Global Atlas of H_2 Potential

Sustainable locations in the world for the green hydrogen economy of tomorrow:
Technical, economic and social analyses of the development of a sustainable global hydrogen atlas.

Position paper

What do we know about importing green hydrogen and its derivatives and what can be derived from this for Germany's import strategy?

Authors:

Martin Wietschel (Fraunhofer ISI)

Bastian Weißenburger (Fraunhofer ISI)

Jakob Wachsmuth (Fraunhofer ISI)

Viktor Paul Müller (Fraunhofer ISI)

Fraunhofer ISI

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Project lead

Prof. Martin Wietschel
Fraunhofer Institute for Systems and Innovation Research ISI
Breslauer Str. 48, 76139 Karlsruhe, Germany
martin.wietschel@isi.fraunhofer.de

Project website

www.hypat.de/hypat-en/

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1 Introduction

In its revised National Hydrogen Strategy, the German government has set a target of establishing 10 gigawatts of electrolysis capacity in Germany by 2030 (Bundesregierung 2023). Based on assessments of current scenarios, the government estimates that around 50 % to 70 % (45 to 90 TWh) of the forecast demand of 95 to 130 TWh will be met by imports from other countries (in the form of hydrogen and hydrogen derivatives). What its strategy should look like in more detail is to be defined by the government in its Import Strategy for Hydrogen and Hydrogen Derivatives that is currently being developed.

A number of recent studies have dealt with the costs of production and transport as well as the export prices and international trade flows for hydrogen and/or its derivatives. The aim of this position paper is to compile the main findings of these studies and, based on this, to make recommendations for Germany's import strategy.

It must be pointed out that these studies essentially take a techno-economic perspective, but that an import strategy encompasses more far-reaching aspects as well. For instance, the German import strategy should also take sustainability criteria into account as defined by the 2030 Agenda (SDGs) and local value creation. In partner countries, development cooperation should target maximum synergies with the goals of the 2030 Agenda, in particular supporting local energy transitions in line with the socio-ecological transformation of society and the economy and the Sustainable Development Goals (see Bundesregierung 2023). These aspects are very relevant, but are not considered in the position paper, or only referred to in passing. In addition, the analyses refer to green hydrogen and its derivatives. Blue, turquoise and orange hydrogen, which could help to bridge gaps during market ramp-up according to the revised National Hydrogen Strategy (Bundesregierung 2023), are not considered.

Chapter 2 compiles the main findings of the studies. Chapter 3 draws conclusions for Germany's import strategy. Chapter 4, the final chapter, provides a summary.

2 Conclusions from techno-economic studies on importing green hydrogen and its derivatives

The main findings from current international studies on importing green hydrogen and its derivatives are outlined in the following. These are divided into three sub-chapters. The first deals with production, the second with local production in relation to imports, and the third with trade.

2.1 Production

The global potential for green hydrogen and its derivatives is sufficient to meet even ambitious demand developments

Based on the analysis of numerous international studies and ignoring outliers, Riemer et al. (2022) show that with ambitious climate targets, the global demand for hydrogen could amount to 4 % to 11 % of final energy demand by 2050. But even when considering maximum outliers, demand is not expected to exceed 23 %. Various studies demonstrate in their techno-economic analyses that the global renewable potential is sufficient to meet this projected global demand for hydrogen with green hydrogen (see Franzmann et al. 2023 and Shirizadeh et al. 2023). This is valid even when assuming much stricter underlying criteria and, for example, excluding regions subject to water stress or geopolitical instability (see Pfenning et al. 2021 and Forschungszentrum Jülich et al. 2023).

There is a large gap between today's supply and future demand

As the IEA illustrates in their latest review (IEA 2023b), there has been a recent sharp increase in the number of announced projects to produce low-emission hydrogen, although a final investment decision has only been made for 4 % of this potential production. The number of electrolyzer manufacturers who have announced ambitious expansion plans is also climbing rapidly. At present, however, only 0.7 GW of electrolysis capacity is installed worldwide (IEA 2023b).

Approx. 3500 GW of electrolysis capacity is required to cover 10 % of the final energy demand using hydrogen and its derivatives. In addition to this, approx. 4500 GW of renewable electricity generation capacity is required if demand is to be met using green hydrogen. At present, the total globally installed renewable electricity production amounts to 3100 GW (proportion of renewables in final energy consumption was 12.6 % worldwide in 2021). This implies that the installed renewable capacity would have to be increased by around 130 % just to meet the demand for green hydrogen and its derivatives, without including the use of renewables, e.g., to replace existing fossil-based plants. Direct Air Capture plants would also have to be constructed for carbonaceous hydrogen derivatives, which would also have to be operated on a renewables-only basis if the aim is to be greenhouse gas-neutral. These plants are not yet commercially available. And the corresponding synthesis plants would also have to be constructed.

