


HYPAT H₂ Potential

Global H₂potential atlas

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

HYPAT final report

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1 Introduction

Hydrogen and its synthesis products are considered globally to be important future energy sources that can be used in many areas. In the revision of the National Hydrogen Strategy (NWS) (Federal Government 2023) and the published import strategy (Federal Government 2024), the Federal Government is aiming to build 10 gigawatts of electrolysis capacity in Germany by 2030. According to the Federal Government's assessment, based on an evaluation of the current scenarios, a potential demand for hydrogen and derivatives of 95 to 130 TWh is expected for 2030. Of this, around 50 to 70% (45 to 90 TWh) will be covered by imports from abroad. By 2045, the Federal Government sees demand increasing to 360-500 TWh for hydrogen and 200 TWh for hydrogen derivatives (BMWK 2024).

The need to meet the demand for green hydrogen and its derivatives from countries with favorable climatic and geographical conditions is mainly addressed in studies from a technical-economic perspective (see, e.g., IRENA (2022), Franzmann et al. 2023, Shirizadeh et al. 2023, Pfenning et al. 2021 and Forschungszentrum Jülich et al. 2023). In contrast, HYPAT takes a much more comprehensive approach.

In accordance with the objectives of the NWS, including its update, the international agreements on climate protection and the Sustainable Development Goals (SDG), and taking into account the current EU hydrogen strategy, this study develops a comprehensive global hydrogen atlas (including derivatives). The focus of the analyses is on green hydrogen and its derivatives, as other production pathways are seen as bridging technologies. The study looks at the global situation with potential suppliers (exporters) and buyers (importers) and then at the specific situation of the EU, and in particular for Germany.

This study is the first to identify and in-depth analyze possible partner countries for Germany in a future hydrogen economy based on a new methodological approach and an analysis grid. To this end, detailed global techno-economic potentials are collected using models and hydrogen value chains, including transport, are examined. The analyses carried out include the needs of the partner countries. The latter include the sustainable coverage of their own energy demand, the achievement of their own climate goals using the economic development opportunities of a hydrogen economy, and compliance with specific sustainability criteria for the hydrogen economy in the partner countries. Furthermore, the countries' abilities to build such capital and technology-intensive plants are analyzed (e.g. access to capital and geopolitical stability). The opportunities arising for these countries are also identified (e.g. impacts on local value creation, capacity building opportunities), and acceptance and stakeholder analyses are carried out. In a further analysis step, the resulting supply of hydrogen and synthesis products is then compared with the global demand of the importing countries, thus drawing an overall picture for the first time that takes economic, technical, social and ecological aspects into account equally. The analyses provide policy recommendations regarding the development of a sustainable import strategy for Germany.

In the first step, a criteria grid was developed to evaluate possible production countries and to make a pre-selection of relevant production countries.

extensive modeling work was carried out, both globally for all relevant countries and specifically for selected individual countries. For the latter, the entire energy system in particular was mapped in great detail in order to be able to map the corresponding repercussions of an export of green hydrogen and its derivatives. Furthermore, global demand and global supply were modeled in order to be able to show the most holistic picture possible. In addition, extensive discussions were carried out with national and international stakeholders as part of potential and acceptance studies in order to capture different perspectives on the topic. Policy measures were also collected and analyzed and conclusions for policy were drawn.

This report presents a synthesis of the approach as well as the most important findings and conclusions. A detailed documentation of methods, data sources and further results can be found on the HYPAT website. There is also an appendix at the end of this report with an overview of previous publications.

The report is structured as follows. Chapter 2 presents the key results from the perspective of the importing countries. Global demand and global supply for hydrogen and its derivatives are shown. The countries that will have a need for imports in the future are identified. It analyzes which aspects are important when identifying potential partner countries for imports and which countries are suitable as possible partners. Questions as to whether hydrogen or derivatives and, if so, which derivatives should be imported are answered. The choice of transport mode (ship or pipeline) and social acceptance are also taken into account. Finally, it shows which obstacles currently still exist for a successful market ramp-up for a hydrogen economy.

Chapter 3 takes the perspective of potential export countries. The positive aspects as well as possible negative consequences of exporting hydrogen and its derivatives are discussed and the most important influencing factors are highlighted. The following topics are dealt with in depth: sustainability, the necessary industrial requirements, the interactions with national energy policies and possible conflict potential in projects.

Chapter 4 then deals with conclusions for German policy. Topics of cooperation with other countries and further measures to further develop an import strategy are discussed.

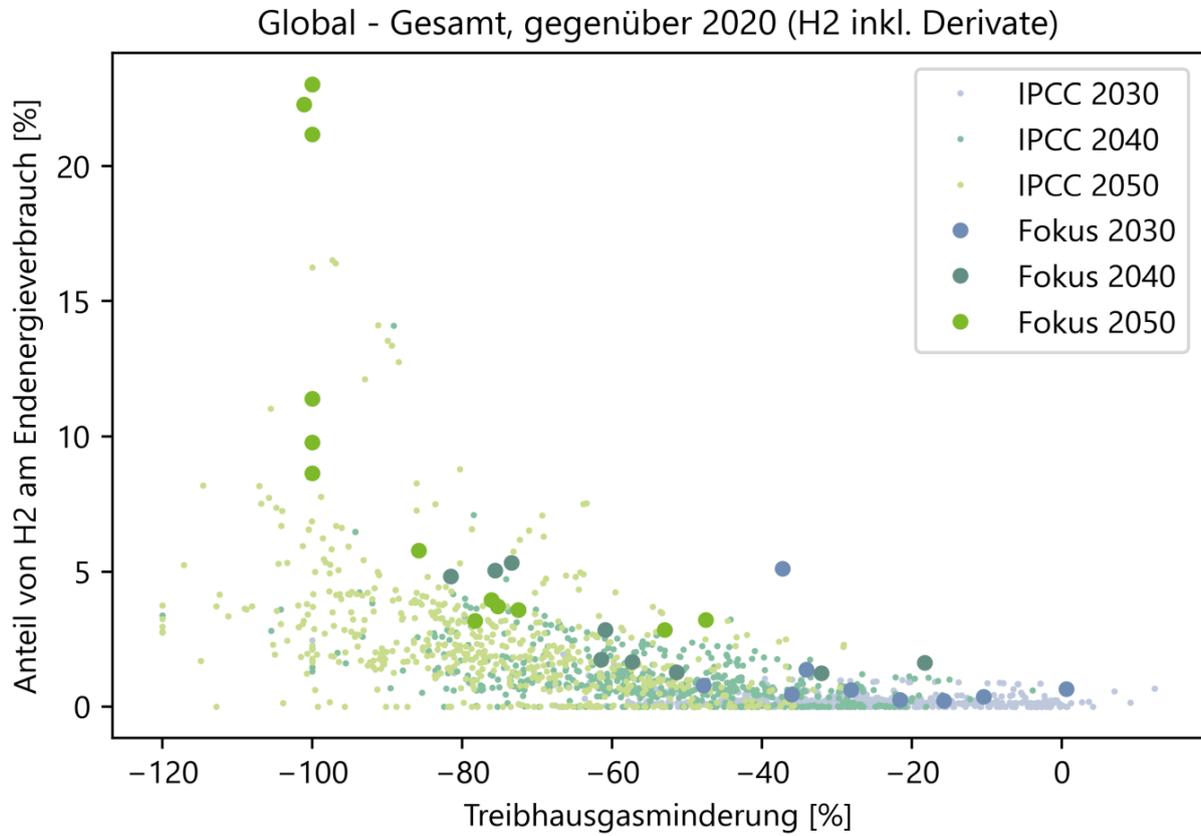
The last chapter summarizes the main project results and draws conclusions. The appendix contains an overview of all HYPAT publications to date.

