/2022 range between 2.91 and 7.32 EUR/kgH2. Falling costs for electrolysers and electricity from solar and wind could bring production costs to 2.2 – 3.9 EUR/kgH2 by 2030, 1.6-3.6 EUR/kgH2 by 2040 and potentially to 0.9-2.8 EUR/kgH2 in 2050. The large differences in cost estimates stem from different renewables sources with varying capacity factors (e.g.: onshore wind, solar PV) used in the modelling as well as different interest rates and cost estimates for electrolysers in the future.

Figure 8: Cost Estimates for Green Hydrogen Production in Spain



Sources: Fuel Cells and Hydrogen Observatory (2023), Aurora Energy Research (2023), DNV (2023), Frontier Economics (2023), Hydrogen Europe (2022), Guidehouse (2022b), International Renewable Energy Agency (2022b), Agora Energiewende (2021), Stiftung Arbeit und Umwelt der IG BCE (2021), Statista (2021a), EWI (2021)

It is worth noting that most of the price estimates for 2030 highlighted in the graph are well above the price goal that the HyDeal Ambition consortium predicts– 1.5 EUR/kgH2 by 2030.[34]

Potential for Export and Transport Corridors

One of the obstacles Spain faces is its weak integration via physical infrastructure (pipelines, power lines) to the rest of Europe. Key to any ambition of exporting hydrogen to the demand centres of Northwest Europe will hinge on the success of the H2Med pipeline – a contentious pipeline that plans to bring hydrogen from the Iberian Peninsula to France and ultimately to Germany, the latter joining the project in 2023. The pipeline is planned to begin operations in 2030 and also includes Portugal. The Spanish government estimates H2Med will be able to supply some two million metric tons of hydrogen annually, equal to supplying about 10% of the European Union's hydrogen demand by 2030 as outlined in the RePower EU plans.[35] The project was submitted to the call for Projects of Common Interest (PCI) of the European Union in December 2022.[36]

[34] HyDeal Ambition (n.d.)
[35] DW (2023)
[36] Financial Times (2022)

Map 2: Hydrogen Pipeline Plans in South-Western Europe

Source: Financial Times (2022)

RePowerEU also identified the development of a new subsea pipeline connecting Spain and Italy, expected to be available for hydrogen transport by 2030.[37] However, no concrete plans have yet been made public regarding this project.

Another export route is being developed by the Spanish private sector. Spanish energy company Cepsa announced, together with the Port of Rotterdam, the establishment of an ammonia/methanol-based hydrogen shipping corridor. The ambition is to supply Northwest Europe with 4.6 million tons of green hydrogen derivatives (from multiple countries) by 2030.[38]

In the long run, the Iberian-Central Europe hydrogen corridor from Spain and Portugal could also become part of a larger export corridor that could be extended to included North African exporters, which face similar obstacles in reaching Northwest European markets. Morocco and possibly Algeria could also become suppliers of hydrogen to Europe. Existing natural gas pipelines from Algeria, partly via Morocco, to Spain could offer the possibility of establishing a trans-Mediterranean hydrogen corridor.

[37] European Hydrogen Backbone (2023)
[38] CEPSA (2022)

The economics of hydrogen transport favour pipelines over seaborne transport up to a distance of about 3,000 km for new hydrogen pipelines.[39] Estimates for additional transport costs via pipeline linking Spain and Germany range from 0.5 to 1.8 EUR/kgH2 in 2030, to 0.1-1.8 EUR/kgH2 in 2050, depending on the CAPEX, interest rates and size and route of the pipeline.[40] Spain is already linked to France via the Lacal gas interconnector. Whether this pipeline could be repurposed to carry hydrogen is unclear but is currently also not being discussed. Alternative transport carriers like ammonia or methanol entail costly efficiency losses associated with the conversion and reconversion processes.

Spain does not have caverns suitable for hydrogen storage, which could additionally increase transport costs. However, the integration into a European hydrogen backbone would soften such negative effects.

Another important factor for the hydrogen export potential of Spain is the potential volume of supply and the domestic supply needs in Spain itself. Estimates for demand in Spain and other countries are very uncertain and do not necessarily match with announced projects. The table below is based on multiple sources and gives ranges for estimates green hydrogen demand where possible.

Table 2: Export Potential of Green Hydrogen in Million tons of H2

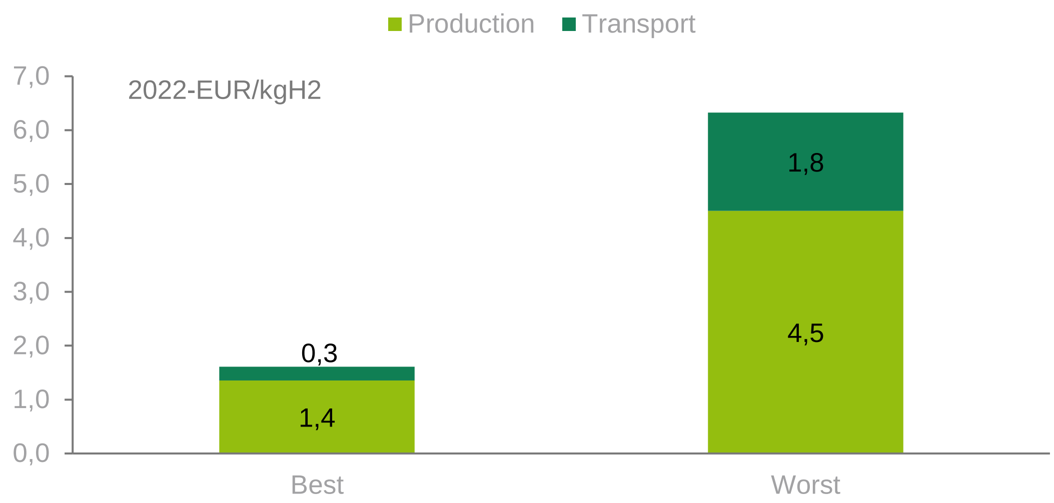
Million tons of H2	2030	2040	2050
Supply Potential	2.2	6.7	11.2 - 12.0
Demand Potential	0.9 - 1.4	3.2 - 4.7	5.0 - 7.8
Export Potential	0.8 - 1.3	2.0 - 3.5	3.4 - 7.0

Sources: DNV (2023), Guidehouse (2022b), Guidehouse (2021b)

As highlighted in Table 2, Spain could have excess green hydrogen production capacity. The net supply of green hydrogen could reach up to 3.5 million tons in 2040 and up to 7 million tons in 2050. Spain could therefore potentially export significant amounts of hydrogen at competitive prices, although there is a significant degree of uncertainty attached to all estimates as can be seen in Figure 9 below, which plots the best and worst estimates for production and transport costs to Germany in 2030. The large differences stem from different assumptions in the respective models as explained in chapter four.

[39] International Renewable Energy Agency (2022
[40] This assumes a pipeline length of 2000 km.

Figure 9: Best- and Worst-Case Projections for Costs to Export Green Hydrogen from Spain to Germany in 2030



Sources: Agora Energiewende (2021), Stiftung Arbeit und Umwelt der IG BCE (2021), EWI (2021)

Exports will likely only be available after 2030 when supply overtakes domestic demand. It is also worth noting that the estimates for 2030 would roughly require all projects listed in the IEA database (Figure 7) to materialise. Nonetheless, about 96% have not yet secured final investment decision. Another key consideration is also that potential forecasted demand could significantly decline if certain industries decide to relocate to countries with cheaper energy prices and looser regulations.

How much of Spain's exports would ultimately be available to Germany is unclear and cannot be estimated credibly as much depends on how the market develops, e.g., who locks in exports via long term contracts. Given the planned route for Spanish hydrogen exports to the Northwest European industrial demand centres for hydrogen, the Netherlands and Belgium could also become importers, while France so far puts great emphasis on remaining independent of imports and utilising its growing nuclear fleet for hydrogen production.

Other Factors

As Spain is a member of the European Union, concerns regarding security of supply and poor environmental and labour standards that come along with other potential hydrogen suppliers are largely mitigated. Spain is a strong advocate for stricter sustainability and governance criteria of hydrogen production at the EU level. Stricter standards as well as security of supply concerns for hydrogen imports would favour hydrogen production and trade within the EU (and thereby implicitly from Spain).

Spain also advocated for favouring renewable hydrogen over alternatives like blue hydrogen and nuclear based hydrogen.[41]

There are other potential obstacles that Spain could face, and which could negatively affect the competitiveness and prospects of its hydrogen exports, but going in detail is beyond the scope of this study. Among them are potential water availability concerns in the long run as hydrogen production from electrolysis might have to compete with water use in agriculture. The lack of skilled labour necessary of a rapid large scale hydrogen market ramp up in Spain can also present a bottleneck for the countries ambition and existing plans.

Conclusion

Spain fulfils many of the criteria necessary to export hydrogen to European demand centres – high renewable potential and low production costs, stable political and regulatory environment, and a large project pipeline - and could thus become a key green hydrogen supplier to Europe by 2030.
However, the competitiveness and feasibility of exports could be severely hampered by several factors stressed in this chapter. On the one hand, only a fraction of mentioned projects has secured a final investment decision. On the other hand, the primary envisaged export route is a long subsea pipeline at great depth which potentially includes costly delays. Furthermore, there is an inherent tension between hydrogen used for domestic industrial policy versus for exports. Spain has a significant demand for hydrogen on its own and will only develop large excess production capacities from 2030 onwards. Other factors such as water availability concerns and lack of skilled labour could cause additional obstacles. However, overall Spain is better suited to become an exporter than most countries in Europe and beyond.

[41] Escribano E. & Urbasos I. (2023)

United Kingdom

Introduction

The United Kingdom (UK) is determined to become one of the global leaders in the Green Industrial Revolution. Guided by the initial "Ten Point Plan for a Green Industrial Revolution"[42], the UK is committed to be at the forefront of spearheading sustainable energy initiatives. In 2019, the UK set a historic precedent by adopting binding legislation to achieve net zero emissions by 2050.[43]

Leveraging its strategic advantages, such as offshore wind potential and large gas reserves, the UK is well-positioned to establish a robust hydrogen sector. The country recognizes the potential of both green as well as blue hydrogen with CCUS (twin-track approach) and aims to scale up the demand and supply side of its hydrogen market by 2030.[44] Anticipating a surge in demand from 2030 onwards, hydrogen is set to play a pivotal role in various domestic sectors. However, the UK's ambitious goals also open opportunities for hydrogen export, especially to Europe and Germany, positioning the nation as a key player in the global energy transition.

However, the UK's efforts to expand the hydrogen sector also faces various challenges, including ensuring the development of balanced supply and demand markets for hydrogen, as well as specific regulatory and infrastructure-related aspects.

National Energy Strategy and Plans

The foundations of the current British framework for energy and climate policy are based on the "Power up Britain"[45] package (2023), which is based on the former British Energy Security Strategy[46] (2022), the Net Zero Growth Strategy[47] (2021), the Energy White Paper[48] and the "Ten Point Plan for a Green Industrial Revolution: Powering our net zero future"[49] (2020). While these strategies encompass the entirety of the UK, the individual constituent countries have also established their own additional strategies and targets. For instance, Scotland aims to achieve its net zero target by 2045.[50] These

[42] HM Government (2020a)
[43] HM Government (2019)
[44] Deloitte (2022)
[45] HM Government (2023)
[46] HM Government (2022a)
[47] HM Government (2021b)
[48] HM Government (2020b)
[49] HM Government (2020a)
[50] HM Government (2021b)

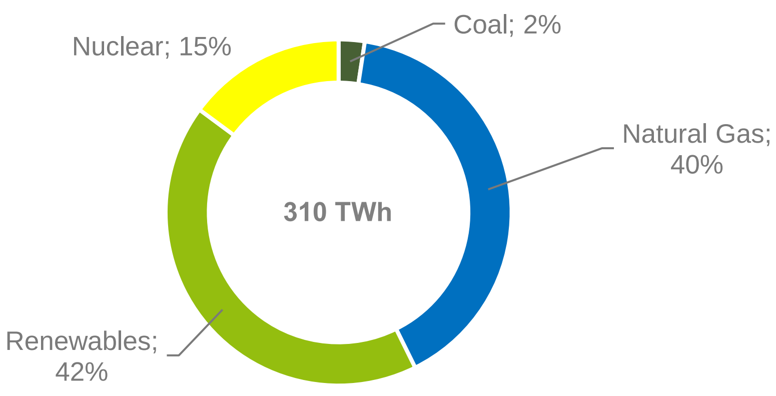
varied timelines reflect the unique circumstances and priorities of each constituent country within the United Kingdom.

By the end of 2035, the UK wants to fully decarbonise its electricity system. The primary focus is on the installation of renewable energy sources, especially solar PV and wind power, alongside notable deployments in nuclear power. [51]

However, the UK's energy mix as of 2021 remains heavily reliant on fossil fuels, with natural gas comprising 40%, oil 35%, and coal 4%, making up nearly 80% of the total energy mix. Nuclear power contributes an additional 7%. In contrast, renewable energy sources, including wind, solar PV, hydrogen, and biofuels, account for a mere 14%, with biofuels alone representing 10%.

Nonetheless, as of 2021, renewables have taken the lead in electricity generation, constituting the largest share at 44%. This includes wind power at 21%, biofuels at 11%, and solar at 4%. Natural gas follows closely behind at 40%, while nuclear power contributes 15%. Coal makes only a minimal contribution, amounting to 2% of the overall electricity mix.[52] In 2022, the proportion of wind power surged to 26%, while the shares of natural gas (38%) and coal (1.5%) witnessed slight declines.[53]

Figure 10: Electricity Mix in 2021



Source: IEA (2022b)

[51] HM Government (2022a)
[52] IEA (2022b)
[53] ESO (2023)

Concurrently, the estimated potential for renewable energy stands at 384 TWh (2030), 628 TWh (2040), and 860 TWh (2050).[54] However, the projected electricity demand in the UK is expected to reach 415 TWh by 2030, 484 TWh by 2040, and 557 TWh by 2050. According to the "Powering Up Britain - Net Zero Growth Plan," this implies that the UK is faced with a projected 60% increase in electricity demand by 2035.[55]

To achieve their projected demands and tap into their renewable potential, the UK has established several development goals. One of the UK's key objectives is to significantly increase their offshore wind capacity to 50 GW by 2030, including the incorporation of 5 GW from floating offshore wind power plants.[56] Recent data indicates that the 70 announced offshore wind projects have the potential to surpass these targets, reaching offshore wind capacity of 71.8 GW by 2032.[57] Furthermore, the UK aims to install 70 GW of ground and rooftop solar capacity by 2035.[58]

Regarding nuclear power, the UK plans to reach a nuclear capacity of 24 GW by 2050, which is approximately four times the capacity available in 2021 (6 GW). This planned capacity would account for approximately 25% of the projected electricity demand for 2050.

According to the "Balanced Net Zero Pathway", the UK has to reduce oil and gas production and demand by 50% by 2037.[59,60] However, to address the current challenge of reducing dependence on gas imports, the country intends to increase oil and gas production in the North Sea in the short term.[61] As of the end of 2021, estimated oil and gas reserves were approximately 2.7 billion boe, with oil reserves accounting for 1.8 billion boe and gas reserves at 0.9 billion boe.[62] In 2021, annual crude oil production was 44.8 million toe, while gas production reached 27.6 million toe.[63] These numbers indicate UK's abundant reserves and shows the significant potential that natural gas could play in blue hydrogen production.

If all these deployment goals are successfully achieved, the UK's energy sector will undergo a transformative change in alignment with its Net Zero Target.

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[54] Guidehouse (2021a)
[55] HM Government (2023)
[56] HM Government (2023)
[57] Westwood Global Energy Group (2023a)
[58] HM Government (2023)
[59] HM Government (2023)
[60] North Sea Transition Authority (2023)
[61] HM Government (2023)
[62] North Sea Transition Authority (2021)
[63] North Sea Transition Authority (2023)

Hydrogen Strategy

The UK's hydrogen strategy and targets emphasize the country's commitment to building a robust low-carbon hydrogen industry. The publication of the UK Hydrogen Strategy in 2021[64], based on the 10-point plan, laid the foundation for creating a framework conducive to the development of a hydrogen market, including a twin-track approach, supporting the production of both blue and green hydrogen, as each approach offers distinct advantages. This strategy was further supplemented by the introduction of a hydrogen business model (HPBM)[65], a net-zero hydrogen fund (NZHF)[66], and a low-carbon hydrogen standard.[67] There is also the plan to implement a future hydrogen certification scheme in line with the EU for low carbon hydrogen by the mid-2020s.[68,69]

Blue hydrogen can serve as one solution for UK's decarbonization. Given the UK's heavy reliance on natural gas for critical applications like power generation and heating in industries and homes, this dependency also presents a significant opportunity for decarbonization by substituting natural gas with blue hydrogen.

The UK also possesses a possible competitive advantage in green hydrogen production, as it is surrounded by seas that offer excellent wind conditions. The shallow seabed along the coastline makes offshore wind projects more accessible and cost-effective to develop, which could in turn decrease the costs for green hydrogen production.[70]

However, as stated in the latest "Powering up Britain" package, the UK follows a twin-track approach, which reflects the UK's aspirations to achieve a hydrogen production capacity of 2 GW, which consists of 1 GW electrolytic and of 1 GW CCUS-enabled hydrogen by 2025, and 10 GW (5 GW green and 5 GW blue hydrogen) by 2030.[71] Moreover, the earlier published UK Hydrogen Strategy outlines that 7-20 GW of production capacity of low carbon hydrogen may be needed by 2035 and 15-60 GW by 2050.

Looking ahead to 2050, it is estimated that the UK will require approximately 6.3 - 11.6 million tons of hydrogen, constituting 20-35% of the country's final energy consumption.[72] Additionally, Scotland, Wales and Northern Ireland published their own hydrogen strategies and investment programmes as

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[64] HM Government (2021a)
[65] HM Government (2022b)
[66] Department for Business, Energy & Industrial Strategy (2022a)
[67] Department for Energy Security & Net Zero (2023)
[68] HM Government (2021a)
[69] The UK plans to launch their hydrogen certification scheme by 2025.
[70] Westwood Global Energy Group (2023b)
[71] HM Government (2023)
[72] HM Government (2021a)

early as 2020 and 2021. Wales, for instance, aims to significantly increase its annual hydrogen production to a range of 0.5 – 3.0 million tons by 2050, with a notable portion of 2.4 million tons designated for export.[73]

Currently, hydrogen production is taking place at approximately 30 sites across different sectors in the UK, with an estimated production capacity of 2.5 GW.[74] Most of the hydrogen production is still reliant on fossil energy sources (grey hydrogen).

However, the UK government has already delineated four distinct clusters for the transition from natural gas to blue hydrogen with CCUS production. [75] The objective is to implement CCUS within two clusters; the HyNet cluster and the East Coast cluster, by the mid-2020s, followed by an additional two clusters by 2030. The HyNet cluster, for instance, encompasses 28 manufacturers spanning various sectors such as metals, automobiles and chemicals. All these manufacturers have endorsed a "Memorandum of Understanding" (MoU) signalling their commitment to shift from natural gas to locally produced blue hydrogen in their production processes, which holds the potential to curtail CO_2 emissions by up to 10 million tons annually by 2030.[76]

The clusters will be the first to be considered for support under the government's CCUS Programme, which includes the CCS Infrastructure Fund amounting to GBP 1 billion (EUR 1.17 billion).[77,78] Furthermore, the UK's government implemented the HPBM, which provides support to selected low-carbon hydrogen producers through measures like Contracts for Difference (CFDs). Additionally, a Net Zero Hydrogen Fund of GBP 240 million (EUR 281 million) has been allocated, with GBP 100 million (EUR 117 million) specifically designated for financing contracts related to up to 250 MW of electrolytic hydrogen production between 2022 and 2025.[79] Private sector co-investment in the hydrogen sector is estimated to reach GBP 4 billion (EUR 4.7 billion) until 2030.[80] In total, public funds will be about GBP 2.3 billion (EUR 2.7 billion) until 2030.[81] The regulatory frameworks being put in place and funding being allocated should bolster the government's productions capacity milestones.

[73] HM Government (2021a)
[74] HM Government (2021a)
[75] HM Government (2020a)
[76] HyNet North West (2022)
[77] Department for Business, Energy & Industrial Strategy (2022b)
[78] HM Government (2020b)
[79] Department for Business, Energy & Industrial Strategy (2022a)
[80] HM Government (2021a)
[81] Guidehouse (2021a)

As a result of the potential scale-up of green and blue hydrogen production, there is a growing demand for hydrogen and Carbon Storage (CS) sites. The UK possesses a significant advantage with its geological formations, which can be utilized for the storage of both hydrogen and carbon. There are two primary types of geological options for hydrogen storage in the UK: salt caverns and depleted oil and gas reservoirs. The storage of hydrogen can play a vital role in establishing a more secure energy system and can act as a solution to address curtailment, such as the case of offshore wind farms being curtailed due to grid limitations and lack of storage, which cost the UK over GBP 500 million (EUR 585 million) in 2021.[82]

The country is home to one of the four salt caverns globally that are currently utilized for hydrogen storage, boasting a capacity of 25 GWh of hydrogen. Furthermore, there is potential to convert additional salt caverns (currently used for natural gas storage) into hydrogen storage facilities. Examples include projects such as HySecure (with a potential capacity of 250 GWh of hydrogen) and Keuper Gas Storage Limited (with a potential capacity of 1.3 TWh of hydrogen). These projects have the potential to be ready to store hydrogen by 2030.[83]

Carbon storage is most economically viable when located near blue hydrogen production sites. Consequently, central England has been identified as the primary hub for CS, given its potential for offshore CO_2 storage. Currently, six active CS licenses are in use. According to the Net Zero Growth Strategy, the UK will require storing 104 million tons of carbon annually by 2050.[84] Projections indicate a total potential offshore CS capacity of 70 gigatons across 600 storage sites, with 61 gigatons in saline aquifers and 9 gigatons in depleted hydrocarbon fields.[85]

As outlined, the UK possesses all the necessary factors to be among the pioneering European countries in successfully scaling up its domestic hydrogen market.