Production costs are dominated by the costs for electricity generation, capital and electrolyzers

Low costs for electricity generation make up the largest share in the production costs for hydrogen and derivatives, followed by investments and operating costs for the electrolyzers as well as capital costs on the total investments (see Lux et. al. 2021, IRENA 2022, Brändle et al. 2021, Hank et al. 2023 and Frazmann et al. 2023, among others). An additional factor for hydrogen derivatives is the supply of CO_2 and, to a lower extent, the investments in the synthesis plants.

Sunny regions, combined where possible with good wind potential, offer the cheapest production costs from a techno-economic perspective

Under the right climatic conditions, it is often cheaper to produce electricity using photovoltaics (PV) than using wind and there is a high technical potential for such energy generation (see Franke et al. 2023). However, compared to wind turbines, the full-load hours of PV are often lower, which leads to lower utilization of the electrolyzers, thereby increasing their proportional costs or making electricity storage necessary. The seasonality of PV can also have an unfavorable impact on the economic situation.

Many studies see a trend toward using PV for hydrogen production (see, e.g., Brändle et al. 2021). In both the scenarios analyzed in IRENA (2022) as well, the biggest share of electricity for hydrogen production is from countries with good solar energy potentials. The lower capital expenditure (CAPEX) of PV installations make their use for electrolysis more attractive than onshore wind, despite the resulting lower capacity factors (utilization rates). However, it depends on the regional situation and the combination of both technologies can then also be economically attractive.

Franzmann et al. (2023) see the sunny countries in Africa and the Middle East as the main favorable locations for hydrogen production. According to their analyses, decentralized PV-based hydrogen production is always preferable, even in windy countries.

The PtX-Atlas of Fraunhofer IEE (Pfenning et al. 2021) lists ten countries with the biggest potential for producing hydrogen and its derivatives outside Europe: USA, Australia, Argentina, Russia, Egypt, Canada, Mexico, Libya, Chile and Saudi Arabia. A large proportion of this potential is located in regions able to produce power using both wind and solar energy, which makes high capacity utilization of electrolyzers possible. Australia and the US also offer considerable potential for pure solar energy. Pure wind locations in the USA, Canada and Russia represent another significant source according to this study (Pfenning et al. 2021).

Hank et al. (2023) examined a selected number of countries and of these, Brazil, Australia and Spain offer very good conditions for the production of hydrogen and derivatives. Countries from the MENA region or South America also show good potential. In Viehbahn et al. (2022), the potential for PV and CSP (concentrated solar power) in the MENA region is often seen as more cost-effective compared to wind power.

The calculations made in Verschuur et al. (2024) indicate that green ammonia will be produced near the equator in countries with high solar potential and ample land.

Countries with low capital costs will have cost advantages from a techno-economic perspective

Since the operating costs for renewable energies are at a comparable level and very low in many regions, low capital costs are correspondingly important for the cost-effectiveness of trade (see IRENA 2022, Hank et al. 2023, IRENA 2023 and Lux et al. 2021). Countries with access to low-cost financing due to government initiatives and national funds are in a better position to manage the complex challenges of green hydrogen projects. This type of financial support goes beyond the mere funds provided; it serves as a powerful catalyst for overcoming the uncertainties associated with pioneering technologies (IRENA 2023). Financially strong oil and gas countries with substantial sovereign funds have advantages here.

To mobilize private capital, the expected return taking into account existing risks is decisive, while the default risk is relevant if borrowed capital is provided. A company's weighted average cost of capital (WACC) is often used as a guiding principle here, but this varies widely from company to company. However, there are approaches to calculate an average WACC for countries (see Damodaran 2019). These indicate that the WACC vary widely and countries from Africa or South America often have high WACC. For example, Lux et al. (2021) show that the cost advantages of the MENA region based on better renewable potentials are offset by a high WACC compared to hydrogen production in the EU.

Both the level of WACC in absolute terms and the differences between countries have significant impacts on trade prospects and are a very important factor for the potential of a country to become an exporter. If the WACC remain roughly at today's levels, countries with low-cost renewable potential and low WACC will become the biggest exporters of green hydrogen and its derivatives (IRENA 2022). However, such countries also differ in other ways including factors such as water availability, political stability, availability of skilled workers, infrastructures and transportation distances to buyers, which also influence the competition between them.

Neglecting to include the costs of national and international transport infrastructure leads to a significant underestimation of the achievable import costs and establishing international transport capacities takes time

Based on a study comparison, Franzmann et al. (2023) show that this aspect can explain some of the cost differences in the studies. Hank et al. (2023) also emphasize that in the event of infrastructural bottlenecks, it is important not only to focus on power-to-X generation, but also to develop the downstream process chains that are required for imports. Ishimoto, Y. et al. (2020) also show the comparatively high cost share of transportation infrastructures in the delivery costs of liquid hydrogen and ammonia. In a meta-study, Genge et al. (2023) show that transport costs can range between 16 and 54 % of the import costs, depending on the derivative.