2 Results from the perspective of importing countries

2.1 The global demand for green hydrogen and its derivatives is expected to grow particularly in the case of ambitious greenhouse gas reduction targets increase significantly

Hydrogen and its synthesis products are considered globally to be important future energy sources that could be used in many areas. However, there is still a high degree of uncertainty regarding the future global role of hydrogen, as different studies have reached very different conclusions. The meta-analysis carried out in the HYPAT project therefore examined how global hydrogen demand might develop in the future. More than 40 current energy system and hydrogen scenarios were re-evaluated, with a particular focus on scenarios with ambitious reduction targets for greenhouse gas emissions. The following figure shows the share of hydrogen in final energy use depending on greenhouse gas reduction for various scenarios in studies, which are referred to as "focus scenarios". In addition, the hydrogen demand projections were compared with the range of demand from over 300 reduction scenarios in the 6th Assessment Report of the Intergovernmental Panel on Climate Change (IPCC). These are referred to as "IPCC scenarios". The majority of studies predict a significant increase in global hydrogen demand, which is expected to be particularly strong when regions or countries have ambitious greenhouse gas reduction targets. Once a threshold of 80% GHG reduction compared to 1990 is reached, the use of hydrogen is often seen as the only alternative (see Figure 1 and Figure 2).

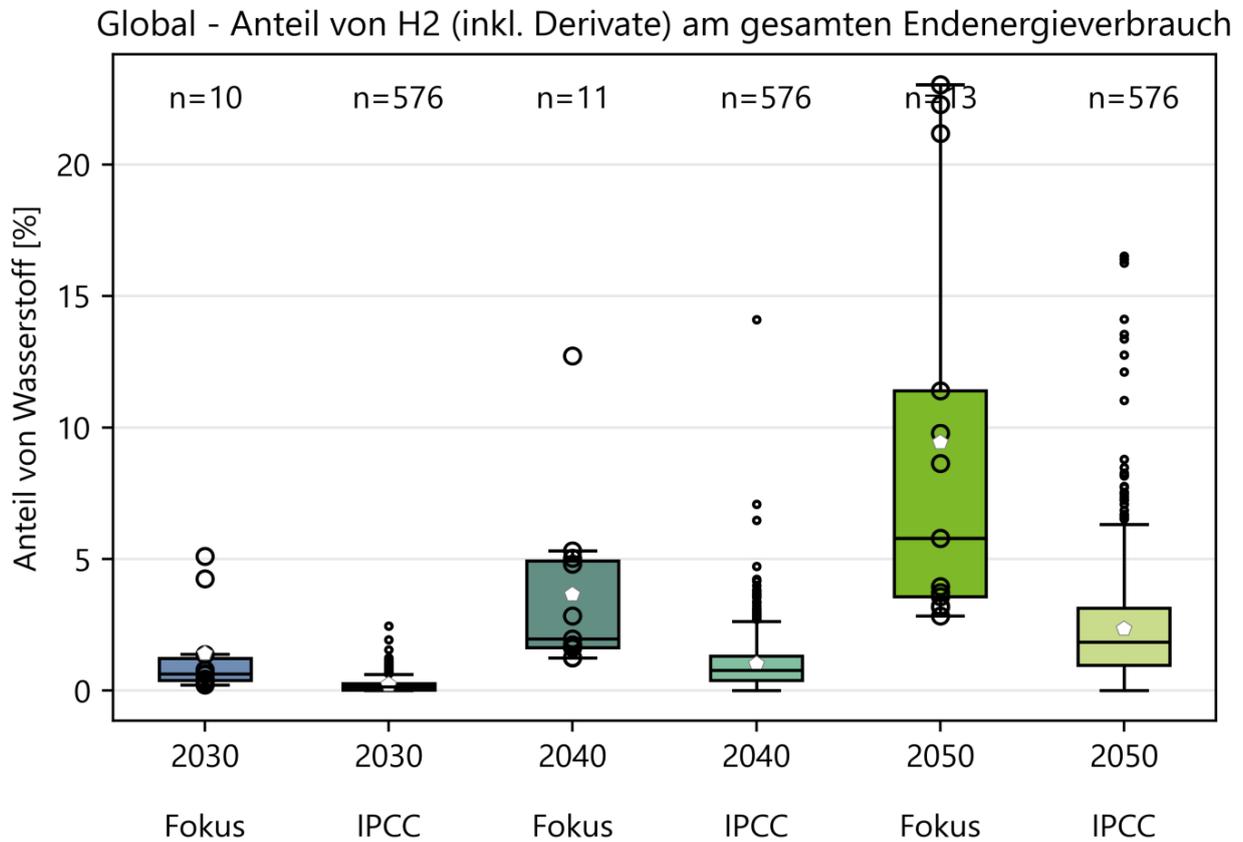
Figure 1: Global share of hydrogen including derivatives in worldwide scenarios depending on the greenhouse gas reduction rate



Source: Riemer et al. (2022)

Global hydrogen demand therefore also depends heavily on the respective regional climate policy and how ambitious it is. The range of total hydrogen demand in 2050 is between 4 and 11% of global final energy demand (see Figure 2).