Hydrogen Production Projects and Costs Estimates

The UK currently has 10 operational electrolyser sites for green hydrogen production with a combined capacity of approximately 0.001 million tons, as reported by the IEA Hydrogen Project Database.[86] Additionally, there are 0.0033 million tons of capacity under construction.

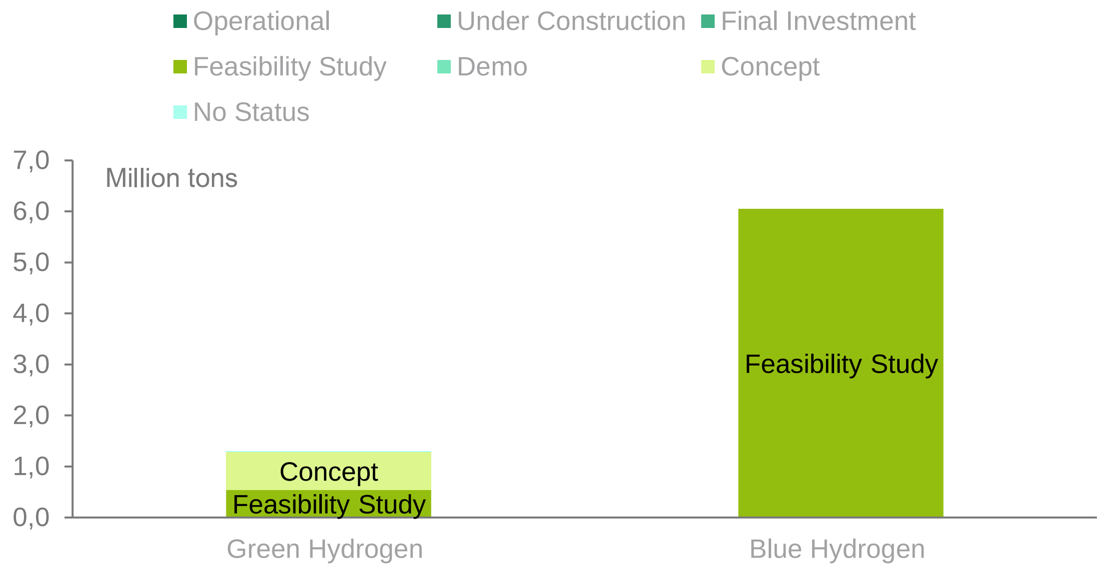
However, the potential capacities for electrolysers outlined in concepts and projects that have not yet received a final investment decision are significantly higher than what was initially outlined in UK's

[82] Current News (2022)
[83] Westwood Global Energy Group (2023b)
[84] HM Government (2021b)
[85] Westwood Global Energy Group (2023b)
[86] IEA (2022d), accessed July 2023

hydrogen strategy from 2021. The IEA database includes 0.74 million tons for which there are existing conceptual plans, and feasibility studies have been conducted for a total of 0.54 million tons of capacity. However, green hydrogen projects are very fragmented, with smaller project sizes and a larger number of developers involved relative to blue hydrogen projects. Nonetheless, there is a bigger green hydrogen project under development in Aberdeenshire with a potential production capacity of 3 GW of green hydrogen by 2030.[87]

The UK holds a notable advantage in the realm of green hydrogen with its electrolyser manufacturing capabilities. One example is ITM Power, one of the world's leading manufacturers of PEM electrolyser technology. The establishment of these gigafactories is crucial for scaling up green hydrogen production, as current constraints primarily revolve around electrolyser size and cost. ITM Power's gigafactory is expected to reduce electrolyser stack costs by 40% over the next three years.[88] The figure below illustrates the pipeline of green and blue hydrogen projects categorized according to their respective stages of development. Total project pipeline for blue hydrogen is approximately 6 million tons.

Figure 11: Hydrogen Projects in the UK



Source: IEA (2022d)

However, in contrast to the substantial project pipeline for green hydrogen, more recent data from 2023 reveals that by 2030, a total of 13 blue hydrogen projects have the potential to come into production.[89]

[87] Kintore Hydrogen (2023)
[88] Department for Business, Energy & Industrial Strategy (2021a)
[89] Westwood Global Energy Group (2023b)

These projects have a capacity of 14.3 GW. This capacity, in addition with the above stated capacity for green hydrogen exceeds the government's target of 10 GW almost twofold. But it is important to note that only a small number of hydrogen projects have reached the final investment decision (FID) stage.

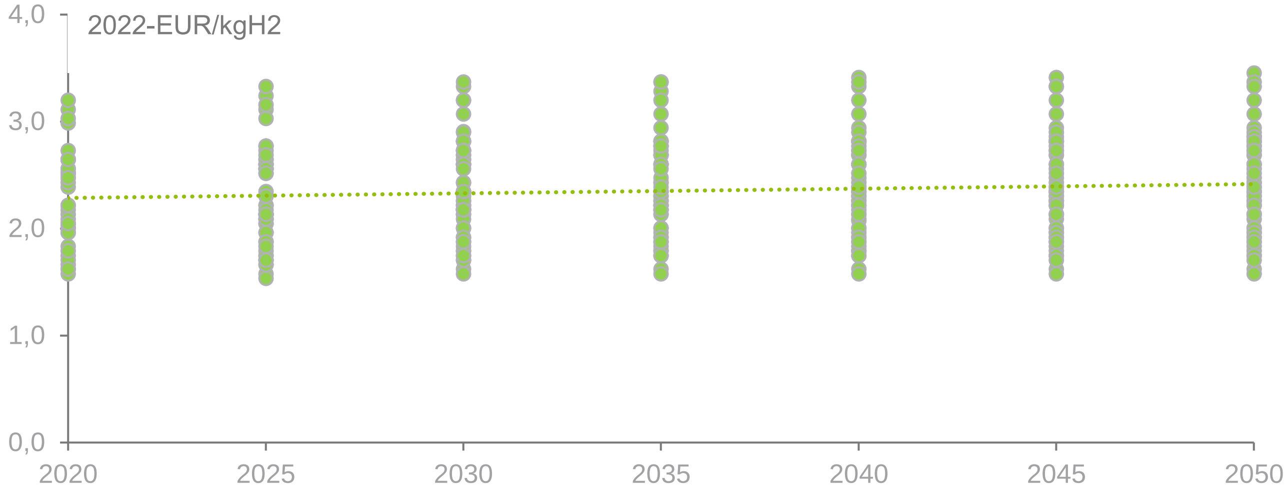
The development of blue hydrogen projects is primarily spearheaded by major players in the traditional oil and gas sector, underscoring their significant role in the initial scaling of blue hydrogen. These companies possess access to existing hydrogen production facilities, natural gas supplies, and extensive pipeline networks. For instance, Shell, is engaged in the development of three blue hydrogen projects in the UK, collectively amounting to a capacity of 3.3 GW.[90] It is worth noting that all proposed projects are strategically located along the coastline, facilitating convenient access to vital natural gas supplies and CO2 storage facilities, including both new production projects and existing ones planned for enhancement through the implementation of CCUS technology.

The geographical location of UK brings significant benefits for the prospects of producing green and blue hydrogen at favourable costs as the region benefits from a well-established offshore wind supply chain and platforms that can be repurposed to accommodate electrolysers and its vast natural gas reserves. The graphs below show the estimated costs of producing green and blue hydrogen within the time horizon between 2020 and 2050 based on various publications and forecasts.

Production costs of blue hydrogen are heavily related to natural gas prices and carbon prices. Thus, future blue hydrogen production costs largely depend on fossil fuel price forecasts. The production cost in 2020 fluctuated between 1.58 and 3.12 EUR/kgH2. Further estimates range from 1.58 – 3.20 EUR/kgH2 in 2030, 1.58 – 3.41 EUR/kgH2 in 2040, and 1.58 – 3.46 EUR/kgH2 in 2050. Natural gas costs are assumed to account for 0.68 - 1.92 EUR/kgH2 in 2020 and in 2050 0.73 - 2.39 EUR/kgH2. Furthermore, Carbon prices are assumed to be between 0.04 - 0.09 EUR/kgH2 in 2020 and in 2050 0.13 - 0.34 EUR/kgH2.

[90] Shell in UK (2022)

Figure 12: Cost Estimates for Blue Hydrogen Production in the UK[91]



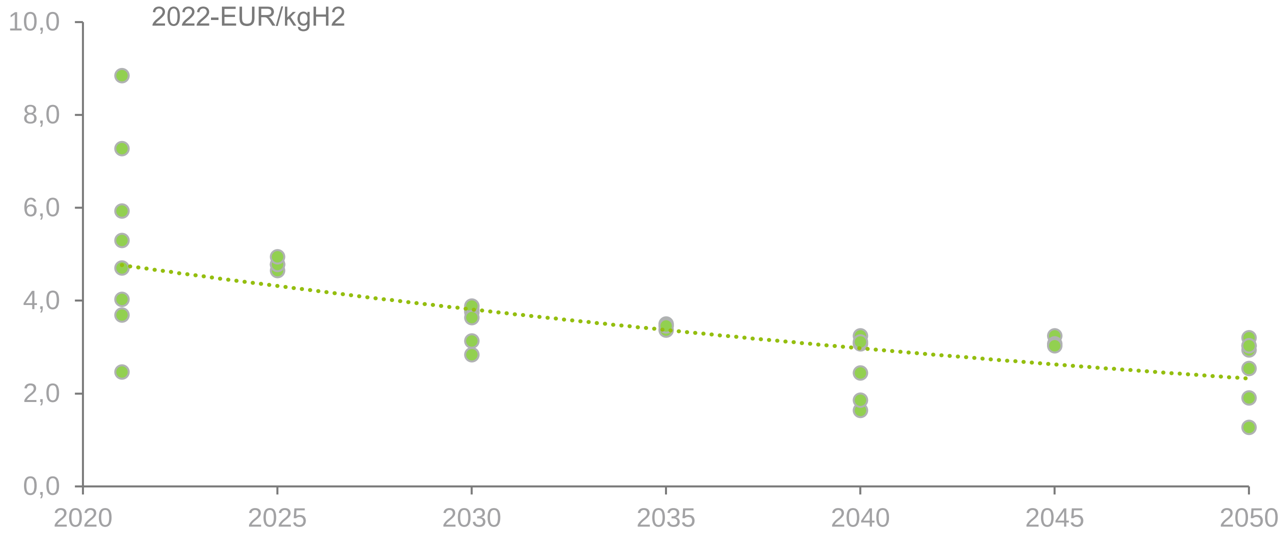
Sources: Goldman Sachs (2022), Guidehouse (2022b), UK Hydrogen Strategy (2021), Department for Business, Energy & Industrial Strategy (2021)

The significant variations in cost estimates depend also on different technologies with varying capacities employed in the modelling process, as well as different interest rates and future cost projections for mentioned technologies.[92]

The production cost of green hydrogen in 2020 ranges from 2.46 to 8.85 EUR/kgH2. By the year 2030, it is estimated that the production cost will fall to 2.84 – 3.88 EUR/kgH2. This downward trend is expected to continue, with anticipated costs of 1.64 - 3.24 EUR/kgH2 by 2040 and a potential range of 1.27 - 3.20 EUR/kgH2 by 2050. The substantial variations in cost estimates can be attributed to the utilization of different renewable energy sources with varying capacities, such as offshore wind and solar PV, in the modelling process. Additionally, different interest rates and future cost projections for electrolysers applied in the model also contribute to the discrepancies in the estimated costs.

[91] Similar results in Agora Energiewende & AFRY Management (2021) (no cost increase assumed between 2030-2050).
[92] Capacity ranges between 300 and 1000 MW. Capacity factors are assumed to be equal.

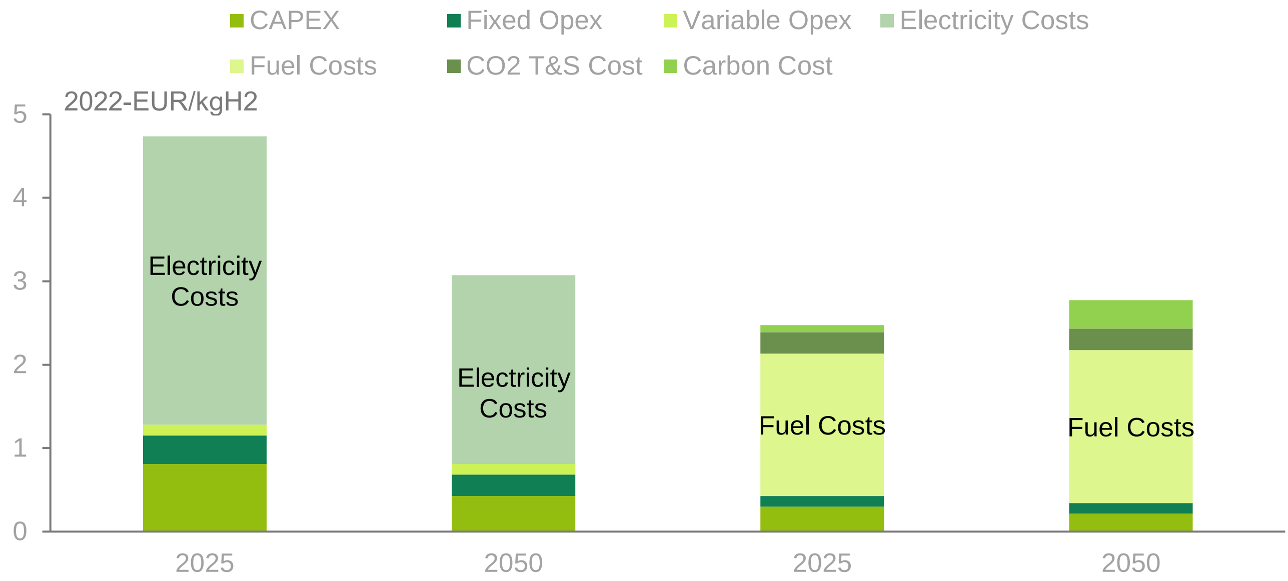
Figure 13: Cost Estimates for Green Hydrogen Production in the UK



Sources: Goldman Sachs (2022), Irena (2022), UK Hydrogen Strategy (2021), Guidehouse (2022b), Hydrogen Europe (2022), BEIS (2021), Enervis (2021)

The below detailed breakdown of cost components within the LCOH for green and blue hydrogen reveals that, in comparison to 2025, the production of green hydrogen becomes nearly cost-effective relative to blue hydrogen by 2050. In this analysis, the production of green hydrogen assumes an average cost-intensive dedicated offshore project, while blue hydrogen assumes an average cost-intensive steam methane reforming (SMR) with CCUS project with a capacity of 1000 MW. The projected trends in fuel and carbon prices align with the aforementioned figures.

Figure 14: Breakdown of Estimated Production Cost for Green (left) and Blue (right) Hydrogen Production in 2025 and 2050



Source: BEIS (2021)

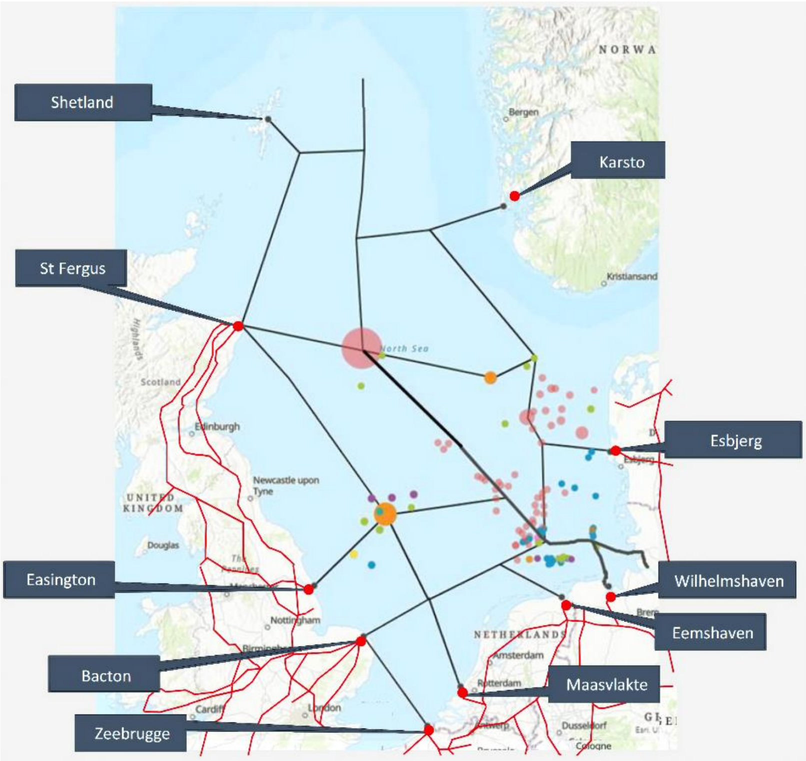
Potential for Export and Transport Corridors

There are several ongoing projects aimed at establishing a hydrogen transport corridor throughout the UK as well as establishing connections with EU member states. Domestically, UK adjusted its regulation regarding their gas grid system to blend up to 20% hydrogen into gas networks across the country from 2023 onwards (more than a doubling of the current possible blending rate).[93]

There are multiple proposals for various export routes to Europe. On the one hand, via pipelines, either repurposed or newly constructed. One hydrogen hub can be Bacton, which has one of the country's three interconnectors linking gas supply between UK and Europe. By 2035, the conversion of the gas pipeline could enable the transportation of hydrogen through interconnectors linking the UK with Belgium.[94]

[93] Goldman Sachs (2022)
[94] Fluxys (2023)

Map 3: Hydrogen Pipeline Planes in the North-Sea Corridor



Source: DNV (2023)

Another project is led by German and Belgium pipeline operator Gascade and Fluxys, who are planning to construct a new 400km hydrogen pipeline in the North Sea, facilitating the transportation of green hydrogen produced by offshore wind farms to Germany and Belgium. By 2035, the pipeline is projected to have the capacity to transport 1 million tons of hydrogen annually.[95] Also the REPowerEU plans support the establishment of connections in a North Sea corridor, as one of the three identified major import corridors, besides the Mediterranean and the Ukraine corridor, which includes the UK.[96]

On the other hand, a potential avenue for exporting hydrogen is through shipping. In 2022, the Net Zero Technology Centre and ERM announced the initiation of the Liquid Organic Hydrogen Carrier (LOHC) for Hydrogen Transport from Scotland's LHyTS project, aimed at transporting hydrogen from Scotland to Rotterdam.[97]

[95] Construction Europe (2023)
[96] Hydrogen Europe (2022)
[97] UK-Ports.org (2023)

However, potential volumes of supply and the domestic demand needs within the UK are crucial factors that contribute to UK’s hydrogen export potential. To provide some insights into the estimated green and blue hydrogen demand, the table below presents a range of estimates sourced from multiple references.

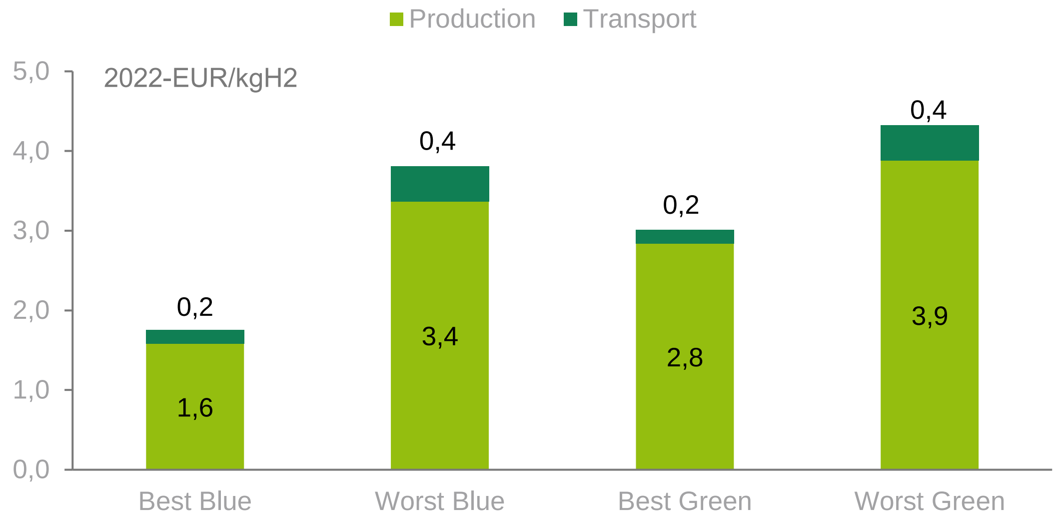
Table 3: Export Potential of Green and Blue Hydrogen in Million tons of H2

Million tons of H2	2030	2040	2050
Supply Potential	0.29 - 3.13	1.61 - 8.22	8.86 - 15.82
Green Supply	0.07	0.71 - 4.80	1.42 - 8.36
Blue Supply	0.22 - 3.06	0.90 - 3.43	7.44
Demand Potential	0.82 - 1.15	1.65 - 5.13	7.44 - 13.91
Export Potential	-0.86 - 2.31	-3.52 - 6.57	-5.05 - 8.38

Sources: Hydrogen Europe (2022), Guidehouse (2022b), Net Zero Strategy UK (2021), UK Hydrogen Strategy (2021), Guidehouse (2021a), UKCS Energy Integration (2021), Oil & Gas Authority (2021)

Table 3 illustrates significant variations in the UK's net supply potential for export, including negative ranges. Consequently, it remains highly uncertain whether the UK can emerge as a major hydrogen exporter in the coming decades as forecasts show that it may itself become an importer of hydrogen. The projected export potential for 2030 can be up to 2.3 million tons of hydrogen annually, with a potential increase to approximately 8.4 million tons by 2050.