Import ports must have suitable unloading and local storage infrastructure for power-to-X products. If there is a pipeline connection for transporting hydrogen within a country, energy-efficient conversion plants must be taken into account such as regasification plants for liquid hydrogen or ammonia reformers. The development of shipping capacities over longer transport distances also has to be planned over a longer period and requires the corresponding investments. In principle, transporting hydrogen via pipelines is the cheapest option, especially if repurposed gas pipelines can be used (Agora Industrie and TU Hamburg 2023). Transporting hydrogen via pipelines is sometimes not possible for geographical reasons, such as ocean depth. If the distances involved are too great (approx. > 4000 km for newly constructed pipelines, approx. 8000 km for repurposed gas pipelines (see IRENA 2022)), transportation by ship becomes cheaper. Different options are being discussed here such as liquid hydrogen, liquid organic hydrogen carriers (LOHC), ammonia or methanol (Kreidelmeyer et al. 2023). In each case, the best respective transportation option depends on the final application as well as the availability of ships and infrastructure. While it is possible to transport ammonia, LOHC and liquid carbon-containing molecules using existing shipping technologies, there is currently only a prototype for liquid hydrogen. Large liquid hydrogen tankers are only likely to become available after 2030 (SCI4climate.NRW.2021). Verschuur, J. et al. (2024) also argue that developing shipping, e.g., for larger quantities of ammonia, will take time and there is little evidence of activities in this field so far. Compared to LNG, the energy density for transporting liquid hydrogen, ammonia and LOHC is lower so that the number of ships required per quantity of energy traded is significantly larger. The production capacity for ships could therefore be a limiting factor, especially up to 2030 and in particular because liquid tankers are more complex to produce than other ships, which makes it harder for new manufacturers to enter the market. At present, this market is dominated by shipyards in Korea, China and Japan (IEA 2023a) meaning that Germany and Europe are dependent on technology imports. In terms of costs, it can be assumed that transporting hydrogen by ship, regardless of whether in liquid form, ammonia or LOHC, will be well above today's costs of LNG (IEA 2023a, Verschuur et al. 2024).

2.2 Local production vs. imports

Only a small proportion of the demand for hydrogen and its derivatives will be traded internationally; most will be covered by domestic resources.

A number of studies conclude that the hydrogen and derivatives produced will be mainly used on national markets (see IRENA 2022, Shirizadeh et al. 2023 and Hydrogen Council, McKinsey & Company 2022). According to the scenario in IRENA (2022), three quarters will be produced and consumed domestically. This is a significant change compared to today's oil market, where the majority (approx. 74 %) is traded internationally: But it is similar to today's gas market, where only 33 % of the gas is traded across borders (see IRENA 2022).

According to Shirizadeh et al. (2023) as well, global trade will cover about one-fifth of total demand between 2030 and 2050. This study also points out the role of trade in minimizing costs. The trade in hydrogen is dominated by hydrogen-derived molecules (ammonia, methanol and e-kerosene), which are easier to transport over long distances than trading pure hydrogen. International trade with ammonia will be very important, especially in the next few years (see also Verschuur et al. 2024 on this issue).

The number of countries relying on imports is limited

Analyzing the various studies (Shirizadeh, B. et al. 2023, Hydrogen Council, McKinsey & Company 2022, IRENA 2022, iLF et al. 2023) shows that only a limited number of countries have a higher import demand from today's perspective. In the EU, these are essentially Germany, the Netherlands and Belgium, which do not have enough economical renewable potential to cover the expected high demand (result of the Long-Term Scenarios, see Sensfuß, F. et al. (2023)). Internationally, primarily Japan and South Korea continue to be seen as candidates with a high demand for imports in the future. High demand is expected in these countries, because they have strong steel and chemical sectors on the one hand, and ambitious greenhouse gas mitigation targets on the other.

Several studies also see the need for imports in China and perhaps the USA. Both are countries with comparatively low production costs for hydrogen and its derivatives as well as a high expected demand for them. Here, the results are quite sensitive to whether they will need imports or will be able to cover their own demand themselves and possibly even become exporters. For instance, the Hydrogen Council, McKinsey & Company (2022) assume that these countries will cover their own demand, with hydrogen and its derivatives transported over long distances within the countries. Other studies see at least China as more of an importer and North America even as an export region (see Shirizadeh et al. 2023 and iLF et al. 2023). According to Shirizadeh et al. (2023) and iLF et al. (2023), India will also take on the role of an importer, although other studies do not see this (see IRENA 2022).

The EU can cover most of its own demand for hydrogen cost-efficiently, but is dependent on imports for derivatives.

The Long-Term Scenarios system study (Sensfuß et al. 2023), which covers multiple aspects and dependencies, shows that the EU will largely be able to meet its own demand for hydrogen (excluding derivatives) and that this also makes sense economically. However, this assumes, among other things, the success of the necessary development of a hydrogen infrastructure and a joint strategy by the EU countries Only larger import volumes from Norway and smaller imports from the MENA region are economically viable according to the study. Within the EU, there is a high demand for trade, mainly with Germany, the Netherlands and Belgium. These results can be attributed to the fact that imports from the MENA region are less attractive when including country-specific risks via the capital costs and the higher transport costs involved also influence this. In addition, due to the optimization of the overall system, there are certain advantages to producing hydrogen in the EU. These include using low electricity generation costs in specific hours of the year, avoiding curtailment of renewable power and using hydrogen storages during cold dark doldrums.