Figure 2: Global share of hydrogen including derivatives in total final energy consumption in worldwide scenarios with ambitious greenhouse gas reduction targets



Source: Riemer et al. (2022)

However, there are large regional differences: For the EU, the hydrogen share could be as high as 14%, whereas for China the majority of scenarios only show a maximum share of 4% of final energy. The wide range of expectations regarding future hydrogen demand implies a high degree of uncertainty in the development of hydrogen markets, which hinders investments in the production, transport and use of hydrogen. On the one hand, hydrogen demand is estimated inconsistently in the various studies and comparatively more optimistically in hydrogen-specific studies. On the other hand, hydrogen partly competes with direct electrification and biomass, and the demand is highly regionally dependent (including on national ambitions for greenhouse gas neutrality and on existing infrastructure). The forecast uncertainty increases over time, so that hydrogen demand in 2050 has the greatest range, with the exception of the building sector.

The results are presented in detail in Riemer et al. (2022).

2.2 The global supply potential of renewable electricity generation is sufficient to meet global final energy demand

After analyzing the global demand for hydrogen and its derivatives in Chapter 2.1, the question arises whether there is the supply potential to meet it. It should be noted that not only the energy demand for hydrogen and its derivatives must be met predominantly from renewable sources, but also the remaining final energy demand. There are also other sources available for low-greenhouse gas hydrogen and hydrogen derivative production, such as the use of natural gas together with carbon capture and storage (CCS) to produce so-called blue hydrogen. However, these are not considered here. One reason for this is that most studies currently assume that green hydrogen will dominate in the medium and long term and the other options are seen more as bridging technologies (see Economic Commission for Europe 2022). This chapter discusses the potential of electricity generation from renewable energy sources.

For the calculation, the Enertile model's Renewable Potential Calculator 2.0 was used to calculate the global renewable electricity generation potentials for photovoltaics (PV), onshore wind and offshore wind. Detailed information on the methodology can be found in Franke et al. (2024) and Kleinschmitt et al. (2021). The potential for geothermal and hydropower was determined based on an extensive literature review. Further details can be found in Kleinschmitt et al. (2021).

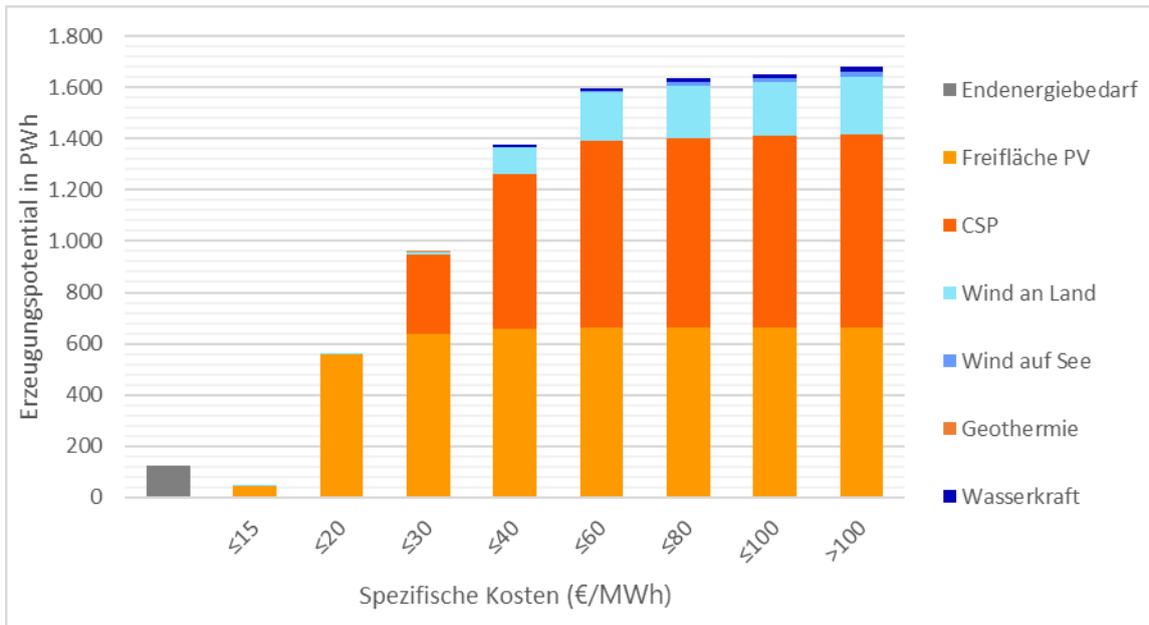
To determine final energy demand, projections for primary energy consumption in 2050 were derived from the 1.5°C scenario of the JRC Global Energy and Climate Outlook 2020 (European Commission, 2020). This scenario covers 23 countries and 14 aggregated world regions up to 2050. Further information can be found in Breitschopf et al. (2022).

The analyses show that the global potential of comparatively inexpensive renewable energies (RE) is sufficient to cover the forecast global total final energy demand in 2050 and thus also the demand for hydrogen and hydrogen derivatives. Figure 3 illustrates the potential of renewable energies at different specific costs and assuming a globally uniform weighted average cost of capital (WACC) of 2%.

These calculations highlight the enormous renewable energy resources available at different cost thresholds. Photovoltaics (PV) and concentrated solar power (CSP) dominate at the lower cost ranges, and onshore and offshore wind become increasingly important at higher costs.

To cover the global final energy demand of 122 PWh, the potential coverage for 20 EUR/MWh is already sufficient. This is based mainly on photovoltaics, with a small contribution from onshore wind.