Figure 15: Best- and Worst-Case Projections for Costs to Export Blue and Green Hydrogen from the UK to Germany in 2030



Sources: Guidehouse (2022b) EWI (2021), BEIS (2021)

According to the national hydrogen strategy, small quantities of hydrogen could be available for export in the early 2030s. As observed, the export cost for blue hydrogen is projected to be more cost-competitive than green hydrogen in both scenarios. Additionally, transport costs are assumed to be based on pipeline infrastructure (equal for blue and green hydrogen).[98] As previously discussed, the potential export routes via pipelines and the expected net hydrogen exports from the UK position it as a potentially hydrogen export partner for Germany in the late 2030s.

Other Factors

Several additional factors could affect the UK's hydrogen export potential. The UK has witnessed a thriving domestic gas boiler market, with approximately 1.8 million gas boilers sold in 2020-2021. This underscores the country's significant reliance on gas heating appliances, which account for around 90% of heating systems.[99] There is a Hydrogen Village Trail project ongoing in the UK which tests hydrogen usage for heating purposes, due to be operational by 2025.[100] If this project would be adopted on a broad scale and gas boilers for domestic heating indeed be retrofitted for hydrogen usage, then this would drastically increase domestic hydrogen demand, which would subsequently reduce available supply for export or even turn the country into a net importer.

[98] Pipeline length is assumed by 600 km.
[99] Department for Business, Energy & Industrial Strategy (2022c)
[100] Department for Energy Security & Net Zero (2023)

Furthermore, the UK has also faced political uncertainty in recent years, marked by a series of government leadership changes. These disruptions have resulted in fiscal instability and policy uncertainty, leading to delays in projects and funding.

Another challenge arises from competition in the global hydrogen market. Major players like the US and Europe have announced significant investment programs, such as the Inflation Reduction Act (which features, for example hydrogen tax credits of up to $3 per H2/kg)[101] or the REPowerEU (e.g. a fund of EUR 3 billion for hydrogen uptake in industrial sectors)[102]. These initiatives have the potential to pose a threat to hydrogen production and investments in the UK, as policies and tax incentives from these competitors may divert investment away from the UK.

Additionally, there is an international lack of clear legislation and consensus on the definition of low-carbon hydrogen. Different countries have announced their own definitions, creating a need for mutual recognition of international standards and certifications to facilitate cross-border trade. To address this, the UK has plans to launch its hydrogen certification scheme by 2025, aiming to provide a clear framework and promote harmonization in the industry.

Conclusion

The United Kingdom exhibits solid potential for both green and blue hydrogen production due to its offshore wind potential, natural gas resources, and support for CCS technologies. By leveraging these assets, the development of hydrogen production can be accelerated. The government has already established a comprehensive regulatory framework for the hydrogen market, fostering a diverse portfolio of forthcoming blue and green hydrogen projects.

On the other hand, the prospects for hydrogen exports are heavily contingent on domestic demand and supply, which are inherently uncertain to estimate. Consequently, the evolution of the hydrogen sector and the domestic distribution of hydrogen across various industries will ultimately determine whether the UK can emerge as a significant player in hydrogen exports or not. In addition, the UK currently faces a lack of comprehensive export plans for hydrogen to Europe, as well as insufficient infrastructure for transporting hydrogen to European markets, despite the presence of existing interconnectors.

However, overall, the UK possesses all the essential foundations to become a leading player in exporting hydrogen to Europe.

[101] The White House (2023)
[102] European Commission (2022)

Norway

Introduction

Today, Norway is one of the largest gas exporters to the EU. Consequently, the EU's plans to significantly reduce its gas demand in the coming decades will also have a major impact on Norway’s gas export revenues. As a result, the country is finding substitutes for gas exports by the 2030s, with hydrogen emerging as a promising alternative. Norway's small population size and corresponding low energy demand relative to its production capacity present a tremendous opportunity for the country to play a significant role in exporting hydrogen instead of natural gas. Consequently, the Norwegian government envisions Norway taking a leading role in hydrogen exports to Europe by 2050.

This ambition is supported by several advantages Norway possesses. Firstly, the country boasts substantial natural gas reserves and possesses industrial expertise across the entire hydrogen value chain, allowing it to scale up blue hydrogen production in the short to medium term. Secondly, Norway's continental shelf has the potential to serve as an ideal CO_2 storage site. Thirdly, Norway's energy system and natural environment are well-suited for significant green hydrogen capacity, leveraging wind and hydro power resources. Lastly, the well-developed pipeline system between Norway and the EU can be retrofitted for hydrogen by the 2030s, resulting in highly cost-effective hydrogen transport routes. However, challenges remain, including divided electricity price zones and the need for clearer government goals for hydrogen production and market establishment in Norway.

National Energy Strategy and Plans

Norway's energy strategy is founded on the Energy White Paper "Putting Energy to Work"[103], which was issued in 2021 in line with the "Climate Action Plan 2030"[104]. In 2022, this White Paper was complemented by an additional government energy document, providing a more comprehensive outlook on Norway's journey towards decarbonization.[105]

As stated in the Climate Change Act of 2017, Norway has set ambitious targets to reduce emissions by 50%-55% by 2030, and by 90% to 95% by 2050.[106] The focus of these emission reductions is particularly on the oil and gas industry. To achieve these targets, Norway has implemented a policy mix that combines regulations and market-based solutions.

[103] Norwegian Ministry of Climate and Environment (2021)
[104] Norwegian Ministry of Climate and Environment (2020)
[105] Norwegian Ministry of Climate and Environment (2022)
[106] Norwegian Government (2017)

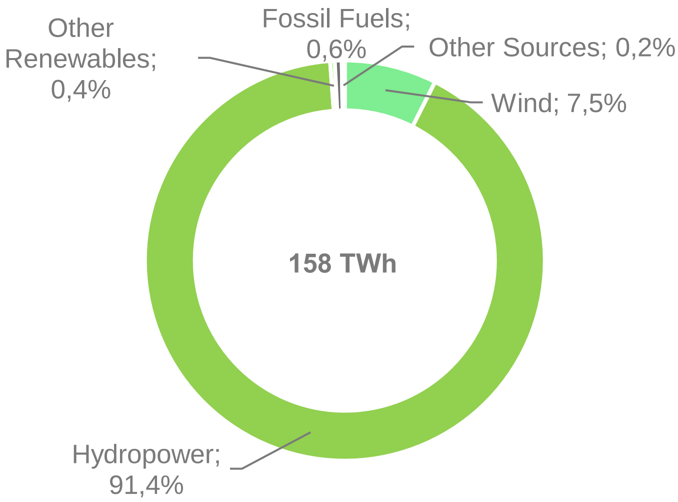
For instance, within the transport sector, the ferry sector is required to obtain 2/3 of their energy from electricity, and the use of fossil fuels in new vehicles will be prohibited by 2025, the most ambitious ICE ban seen globally.[107] Additionally, a carbon tax has been introduced, covering approximately 85% of domestic greenhouse gas emissions in 2022. The initial price of this tax was around EUR 70 per ton and will steadily increase to EUR 200 per ton by 2030.[108] Furthermore, Norway plans to reduce oil and gas exports significantly. In 2020, these exports accounted for about 2,200 TWh (2-3% worldwide) but are projected to decrease to 600 - 1000 TWh per year by 2050 (oil export will be 5% of today's level and gas export will be 40% of today's level).[109, 110, 111] As a result of these efforts, the degree of electrification is set to rise from 45% in 2022 to 61% by 2050, driven by the electrification of the offshore industry, including oil and gas and ferry industry, and road transport.[112]

However, despite Norway's energy mix 2021 being dominated by hydropower, with over 1,600 hydropower plants contributing to 40% of the energy mix, oil and natural gas combined still account for approximately 50% of energy supply (32% and 16% respectively). Renewable sources, including biofuels, onshore wind, and solar PV, only make up 10% of the energy mix.

About 90% of Norway's electricity is generated by hydro power plants, with wind power is accounting for 8%. Consequently, Norway's electricity mix stands as one of the first in Europe to consist of nearly 100% renewable sources. Additionally, Norway already possesses a hydropower storage reservoir capacity of more than 87 TWh, approximately 70% of the country's annual electricity consumption from hydropower.[113]

[107] Norwegian Ministry of Petroleum and Energy & Norwegian Ministry of Climate and Environment (2020)
[108] Skjaerseth et al. (2023)
[109] Cloete et al. (2022)
[110] Norwegian Ministry of Climate and Environment (2022)
[111] DNV (2022)
[112] DNV (2022)
[113] IEA (2022b)

Figure 16: Electricity Mix in 2021



Source: IEA (2022b)

Regarding renewable development plans, Norway currently aims to construct offshore wind turbines with a combined capacity of 30 GW by 2040.[114] Further specific development goals are not explicitly stated. However, projections indicate that by 2040, Norway will require further development of 2 GW of hydropower, 5 GW of onshore wind, and 7 GW of solar PV capacity.[115] Consequently, if all the proposed plans were successfully executed, the Norwegian energy system would experience a swift and profound transformation in the upcoming decades.

Hydrogen Strategy

Norway's hydrogen strategy is based on the "Norwegian Government's Hydrogen Strategy – Towards a Low Emission Society"[116], which was formulated in 2020. It is further supplemented by the Hydrogen Roadmap[117] (2021) and a supplementary White Paper[118] (2022). The government envisions two methods for hydrogen production: one involves extracting hydrogen from natural gas through steam methane reforming (SMR) with CCS, and the other involves using renewable electricity for electrolysis.

All three documents primarily emphasize R&D efforts. However, they lack specific targets for the development, production, and export potential of both blue and green hydrogen, but in the short to mid-term, the focus is on the development of blue hydrogen. This absence of precise goals could pose

114 Norwegian Ministry of Climate and Environment (2022)
115 DNV (2022)
116 Norwegian Ministry of Petroleum and Energy & Norwegian Ministry of Climate and environment (2020)
117 Norwegian Ministry of Climate and Environment (2021)
118 Norwegian Ministry of Climate and Environment (2022)

challenges in establishing a robust national hydrogen market, as it introduces uncertainties in the parallel growth of demand and supply.

Nonetheless, the Hydrogen Strategy (2020) initially laid out a plan for research and funding, highlighting the advantages Norway possesses for hydrogen production, especially in the field of blue hydrogen. The country's expertise in the gas and oil industry, existing infrastructure like pipelines, substantial gas reserves, and the potential for CCUS solutions and storage facilities are all factors that make Norway well-suited for blue hydrogen production.[119]

Furthermore, the "Hydrogen Roadmap" (2021) outlines specific targets for the years 2025, 2030, and 2050.[120] By 2025, the Norwegian government aims to establish five hydrogen hubs for maritime transport. Additionally, they plan to realize one or two industrial projects with associated hydrogen facilities. To foster the development of more cost-effective hydrogen solutions and technologies, 5-10 pilot projects will be implemented. Consequently, the Centres for Environment-friendly research (FME) will receive funding to strengthen research and development efforts in this area. A sum of NOK 2.5 billion (EUR 225 million) will be allocated to support blue hydrogen and CCUS initiatives, with the objective of establishing an operational transport and storage network by 2025.

By 2030, the government's strategy involves adapting Norway's hydrogen production to the development of the European hydrogen market, primarily through exports. To achieve this, policy instruments such as CfDs and a progressively increasing carbon tax or reduced electricity tax for hydrogen production will incentivize investments in low-carbon technology, thus facilitating the implementation of large-scale industrial projects. Domestically, hydrogen will have a broad range of applications in the maritime and transport sectors. Moreover, this will enable Norway to foster the growth of their green steel industry and decarbonize the ammonia sector, as demonstrated by projects like HEGRA.[121,122] Today 400,000 tons of hydrogen are already consumed, while by 2030 demand increases to 1.2 million tons.[123]

The vision for 2050 entails a well-developed hydrogen market for both hydrogen production and utilization. Hydrogen will serve as a fuel for vessels operating in coastal waters and long-distance transport. Thanks to the abundant hydropower, the primary focus for domestic hydrogen usage lies in the transportation sector. As mentioned earlier, the government is actively promoting the green shift

119 Norwegian Ministry of Petroleum and Energy & Norwegian Ministry of Climate and environment (2020)
120 Norwegian Ministry of Climate and Environment (2021)
121 YARA (2021)
122 Bhaskar et al. (2022)
123 DNV (2022)

through financial support and regulation. Moreover, the Shipowner's Association has set the ambitious target of achieving a climate-neutral fleet by 2050. In the ferry sector, the goal is even more immediate, aiming to make all 200 ferries carbon-neutral by 2025 using a combination of hydrogen and battery electric propulsion.[124] Moreover, there are ongoing initiatives in various industrial sectors to substitute fossil fuels with hydrogen. For instance, TiZir Titanium and Iron AS are exploring the use of hydrogen as a reducing agent to replace coal in the production of titanium slag and iron. Additionally, Norway's manufacturing and petroleum industries are participants int the European Emissions Trading System, which would require to shift to hydrogen usage instead of fossil fuels if emission reduction targets are to be met.[125]

The production of hydrogen necessitates significant storage capacity, with Norway holding a distinct advantage in this regard, as it has the option to store hydrogen offshore in salt caverns, with a volumetric capacity of over 7,500 TWh (190 million tons) of H2.[126] Additionally, the storage capacity for CO2, in locations like oil and gas fields, amounts to approximately 16 billion tons of CO2.[127] Today, there are two CCUS processes in Norway, both related to oil and gas. The government approved state funding of NOK 16.1 billion (EUR 1.4 billion) as part of the Longship carbon and capture initiative, will start operating in 2025.[128]

Hydrogen Production Projects and Costs Estimates

Norway can play a pivotal role in hydrogen production and export. However, the government's current stance is that there won't be export capacity available before 2030.[129] According to the IEA hydrogen project database[130], there are currently only 7 operational facilities for green hydrogen, with a combined capacity of 0.0006 million tons of hydrogen actively in operation. An additional 0.014 million tons have secured final investment decisions (FDI). However, there are numerous other capacities for electrolysers outlined in various concepts and projects that are still awaiting final investment decisions. The IEA database includes 0.5 million tons of capacity with existing concepts, and there are feasibility studies for a total of 0.24 million tons, as depicted in the figure below. Compared to other European countries, this represents a relatively modest amount of planned green hydrogen production capacity. The project pipeline for blue hydrogen is approximately one million tons.

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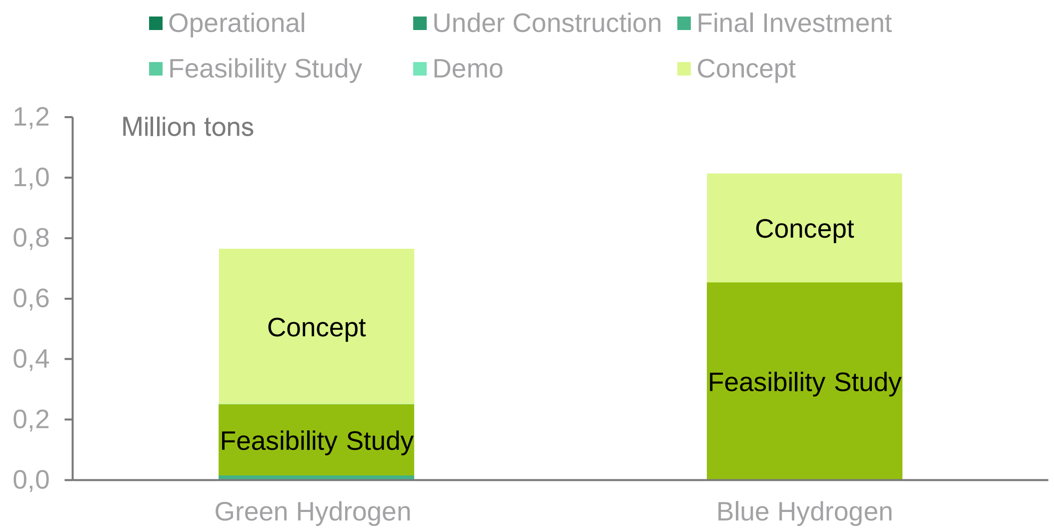
124 International Trade Administration (2021)
125 Norwegian Ministry of Petroleum and Energy & Norwegian Ministry of Climate and environment (2020)
126 Caglayan (2020)
127 Goldman Sachs (2022)
128 DNV (2022)
129 Skjaerseth et al. (2023)
130 IEA (2022d), accessed July 2023

However, it's important to note that there is a considerable number of hydrogen projects currently in the pipeline, as evidenced by recent developments and announcements, which are not stated in the IEA hydrogen database. This trend is expected to significantly increase the overall production capacities. For instance, Norwegian Hydrogen is in the process of developing a green hydrogen project with a capacity of 270 MW, capable of producing 40,000 tons per year.[131] Statkraft has announced its target of achieving 2 GW of green hydrogen production capacity by the year 2030.[132] Moreover, there are five hydrogen hubs, such as Glomfjord (3000 tons of green hydrogen annually)[133] and Hitra, which have received financial support between EUR 10 - 13 million for their proposed green hydrogen plants.[134]

Figure 17: Hydrogen Projects in Norway



Source: IEA (2022d)

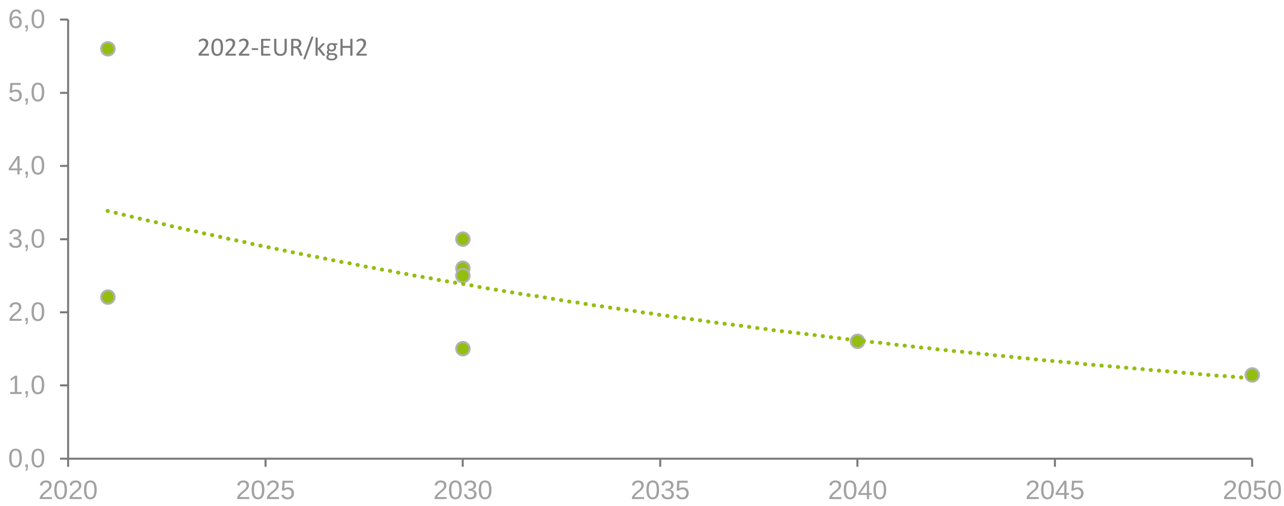
Additionally, the state-owned oil company Equinor has entered a strategic partnership with German utility RWE, committing to provide 2 GW of blue hydrogen by 2030 and 10 GW by 2038.[135] These developments highlight Norway's commitment to both green and blue hydrogen production and underscore its position as a significant player in the global hydrogen market. Also, when considering the geographical advantages mentioned earlier, significant investments are anticipated in the future.

131 Norwegian Hydrogen (2023)
132 Statkraft (2022)
133 Glomfjord Hydrogen (2023)
134 FuelCellsWork (2022)
135 Hydroinsight (2023)

The graph below illustrates the estimated costs of producing blue and green hydrogen at different points in time, based on analyses conducted from numerous publications and forecasts. Production costs of blue hydrogen are heavily related to natural gas prices and carbon prices. Thus, future blue hydrogen production costs largely depend on fossil fuel price forecasts. In 2021, the estimated production costs for blue hydrogen ranged between 2.21 – 5.6 EUR/kgH2. By 2030, it is projected that the costs will decrease to between 1.5 – 3.0 EUR/kgH2, and further decline to around 1.6 EUR/kgH2 by 2040. Looking even further ahead to 2050, production costs are anticipated to be approximately 1.1 EUR/kgH2. It is important to note that these estimates do not encompass CO2 prices and taxes.

In 2021, production cost estimates for green hydrogen range between 3.80 and 6.50 EUR/kgH2. By 2030, the costs are estimated to fall to a range between 4.60 and 5.27 EUR/kgH2, while by 2040, they are expected to range between 3.79 and 4.60 EUR/kgH2. Looking ahead to 2050, it is anticipated that production costs will decrease even more, reaching between 2.00 and 3.96 EUR/kgH2. Comparing with blue hydrogen production costs in 2050 the estimates are relatively high.