Sprenger et al. (2023) also emphasize the attractiveness of supply within the EU by weighing up different criteria (including country-specific risks alongside costs). Other studies tend to see a larger need of the EU to import hydrogen (Shirizadeh, B. et al. 2023, IRENA 2022), predominantly met by the MENA region. The analyses in the Hydrogen Council, McKinsey & Company (2022) study conclude that the EU will import hydrogen from Norway in 2030. And in 2050, there will be additional imports from the MENA region as well as Eastern Europe.

There is a different picture for hydrogen derivatives. Here, the EU is reliant on imports from other world regions because it does not have the lowest-cost production potential and because transport costs play a smaller role for derivatives.

2.3 Trade

Hydrogen will be mainly traded using pipelines and comes from neighboring regions; derivatives, on the other hand, will be traded globally by ship

About 55 % of the internationally traded hydrogen in the 1.5°C scenario of IRENA (2022) up to 2050 would be transported by pipeline and the biggest part of this hydrogen network would be based on existing natural gas pipelines repurposed to transport pure hydrogen. This significantly decreases the transportation costs compared to other transport options. Brändle et al. (2021), Moritz et al. (2023), IRENA (2022) and Hydrogen Council, McKinsey & Company (2022) all consider it more advantageous to transport hydrogen by pipeline and conclude that ships will transport hydrogen derivatives rather than liquid hydrogen.

Importing hydrogen-based products can be more economical than importing pure hydrogen

In addition to the production and export of hydrogen and its derivatives, higher value products can also be produced and exported.

In the scenarios of IRENA (2022), almost three quarters of the hydrogen produced would be used to make globally traded methanol, steel, ammonia (as a fuel and feedstock) and synthetic aviation fuels. The biggest share of the ammonia trade would be for direct consumption and not for reconversion into hydrogen. Further processing hydrogen into synthetic fuels or using it to produce sponge iron would be even more attractive since both are cheaper to transport than hydrogen.

Moritz et al. (2023) also conclude that directly importing green ammonia to Germany by ship is still more cost efficient in 2030 than its domestic production using domestically produced or imported hydrogen.

From their analyses, Veerport et al. (2023) conclude that an economical and environmentally-friendly displacement could take place based on the cost advantages of renewable production for three key tradable energy-intensive industrial commodities (steel, urea and ethylene for different levels of displacement). Retaining today's production patterns by importing hydrogen is much more costly, whereas importing intermediate products could be almost as cost-effective. At the same time, a large part of the value creation remains in the importing regions.

However, the study situation here is still in its infancy and more in-depth analyses are required in this complex field.

Several relatively stable trading routes could emerge

Shirizadeh, B. et al. (2023) identify the most important trade routes as those linking North Africa with Europe, the Middle East with India, Australia with China and North America with Japan and Korea. Comparable results are found in the Hydrogen Council, McKinsey & Company (2022) and IRENA (2022).

There are various reasons for the high uncertainties associated with the cost and potential estimates

Genge et al. (2023) evaluated various studies on supply cost differences for green chemical energy carriers at the European border. They found substantial differences, with a four-fold difference identified for all energy carriers in 2030 and a five-fold difference in 2050. The key factors behind the cost differences were the different production costs that depend on the average weighted costs of capital and the capital expenditure on renewable energy sources, electrolyzers and energy carrier-specific conversion processes. Transportation costs also contribute to the differences, which are mainly influenced by the choice of energy carrier and the weighted average costs of capital.

The different studies assume significantly different values here, especially with regard to future development, which is associated with high uncertainties because the majority of the plants still have development potential (see Franzmann et al. 2023, who elaborate the differences in this respect in different studies). Cost degressions are also subject to uncertainty due to economies of scale effects (see IEA 2020). The selection of the underlying technology is also relevant for the result, e.g., PEM electrolyzers and/or high-temperature electrolyzers.

Several studies do not take all the cost components into account, e.g., the costs for transportation or for storage at ports (which can be very high according to IEA (2023a) and Ishimoto, Y. et al. (2020)). Franzmann et al. (2023) point out that considering the entire process chain in high spatial and temporal resolution strongly influences the resulting hydrogen costs, but that this is often not done, which is why there is a tendency for these kinds of study to have lower costs.

The system boundaries represent another difference in the cost analyses. If, for example, the studies do not consider any feedback to the entire energy system, all the low-cost renewable potentials are used exclusively to produce hydrogen. However, according to Dickel (2020), decarbonizing the electricity sector should be given priority over hydrogen production, as using electricity directly results in lower efficiency losses. This means there is the possibility in the medium term that some regions will not have sufficient surplus renewable power generation capacities to serve the hydrogen market. If the domestic demand for hydrogen and derivatives in the hydrogen-producing countries is not taken into account, this leads to overestimating their low-priced export potential.

Furthermore, regulations, for example for renewables or subsidies for producing and transporting hydrogen and its derivatives have an influence on costs. This aspect is generally not considered in the evaluated studies.