Figure 3: Global electricity generation potential from renewable energies for different specific costs and 2% WACC. as well as the global final energy demand in 2025



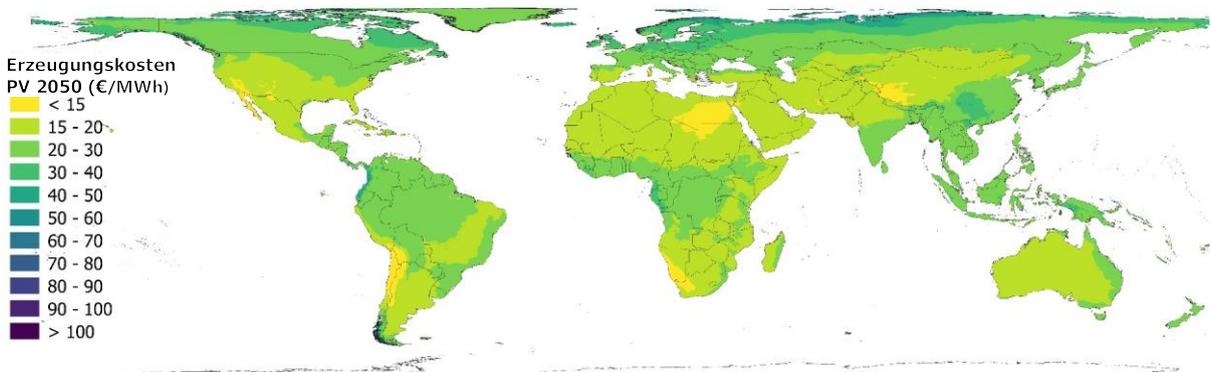
Source: Franke et al. (2024)

Potential PV resources are evenly distributed around the world, especially at costs below 30 EUR/MWh. The cheapest PV resources are located in the Atacama region (Chile), where solar energy potential is exceptionally high and temperatures are moderate (Figure 4) (the optimal temperature for PV systems is around 20 to 25°C). In contrast, onshore and offshore wind resources are more geographically limited and w

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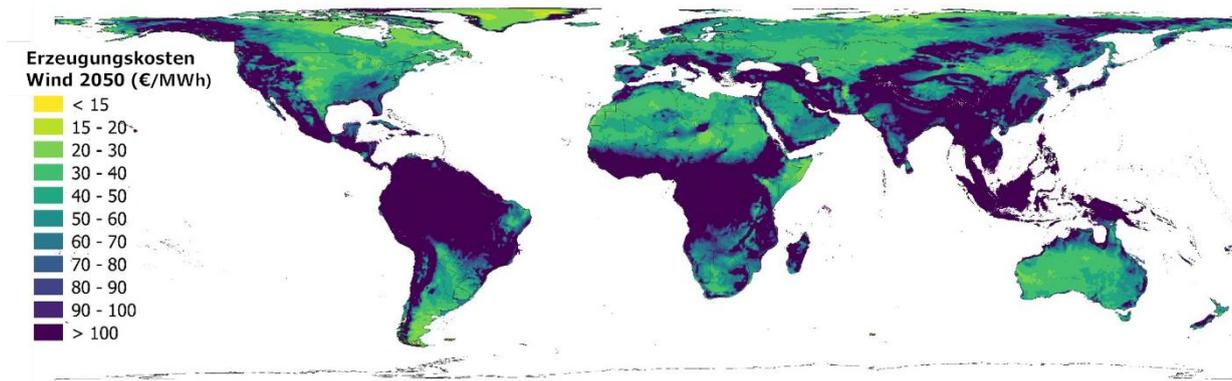
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Figure 5: Specific electricity generation costs for wind in 2050.

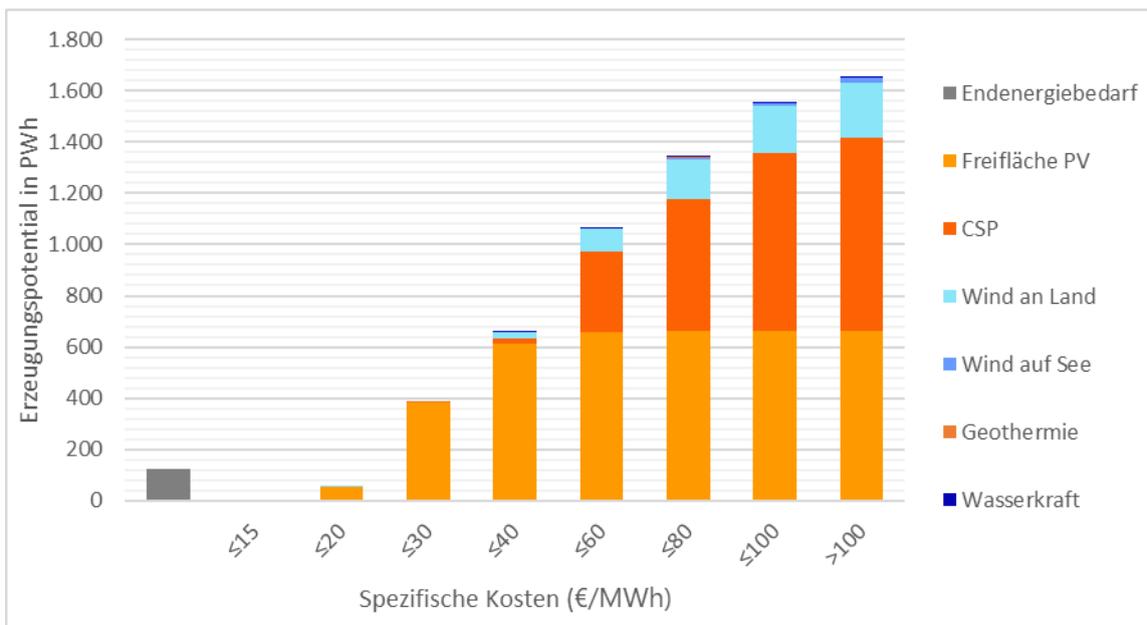


Source: own analyses, based on preliminary work by Kleinschmitt et al. (2021)

The weighted average cost of capital (WACC) plays a crucial role in determining the costs associated with the RE potential. Figure 6 shows the production potential at different cost levels calculated with specific WACC values for each country (for the discussion on WACC, see Wietschel et al. 2021 and for the specific WACC assumptions, see Damodaran (2021)). At a cost of 20 EUR/MWh, the final energy demand is not covered as the available potential is only 53 PWh. At a cost of 30 EUR/MWh, the potential increases to 382 PWh, which is sufficient to cover the final energy demand. However, this potential is still lower than in the scenario with a uniform WACC of 2% below 20 EUR/MWh (Figure 6).