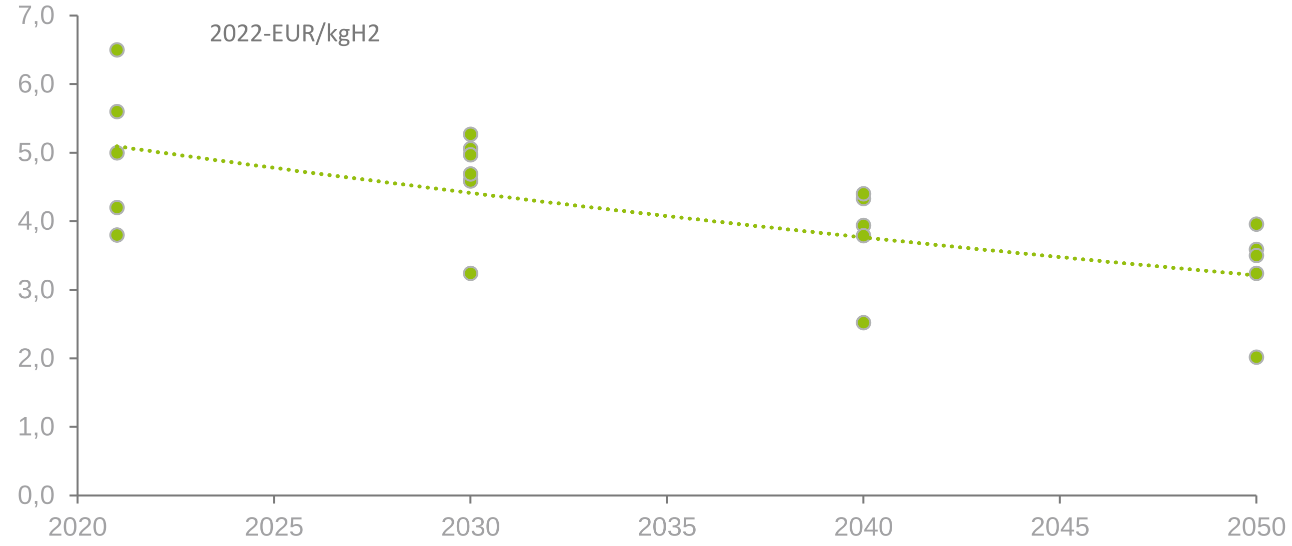
Figure 18: Cost Estimates for Blue Hydrogen Production in Norway



Sources: Deloitte (2023), Hydrogen Europe (2022), Guidehouse (2022b), EWI (2021), Guidehouse (2021b), OIES (2022)

The variations in cost estimates stem from the use of different renewable sources with varying capacity factors, such as hydropower, onshore/offshore wind, and solar PV, in the models. Additionally, there are differences in the assumed interest rates and cost estimates for electrolysers within the model settings. These factors contribute to the range of cost projections for producing green hydrogen.

Figure 19: Cost Estimates for Green Hydrogen Production in Norway



Sources: DNV (2023), Hydrogen Europe (2022), Guidehouse (2022b), Janssen et al. (2022), Stiftung Arbeit & Umwelt (2021)

Potential for Export and Transport Corridors

The success of Norway's ambition to export hydrogen to demand centres like Germany will largely depend on effectively repurposing existing pipelines or constructing new ones. Given Norway's extensive history of gas exports, there are already potential pipelines that could be repurposed for transporting hydrogen. Examples include Europipe (to Germany), Zeepipe, Franpipe, and Langeled South (to the UK).

By 2030, one potential export route could involve repurposing these existing pipelines to transport hydrogen from rise platforms such as Draupner or Slauper to Germany, leveraging the available system capacity. Another possibility could be blending hydrogen into the natural gas export streams, enabling the utilization of existing natural gas pipelines from 2030 onwards.

Norwegian gas transmission system operator Gassco is conducting a feasibility study to assess whether building a new pipeline is commercially and technically feasible. Once completed, the hydrogen pipeline is projected to be operational and ready for use by 2030. This pipeline is expected to have the capacity to deliver up to 4 million tons of hydrogen annually. The estimated costs for this project, depending on whether repurposing existing pipelines or building new ones is pursued, are approximately NOK 20 billion (EUR 1.9 billion). [136]

[136] Montel (2022)

In a joint effort, Norway and Germany have announced plans to construct a large-scale hydrogen pipeline by 2030. The initial focus will be on transporting blue hydrogen, with the intention of transitioning to green hydrogen in the future. As part of this collaboration, Equinor has set ambitious goals to send up to 10 GW of blue hydrogen through the pipeline from Norway. By 2030, they aim to deliver 2 GW (equivalent to 0.5 million tons) of blue hydrogen, and this capacity is expected to increase significantly to 10 GW (equivalent to 2 million tons) by 2038.[137]

Map 4: Hydrogen Pipeline Plans between Norway and Germany[138]

Source: DNV (2023)

In the long run, Norway has the potential to become an integral part of a vast North Sea hydrogen backbone, connecting the UK, Netherlands, Belgium, and Germany. This ambitious project is spearheaded by the German and Belgian pipeline operators, Gascade and Fluxys. By 2035, the pipeline is projected to have the capacity to transport an impressive one million tons of hydrogen annually.[139]

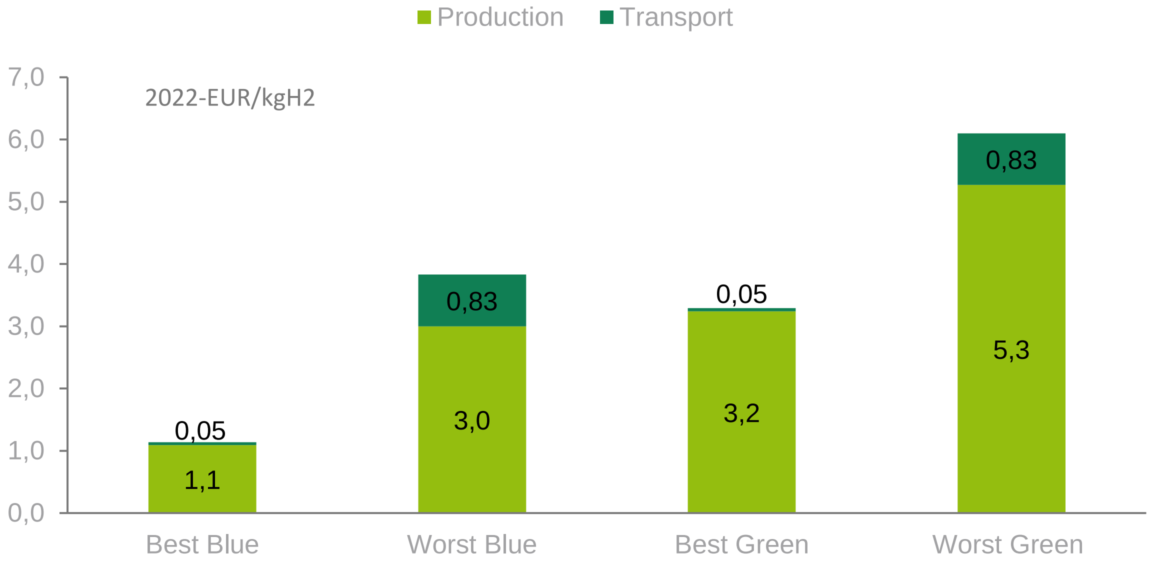
An analysis by DNV shows the following parameters for the North Sea Hydrogen Backbone. The total length of repurposed and new built pipelines is about 4,200 km, including existing projects like the

[137] Hydroinsight (2023)
[138] For broader map of the North Sea hydrogen backbone see UK chapter 3.
[139] Construction Europe (2023)

AquaVentus initiative and the mentioned pipeline projects above. The pipelines diameter is assumed between 38-48 inch. The construction costs of these pipelines would be between 3000 and 4500 EUR/m pipeline, implying additional 0.13-0.20 EUR/kgH2 to account for transport costs. Another aspect is compression, which will add a further 0.06-0.08 EUR/kgH2 to the overall costs.

In summary, the stated plans to build up a North Sea Hydrogen Backbone will cost between EUR 35 and EUR 52 billion, leading to a total cost of production and transport of green hydrogen to Germany between 4.69 and 4.97 EUR/kgH2 in 2030.[140] Another viable export option involves utilizing shipping routes. By 2024, a liquid hydrogen project at Mongstad will become operational, boasting a production capacity of 6 tons of liquid hydrogen per day, which can be shipped to Germany. 141 The estimated production and transport costs between Norway and Germany via ship are projected to be 3.9 EUR/kgH2 by 2030, with transport costs accounting for 0.69 EUR/kgH2.142,143

Figure 20: Best- and Worst-Case Projections for Costs to Export Blue and Green Hydrogen from Norway to Germany in 2030



Sources: DNV (2023), OIES (2022), EWI (2021), Guidehouse (2021b), Reinertsen New Energy (2021)

Estimates for additional transportation costs through the mentioned pipelines, particularly connecting Norway and Germany, vary depending on several factors. For existing pipelines, the cost ranges

[140] DNV (2023)
[141] SCI4climate.NRW (2021)
[142] OIES (2022)
[143] Stiftung Arbeit und Umwelt der IG BCE (2021)

between 0.05 and 0.18 EUR/kgH2, while for new pipelines, the range is wider, between 0.07 and 0.83 EUR/kgH2. These variations in costs are influenced by factors such as the pipeline's CAPEX, interest rates, size, and chosen route.[144] Following figure 20 illustrates the best and worst estimates for production and transportation costs to Germany in 2030.

Another critical aspect affecting Norway's hydrogen export potential is the volume of domestic demand and supply. Estimations for demand in both Norway and other countries are highly uncertain and may not necessarily align with the announced projects. The table below presents a range of estimates for green hydrogen demand, compiled from multiple sources wherever possible.

Table 4: Export Potential of Blue and Green Hydrogen in Million tons of H2

Million tons of H2	2030	2040	2050
Supply Potential	0.33 - 2.24	1.01 - 7.45	4.13 - 4.91
Green Supply	0.12 - 1.42	0.45 - 4.50	2.83 - 3.60
Blue Supply	0.20 - 0.82	0.56 - 2.95	1.3
Demand Potential	0.05 - 0.24	0.25 - 0.51	0.63 - 2.04
Export Potential	0.09 - 2.19	0.59 - 7.20	2.09 - 4.28

Sources: BMWK (2023), DNV (2022), Guidehouse (2022), Cloete et al. (2022)

As shown in Table 4, Norway possesses the potential for surplus green and blue hydrogen production capacity. By 2040, the net supply of green hydrogen could potentially reach up to 7.5 million tons. Consequently, Norway could become a significant exporter of hydrogen, offering competitive prices. However, it is essential to note that all estimates carry a substantial degree of uncertainty.

Exports will likely only be available after 2030 when supply overtakes domestic demand in a significant amount. It is also worth noting that the estimates for 2030 would roughly require all projects listed in the IEA database (Figure 17) to materialise. As previously discussed, the potential export routes via pipelines and the expected net hydrogen exports from Norway position it as a potentially significant hydrogen export partner for Germany.

[144] This assumes a pipeline length of 800 km.

Other factors

To establish a well-developed hydrogen market, it is crucial for supply and demand to grow equally, reducing uncertainty and encouraging further investments. However, Norway faces a challenge as the government has not clearly defined hydrogen production capacity development goals. Additionally, many of the hydrogen projects lack final investment decisions. This lack of clarity creates uncertainty about future supply developments, potentially deterring investments. Consequently, this situation may put Norway at a disadvantage compared to other European countries like Spain or the UK, which have more defined and developed strategies.

Another issue lies in the discrepancy between Norwegian companies' ambitious export goals for both green and blue hydrogen relative to its current domestic energy production capacity. To address this for green hydrogen, there is a need to boost renewable energy capacity development in line with the increasing hydrogen production, particularly in offshore wind. By aligning these developments, Norway can ensure a more sustainable and efficient hydrogen production process.

Furthermore, the record-high electricity prices in the Southern price zone and the projected electricity deficit between 2026 and 2030 present challenges to the hydrogen industry's growth.[145] Norway is divided into two electricity price zones: a Southern zone and a Northern zone. While the Northern zone experiences relatively low electricity prices, the Southern zone faces higher electricity prices due to its connection to the EU price zones. Furthermore, importing electricity to cover this deficit may introduce volatility and potentially lead to higher prices, eroding the competitive advantage of low-priced green electricity required for industrial hydrogen production. However, it is noteworthy that this problem depends on specific projects. If the electrolysers are directly connected to renewable plants, then grid prices don't have an effect. Conversely, if the electrolysers are connected to the grid, higher electricity prices will significantly impact production costs. Thus, finding solutions to stabilize electricity prices and enhance domestic energy capacity becomes crucial for the successful advancement of the hydrogen industry in Norway.

Conclusion

Norway possesses all the necessary factors for blue and green hydrogen production. Moreover, its experience in the hydrogen value chain, gained from its oil and gas industry, further strengthens its position. Additionally, the country has ample opportunities for large-scale hydrogen and CO2 storage.

Despite these promising factors, there appears to be a discrepancy between projections and signed export contracts concerning announced projects. Furthermore, the government has not yet provided a

[145] DNV (2022)

clear outline of capacity and production goals. This uncertainty may deter potential investors, leading to project delays and a mismatch between hydrogen demand and supply, which could put Norway at a competitive disadvantage compared to other leading hydrogen-producing countries like Spain or the UK. However, Norway has already signed contracts to export hydrogen to countries like Germany by 2030, and some ambitious green hydrogen projects are in progress.
In conclusion, Norway has the potential to secure a significant market share in hydrogen exports to the EU and can become one of the first exporting hydrogen countries in Europe. However, the roadmap to achieve this goal remains unclear.

Ukraine

Introduction

Ukraine has significant ambitions to emerge from the war with Russia not only victorious but is also laying the foundations to become a green industrial powerhouse in the future. In principle, many factors point in favour of Ukraine producing hydrogen at scale and transporting it to demand centres in Europe at favourable costs. However, equally large stumbling blocks exist and the ongoing war and occupation in its renewable potential rich regions cast large uncertainty on the country's future hydrogen ambitions.

National Energy Strategy and Plans

The full-scale Russian invasion of Ukraine in 2022 has led to significant damage to the Ukrainian energy system and has highlighted the need to boost resilience and energy security in the face of targeted attacks on energy infrastructure and high and volatile fossil fuel prices. Additionally, Ukraine in now an accession candidate to the European Union, further adding to the need to transform its energy system. Hence, in the midst of the ongoing Russian invasion, the country revealed its National Energy Strategy until 2050 which was presented at the 2023 Ukraine Recovery Conference in London, although the full publication of the strategy is still pending.

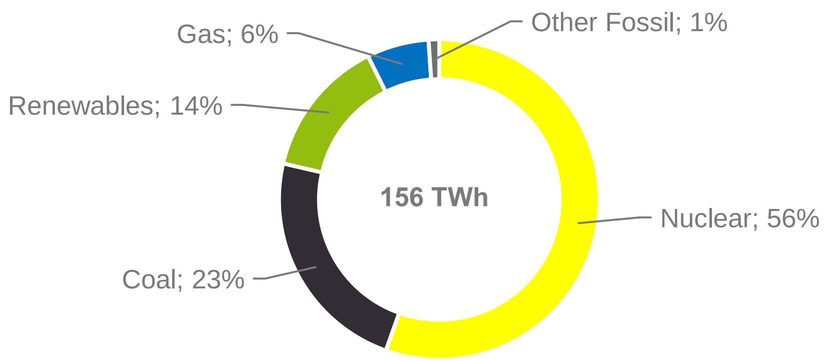
The new strategy forms the basis for the countries energy policy and outlines a radical overhaul of the energy system by setting the target to achieve carbon neutrality by 2050 - ten years sooner than was planned in previous documents. Ukraine envisages to become an exporter of green energy and industrial goods made with green energy.

The strategy assumes that electricity demand will increase more than six-fold and reach 700 TWh in 2050, up from 109 TWh in 2022. In order to achieve set goals, the strategy focuses on large scale renewable but also nuclear power capacity expansion. The strategy foresees to increase the installed power plant capacity 10-fold and aims to have 140 GW of wind, 94 GW of solar, 38 GW of energy storage, 30 GW of nuclear, 18 GW of combined cycle & bioenergy as well as 9 GW of hydro installed within the next 20 years, while also phasing-out all coal-fired power plants by 2035. The numbers are extremely ambitious given that currently there are only 0.4 GW of wind, 7 GW of solar and 14 GW of nuclear installed. The presentation held at the conference estimates investment needs of over USD 380 bn while financing remains unclear.[146]

Ukraine holds large renewable energy potential, in particular for wind. In 2020, the National Academy of Science of Ukraine assessed the renewable energy potential in Ukraine to amount to 438 GW of Wind, 83 GW of Solar, 22 GW of Geothermal and 92 GW of Biomass.[147] Noteworthy is also the fact that the envisaged solar capacity from the Ukrainian Energy Strategy is higher than the theoretical potential given by the National Academy of Science.

Ukraine's pre-war energy system was dominated by coal, natural gas and nuclear energy, making up 29%, 28% and 23% of primary energy consumption respectively. Oil was responsible for another 14% while hydro and renewables each accounted for 3%.[148] The countries electricity system is and was less carbon intensive than of many if its neighbouring country thanks to a large share of nuclear power (56%). Coal still played an important role with 23% while renewables make up the bulk of the remaining shares (14%).

Figure 21: Electricity Mix in 2021



Source: Ember-Climate (2023)

[146] Based on slide deck presented at the URC in London; CEE Energy News (2023)
[147] Institute of Renewable Energy & National Academy of Sciences of Ukraine (2020)
[148] BP (2023)

If Ukraine's new ambitious energy strategy would indeed be realised, the energy system would undergo a rapid and deep transformation. However, given the current situation, the prospects of realistically doing so remain unclear.

Hydrogen Strategy

Compared to other European countries that already published national hydrogen strategies, Ukraine is still in the early stages of formulating its hydrogen policy. The Russian invasion of Ukraine and the ongoing war have delayed the development of Ukraine's hydrogen strategy, which calls into question the country's prospects on the European hydrogen market. Nevertheless, there is large interest from national and international stakeholders from business, industry and politics in the development of a Ukrainian hydrogen strategy.

A first draft of Ukraine's hydrogen strategy was presented in 2021.[149] According to the strategy, Ukraine can produce up to 45 million tons of hydrogen per year. While the draft strategy does not contain exact figures and strategic plans for Ukraine, it emphasizes green hydrogen as an instrument both for domestic decarbonisation as well as an export product and outlines a draft roadmap in three phases. In the short term (2022-2025), the foundation for launching exports is supposed to be started by creating the legal framework, strengthening the partnerships with potential off takers, and preparing the gas transport system. In the medium term (2026-2030), the scaling up of electrolysis capacity to cover both export and internal demand is foreseen. Lastly, 2030-2050 the goal is for Ukraine to become a hydrogen hub for Europe and undertake the transition from mixed natural gas/hydrogen to pure hydrogen in the gas transport system.[150]

During the Ukraine recovery conference in Lugano in 2022 as well as in London in 2023, further goals and plans regarding hydrogen were presented. By 2032, the country aims to install 15 GW of electrolysers and export 1.5 million tons of hydrogen.[151] By 2050 the country wants to produce 7.2 million tons of hydrogen per year. Out of those, 3.5 million tons are supposed to be exported, while 2.3 million tons will be used for the production of green steel and 1.5 million tons for the production of fertilizers. Most of the green steel and part of the fertilisers are then again earmarked for exports. For doing so, the country aims at installing 43 GW of electrolysers for the production of hydrogen by 2050 as well as having domestic electrolyser manufacturing capacities.[152] Hydrogen is also expected to replace fossil fuels in the transport sector (especially for railroads and buses) and in part for heating

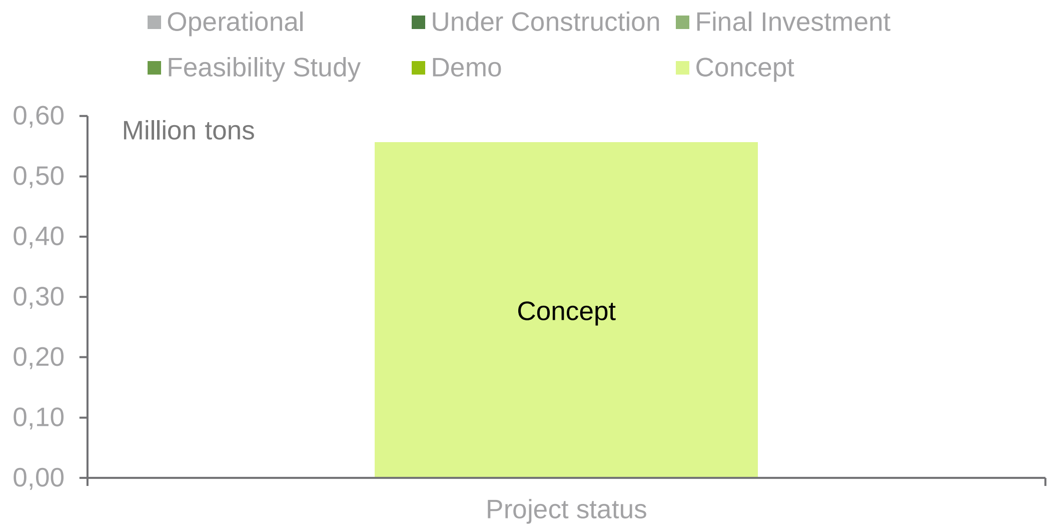
[149] Institute of Renewable Energy & National Academy of Sciences of Ukraine (2021)
[150] Fraunhofer ISI/HYPAT (2023)
[151] The National Council for the Recovery of Ukraine from the Consequences of the War (2022)
[152] Based on slide deck presented at the URC in London.

residential and non-residential buildings. Ukraine's pre-war grey hydrogen demand was 1.2 million tons annually, mostly for the production of ammonia and smaller volumes of methanol.[153]

Hydrogen Production Projects and Costs Estimates

According to the IEA Hydrogen Project Database, there are a variety of pilot projects, all only at the conceptual stage, although more concrete plans concerning project design, costs, and technological options already exist to some degree. However, concrete financial commitments resulting in final investment decisions are lacking. Among the reasons are large uncertainties regarding demand, but also the lack of viable transportation options as well as lack of regulatory support or even a hydrogen strategy itself. These factors, as a recent study by dena[154] has shown, may heavily influence capital costs and as such are crucial to the economic viability of hydrogen projects.