3 Findings and recommendations for Germany's import strategy

This chapter derives insights and recommendations for Germany's import strategy from evaluating the studies in chapter two and supplements these by analyzing other studies on the German import strategy or on general import strategies for hydrogen and its derivatives. This chapter is divided into three parts. The first part deals with aspects that concern hydrogen as well as hydrogen derivatives. The second part discusses the findings and recommendations for hydrogen imports and the third part does the same for importing hydrogen derivatives.

3.1 General findings and recommendations for action

The prices for hydrogen and its derivatives tend to be underestimated - therefore there should be a focus on specific applications

There is currently a great deal of uncertainty concerning the development of hydrogen prices. Many studies work with production costs that do not or only insufficiently reflect future market prices. Due to the market situation - currently only a limited supply and the expectation of rising demand even if this is only just becoming apparent - green hydrogen and derivatives are likely to be in short supply and expensive in the short to medium term. This is the assessment of a number of studies (see, e.g., SRU 2021, Odenweller et al. 2022, Ansari et al. 2023, Wietschel et al. 2023).

Current obstacles are listed in the IEA study (2023b): The interests and policies of potential hydrogen-exporting countries are not always geared toward exports and potential investments are hindered by the lack of planning certainty. The costs of equipment and financing are rising and banks are becoming more skeptical. Clear commitments to creating production capacities on the one hand and guaranteed off-take pledges from users on the other are few and far between. Regulations vary internationally which is slowing down cross-border projects. Various geopolitical crises create new uncertainties.

In addition, the build-up of production capacities and transport infrastructure takes time. The production of hydrogen and hydrogen derivatives calls for large investments and comparatively high energy losses occur across the entire production, transportation and use chain meaning that hydrogen and its derivatives will tend to be more expensive than other energy sources.

An import strategy should therefore set clear priorities on areas in which hydrogen and its derivatives are essential to achieve climate targets: steel and basic chemicals, international aviation and shipping, refineries and residual power generation. If other sectors such as building heating or road transport are included on a much larger scale, this may lead to misallocations and could make the prices for other sectors rocket unnecessarily. This strategy would not make sense from the viewpoint of a national economy.

An import strategy should also attempt to obtain price signals from the market as early as possible and interpret these. The ongoing auctions from H2Global or similar support schemes in other countries could be used for this. However, detailed analyses are required here because existing regulatory instruments, such as the obligation to reduce greenhouse gas emissions with the simultaneously high costs of alternatives might mean there are incentives in certain applications to get by with low subsidies for hydrogen. Or suppliers could first enter the market with lower prices for strategic reasons in order to gain market shares.

Potential export countries sometimes pursue other objectives that could conflict with those of Germany

In this context, it should also be mentioned that the interests and policies of potential export countries are not always export-oriented. Many are pursuing a policy of first supplying the domestic market with hydrogen and its derivatives, such as the USA (see Ansari et al. 2023) or are giving priority to decarbonizing the electricity sector over producing hydrogen, since the direct use of electricity directly has lower efficiency losses. In addition, securing the supply of electricity for national industries and the population might stand in the way of an export strategy. Germany's import strategy should clearly demonstrate the benefits of exports for these countries and, at the same time, should support the exporting countries in achieving their supply and climate protection goals.

The anticipated relocation of larger shares of value creation to export countries puts Germany under pressure, but offers opportunities as well

Countries such as the United States or Canada that have large and low-cost resources to produce green hydrogen as well as having substantial market shares in today's industrial hydrogen applications, could become market leaders by integrating segments of the value chain for green hydrogen into production and industrial applications (see Eicke et al. 2022). This is a threat to Germany's economic position.

The relevant economic sectors for Germany are the iron and steel and basic chemicals industries. However, analyses have shown that importing hydrogen-based products such as ammonia or steel or intermediate products such as sponge iron may well be more cost-effective than importing hydrogen. Hydrogen-exporting countries are backing such a strategy, which is understandable due to the higher value added that remains with them. Oil-rich countries in the Middle East are already pursuing this strategy, at least to some extent (see Ansari et al. 2023). This is a threat to Germany's competitive position for these products and there is the risk of production relocation. One opportunity may be to accept a certain degree of relocation and develop new business models by cleverly reconfiguring value chains (see Klessmann 2022). This could be a successful strategy for tackling the frontrunners in hydrogen.

An import strategy should be aware of these conflicting goals, but of the new opportunities as well. One strategy element could be to enter into energy partnerships with countries that are less likely to be able to produce such products themselves in the near future due to their technological capabilities or financial strength. However, this raises issues of how to design a fair partnership as called for in the National Hydrogen Strategy (Bundesregierung 2023).

There are conflicting goals in an import strategy that have to be identified and resolved by a political process weighing up the pros and cons

As has been shown above and as illustrated for additional aspects below, there are a number of different objectives in an import strategy (see Wietschel et al. 2022, Piria et al. 2022 and Ansari et al. 2023 on conflicting goals). It should be recognized that this inevitably leads to conflicting and contradictory goals and involves various risks. A systematic and honest assessment can, however, provide a valuable foundation for the political weighing-up process.