This comparison highlights the significant impact that different WACC values have on the economic viability and availability of renewable energies.

Figure 6: Global electricity generation potential for different specific costs and country-specific capital costs (specific WACC).

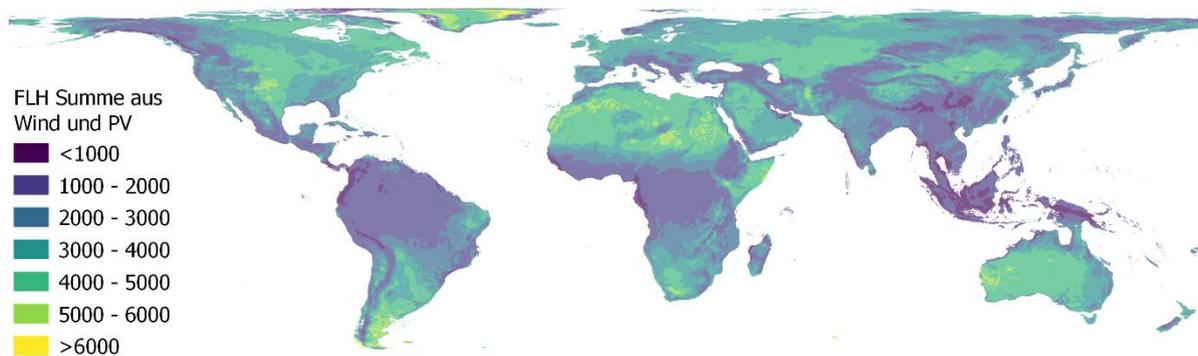


Source: Franke et al. (2024)

For the initial installation of island systems, where hydrogen production is completely independent of the grid and is carried out using local green electricity, regions with higher

Full load hours (FLH) have a significant advantage in terms of generation costs. In these areas, the electrolyzer can achieve high continuous utilization, which reduces the levelized cost of hydrogen (LCOH). Figure 7 shows the combined FLH for wind and photovoltaic (PV) plants. It demonstrates that regions such as southern Chile, known for their exceptional wind resources, also have some of the highest combined FLH. Other regions with high combined FLH include the MENA region, the Midwest of the United States, and Australia.

Figure 7: Sum of full load hours of wind and PV.



Source: own analyses, based on preliminary work by Kleinschmitt et al. (2021)

The results are presented in detail in Franke et al. (2024) and Kleinschmitt et al. (2021).

2.3 Many countries have high renewable potential and low renewable costs, which means that other aspects of hydrogen production and export come to the fore.

Sunny regions, especially in combination with good wind conditions, offer low production costs for green hydrogen and its derivatives from a techno-economic point of view. As shown in the previous chapter, this is the case for many countries. Therefore, other techno-economic aspects come to the fore when identifying possible supplier countries (e.g. access to cheap capital, opportunities and costs for underground storage (UGS), etc.). In addition to low WACC, which are relevant for cost-effective use of renewable energy potential and the development of infrastructure, other factors are just as important for the realization of hydrogen export projects. An optimally coordinated design of the capacities for renewable electricity generation, electrolysis and UGS in conjunction with the selection of suitable export points and forms (via pipeline or liquefied or as a synthesis product by ship) can partially compensate for the influence of WACC on the total export costs.

To estimate the costs of hydrogen and hydrogen derivatives in the HYPAT project, a comprehensive model of the supply chain was built. This includes the temporally and spatially resolved renewable energy production potentials (model *Enertile*) (see previous chapters), which are integrated into a national energy system model (model *Sector-Coupled PyPSA-Earth*) for the countries examined in more detail (Brazil, Ukraine, Canada, Morocco, United Arab Emirates, Turkey, Chile and Namibia). In this energy system model, in addition to the decarbonisation paths of the potential export countries (model *LEAP*, *Excel*

*templates*¹) also takes into account different export volumes and local conditions, such as the geographical distribution of renewable energy potentials and export infrastructures, the availability of potentials for UGS and the transport distance to these. All of the factors mentioned have a major influence on the extent of national infrastructure development and on the development of the national hydrogen infrastructure (production, storage, transport). To analyse the (production and) export costs for hydrogen and hydrogen derivatives, models for export via pipelines (model *Hytrafor* for compressed hydrogen) and by ship from liquid PtX energy sources (model *H₂ProSim* for liquid hydrogen, ammonia, LOHC, methanol and Fischer Tropsch fuels). The model results provide information on the expected import costs of hydrogen and hydrogen derivatives for net demand countries and show the impact of exports on the national energy systems of net producer countries. Details and details on the methodology of the models and the parameters used can be found in the methodological working paper (Pieton et al. 2024a). However, the costs should not be confused with the market prices for green hydrogen (see Wietschel et al. 2021 for this issue). Hydrogen prices are discussed in Chapter 2.7.

The main cost driver for imported hydrogen is the H₂ production costs, which consist essentially of the electricity generation costs and the investments plus capital costs of electrolysis. But the costs of the PtX production chain, consisting of infrastructure costs for intermediate storage of hydrogen and PtX product as well as synthesis or liquefaction, also make up a significant part of the import costs. The case-specific breakdown of the import cost components can be viewed in the set of results slides of the techno-economic assessment (Pieton et al. 2024b).

The transport distance between an exporting and an importing country, however, is not a decisive factor for the provision of hydrogen derivatives. For the PtX products ammonia (NH₃), liquid organic hydrogen carriers (LOHC), methanol (CH₃OH) and Fischer-Tropsch (FTS) products, the transport cost share is via ship below 3% and even in the worst case scenario, the export of small quantities of liquid hydrogen over a long transport distance³, in 2030 less than 15% and in 2050 less than 5% of the total import costs. For this reason, import costs by ship are also comparable between countries with very different transport distances to Germany, e.g. for Morocco and Canada. For pipeline imports from Europe and the MENA region, many cost components depend on the transport distance (length of the pipeline, number of compression stations and the amount of energy required for intermediate compression), but the hydrogen production costs including electricity generation clearly outweigh the distance-dependent transport costs: For 2030, in the moderate scenario and with import volumes of 50 TWh, the distance-dependent cost share for newly constructed pipelines is 23% for Morocco (2,132 km transport distance), 17% for Turkey (1,462 km) and 9% for Ukraine (871 km). The longer the transport route, the higher the pipeline import costs. This makes it clear that there is an economic upper limit to the distance from pipeline importing countries.