Figure 22: Hydrogen Projects in Ukraine



Source: IEA (2022d)

As can be seen in Figure 22, the International Energy Agency Project database lists projects capable of producing 556 thousand tons of hydrogen per year (~3 GW electrolyser capacity), although all of them remain in the concept stage. Other studies on the country's export potential list more projects than the IEA database with different stages and increasing capacity for electrolysis.[155] Combined, the total capacity of the projects listed would be 16 GW by 2050. This would be well below the 43 GW the new presented Energy Strategy from 2023 envisages.

[153] UNECE (2021)
[154] dena (2021)
[155] Frauenhofer ISI/HYPAT (2023)

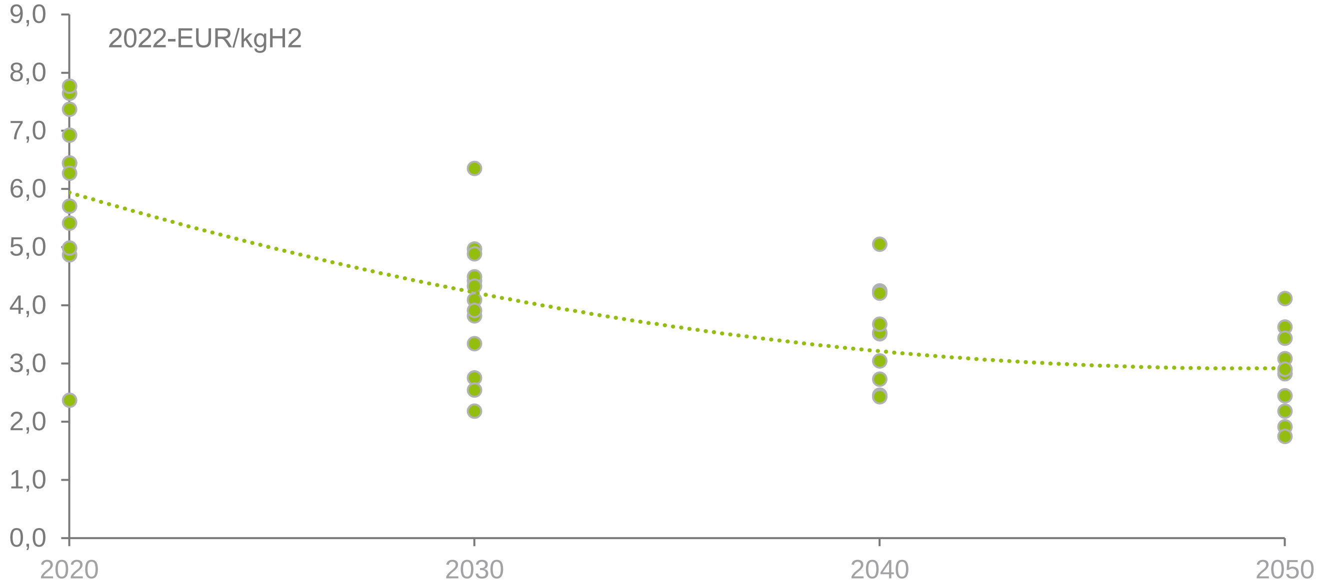
While some of the projects are located in Western Ukraine and were not as significantly affected by the Russian invasion of Ukraine, some other projects were expected to be built in the areas currently under Russian occupation, and their future has not yet been assessed or publicly announced. Among them is for example the Ukraine Hydrogen Valley project in the area of the reservoir of the recently destroyed the Kakhovka Dam[156] while the largest project is the Green Hydrogen Industrial Cluster located in the Southeast of Ukraine by DTEK (up to 10 GW of planned electrolyser capacity). Some of these projects were expected to be commissioned last year, but due to the Russian invasion, the status and timelines of their implementation is questionable. These projects were expected to be commissioned between 2025-2050 (with the first phases of the projects reaching commercial operation in 2026-2027).[157]

Numerous projects are also planned in the Zakapattya region which are particularly well suited in regard to transportation to European markets due to their geographical proximity. Furthermore, the projects "Salt for Life" in Solotvyno and the H2EU project initiative envisage cooperation between local investors and European parties interested in the development of hydrogen in Ukraine.

The graph below shows the estimated costs of producing green hydrogen at various points in time based on estimates gathered from various publications and forecasts. Production cost estimates for 2020 range between 2.37 and 7.77 EUR/kgH2. Falling costs for electrolysers and electricity from solar and wind could bring production costs to 2.18 – 6.35 EUR/kgH2 by 2030, 2.43-5.05 EUR/kgH2 by 2040 and potentially to 1.75-4.12 EUR/kgH2 in 2050. The large differences in cost estimates stem from different renewables sources with varying capacity factors (e.g.: onshore wind, solar PV) used in the modelling as well as different interest rates and cost estimates for electrolysers in the future.

[156] River Wind Ukraine (2020)
[157] DENA (2021)

Figure 23: Cost Estimates for Green Hydrogen Production in Ukraine



Sources: PwC (2021), Kovalenko et al. (2021), Frontier Economics (2021), EWI (2021), Guidehouse (2021)

Potential for Export and Transport Corridors

Generally speaking, Ukraine has ample space and renewable endowments (as well as nuclear capacity) to produce green hydrogen at scale and favourable costs, while Ukraine's proximity to EU demand centres and existing infrastructure links allows, in principle, for multiple export corridors.

However, given the large uncertainties surrounding the country, estimates for domestic demand and export potential are inherently hard to quantify. While the technical potential of the country lies somewhere in the range of 30 - 45 million tons of hydrogen,[158] realizable potential naturally is much lower. The table below is based on multiple sources and gives ranges for estimates of annual green hydrogen demand and export potential. The 2050 targets given in the current Energy Strategy are significantly higher than what has been estimated elsewhere and are included in Table X (7.2 million tons production out of which 3.5 million tons for export in 2050).

In general, Ukraine's economy, traditionally shaped by iron and steel and agricultural industrial sectors, provides large potential for hydrogen usage. Moreover, the reconstruction process itself could significantly impact domestic demand for hydrogen. In principle, hydrogen could find application in the production of construction related materials process like iron, steel, cement and glass which in turn could conflict with export ambitions but could support the localisation of many of those industries.

[158] Guidehouse (2022b)

Domestic demand for the iron and steel sector in particular is however contingent on the reconstruction and recovery of those sectors in the first place.

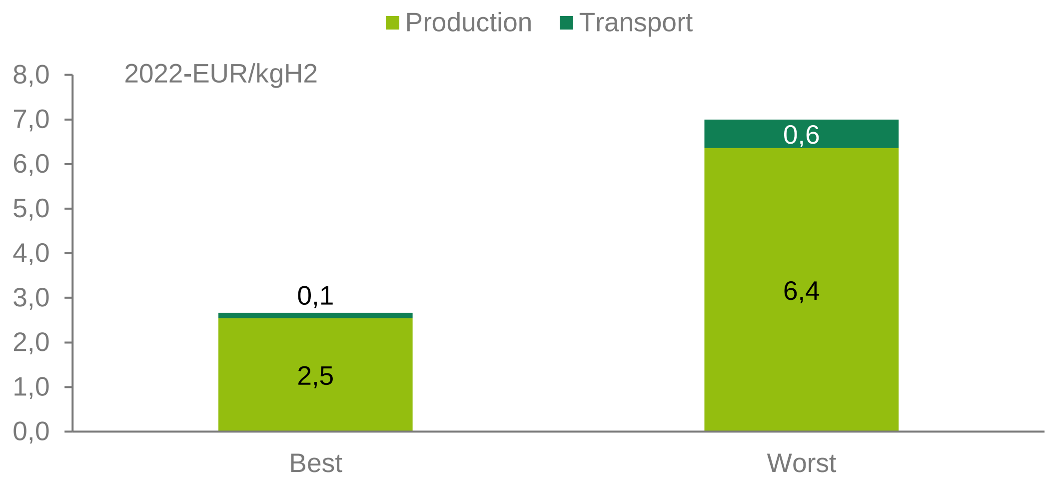
Table 5: Export Potential of Green Hydrogen in Million Tons of H2

Million Tons of H2	2030	2040	2050
Supply Potential	0.7 - 1.0		3.8 - 7.2
Demand Potential	0.3		0.8 - 3.7
Export Potential	0.4 - 0.7	1.5	0.1 - 6.4

Sources: Frauhenhofer ISI/Hypat (2023), Presentation at the URC (2023), Guidehouse (2022b)

Best- and worst-case cost estimates, including transport to Germany, widely differ from one another as can be seen in Figure 24 below.

Figure 24: Best- and Worst-Case Projections for Costs to Export Hydrogen from the Ukraine to Germany in 2030



Sources: EWI (2021), Guidehouse (2021b), Frontier Economics (2021)

Widely regarded as one of the biggest assets is the country's large natural gas transmission and distribution system, that is in part still used to transport Russian natural gas to Europe. Since 2014, the United States and the EU have assisted the country in improving the state of Ukraine's natural gas infrastructure to boost energy security by reducing losses. The potential option to repurpose gas pipelines for hydrogen and biomethane blending provides additional arguments to invest and modernise the grid.[159]

Map 5: Gas Transmission System of Ukraine

Source: The National Gas Union of Ukraine (2019)

This extensive gas transmission network could allow Ukraine to transport large quantities of hydrogen at low cost to the EU. This would however require repurposing entire pipelines or parts of them for hydrogen transport. It is very likely that the current configuration of the gas transmission network in Ukraine will not allow the transport of hydrogen due to its age and the condition of the pipeline materials. Hence, a thorough assessment of the state of the Ukrainian natural gas networks is required.[160]

In 2021, the gas transportation system operator of Ukraine started undertaking a study to examine the effects of hydrogen blending within pipelines. The study was supposed to be concluded in 2022, but due to the ongoing war, was never completed.[161] Hence, the construction of new hydrogen pipelines within Ukraine might be necessary, which could significantly add to transportation costs but would still be favourable over transport via roads and trucks. The southern oblasts of Kherson and Zaporizhzhia hold some of the largest renewable potential but are less well connected, and currently partly occupied.

[159] CSIS (2023)
[160] Frauenhofer ISI/HYPAT (2023)
[161] Gas Transmission System Operator of Ukraine (2021)

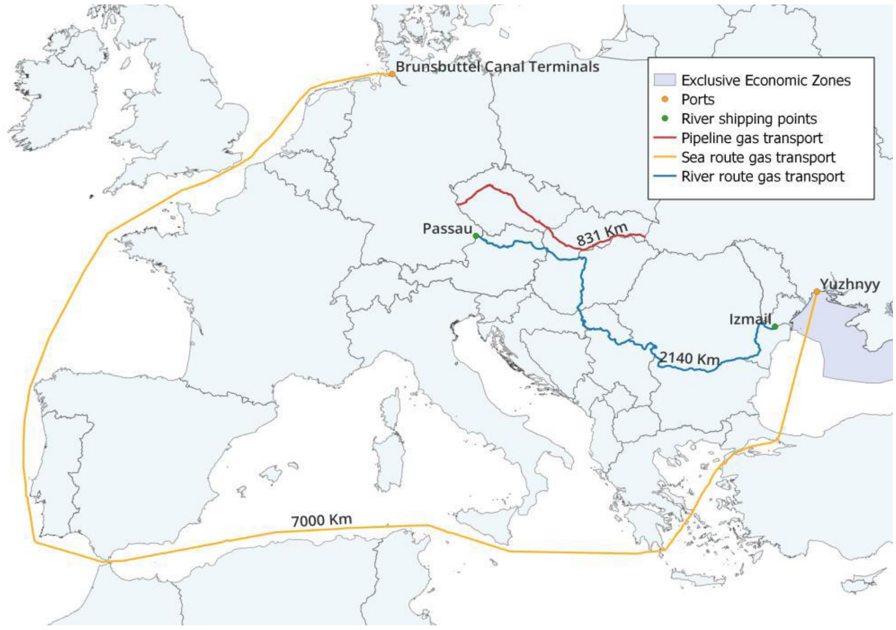
New infrastructure links would be needed to transport green electricity or green hydrogen to other parts of the country and to the EU.[162]

In 2021, Ukraine, Slovakia, Czech Republic and Germany presented the idea of a Central European Hydrogen Corridor. This joint initiative of four gas transmission system operators creates an opportunity to use the current reused gas transmission system to connect potential hydrogen production in Ukraine with potential hydrogen consumers in Slovakia, the Czech Republic and Germany. The project is currently in the pre-feasibility stage and according to the project website is expected to have a capacity to transport up to 144 GWh of pure hydrogen per day by 2030 (~1.6 million tons of hydrogen per year[163]). The pipeline requires an estimated investment between EUR 1 and 1.5 billion. The estimated investment cost is relatively low and covers required upgrades to pipelines, cross-border stations, and selected compressor units and ranges between 0.10 – 0.15 EUR/kgH2 per 1000 km. However, CAPEX requirements for the Ukrainian section of pipeline will ultimately also depend on the exact locations of the hydrogen production within Ukraine.[164] There is no information to be found on assumed pressure, OPEX, and fuel source to power the pipeline.

To produce stated volumes of hydrogen, assuming an efficiency factor for the electrolyser of 75%, an estimated 70.8 TWh of electricity per year would be required.[165] Total electricity demand in Ukraine in 2021 was 156 TWh, which highlights the large increase in clean electricity demand if this pipeline were to be filled at maximum capacity and run continuously throughout the year. The required capacity of electrolysers needed to produce such quantity depends on its load hours. Assuming the electrolyser runs 4000 hours a year with an efficiency of 75%, it would require about 17.5 GW[166] of electrolysers to produce the 52.56 TWh of hydrogen per year. A lower utilisation of the pipeline as well as a higher capacity factor for the electrolyser (i.e. using nuclear power or grid electricity) would result in significantly less electrolyser capacity needed. These numbers are very high and are unlikely to be achieved by 2030. If these 70.8 TWh would be produced by onshore wind only, this would require about 27 GW of dedicated wind power capacity installed assuming a 30% capacity factor.[167]

[162] Frauenhofer ISI/HYPAT (2023)
[163] 144 GWh/day*365/1000 = 52.56 TWh/year. 52.56 TWh/33.3 =1.58 million tons H2;
1 million tons of H2 has an energy value of 33.3 TWh.
[164] Central European Hydrogen Corridor (n.d.)
[165] 52.56 TWh / 75% = 70.08 TWh/year electricity.
[166] 52.56 TWh/4000h*1000/75% = 17.52 GW.
[167] 70800 GWh/8760h/30% = 26.9 GW.

Map 6: Possible Export Route of Transportation of Hydrogen



Source: Frauenhofer ISI/ HYPAT (2023)

As the map above shows, other transport options are in principle available too – via river, rail and sea. River transport could occur via the Danube and the ports of Reni and Izmail. Noteworthy here is the project Green Hydrogen Danube in which Austrian utility VERBUND is developing a trade corridor to ship hydrogen from the Romanian black seacoast to industrial demand centres.[168] The project is part of the European Commission's Important Projects of Common European Interest (IPCEIs) initiative. Potentially, hydrogen would be converted to liquid organic hydrogen carrier (LOHC) as a transport medium and the project could in theory be extended to include Ukraine.[169]

Railroad transport could in theory be used as well. However, the country still uses different standards for railroad gauges vis-à-vis the majority of Europe. Smooth cross-border transport thus requires construction and/or modifications of the existing railroad system. Lastly, sea-based transport, possibly using ammonia as a derivative could be an option but would require open access to the Black Sea.

Hence, while there are many potential export options, large uncertainties and stumbling blocks still remain. Exports via pipelines and to a lesser extent river-based transport seem to be most promising. The potential offtakers could differ depending on the export route taken. If sea route transport is taken,

[168] VERBUND (2020)
[169] Ukraine Hydrogen Council (2021)

exports are in principle much more flexible, while pipe, river and trail transport would favour customers in Germany and Austria.

Other Factors

There are many other factors affecting Ukraine's prospects as a potential future hydrogen supplier to the EU. While we list a number of them below, a detailed elaboration is beyond the scope of this chapter. On the one hand, in principle, the country has ample space for renewable installations and sufficient availability of water for electrolysis. However, there are concerns about a potential trade of between land and water-use for agriculture versus green hydrogen, in particular in the southern regions of Ukraine and following the destruction of the Kakhovka dam in June 2023.

In regard to water usage, as Frauenhofer ISI/Hypat (2023) reports, the Institute of Geological Sciences of the National Academy of Science of Ukraine concluded that only 0.36 % of river runoff resources in the regions of Reni/Ismail, Odesa are required to produce the total estimated potential of green hydrogen and that hence available water resources are sufficiently available. Whether the destruction of the Kakhovka dam changes this assessment is unclear. Generally speaking, green hydrogen production via electrolysis requires roughly 9 Liters (L) of water per kg of H2 produced. However, this assumes that the water used is of high and pure quality and does not require pre-treatment. Moreover, this number does not include water usage and evaporation as part of the cooling needs for the electrolyser. Accounting for these additional requirements, water usage can reach up to 80 L per kg of hydrogen.[170] Assuming 80 L of water required per kg of H2 would translate to 128 million m³ of water per year for 1.6 million tons of hydrogen[171] - equivalent to 1.2% of total annual freshwater withdrawal in Ukraine for agriculture, industry and domestic uses, which was 10.6 billion m³ in 2019.[172] If this would indeed lead to water stress, the usage of desalination plants at the black sea-coast are in principle also thinkable. While seawater desalination would increase water usage overall even further and require high initial CAPEX investments, the levelized cost of hydrogen production would only marginally increase as a result.[173] If desalination plants are powered by renewable energy and their waste products, such as concentrated brine, are properly disposed, it could be a sustainable solution and also help provide the country with fresh water for other uses. Moreover, scientists are making progress in improving electrolysers to withstand saltwater corrosion, which could in the future eliminate the need to use freshwater sources for electrolysis.[174]

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[170] AWA (2021)
[171] 80 L/kgH2 * 1.6 million tons H2 = 128 billion L = 128 million m³.
[172] World Bank (n.d.)
[173] Water desalination only adds 0.5% to the total cost of green hydrogen production according to IEA (2022a).
[174] Science (2023)

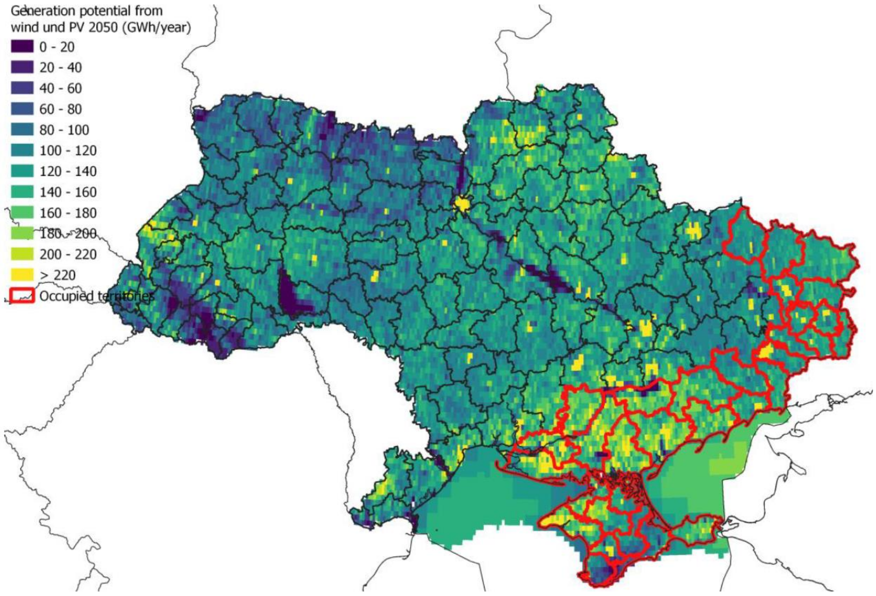
Land use requirements in terms of area occupied stem would stem mostly from renewable installations. The mean output in Europe for an onshore wind is estimated at 19.8 MW per km².[175] Assuming the numbers calculated in the preceding chapter for the CEHC project (27 GW onshore wind) the required land use for dedicated onshore wind to produce 1.6 million tons of hydrogen would be 1364 km²,[176] or merely about 0.23% of total land mass in Ukraine. However, onshore windfarms don't necessarily conflict with agricultural use if designed accordingly. Careful consideration of potential trade-offs between agriculture and hydrogen production would nonetheless need to be part of upcoming projects, both for water and land use requirements.

In addition, Ukraine is known for its huge gas storage facilities that can be repurposed for hydrogen storage. Currently, a total of 322.1 TWh of gas storage facilities are available at 13 sites. According to recent studies, if reconverted the total capacity for hydrogen storage is estimated at 109 TWh (3.3 million tons of hydrogen), also taking into account all possible future storage facilities.[177] Moreover, the country has large capacities of nuclear power plants, which in theory could be used in a transitional period to also produce zero carbon hydrogen, benefiting from high-capacity factors for the electrolysers and putting to use any existing generation overcapacities in the system, while electrolysers could also be adding flexibility to the system as a whole. However, the nuclear power plant park is outdated and in need of modernisation and replacement.

On the other hand, as of beginning of August 2023, Russia still occupies about one fifth of Ukraine's territory, including much of the land with the highest renewable energy and industrial potential.

[175] Enevoldsen, P. and Jacobson, M. (2021)
[176] 0.0198 GW/km²; 27GW/0.0198 GW/km² = 1364 km².
[177] Frauenhofer ISI/HYPAT (2023)

Map 7: Renewable Potential and War Related Activity



Source: Frauenhofer ISI/Hypat (2023)

Even following the liberation, it will take many years to recover and demine these territories. This seriously dampens the prospects of realising the countries full renewable energy and thus hydrogen export potential. Moreover, investor confidence dropped even before the war as Ukraine walked back on its commitments to pay generous feed in tariffs for renewable installations as the state-owned off-takers struggled to pay the renewable electricity producers.[178] General concerns regarding corruption as well as the outsized role of monopolies and the lack of competition in energy markets continue to apply and are another concern for investors, although Ukraine made significant progress along those dimensions in recent years.