Sellers will have significant market power in the short and medium term

As the statements above have indicated, the market for hydrogen and its derivatives will be a seller's market at least in the short and medium term. This means that exporters' preferences will inevitably become more important. This can mean that European players will not only have to make compromises on regulation, but also - and even more importantly - they should also be prepared to work out business models with exporters that represent a fair spread of the risks involved (see Ansari et al. 2023). Secondly, a seller's market means that countries that drag out negotiations and make exporters wait are playing with fire – the initial suppliers, i.e., the first movers, may well lose interest and/or consider other importers.

When developing an import strategy, a clear distinction should be made between hydrogen and hydrogen derivatives and the specifics of each should be taken into account

As the following sections show, there are clear differences between hydrogen and its derivatives, such as the regional market for hydrogen vs. a global market for derivatives, the relevance of the EU for hydrogen and of other international actors for derivatives, as well as different import countries and different fields of application. These special characteristics should be taken into account in the import strategy. Merten et al. (2023) and Klessmann et al. (2022) also call for a clear separation between hydrogen and its derivatives in an import strategy.

3.2 Import strategy for pure hydrogen

Prompt action to create the conditions needed to develop regional markets for hydrogen

In all likelihood, regional markets will emerge for pure hydrogen, similar to today's gas markets (cp. Van der Graf et al. 2020 and Dejonghe et al. 2023). These will be dominated by pipeline transport, which is why an import strategy should focus on the construction of the pipeline network needed, which is time and capital-intensive and will take several years (see IEA 2023a). The necessary pre-financing and financial security for investors play an important role here. Appropriate regulations must be created for this. Reliable estimates of the required quantities of hydrogen are needed to avoid government-backed misinvestment in oversized infrastructure on the one hand, and obstacles due to a lack of infrastructure on the other. The robustness of the required quantities of hydrogen listed in Germany's National Hydrogen Strategy should be examined - also given that the international market ramp-up is currently only progressing very slowly, as outlined above. An import strategy should also include safeguarding the pipelines against technical failures or terrorist attacks.

A hydrogen import strategy should learn from the experiences of trading European natural gas

Because of the physical analogies, the import strategy for hydrogen should learn from the natural gas trade in Europe and the experiences gained, especially from the Russian war of aggression against Ukraine and the resulting consequences for the gas markets (see Dejonghe 2023). The hydrogen market has considerable potential to be less uniform and concentrated than the markets for natural gas, which will reduce the risk of supply disruptions if the political framework is set accordingly. The precise impacts of hydrogen imports on energy security depend on the decisions made now, which are likely to create lasting path dependencies. Therefore, political decision-makers should not automatically favor the most cost-effective import pathway, but should also pay heed to the following aspects:

- Efficiency-related **demand reduction** (the recent gas crisis in Germany and the EU demonstrated the large potential here, but it is often very difficult to exploit at short notice because of path dependencies), and a focus on the essential applications for hydrogen use.

- **Diversification** via different suppliers, routes and transport options (e.g., in addition to pipelines, enable transport by ship to a certain extent, even if this is usually more expensive) as well as producing certain quantities of hydrogen domestically.
- **Resilience** to shocks by storing hydrogen (large quantities of hydrogen can be stored geologically and Germany has the relevant potential for this in salt caverns, although there is competition for their use with natural gas and therefore a storage strategy is required) and enhanced emergency response planning.
- **Market differentiation** due to different production routes (hydrogen colors) and different sustainability requirements can result in smaller markets and therefore higher prices, strong price volatility and dependencies and should be avoided from the viewpoint of economic efficiency as well as investment and supply security.
- **Long-term supply contracts** to safeguard supply, possibly featuring flexibility with regard to purchase quantities.

Germany should concentrate on the EU and its neighboring countries when importing hydrogen

One objective of the National Hydrogen Strategy for a German import strategy is to develop widely diverse import channels and avoid new dependencies (Bundesregierung 2023). This is more challenging for hydrogen imports as the regions worth considering as suppliers will be determined by pipeline distance. EU countries with good renewable potential like Spain and EU neighboring countries like Norway are particularly suitable when considering low-cost generation potentials that also take into account renewable potentials, financing costs (country risks) and geopolitical stability. This means relevant value added shares and jobs can be created in Europe. These partners are also likely to be more reliable than many other international partners and it would make the EU stronger. Therefore, the German import strategy for hydrogen should feature a strong focus on these countries. However, at present there is considerable disparity between the EU countries with large low-cost renewable potential (Norway, Spain, France, Sweden) and those most actively investing in the development of the hydrogen sector (Germany, the Netherlands, Belgium). As a result the EU is not fully exploiting its potential to achieve its ambitious targets for renewable hydrogen. In addition to negotiating bilateral agreements with individual EU countries and EU neighboring states, Germany's import strategy should also use its influence in the EU Commission. The EU Commission has an important role to play in designing a European hydrogen strategy, which is why Germany's import strategy should be closely coordinated with the EU Commission.