The use of large-scale UGS near favorable renewable energy sites, a H₂ network or an export point is an important flexibility option and can reduce hydrogen costs for both the

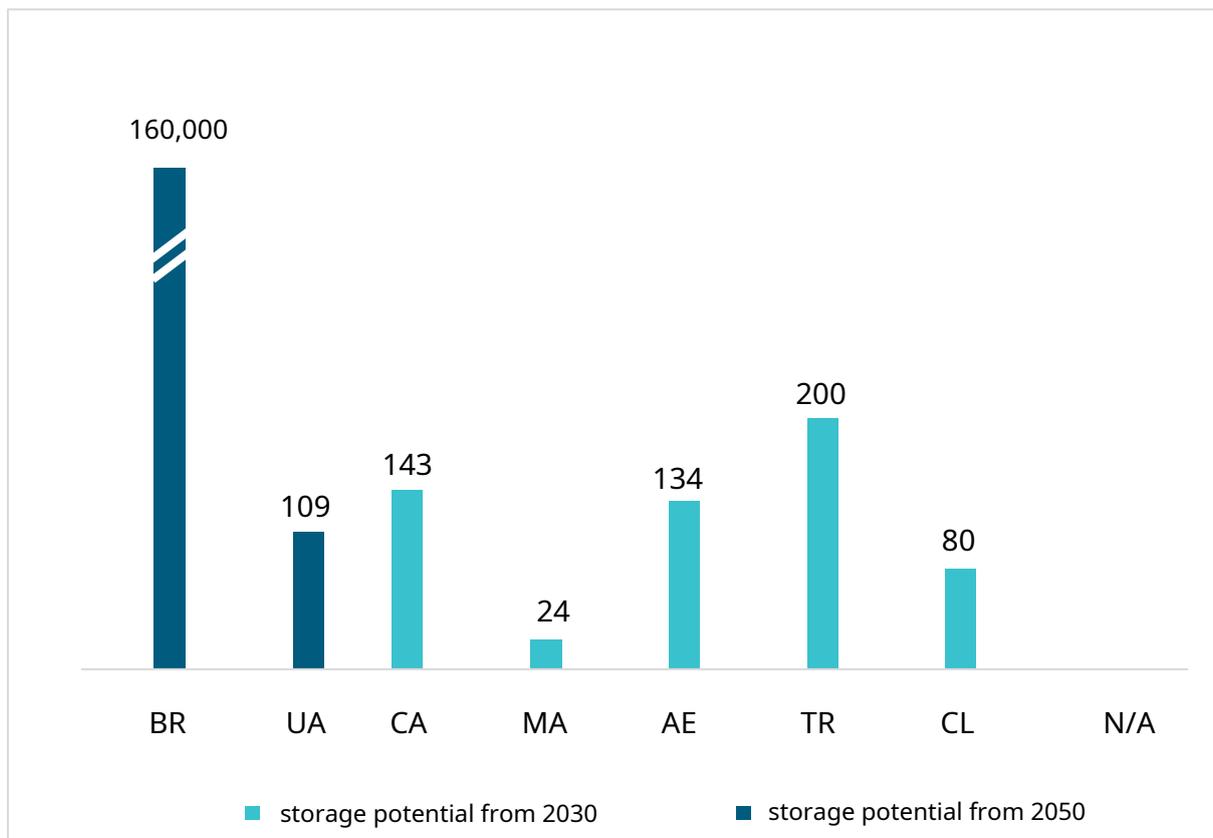
¹ National energy demand projections using LEAP and Excel

² Costs of pure shipping without the cost shares of the remaining hydrogen export infrastructure For

³ example from Brazil with a transport distance of 8,437 km (Pecem) to 11,475 km (Rio Grande)

domestic energy system and for export. UGS are important to compensate for fluctuations in hydrogen production (through surplus electricity) and hydrogen supply to the export industry (synthesis, liquefaction). Their availability in principle reduces overcapacity of renewable energy plants and electrolyzers. A more uniform hydrogen supply profile enables the continuous operation of PtX synthesis plants, as this reduces the costly start-up and shutdown of these plants and optimizes their use. Especially in the case of strong seasonal fluctuations, storage is indispensable in order to ensure that the plants operate as continuously as possible throughout the year. Details on the economic impact of fluctuations in hydrogen production for export can be found in the set of results slides of the techno-economic assessment (Pieton et al. 2024b). The availability of UGS in the countries studied differs greatly and also depends on assumptions, e.g. on storage types and possible geological formations. Figure 8 shows the UGS potentials, whereby these for 2030 are based on announced projects from the literature. The construction or conversion of storage facilities is very time-consuming. Therefore, for countries for which no concrete implementation projects for the use of H2 storage potential by 2030 are known, the use of H2 storage facilities was only assumed from 2050 onwards. More information on hydrogen UGS and its role in the energy transition can also be found in episode 9 of the HYPAT Podcast (HYPAT Podcast 2024).

Figure 8: UGS potentials of hydrogen in the export countries examined in TWh.
Country codes: BR - Brazil, UA - Ukraine, CA - Canada, MA - Morocco, AE - United Arab Emirates, TR - Turkey, CL - Chile, NA - Namibia.