Conclusion

Ukraine, bordering the EU, connected via existing infrastructure and with large renewable and nuclear potential, in principle is well endowed to becoming a hydrogen supplier to the EU. However, the country faces many obstacles compared it its competitors, most importantly the ongoing war and the uncertainties coming along with it. However, even without large scale conflict and occupation of its territory, the country would need to seriously address more general problems like its chronically high interest rate environment, the lack of regulatory clarity and hydrogen strategy, as well as potentially large investments needed into the upgrading of its gas infrastructure. Overall, the countries prospects for large-scale hydrogen production and export remain uncertain.

[178] LCF (2021)

Synthesis and Comparison

The preceding analysis in the supply country chapters allows for a first comparison and evaluation of the export competitiveness of hydrogen of Ukraine and selected competitors in the wider European and North African contexts.

Limitations

Several limitations and caveats that apply for all supply side countries under consideration and must be noted.

Firstly, wide uncertainty regarding production and transport prices as well as regarding the actual volumes available for export apply. The lack of transparency regarding assumptions underlying most production cost estimates, as well as the uncertainty of the viability of domestic ambitions to, for example, use hydrogen for domestic purposes like industrial decarbonisation and higher value-added production, make reliable estimates and a fair comparison difficult. Moreover, some of the graphs on best- and worst-case estimates for production and transport costs combine estimates from different sources but are represented in one bar chart. Hence, the possibility exists that these estimates are based on different assumptions regarding interest rates which would limit the comparability.

Secondly, if political ambitions to import from a particular country exist, then the economics of production can either change considerably (e.g., via granting preferential interest rates for financing, subsidization schemes), or lose relevance as energy security considerations and development goals can trump pure economic considerations for imports.

Thirdly, this study only looked at a small selection of prospective exporting countries. In reality, these aforementioned countries will compete with other frontrunner states in the emerging hydrogen market, such as Saudi Arabia, Oman, Chile, Australia and others. Some of these countries potentially have lower costs and larger project pipelines, and as much of the early market development will be characterized by long term offtake agreements, these countries could capture and lock in a significant share of the market early on.

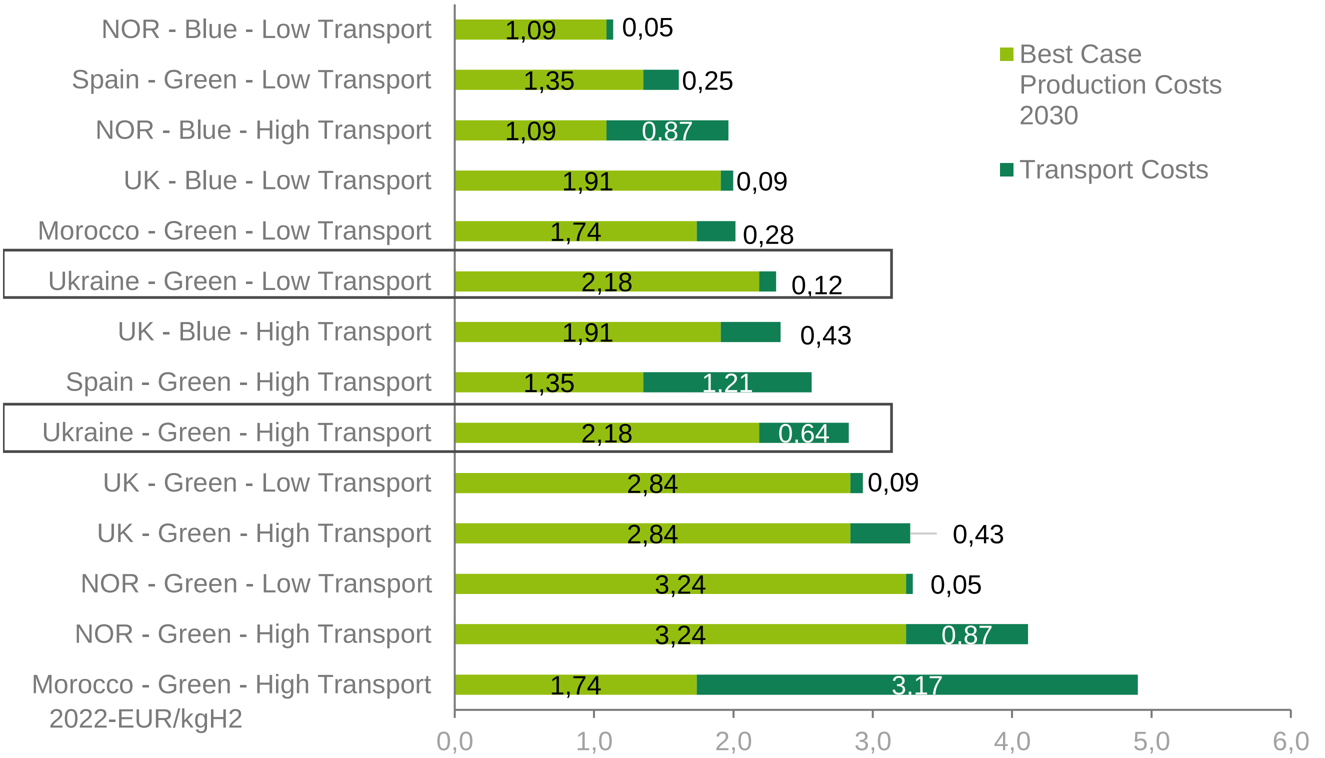
Fourthly, potential changes in the approach to industrial policy as well in the structure of the industry itself from demand and supply side countries (importing/exporting energy intensive goods instead of energy carriers) would drastically change the nature of trade flows as well as potentially the location of industrial activity and thereby the volumes of hydrogen exports.[179]

[179] A more detailed discussion on this can be found in chapter 3 in the demand side part of this study.

Comparing the Key Factors Influencing Export Competitiveness

While there are many factors influencing the competitiveness of exports, several stand out in importance: production costs, transport costs, available supply for export, existing project pipeline, political and regulatory aspects as well as water availability and environmental considerations.

Figure 25: Optimistic Case Cost Estimates and Low and High Scenario Transport Costs to Germany in 2030



Sources: DNV (2023), Deloitte (2023), Guidehouse (2021b), CEHC (n.d.), EWI (2021), Stiftung Arbeit und Umwelt der IG BCE (2021), Department for Business, Energy & Industrial Strategy (2021), Reinertsen New Energy (2021), Frontier Economics (2021), Adelphi (2020)

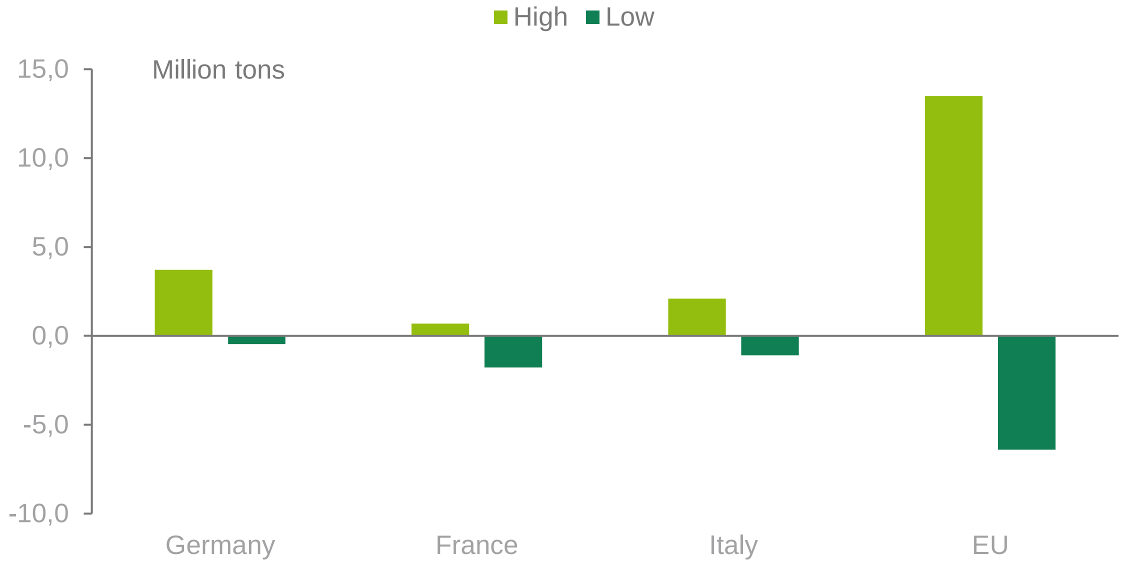
Looking at the first major factor determining the export competitiveness, best case production prices combined with highest and lowest estimates for transport costs in 2030, reveal that Ukraine is in principle in a good position vis-à-vis selected competitors with potential to be able to deliver green hydrogen to Germany at a cost of 2.3-2.8 EUR/kgH2. Ukraine's potentially very low transport costs[180]

[180] The transport costs of Ukraine in Figure 25 are taken from CEHC (n.d.) (0.12 EUR/kgH2) and Frontier Economics (2021), are adjusted to a length of 1225 km and inflated to 2022 EUR. CEHC costs refer to repurposed pipelines and include necessary upgrades to compressor stations. Frontier Economics (2021) costs refer to the upper bound costs of building a 48-inch new pipeline including costs for compression.

of only 0.1 EUR/kgH2 give it a competitive edge over other prospective exporters like Morocco which potentially could have lower production costs, but significantly higher transport costs. Only Spain and Morocco have lower costs for green hydrogen, and the UK and Norway outcompete Ukraine cost wise with their blue hydrogen production potential. It is noteworthy to point out that blue hydrogen production from natural gas with carbon capture cannot avoid all emissions, but a small share of CO_2 is released to the atmosphere, making its usage disputed.

Another dimension considered are available volumes of hydrogen for export in 2030. An obvious caveat in this regard is that the ongoing war in Ukraine and its potential effects on production potential but also domestic demand are not accounted for. Disregarding this limitation, Ukraine's export potential could in theory range between 0.4 - 0.7 million tons of hydrogen in 2030. It is noteworthy that according to plans presented at the Lugano recovery conference in 2022, Ukraine aims to export 1.5 million tons in 2032. The export potential in 2030 is thus similar to that of Morocco, but significantly less than the upper bound estimates for Spain, Norway and the UK. However, lower bound estimates for Norway and particularly the UK are worse than Ukraine's and even result in import needs in the case of the latter.

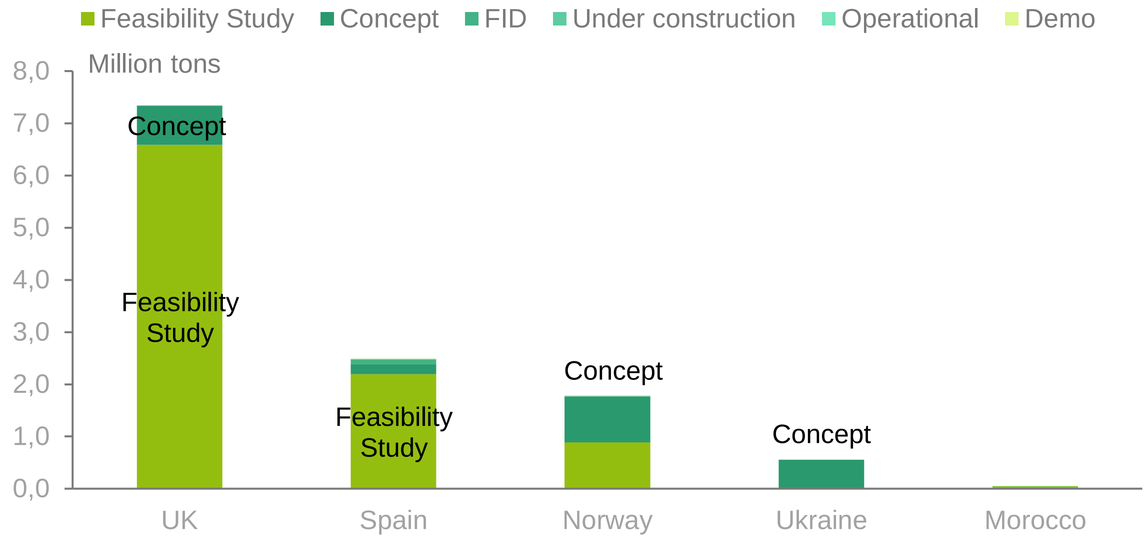
Figure 26: Net Export Potential High and Low Estimate in 2030



Sources: Frauenhofer ISI/HYPAT (2023), BMWK (2023), DNV (2022), Guidehouse (2022b), Cloete et al. (2022), Hydrogen Europe (2022), Net Zero Strategy UK (2021), UK Hydrogen Strategy (2021), Guidehouse (2021a), UKCS Energy Integration (2021), Ministry for Energy, Mining and Environment (2021)

Equally important to the theoretical production and transportation prices and potential is the actual project pipeline, indicating investors interest and bankability of real-world projects. In this regard, none of the countries can point to a significant number of projects currently at the final investment decision stage.[181] Looking at the project volumes in the pipeline and their project cycle stage, it becomes clear that almost all projects are either in feasibility study or still at the concept stage, with the UK leading by far, mostly due to their H21 project which aims at utilising hydrogen for domestic heating, not for export. Ukraine in this metric can only point to a few projects totalling 0.6 million tons, all at the concept stage and far behind all competitors besides Morocco. While there are (as pointed out in Ukraine country chapter) more projects that the database does not cover, the uncertainties surrounding the war won't allow for much progress in regard to the country's project pipeline. The other countries, however, will continue with their efforts for a hydrogen market ramp up even more strongly because of the war in order to achieve energy independence of Russian natural gas supplies, which puts Ukraine at a relative disadvantage.

Figure 27: Hydrogen Projects Overview



Source: IEA (2022d)

The political risk and governance as well as regulatory capacity criteria equally play a role. Here, the forerunners are Norway, the UK and Spain as they are developed democracies with stable political systems and the ability to pursue industrial policy and complex certification and regulations. Morocco, albeit being a rapidly growing and developing economy, is still a closed autocracy with border disputes with neighbouring countries, while Ukraine is in a protracted military conflict with its largest neighbour, mostly on its renewable rich territory. However, in contrast to Morocco, Ukraine recently gained

[181] It is important to note that the project data base of the International Energy Agency was last updated in October 2022. However, our research did not indicate that the situation has significantly changed since then.

candidacy status for the EU membership. Lastly, environmental factors such as water shortages and competing land use can impact export prospects. Here, only Morocco faces significant challenges due its extreme water scarcity and the high requirements posed by EU regulations on additionality of electricity generation for green hydrogen production.

Overall Comparison

Taking a more qualitative approach, the table below presents a qualitative summary of the afore discussed factors:

Table 6: Qualitative Comparison of Individual Factors[182]

	Production Costs	Transport Costs to Germany	Potential Export Volumes	Project Pipeline	Political & Regulatory	Environ-ment
Ukraine	+	++	+	--	--	+
UK	+	++	+	++	-	++
Norway	++	++	+	-	++	++
Spain	++	-	++	++	++	-
Morocco	+	-	+	--	--	--

Source: Authors own deliberation

Assessing all the key factors, the picture for Ukrainian hydrogen exports and their competitiveness is mixed. In an ideal scenario, disregarding the ongoing war and the large uncertainty surrounding it, Ukraine could in principle become a competitive hydrogen exporter if it could secure reasonable financing costs for its projects, (re-)gain investor confidence, successfully upgrade its gas transportation system and manage to balance domestic needs and export ambitions for green hydrogen.

However, given the ongoing hostilities that affect not only the availability of renewable rich regions in the country but also impact transportation options via sea and leave the country in enormous financial problems, the prospects are grim. Even if hostilities cease and all territories were to be liberated, then

182 The assignment of the individual symbols to the factors is based on a qualitative judgement of the data under consideration and discussed in the respective chapters.
(++ very positive, + positive, - negative, -- very negative)

a large-scale reconstruction in a green manner, including the planned rebuilding of the domestic steel industry, would significantly increase domestic demand for hydrogen (e.g. in green steel, fertilisers, cement, glass etc.), which would conflict with export ambitions in the short to mid-term. Moreover, Ukraine will likely face a shortage of skilled labour after the war which may limit the implementation of a large number of projects in a short period of time, further hindering the rapid development of Ukraine as a net exporter of hydrogen. As a result, Ukraine is unlikely to become a significant hydrogen exporter by 2030. In the longer term however, the natural competitive advantages of Ukraine could bear fruit and allow to become a potentially significant producer and exporter of hydrogen.

02

Demand Side & Infrastrucutre

Building upon the insights stemming from the previous chapter on the production of green and blue hydrogen, this chapter focus on three European Union (EU) member states, as well as the EU as a whole, within the context of their potential hydrogen demand, existing production capacities and potential import necessities leading up to 2050. Moreover, Europe is home to the world's largest and densest network of gas infrastructure in the world. The rising importance of hydrogen and the import needs thereof will require changes to this system. Parts of the existing network could be repurposed, while new links dedicated to hydrogen will complement the existing network and connect new suppliers who were and are gas importers themselves. Hence, this chapter will also discuss ongoing infrastructure developments.

European Union

The European Commission unveiled the EU Hydrogen Strategy in 2020[183], foreseeing three distinct phases. In the initial phase (2020-2024), the primary objective revolves around generating one million tons of green hydrogen by 2024. Collaborating with complementary programmes like the European Clean Hydrogen Alliance, Next Generation EU, the Strategic European Investment Window within the InvestEU program, and the ETS Innovation Fund, an extensive lineup of green hydrogen production projects—particularly leveraging wind and solar energy— projected to be announced within this timeframe. Emphasis is placed on projects up to 100 MW in proximity to existing demand centres like large refineries, steel plants, and chemical complexes, aimed at decarbonizing the prevailing hydrogen production within the chemical sector and other industrial processes.

In the second phase (2025-2030), the focal point shifts to the upscaling of hydrogen production to a magnitude of ten million tons per year. This phase prioritizes the production of both green and blue hydrogen with Carbon Capture, Utilization and Storage (CCUS). Hydrogen is envisaged to be utilised in multiple sectors, including transportation. Additionally, hydrogen assumes a role in the energy grid by converting surplus renewable electricity into hydrogen for system flexibility, and as a storage backup to ensure medium-term supply security. Furthermore, the establishment of hydrogen clusters is planned, leveraging locally produced renewable energy to support nearby production and short-distance transport. By 2030, the EU envisions the realization of an entirely open and competitive hydrogen market within its borders, characterized by unrestricted cross-border trade and optimal allocation of hydrogen resources across diverse sectors.

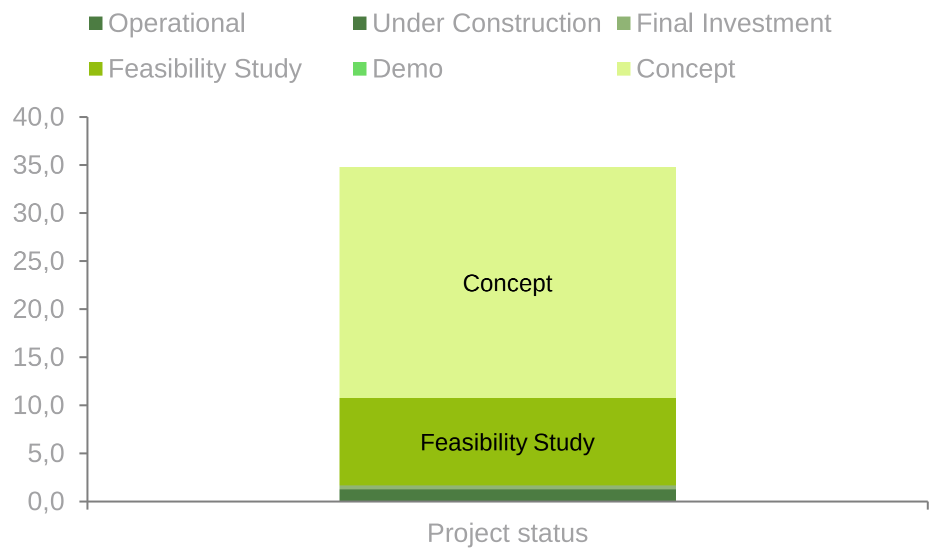
The third phase (2030-2050) strives to dedicate around a quarter of renewable electricity generation for green hydrogen production by 2050. Additionally, innovative technologies like sustainable biogas may

[183] European Commission (2020)

emerge to supplant portions of blue hydrogen production derived from natural gas, in alignment with the EU 2030 Biodiversity Strategy.[184]

According to the IEA database[185], the collective sum of hydrogen projects that have been disclosed across the 27 European Union member states is projected to yield an annual capacity of approximately 35 million tons, if the entire project pipeline was to be realised. Nevertheless, at present, only 1.1 million tons are operational, with 9.1 million tons undergoing feasibility studies, and the largest segment, encompassing 24 million tons, residing within the concept stage.