An analysis of the EU's hydrogen policy and governance reveals that its approach to promoting its hydrogen sector suffers from a high degree of complexity (see Quitzow et al. 2023). This makes the EU less attractive as a location for investment in hydrogen-related technologies and infrastructures. There is the need for action here (see Quitzow et al. 2023).

Special measures are needed to integrate the MENA countries in a hydrogen import strategy

It is challenging to integrate the MENA countries into a hydrogen import strategy. There are specific obstacles here, which were also responsible for the failure of the DESERTEC project many years ago. DESERTEC is an initiative pursuing the goal of generating green electricity at energy-rich locations such as the MENA region and, in addition to covering domestic demand, exporting it via high-voltage direct current cables by expanding transnational power grids. The goal of covering a substantial share of Europe's electricity supply has since been abandoned. Several studies analyzed the failure of the project (see Looney et al 2018, Schmitt 2018, Stegen et al. 2012). The identified problems with regard to political instability in the MENA region can be divided into:

- planning uncertainty due to political events (civil war etc.),
- fear of terrorist attacks (power lines, plants),
- breach of contract due to political changes (power shifts in MENA countries) and
- problematic communication with MENA countries due to political uncertainties.

However, other viewpoints such as geopolitical interests or the diversification of supply countries could lead to the inclusion of the MENA region as well. Sprenger et al. (2023) highlight different aspects of importing hydrogen from the MENA region and compare this to supply from EU countries. They conclude that countries from the MENA region are often in a good position purely in terms of costs, but that there are risks for investments and the security of supply as well as social factors. EU countries or other countries bordering the EU are often rated better. The same applies to the industrial know-how required for the production of hydrogen-relevant technology components. Müller et al. (2023) show that the fossil fuel exporters in the region, in particular, have hardly any industry so far that could be used to establish local production. Many European countries are in a much better position here. The same thing can be said about other oil- and gas-rich regions of the world, which offsets the advantages these countries have in terms of low capital costs (see explanations above).

The MENA region offers very good renewable potential, but if Germany wants to consider this more closely, issues of securing project financing and risk assumption should be clarified in an import strategy (see Klessmann et al. 2022 and Viebahn et al. 2022, who handle these issues in depth). There are demands here on the EU as well as on a German import strategy. An import strategy should have clear criteria as to which goals it pursues and how it deals with conflicting objectives.

Broader diversification of hydrogen imports comes at a price

If hydrogen is to be imported via ships (directly as liquid hydrogen or in bonded form), this results in much higher import costs, which can be 20 % to 40 % higher than those of gaseous hydrogen. These higher costs must be weighed up against risk hedging through broader diversification. It should be borne in mind that increasing resilience comes at a price.

3.3 Import strategy for hydrogen derivatives

The conditions needed to develop international markets for hydrogen derivatives should be created

There is a different situation for hydrogen-based derivatives compared to importing hydrogen directly. Due to the lower transportation costs and some already existing infrastructures, there is a tendency to assume that global markets will emerge, comparable to today's oil markets. These markets could be established relatively quickly. Coordination with globally active players is needed here. In addition, the production and transport capacities needed (ships, ports and overland transport) must be developed in good time.

Internationally, Germany should consider Japan and South Korea in particular as competitors, but also as potential cooperation partners in its import strategy

Germany is heavily dependent on other countries and their actions when importing derivatives. Within the EU it is one of the few countries to import both hydrogen and its derivatives in the future. From a global perspective, however, only a few countries will be reliant on imports. This makes the German economy vulnerable. An import strategy for derivatives should therefore also be directed toward considering other countries that are likely to have a high need for imports, especially South Korea and Japan. These countries are main competitors for imports on the one hand and special attention must be paid to their actions on international markets. For example, Japan and Korea have already developed market-activating quota regulations and are therefore attractive to exporting countries (see Kessmann et al. 2022). On the other hand, cooperating with these countries could make it possible to develop a certain amount of buying power vis-à-vis supplying countries. For instance, a joint approach to certifying green hydrogen could favor the development of an international market or intensify the competitive situation for green hydrogen if there are varying requirements.

Within the EU, Germany should seek to join forces with the other importing countries (Netherlands and Belgium) and work out a common position.

The EU should form a hydrogen alliance for market power reasons

Following on from the previous statements and in view of the fact that the EU in particular is dependent on imports of hydrogen derivatives: The creation of a multilateral agreement between the EU's hydrogen importers and major exporters (a "Hydrogen Alliance") is geopolitically, economically and technologically advantageous as it would reduce market power imbalances and bilateral dependencies (see Ansari et al. 2023). The alliance would not only be a catalyst for relations between importers and exporters, but also for European importers themselves, who need to be more assertive and coordinated. A rough concept is outlined in Ansari et al. (2023).

The EU and Germany cannot assume preferential treatment when importing hydrogen as the global demand is increasing and supply shortages are imminent. The transition to a seller's market requires both regulatory compromises and the willingness to negotiate a fair distribution of risk with exporters (Ansari et al. 2023).