Source: Pieton et al. 2024b

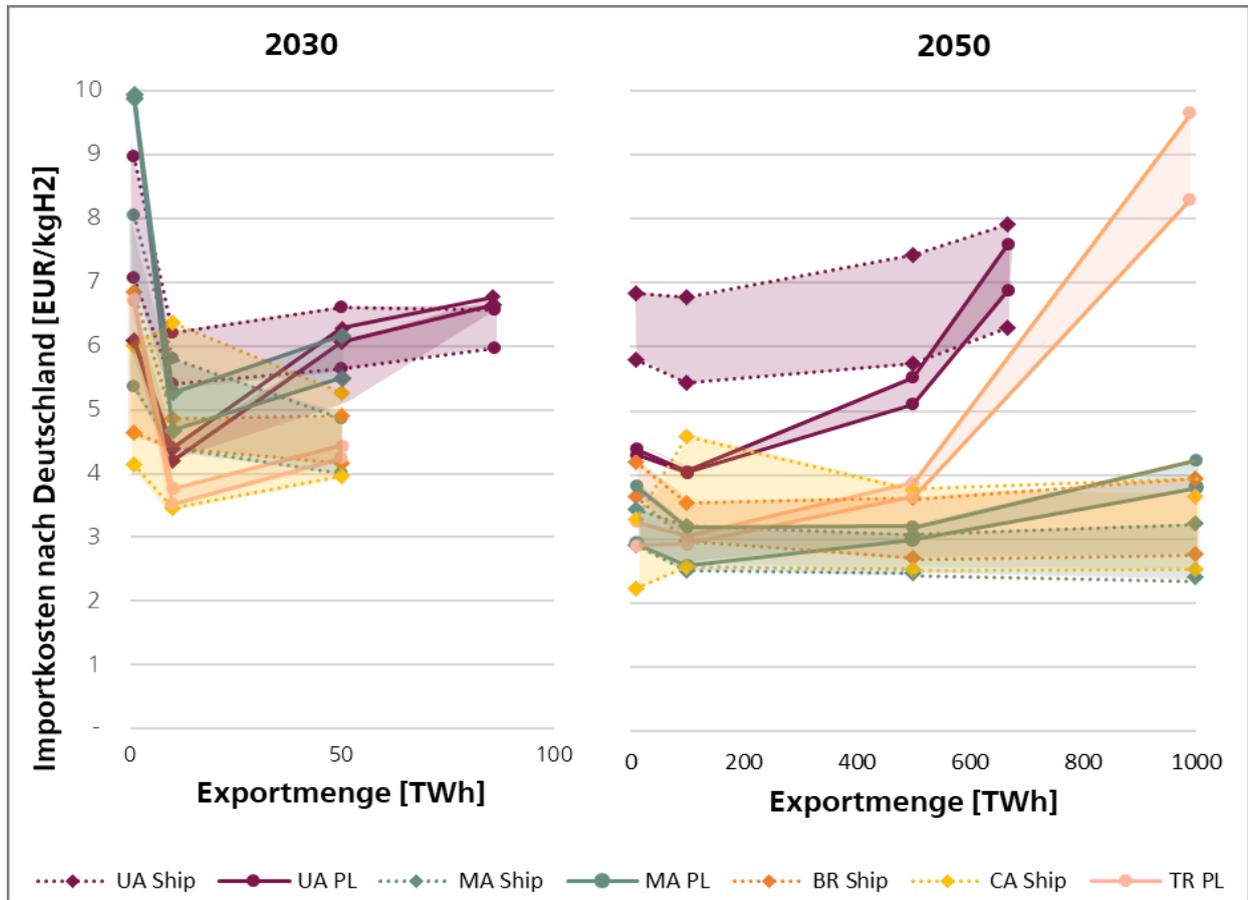
The cost of capital (WACC) is one of the decisive parameters regarding the production and export costs for hydrogen and hydrogen derivatives. In the HYPAT project, country-specific WACC were taken into account across the entire model chain (Pieton et al. 2024a; Damodaran et al. 2021). The lowest WACC were determined for Canada, as it is the most economically and politically stable country among the countries selected for detailed energy system modeling. The highest WACC, on the other hand, are set for Ukraine, as it is currently destabilized by the Russian war of aggression. Since the WACC is subject to uncertainty and can change in the future, it was varied in the scenarios. The WACC decreases from the conservative to the moderate to the optimistic scenario. In the moderate scenario, a historical average is set, in the optimistic scenario a historical minimum and in the conservative scenario a historical maximum. A detailed explanation, justification and the result of the WACC selection can be found in the methodological working paper (Pieton et al. 2024a).

The analysis of hydrogen import costs for Germany was carried out for various country-specific export volumes from the producer countries considered. For Morocco, Brazil, Canada, Ukraine and the United Arab Emirates, shipping (Ship) was considered and for Morocco, Turkey and Ukraine, exports via hydrogen pipelines (PL) to Germany were also analyzed.

Figure 9 shows the hydrogen import costs for Germany from the export countries Ukraine, Morocco, Brazil, Canada and Turkey for the target years 2030 and 2050 in the moderate scenario. The range shown is based on the various hydrogen carriers analyzed for ship transport (LH₂, NH₃ and LOHC) and their included reconversion back to H₂, different assumed hydrogen delivery time series to the synthesis as well as different technical configurations for pipeline transport (new construction or conversion of existing natural gas pipelines, grid electricity or renewable electricity as well as hydrogen as an energy source for hydrogen compression).

Figure 9: Import costs for hydrogen from PtX products to Germany from selected export countries in the moderate scenario.

The range of results is due to the different products and hydrogen delivery time series for shipping and different technical configurations for pipeline transport. UA: Ukraine, MA: Morocco, BR: Brazil, CA: Canada, TR: Turkey; PL: pipeline transport)



Source: Own illustration

If one assumes only deliveries to Germany from the countries considered, hydrogen import costs of between EUR 3.5 and 6.5/kg are to be expected for relevant import quantities in 2030. Import costs of between EUR 2.5 and 4.5/kg were determined for 2050. Higher costs were only calculated for hydrogen imports from Ukraine. Here, the available low-cost renewable energy potential is already exhausted for comparatively small export quantities, so that for higher export quantities, renewable energy potential with high electricity generation costs must be used. This can also be observed in the other countries analyzed, but to a much lesser extent.

It is also worth noting that the costs between pipeline imports and ship imports are roughly the same for the export volumes and bilateral supply relationships considered. For example, there is approximate cost parity between pipeline imports from Morocco and ship imports from Canada and Brazil.

A "bathtub curve" is characteristic of the export costs: It can be observed that higher export costs are shown for smaller export volumes, which reach their minimum for medium-sized volumes and rise again for large export volumes. The reason for this is the initially low economies of scale for shipping and low economies of scale for pipeline transport, which increase as export volumes increase. In contrast, hydrogen production costs are rising as more expensive renewable energy potentials are gradually being developed.