Figure 28: Hydrogen Projects in the EU



Source IEA (2022d)

A number of these initiatives fall within the framework of Important Projects of Common European Interest (IPCEIs). Consequently, 22 EU member countries, alongside Norway, have collectively endorsed a manifesto, committing to initiate IPCEIs within the hydrogen sector. Specifically, this entails the launch of 41 projects spanning 15 EU countries, which started in July 2022. Additionally, another 35 projects spread across 13 EU nations are slated to receive supplementary public funding.[186]
Nonetheless, in the wake of the Russian invasion of Ukraine, the EU has introduced the RePowerEU[187] program, which outlines more ambitious targets for hydrogen demand and supply to help phasing out

[184] European Commission (2020)
[185] IEA (2022d)
[186] European Commission (2022b)
[187] European Commission (2022a)

Russian natural gas. In alignment with this program, the EU envisions a hydrogen demand of up to 20 million tons annually by 2030. While 10 million tons are supposed be produced within the EU, an additional 10 million tons will need to be imported. Nevertheless, it is important to note that the RePowerEU plan was formulated within a very limited timeframe and lacks comprehensive modelling underlying the projections of anticipated future demand.[188] Hence, in contrast to other studies, the numbers presented within the RePowerEU plan tend to be significantly higher than what has been modelled in other studies - the Joint Research Centre's Average EU hydrogen demand projections for 2030 are only 400 TWh (~ 12 million tons), compared to RePowerEU's 20 million tons.[189] Noteworthy in this context is a study by the European Commission, which found that if the EU were to cease the production of energy-intensive products like ammonia, ethylene, and sponge iron and instead relied on imports, by 2050, the overall demand for hydrogen would decrease by one third, and the demand in energy-intensive industries would decrease by roughly two thirds, compared to the baseline scenarios where these production steps remain within the EU. Moreover, the study found that in principle, from a purely techno-economic perspective, the entire demand for hydrogen could be covered from within the EU but that pipeline imports become necessary in the absence of optimal usage of the continent's renewable potential.[190]

Hence, as illustrated in the ensuing table, it is highly likely that the EU as a whole could rely on substantial hydrogen imports from third countries.

Table 7: Hydrogen Demand and Import Potential in Million tons of H2

Million tons of H2	2030	2040	2050
Supply Potential	7.5 - 12.0		12.0 - 39.0
Demand Potential	5.6 - 21.0		16.35 - 52.92
Import Potential	-6.4 - 13.5		-22.65 - 40.92

Sources: Clean Hydrogen Partnership (2023), Bruegel (2023), Guidehouse (2022b)

Considering the aspiration to create a global liquid market for hydrogen as well as to import 10 million tons of hydrogen by 2030, the EU has taken substantial steps by forging partnership agreements with various nations to foster collaboration in fields ranging from technology cooperation, certification and

[188] Bruegel (2023)
[189] Bruegel (2023)
[190] European Commission (2023b)

standard setting, as well as imports facilitation, as outlined in the EU External Energy Strategy (2022).[191] These include significant collaborations such as the EU-Japan Green Alliance (2021), the trilateral partnership involving the European Commission, the United States, and Japan (2019), the EU-India Clean Energy and Climate Partnership, the EU-Chile Green Hydrogen Initiative, as well as the African Green Energy Initiative. Additionally, the EU has established partnerships such as the EU-Egypt Hydrogen Partnership and the EU-Morocco Green Hydrogen Partnership. Moreover, there are alliances geared towards CO2 storage, exemplified by the EU-Norway Green Alliance.[192]

In addition, the EU plans to pool its member states' hydrogen requirements in order to avoid competition between countries, as will be the case for natural gas purchases in 2022, and to strengthen its negotiating power with trading partners. This method strives to ensure the most effective allocation of hydrogen resources within the EU and the joint procurement of hydrogen as a Union. Consequently, the EU has established the EU Energy Platform (2022)[193], which includes a collaborative energy procurement mechanism. Moreover, to close the investment gap and upscale and link future hydrogen exporters to EU markets, the European Commission announced the creation of a European Hydrogen Bank.[194]

According to the EU hydrogen strategy, the development of hydrogen infrastructure will occur step wise. Initial hydrogen demand can be met via local renewable production in industrial clusters followed by the formation of regional hydrogen networks. As demand keeps growing, a transportation system suited for longer ranges is needed and thus an interregional and international network must emerge. Moreover, the strategy names the southern and eastern neighbourhood, and in particular Ukraine, as priority partners given their natural endowments and existing physical connections.

The RePowerEU plan states that accelerated efforts are needed to allow for the incorporation of the roughly 20 million tons of hydrogen by 2030. The extra-EU import of about 10 million tons of hydrogen will require the deployment of cross-border hydrogen infrastructure, which has already been included in the revised trans-European networks for energy planning (TEN-E) guidelines which now also includes hydrogen infrastructure needs.[195] RePowerEU further states that the European Commission will support the development of three major hydrogen import corridors to facilitate green hydrogen imports from partner countries:

[191] European Commission (2022c)
[192] FleishmanHillard (2022)
[193] European Commission (2023)
[194] European Commission (2023a)
[195] Official Journal of the European Union (2022)

- Via the Mediterranean
- Via the North Sea area
- From Ukraine (As soon as conditions allow)

The TEN-Guidelines from 2022, specify three inner-EU priority areas for hydrogen infrastructure:

- Western Europe
- Central Eastern and Southeastern Europe
- Baltic Energy Market Interconnection plan in hydrogen

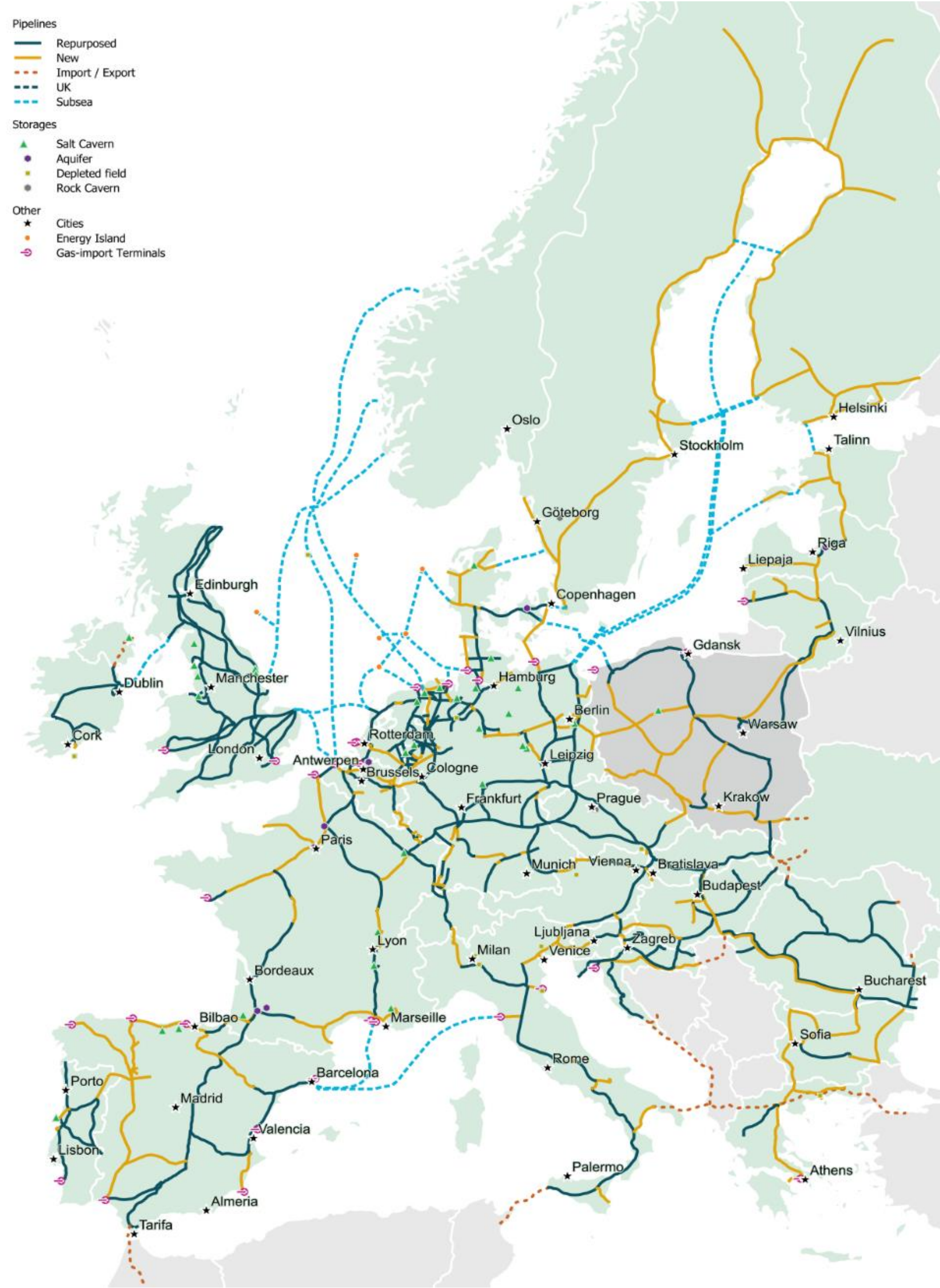
Most prominent in public discussion likely is the European Hydrogen Backbone, which is an initiative by currently 31 European energy infrastructure operators covering 25 EU member states as well as Norway, the UK and Switzerland. Jointly they lay out a vision for a pan-European hydrogen infrastructure network. Their newest version from April 2022[196] incorporates the goals of the RePowerEU plan for 20 million tons of hydrogen by 2030. According to the report, five key transport corridors with a capacity of 65 TWh (~ 2 million tons) each are needed to transport half of the target (~10 million tons or 330 TWh of extra-EU imports). By 2030, the hydrogen infrastructure map is envisaged to consist of 32 600 km of pipelines, reaching 57 662 km by 2040. The network shall consist of about 60% repurposed existing gas infrastructure and 40% newly built hydrogen pipelines.[197] The five corridors include:

- North Africa-Italy Corridor
- Southwest corridor from Spain and Portugal
- The North Sea corridor
- Nordic & Baltic corridor
- Southeastern European Corridor

Thereby the five planned corridors overlap with the three corridors from the REPowerEU plan and Ukraine could be part of the wider Central-Southeastern European export corridor.

[196] Some numbers were updated in July 2023, new full version is expected in fall 2023.
[197] Guidehouse (2023)

Map 8: The European Hydrogen Backbone Vision 2040



Source: Guidehouse (2023)

Germany

With the adoption of the Climate Change Act of 2021[198], Germany set its goal on achieving net zero emissions by 2045, with an intermediate goal of reducing CO2 emissions by 65% by 2030. This ambitious target would make Germany the first major climate neutral industrial power in the world. However, during the last two years, Germany did not achieve its annual emission reduction goals, and the conflict between Russia and Ukraine, which caused the suspension of gas supply from Russia to Germany, further complicates the transition. Consequently, in line with the recently unveiled updated hydrogen strategy[199], Germany is positioning hydrogen to play an amplified role in the energy transition and in substituting natural gas. Germany has revised its hydrogen strategy in July 2023[200], building upon its prior plan from 2020. Similar to the preceding version, this strategic update envisions a prominent role for hydrogen in driving the evolution of the transformation of both the industrial and transportation sectors, with a focus on the period leading up to 2030. Consequently, the outlined objectives are threefold, encompassing short-term (2023), mid-term (2024-2025), and long-term (until 2030) goals.

Ultimately, by 2030, Germany aims to install a minimum of 10 GW of electrolyser capacity for green hydrogen production (expected to yield 1 million tons of hydrogen per year).[201] Additional demand shall be met via imports. Furthermore, the generation facilities for hydrogen and storage hubs are planned to be seamlessly integrated into the existing infrastructure.

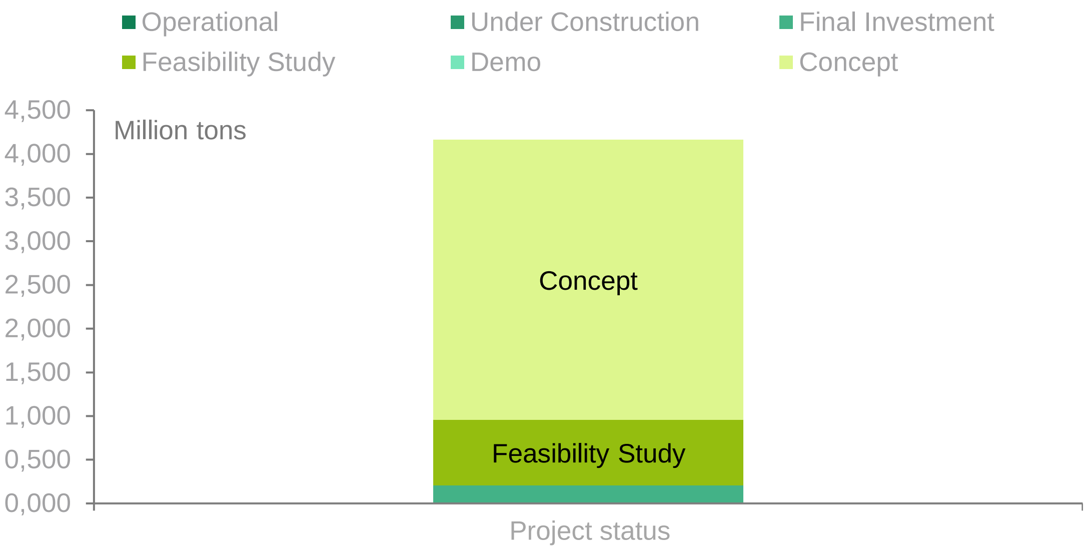
During the phase preceding the upscaling of green hydrogen by 2030, Germany is committed to providing financial backing for various hydrogen production technologies, encompassing blue, turquoise[202], and orange[203] hydrogen. At present, the nation's hydrogen production primarily relies on grey hydrogen, yielding approximately 1.65 million tons per year.[204]

When reviewing the planned hydrogen initiatives outlined in the IEA hydrogen database[205], Germany exhibits the potential to achieve an annual hydrogen production capacity of 4.2 million tons, assuming

198 Federal Ministry of Justice Germany (2021)
199 BMWK (2023)
200 BMWK (2023)
201 Hydrogen Insight (2023)
202 Hydrogen produced through the decomposition of natural gas via methane pyrolysis into hydrogen and solid carbon.
203 Hydrogen produced through chemical reactions within an iron-rich subterranean rock formation, coupled with storing CO2.
204 BMWK (2023)
205 IEA (2022d)

the successful realization of all these projects. Nevertheless, the majority of these endeavours are currently in their initial developmental phases and have not yet reached the stage of final investment decisions. Consequently, a substantial degree of uncertainty surrounds the actual achievable production capacity.

Figure 29: Hydrogen Projects in Germany



Source: IEA (2022d)

Illustrated in Figure 29, a notable portion of the projects remain within the concept phase, accounting for a capacity of 3.2 million tons per year, followed by projects in the feasibility study stage, which collectively contribute 0.7 million tons. Only a limited capacity of 0.2 million tons has secured FID. Additionally, there are currently operational green hydrogen projects with a combined capacity of 0.01 million tons.

Prominent among these projects is the AquaVentus initiative (see Norway chapter 4 for more information), situated offshore near Helgoland, with the ambitious goal of generating one million tons of green hydrogen by 2035. The anticipated expenses for this endeavour amount to approximately 6 billion euros, encompassing the infrastructure requirements such as pipelines and high-voltage transmission lines.[206]

[206] AquaVentus (2023)

Table 8: Hydrogen Demand and Import Potential

Million tons of H2	2030	2040	2050
Supply Potential	0.18 - 1.0	0.57 - 2.94	2.76 - 5.70
Demand Potential	0.54 - 3.90	2.97 - 12.00	7.80 - 25.59
Import Potential	-0.46 - 3.72	0.30 - 11.43	2.10 - 22.83

Sources: Bundesministerium für Wirtschaft und Klimaschutz (BMWK) (2023), Guidehouse (2022a)

As outlined in the hydrogen strategy of 2023, the projected hydrogen demand for the year 2030 is anticipated to be up to 4 million tons annually and between 50% and 70% of it to be sourced through imports. Table 8 also provides projections for the years 2040 and 2050. Despite inherent uncertainties surrounding demand and supply forecasts, it is evident that Germany will heavily rely on imports. By 2040, the volume of imports could potentially increase to 11.43 million tons, and looking further ahead to 2050, estimated imports might reach a substantial 22.83 million tons.

Industries that hold particular significance in terms of replacing fossil fuels with hydrogen encompass the manufacturing, transportation, aviation, and maritime sectors. Within the industrial domain, hydrogen serves a critical role in generating high-temperature heat, as exemplified by its application in primary steel production and the chemical industry. The projected demand for this sector is estimated to fall within the range of 8.7 to 13.2 million tons annually by 2040.[207] To achieve this objective, an illustrative initiative is the Electrolysers Corridor East Germany project, which seeks to establish four electrolysers with a combined capacity of 200 MW. The produced hydrogen will find applications in the manufacturing processes of major companies such as BASF, ArcelorMittal, and Cemex.[208] Additionally, Germany is strategizing the integration of hydrogen within its electricity system. Hydrogen is poised to serve as a robust energy safety net for this system due to its inherent adaptability. As a result, hydrogen use in this sector could range approximately between 2.4 and 3 million tons per year by 2045.[209]

To fulfil its domestic demand, Germany forged partnerships with prospective exporting countries. Germany signed numerous MoUs, including with Canada (2021), Chile (2021), Saudi Arabia (2021), Tunisia (2020), Algeria (2022), and Ukraine (2020). Moreover, Germany is actively participating in several bilateral collaborative ventures, which involve research initiatives and the establishment of hydrogen production capabilities. Notable partners in these endeavours include Denmark (2021),

[207] BMWK (2023)
[208] Ministerium für Wirtschaft, Arbeit und Energie Land Brandenburg (2023)
[209] BMWK (2023)

Netherlands (2020), Australia (2021), China (2020), Japan (2021), New Zealand (2021), Namibia (2021), and Nigeria (2021). Additionally, Germany has embarked on trilateral partnerships, as seen in the Green Octopus partnership focused on hydrogen networking (2019), which includes the Netherlands and Belgium.[210]

It is noteworthy that hydrogen demand projections for Germany are based on the assumption that the existing industrial model will be maintained and that energy-intensive industries will continue to operate in the country. A recent study conducted by Frontier Economics (2023) analysed various relocation scenarios regarding the value chains of German energy intensive industries that produce the basic materials such as aluminium, high-value chemicals, ammonia and steel. The study concluded that producing those basic materials in Germany using domestic and imported hydrogen is, with the exception of green hydrogen import form Norway, almost always the most expensive option. The long-term energy costs of producing industrial basic materials in Germany are 20-% - 80% higher than having them produced elsewhere at lower energy cost locations. However, keeping downstream and further processing steps of the value chain in Germany could still make sense as long as energy intensive intermediate products like sponge iron are imported.[211] Needless to say, if Germany would shift its industrial and hydrogen policy to account for such cost differentials, hydrogen import demand would reduce significantly.

Germany is also taking first important steps to create the future import and transport infrastructure for hydrogen. The transmission system operators, together with the network regulator and the Ministry for Economy and Climate Action (BMWK), submitted their plans for a “hydrogen core” network for Germany which intends to connect large consumption and production regions for hydrogen as well as storage sites and import corridors.[212] The core network is expected to be fully operational by 2032 and to be expanded in further stages.

The updated German hydrogen strategy from 2023[213] emphasises that in the short term (until 2030) the import of hydrogen and in particular derivatives to Germany will largely occur via ships and maritime transport routes. To this end, the accelerated construction of LNG import terminals on the German coasts that can be converted to import hydrogen or hydrogen derivatives is a strategic governmental priority. Pipeline imports of hydrogen from Europe and neighbouring regions is pursued in particular after 2030 but under special consideration of not abandoning the principle of diversification. The priority import corridors named in the strategy are import routes from the North Sea and Baltic Sea, but also

[210] FleishmanHillard (2022)
[211] Frontier Economics (2023)
[212] Bundesministerium für Wirtschaft und Klimaschutz (2023a)
[213] Bundesministerium für Wirtschaft und Klimaschutz (2023b)

from North Africa either via the H2 Med pipeline (See chapter 2.2.5) via France, Spain and Portugal or via a corridor going through Austria and Italy.

For the medium-term expansion (2024/2025 onwards) of a European hydrogen core network, there is already ongoing dialog with fellow EU member states and other partner countries on the establishment of cross-border infrastructures. The dialogue in that regard advanced furthest so far with Norway and Denmark, but there were also talks with Finland and Sweden as well as Austria, Italy and France. Additionally, in the mid to long run (2024-2030) strategic hydrogen pipelines to countries like the UK, Ukraine, Morocco, Tunisia and Algeria should be considered, according to the strategy.[214]

The planned hydrogen pipeline with Norway was already discussed in chapter 4. Moreover, Germany and Denmark signed a MoU to build a hydrogen pipeline by 2028, although the capacity is unknown.[215] Moreover, Italy, Austria and Germany signed an MoU in 2023 for the creation of the SoutH2 pipeline from Tunisia to Germany via Italy and Austria. This initiative is based on the initiative of gas system operators of those countries and would transport four million tons of hydrogen per year from North Africa by 2030 and could be built by mostly repurposing existing pipelines.[216]

As delineated in this chapter, Germany's hydrogen strategy in its current hinges on importing hydrogen. The extent of these imports is contingent upon multiple variables, encompassing factors like domestic production capabilities and the demand from domestic industries.