The specific characteristics of the respective hydrogen derivatives (e-kerosene, ammonia, methanol, Fischer-Tropsch crude) should be taken into account in an import strategy

Different hydrogen derivatives have different fields of application and it is not possible to convert one into another, or only with high conversion losses. This is why an import strategy for derivatives should consider each separately.

E-kerosene is only needed for aviation. However, according to the current state of technology development, there is no clearly visible alternative fuel for this except for sustainable biomass, which has very limited potential. This is why an import strategy for derivatives must explicitly take into account the quantities required to achieve the quotas of the Renewable Energy Directive and the climate targets in aviation. In terms of infrastructure, no significant adjustments are needed compared to the current situation. Today's transportation capacities by ship and pipeline for crude oil and oil-based products could be available for alternative energy carriers in the future.

Methanol can be used as a fuel for different modes of transport and as a raw material in the chemical industry -as is already the case on a small scale - in several different ways, and in the future especially in the methanol-to-olefins route. It is conceivable that methanol could also be used as a raw material to produce higher-value fuels such as e-kerosene. The precise quantities needed here are not yet foreseeable since alternative climate protection options are also being considered. So far, there is only limited infrastructure and ships available for methanol. These should be dynamically adapted to the market ramp-up in good time.

Ammonia is primarily used to produce fertilizers at present and additional smaller amounts are used in a variety of other applications. Ammonia can be directly used in shipping. In addition to this, direct combustion is also being considered, for example, in power stations to generate electricity. This might have extensive infrastructural consequences, because large-scale use would require additional ships and terminals on the one hand as well as completely new infrastructure on the other hand to transport it domestically. This is why it is particularly important that a strategy considers how much ammonia will be used in the future. Fischer-Tropsch crude is very similar to fossil crude oil and therefore has the advantage that infrastructures can continue to be used, both for transporting and producing fuels and platform chemicals in refineries.

4 Summary

Germany will have to cover a substantial proportion of the expected demand for hydrogen and hydrogen derivatives through imports. This is why the German government is currently developing an import strategy. This paper deals with what is known from previous studies on importing green hydrogen and its derivatives and what insights can be derived from them for designing an import strategy. However, an import strategy also includes more far-reaching aspects such as the consideration of sustainability criteria and local value creation in the exporting countries, which are not discussed here.

In the long term, there is enough potential from a global perspective to produce green hydrogen and its derivatives, which is able to meet the high projected demand worldwide, even under highly restrictive assumptions such as excluding regions with water stress or geopolitical instability. At present, however, there are a number of obstacles to a market ramp-up meaning that this is currently only progressing very slowly. Furthermore, the majority of global production will be used on domestic markets and it is estimated that only around one-third will be traded internationally. The trade with hydrogen derivatives is likely to be larger than that with pure hydrogen.

The trade with pure hydrogen will mainly be organized on large scale regional markets for which pipeline transport will be the predominant option because of its cost advantages and ship imports tend to have a more risk hedging function. On the other hand, an international market will emerge for hydrogen derivatives in which shipping will play a vital role. It is conceivable that global markets will evolve, especially for green ammonia and green methanol.

However, considerable time constants are expected for the build-up of production and transport infrastructures so that larger volumes of imports are only expected after 2030. Especially good conditions for exports exist in sunny and windy regions that also have low capital costs. Other factors such as water availability, geopolitical stability and existing infrastructures also influence the attractiveness of countries for the production and export of hydrogen or its derivatives. One important and often underestimated condition is the existence of industrial expertise for the comparatively complex production chain.

Only a few countries are expected to have a high demand for imports. Alongside Japan and South Korea, Germany is likely to be one of the countries with the biggest demand for imports worldwide.

The most important findings that should be taken into account when developing an import strategy are summarized below.

General

- The prices for hydrogen and its derivatives tend to be underestimated. Therefore there should be a focus on specific applications.
- Potential export countries sometimes pursue other objectives that could conflict with those of Germany.
- The anticipated relocation of larger shares of value creation to export countries puts Germany under pressure, but offers opportunities as well.
- There are conflicting goals in an import strategy that have to be identified and resolved by a political process weighing up the pros and cons.
- Sellers will have significant market power in the short and medium term.
- When developing an import strategy, a clear distinction should be made between hydrogen and hydrogen derivatives and the specifics of each should be taken into account.

Import strategy for pure hydrogen

- Prompt action to create the conditions needed to develop regional markets for hydrogen.
- A hydrogen import strategy should learn from the experiences of trading natural gas in Europe.
- Germany should concentrate on the EU and countries bordering the EU when importing hydrogen.
- Special measures are needed to incorporate the MENA countries into a hydrogen import strategy.
- Broader diversification of hydrogen imports comes at a price.

Import strategy for hydrogen derivatives

- The conditions needed to develop international markets for hydrogen derivatives should be created.
- Internationally, Germany should consider Japan and South Korea in particular as competitors, but also as potential cooperation partners in its import strategy.
- The EU should form a hydrogen alliance for market power reasons.
- The specifics of the respective hydrogen derivatives (e-kerosene, ammonia, methanol, Fischer-Tropsch crude) should be taken into account in an import strategy.

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