France

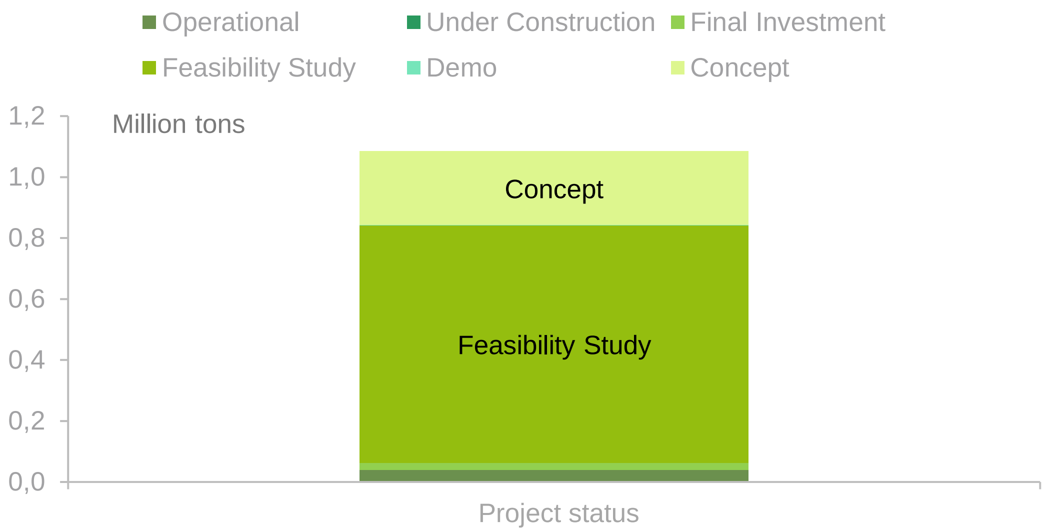
France's position on hydrogen differs significantly from that of Germany. Unlike Germany, France does not pursue an import focused strategy and does not foresee much cooperation at the international level other than scientific and technological collaboration. Instead, the goal is to develop a domestic hydrogen industry based on its vast capacities of nuclear power, which may be large enough to become self-sufficient and not dependent on imports. France unveiled its National Hydrogen Strategy, titled the "National Strategy for the Development of Decarbonized and Renewable Hydrogen in France"[217], in 2020. An updated version of this strategy is anticipated to be launched towards the end of 2023. This strategic blueprint outlines three primary objectives: Firstly, it seeks to establish a green hydrogen sector

214 Bundesministerium für Wirtschaft und Klimaschutz (2023b)
215 EURACTIV (2023)
216 Hydrogen Insight (2023)
217 Gouvernement France (2020)

with a targeted capacity of 6 GW by 2030, aimed at bolstering the utilization of green hydrogen within industrial applications. Secondly, the strategy focuses on fostering the integration of green hydrogen within the transport and mobility sector. Lastly, it aims to operationalize hydrogen for grid stabilization in the energy network. To this end, approximately EUR 9 billion in public funding have been allocated. It is worth noting, however, that the strategy primarily emphasizes regional development and the integration of hydrogen production into the existing processes of nearby industrial companies. As a result, the strategy remains largely silent regarding the establishment of hydrogen transport corridors or specific import/export routes.[218,219]

Presently, approximately one million tons of hydrogen are produced in France, predominantly finding usage in the oil refining and chemical industries, notably in fertilizer production. This hydrogen production primarily relies on fossil fuels. According to data from the IEA database[220], the project pipeline in France exhibits the potential for a capacity of 1.1 million tons of both green and blue hydrogen, assuming the successful realization of all projects. However, only a handful of projects, accounting for a total capacity of 0.022 million tons, have secured final investment decisions (FID). Additionally, around 0.7 million tons are currently undergoing feasibility studies, while 0.24 million tons are in the conceptual stage of project development.

Figure 30: Hydrogen Projects in France



Source: IEA (2022d)

[218] Gouvernement France (2020)
[219] Bouacida (2023)
[220] IEA (2022d)

Within this project pipeline, numerous initiatives are situated in the historically significant industrial region of Hauts-de-France. An illustrative example includes the endeavours of the Liberty Steel Group, which is working towards establishing a steelmaking facility rooted in hydrogen technology in Dunkirk. This ambitious undertaking is geared towards generating two million tons of direct-reduced iron, supported by an integrated hydrogen electrolysis production plant boasting a capacity of 1 GW. By 2030, the steel produced through this process is set to achieve complete carbon neutrality.[221] Another noteworthy large-scale undertaking within this context is the GravitHy project. This initiative also aims to supplant fossil fuels with hydrogen in the production of steel and iron.[222]

Table 9: Hydrogen Demand and Import Potential

Million tons of H2	2030	2040	2050
Supply Potential	0.40 - 1.90		7.80
Demand Potential	0.13 - 1.09	1.74 - 3.73	5.85
Import Potential	-1.77 - 0.69		-1.95

Sources: RVO (2021), Guidehouse (2021b), Guidehouse (2021c), France Hydrogene (2021)

The 2020 national hydrogen strategy does not include cross-border trade of hydrogen or derivatives as a goal. However, due its geographical location in between prospective exporters on the Iberian Peninsula and North-Africa, as well as potential importers in Northwestern Europe like Germany, France could play a key as a transit country without which potentially more expensive transport routes would have to be established. Moreover, France has cross border gas infrastructure linking it to most of its neighbours which potentially could be repurposed. This resulted in diplomatic pressure by Spain and Germany ultimately leading to the H2Med pipeline from Spain to France (H2Med), and ultimately extended to Germany, being built.[223]

In summary, France's current approach doesn't prioritize cross-border hydrogen trade. However, the updated 2023 version of its strategy might incorporate elements related to this topic, given France's participation in the H2Med project. Additionally, France successfully advocated for its nuclear power plants to be designated as sources of sustainable energy in the EU Sustainable Finance Taxonomy. However, in its push to also declare nuclear based hydrogen equivalent to green hydrogen from renewable sources, it was only in part successful. This is reflected in the EU Delegated Act which

[221] Liberty Steel Group (2021)
[222] InnoEnergy (2022)
[223] Prontera A. (2023)

defines what constitutes renewable hydrogen and its derivatives. The act includes a provision that hydrogen producers can count electricity taken from the grid as fully renewable if the emission intensity of electricity in a bidding zone is lower than 18 gCO2eq/MJ. Thanks to its large nuclear fleet, this criterion is usually fulfilled in France. However, this still requires hydrogen producers to also signs a long-term power purchase agreement (PPA) with renewable electricity providers and fulfil criteria of additionality and temporal correlation.[224] Nonetheless, EU members are open to discussing the classification of nuclear-produced hydrogen as “low-carbon” hydrogen. Meanwhile, diplomatic efforts by France continue to advocate for nuclear hydrogen to be considered on par with “renewable” sources.[225]

Italy

Italy unveiled its updated National Energy and Climate Plan in June 2023. Notably, the government set forth an ambitious target of sourcing 65% of its electricity from renewables by 2030, signifying a remarkable 10% increase from its initial target. Furthermore, Italy envisions renewables accounting for 40% of its energy consumption by the same date. Italy articulates its intention to supply 42% of its industrial energy consumption through renewable hydrogen by 2030. Hence, the strategy involves augmenting the installed renewable capacity from its 2022 level of 58 GW to 131 GW by 2030.[226] However, given the degree of uncertainty, it is advisable to approach these plans with a degree of caution. Although these targets are undoubtedly ambitious, there is still a lack of a clearly defined development path to effectively achieve these envisaged goals.

In 2020, Italy unveiled its perspectives on hydrogen through a document titled "Preliminary Guidelines for a National Hydrogen Strategy".[227] Since then, various governments have entertained the idea of formulating an official hydrogen strategy, but none have managed to achieve this thus far. Within its initial strategy, a set of developmental objectives has been outlined. By the year 2030, it is envisaged that 2% of the nation's energy consumption will stem from hydrogen in the medium term, with a longer-term goal of reaching a 20% consumption share by 2050. To be more specific, the government aims to establish an electrolyser capacity of 5 GW by 2030. Consequently, there are plans to invest EUR 3 billion by 2026 for the production, distribution, and research and development of hydrogen. Furthermore, the Ministry of Economics approximates that investment expenses could potentially reach

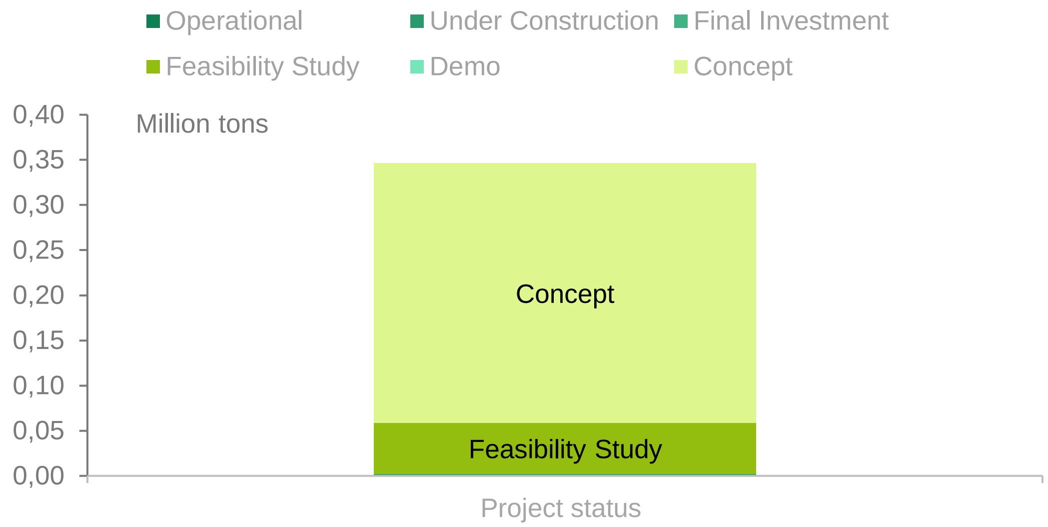
[224] Clearly Gottlieb (2023); Hydrogen Insight (2023)
[225] EURACTIV (2023)
[226] Reuters (2023b)
[227] Ministero dello sviluppo economico (2020)

up to EUR 10 billion by 2030, aimed at catalysing a low-carbon hydrogen economy in Italy and attaining the country's hydrogen demand objectives. According to the Italian National Recovery and Resilience Plan (NRRP)[228], there are intentions to establish 10 hydrogen valleys by 2026 (with 6 valleys slated for establishment by 2022). The first of which is the "H2iseO Hydrogen Valley Project", aiming at hydrogen-based industrial value chain for a sustainable mobility in the Lombardy region with an investment volume of EUR 300 million.[229]

At present, most of the operational hydrogen production facilities rely on grey hydrogen, and its predominant application in Italy pertains to the chemical and metallurgical industries. Consequently, the sectors earmarked for the adoption of green hydrogen include public transportation, as well as the chemical and refining sectors.

As per the IEA hydrogen database[230], Italy's pipeline of hydrogen projects is projected to yield an annual capacity of 0.35 million tons, contingent upon the successful completion of all these initiatives. It's worth noting, however, that most of these projects are currently in the conceptual phase, comprising 0.29 million tons. An additional 0.06 million tons are in the feasibility study stage. Moreover, there are currently no operational projects or projects in the final investment decision (FID) stage. Comparing to the other countries mentioned, this represents a very small project pipeline.

Figure 31: Hydrogen Projects in Italy



Source: IEA (2022d)

[228] Italia Domani (2021)
[229] H2V (n.d)
[230] IEA (2022d)

Many of these projects are spearheaded by prominent state-owned industrial entities, particularly energy giants like ENI, SNAM, and ENEL. These corporations constitute the primary impetus behind Italy's advancements in the hydrogen market. To exemplify, Eni envisions an annual production target of 4 million tons of green hydrogen by 2040 within Italy.

Table 10: Hydrogen Demand and Import Potential

Million tons of H2	2030	2040	2050
Supply Potential	0.60 - 1.20[231]		
Demand Potential	0.03 - 2.70		5.61 - 7.75
Import Potential	-1.10 - 2.10		

Sources: Prontera A. (2023), IAI (2022), Guidehouse (2021b), Guidehouse (2021c), Own calculations based on Ministero dello sviluppo economico (2020)

Furthermore, Italy has entered a memorandum of understanding (MoU) pertaining to hydrogen with India[232], and it is a participant in the Clear Hydrogen Mission (2021) alongside other European nations, as well as countries globally including the United States and Japan.[233] Additionally, it's worth highlighting that the state-owned energy enterprise ENI has entered a MoU with Algerian state-owned oil and gas producer SONATRACH, concerning projects involving the production of green hydrogen.[234]

Notably absent from the preliminary hydrogen strategy, similar to France's strategy, is any mention of cross-border trade. Consequently, there exists a level of uncertainty surrounding Italy's strategies for hydrogen import or export. However, the country expressed its ambition to become a hydrogen hub which links the MENA region to Europe, an undertaking which is actively supported by Italy's energy companies like ENI and SNAM.[235] The geographic position of Italy and its existing natural gas pipeline links to Algeria, Tunisia and Libya favour this approach. This hydrogen hub concept and the idea that Italy develops strong energy ties to Africa gained traction and support after the Russian invasion of Ukraine.[236] This is also reflected in the European Hydrogen Backbone which foresees one of the envisaged export corridors along that route. An MoU between Austria, Italy, Germany and Tunisia about the possibility of a SouthH2 pipeline has been signed.

[231] Due to a lack of other sources, calculated with the planned 5 GW of electrolyser capacity and 4000h-8000h runtime.
[232] Everyone (2021)
[233] FleishmanHillard (2022)
[234] Eni (2022)
[235] Prontera A. (2023)
[236] Financial Times (2023)

Italy's energy companies ENI and SNAM are cooperating with one another and leveraging their relationships with North-African countries in the oil and gas sector to establish hydrogen supply chains.[237] Both companies are involved in blue and green hydrogen projects, while the utility ENEL focuses on green hydrogen projects. Moreover, SNAM, the Italian gas TSO, signed an MoU with its Spanish counterpart to evaluate the construction of a subsea pipeline linking Spain with Italy which would initially transport natural gas but could be repurposed in the longer run to transport hydrogen as well.[238]

As of the present moment, the trajectory of Italy's role as either a significant hydrogen importer or exporter remains uncertain. This ambiguity stems from the absence of an official government strategy for hydrogen after the preliminary one established in 2020 and the National Recovery and Resilience Plan[239]. Nevertheless, considering Italy's favourable conditions such as a substantial proportion of renewable energy sources, well-established pipeline connections with both Europe and North Africa, along with the projected demands for hydrogen, one could infer that Italy is more likely to evolve into a hydrogen exporter, rather than an importer. Furthermore, there is potential for Italy to emerge as a pivotal hydrogen transit hub for Europe, capitalizing on these advantages. If there were indeed a need for imports, it is probable that, subject to the political situation, the main import partners would be based in North Africa, where Italy's energy firms have existing and long-established connections, rather than in Ukraine.

Other Demand Centres in Europe

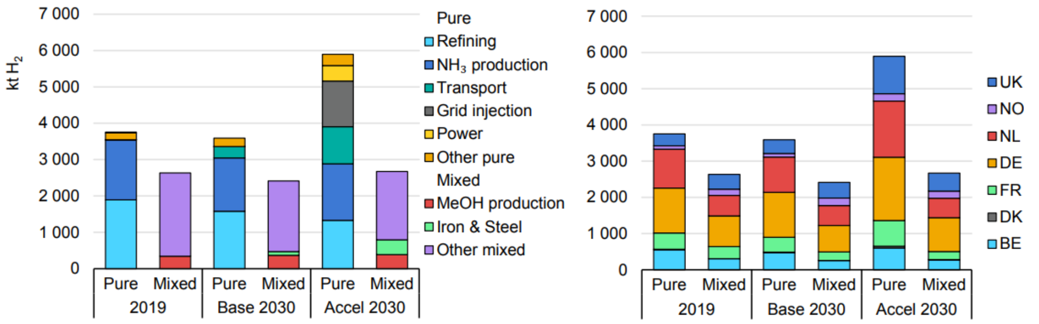
The demand for hydrogen and its derivatives is expected to be greatest in in the vicinity of ports mainly driven by industrial demand and further supplemented by hydrogen demand in the shipping sector from the 2030s onwards. By 2050, up to 42% of hydrogen demand in the EU could be located in such areas.[240] The likely most important hydrogen clusters emerging in the EU are in North-West of Europe[241], in the industrial area of northern Germany, Netherlands, Belgium and their important ports of Rostock, Hamburg, Rotterdam, and Antwerp as well as the inland port of Duisburg. Here lies an extensive and closely meshed industrial cluster, with closely linked electricity and pipeline networks, as well as ports and well-established logistics chains. The existing steel and chemical industry, as well as maritime transportation network, located in this region will provide ample demand for hydrogen. Currently, about 40% of the EU's chemical production is located here. Germany is still the largest

[237] ENI (2021)
[238] Reuters (2022)
[239] Italia Domani (2021)
[240] Clean Hydrogen Partnership (2023)
[241] International Energy Agency (2021)

consumer of hydrogen in the region and will likely continue to do so in the future. However, according to an IEA study[242] on the region, the combined pure hydrogen demand of the Netherlands and Belgium in 2030 could be higher than Germany's and reach an order of magnitude of about 2 million tons.

Figure 32: Projected Hydrogen Demand in North-Western Europe by 2030

Current and projected regional hydrogen demand by sector and country in the Baseline and Accelerated scenarios, 2030



Note: "Base" = Baseline scenario; "Accel" = Accelerated scenario.
NH_3 = ammonia; MeOH = methanol
BE = Belgium; DK = Denmark; FR = France; DE = Germany; NL = Netherlands; NO = Norway; UK = United Kingdom.

Source: IEA (2021)

The regions dense network of pipelines and ports facilitates import from nearby producers like the UK, Denmark and Norway as well as seaborne derivatives import from other global suppliers, including from Spain. According to a study by Clean Hydrogen Partnership (2023), it is expected that this cluster will rely on both blue and green hydrogen imports in an order of magnitude between 40% and 80% of its total hydrogen consumption in 2050.

Conclusion

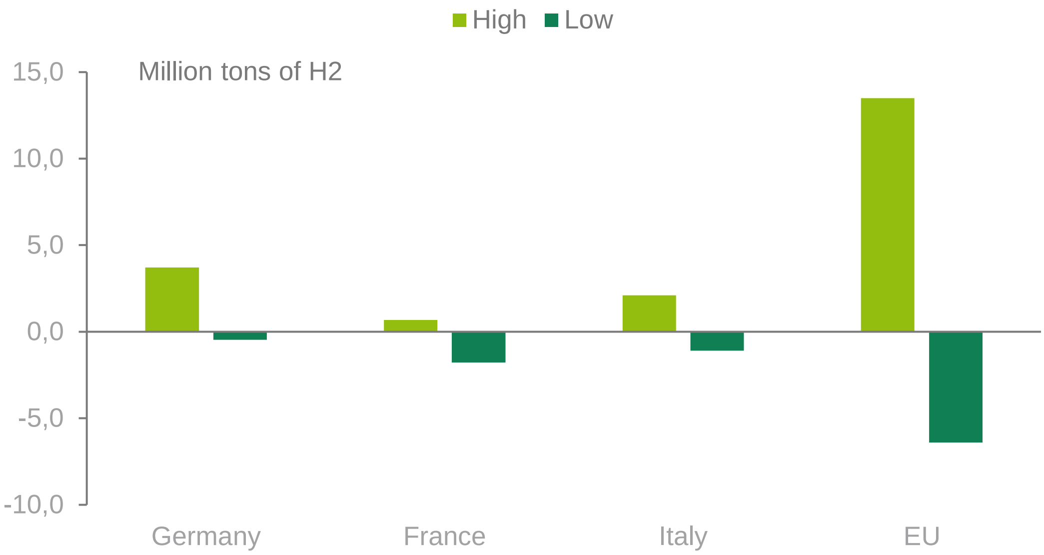
The EU overall, and in particular Germany, are likely to become significant importers of hydrogen – a factor that is reflected in their outward looking policy and engagement with third countries and prospective suppliers as well as in facilitating import mechanisms.

The case for imports to Italy and France is less clear cut. France actively opposes becoming a hydrogen importer and instead places large bets on its domestic nuclear - and to a lesser extent also renewable - capacity to fulfil demand. Only after long negotiations, France has agreed to a hydrogen pipeline from

242 IEA (2021)

Spain to France (H2 Med). The policy of Italy is less clear than Germany's or France's plans, reflected in the lack of a hydrogen strategy. Italy could both become an importer as well as exporter and transit hub for hydrogen leveraging its infrastructural links and business ties to North-Africa.

Figure 32: Hydrogen Import Potential by 2030



Sources: Bundesministerium für Wirtschaft und Klimaschutz (BMWK) (2023), European Commission (2022a), Guidehouse (2021b), Guidehouse (2022c), RVO (2021), Own calculations based on Ministero dello sviluppo economico (2020)

For the demand side countries under consideration, only Germany seems like a potential importer of Ukrainian hydrogen if exports were indeed to manifest. While the German stated priority till 2030 is on maritime imports, gaseous hydrogen pipeline imports will surely equally emerge as a priority, to which end it is already engaging in building a core network within Germany as well as new pipelines to prospective suppliers like Norway.

However, general uncertainty applies to both the EU as well as individual member countries demand. A change in industrial policy or economic structure like the relocation of energy intensive industries to countries with lower energy costs, would have large influence on overall hydrogen demand.

Conclusion

This study aimed to assess Ukraine's hydrogen exports competitiveness against key competitors - Spain, Morocco, the UK and Norway. Additionally, it aimed to provide insights into the import potential and infrastructure developments of numerous EU countries, namely Germany, France and Italy, as well as the EU as a whole.

By employing a multi-criteria approach to assess the potential of supplier countries, this study goes beyond simple evaluations of techno-economic production and transportation costs. It also considers crucial factors such as existing infrastructure, political and regulatory issues, environmental conditions, and attainable net export volumes.

The study concludes that despite its enormous potential for domestic green hydrogen use and exports, Ukraine faces significant obstacles in realizing this potential. As a result, it is unlikely to become a major hydrogen exporter by 2030. The continuing war and occupation of much of its renewables-rich territory, as well as a high interest rate environment and low investor confidence, coupled with uncertainty over the state of its gas grid, result in a very small project pipeline. Consequently, Ukraine falls behind many of its competitors, despite the potential for favourable production costs and potentially very low transportation costs.

In addition to these factors, there likely would be competition with potentially high domestic demand due to Ukraine's announced ambitions to develop green steel and fertiliser industries, as well as demand for materials needed for greener reconstruction. However, it is possible that in the long run, Ukraine may become a green hydrogen exporter. The primary export destination for such potential exports would likely be Germany, which will heavily rely on imports and aims to import via pipeline, particularly from the 2030s onwards. This could potentially align with the medium-to-long term export readiness of Ukrainian hydrogen. In sum, the prospects of utilising Ukrainian hydrogen potential for exports remains uncertain for the nearer future but could become possible in the medium to longer term.

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