Conclusion: If we look at Germany in isolation as a consumer, the expected hydrogen import costs are between EUR 3.5 and 6.5/kg in the short term (in 2030) and between EUR 2.5 and 4.5/kg in the medium to long term (in 2050). Chapter 2.6 looks at global cost and demand potential considerations and the costs that can be derived from them. Chapter 2.7 then determines hydrogen prices for Germany, the EU and EU neighboring countries. At this point, it should only be mentioned that costs should not be confused with market prices.

In addition to the generally important aspects explained so far, country-specific criteria were identified for the countries examined in detail in the project:

- Chile: From a purely economic perspective, Chile offers the lowest production costs for green hydrogen, making it an attractive location for manufacturing while taking advantage of its excellent solar PV potential.
- Canada: Low WACC and short distances between favorable renewable energy locations, UGS and ports make Canada an attractive exporter from 2030 onwards.
- Morocco: The best renewable energy sites are in the south and therefore far from pipeline export points in the north of the country. A H₂Network must be expanded domestically in order to connect the renewable energy sites with the export points.
- Brazil: The high share of biomass in final energy consumption can accelerate the achievement of decarbonization targets. In addition, there is excellent renewable energy potential near overseas ports.
- UAE: Geographical proximity between renewable energy sites, potential export ports and underground storage facilities, low WACC and projected high domestic demand for PtX products make the United Arab Emirates an ideal country for PtX exports from a techno-economic perspective.
- Turkey: Exports by ship have little spatial synergy with the domestic energy distribution and transmission system. Larger export volumes would have to be covered by renewable energies and underground hydrogen storage facilities, which are, however, far away from both demand centers and export ports.
- Ukraine: High WACC overshadows results and causes costly H₂-Exports despite actually relatively good conditions in the energy system and existing export pipelines.
- Namibia: The country offers great renewable energy potential, but the energy infrastructure is poorly developed.

Further techno-economic results and country-specific detailed evaluations can be found in the set of results slides of the techno-economic assessment (Pieton et al. 2024b) and in the working paper on the methodology (Pieton et al. 2024a).

However, in addition to the techno-economic aspects, other factors must be taken into account when evaluating countries. In HYPAT, a comprehensive analysis grid was developed for this purpose and used to evaluate countries (see the comments in Breitschopf et al. 2022). In addition to the topics listed above, an additional important aspect in the country assessment is the availability of water resources. With regard to water resources, three criteria must be taken into account: a country's access to the sea, available freshwater resources per inhabitant per year, and the risk of drought within the country. Since the share of the costs for seawater desalination and the transport of water over long distances in the total production costs of hydrogen and its derivatives plays only a minor role, the availability of water at the electrolysis site itself is in

not a relevant factor in many countries (Mendler et al. 2024 and Lux et al. 2021). Rather, the ethical question arises as to whether the use of water to produce hydrogen for export is justifiable in regions where people have little or poor access to water. Furthermore, the environmental impact of seawater desalination must be taken into account and kept as low as possible.

In addition, security and political stability in supply relationships are becoming increasingly important - not least due to the Russian war of aggression against Ukraine. It is essential to understand political stability as a multidimensional construct that takes into account not only the current political regime and its legitimacy, behavior in accordance with human rights and international law, but also the nature and effectiveness of state institutions. In general, political risks must be given greater weight when assessing trade relations - especially for critical supplies. In addition to technical availability and price, greater attention should therefore also be paid to the assessment of the supply sovereignty of import-dependent nations, foreign and especially domestic policy aspects, governance and the effectiveness of state institutions, and the systemic and political resilience and reliability of partner countries should also be assessed. In addition, geopolitical considerations and value-based trade relations should be sought in the hydrogen strategy. For this discussion, see the HYPAT Impulse Paper (Wietschel et al. 2022a).

2.4 Liquid hydrogen and ammonia are the cheapest export products by ship

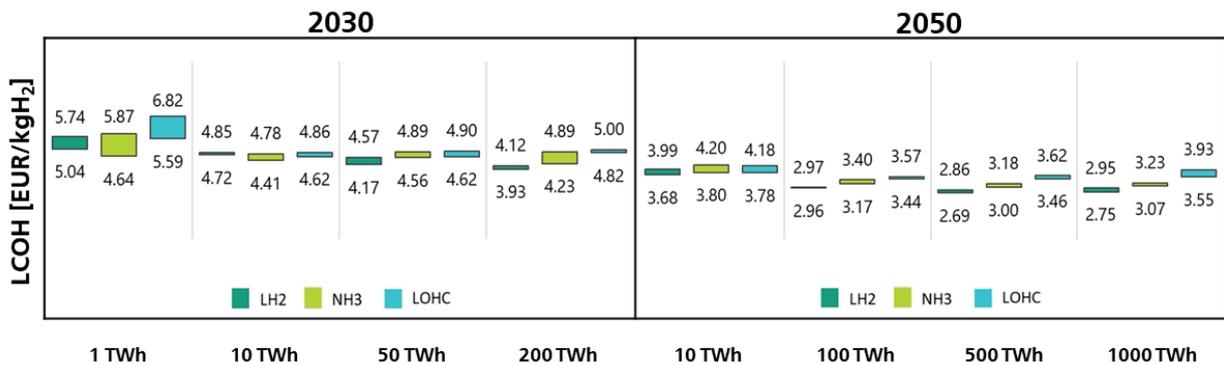
Within the techno-economic analyses in this chapter, the first step is to discuss the provision costs in the event that the energy sources are transported by ship. In a second step, the hydrogen pipeline is specifically addressed and the pipeline-related export cost shares are analyzed. In the case of ship exports, two study frameworks were used. On the one hand, the costs were examined with a reconversion of the energy sources in Germany to gaseous hydrogen (Levelized Cost of Hydrogen - LCOH) and on the other hand without reconversion (Levelized Cost of Power-to-X - LCOPTX). Since these are different study frameworks (gaseous hydrogen vs. liquid energy sources), their respective costs cannot be directly compared with each other. For pipeline-based transport, the hydrogen export costs were analyzed in order to ensure comparability with ship transport, and transport (Levelized Cost of Transport - LCOT) and total export costs were considered separately (see Figure 10). The total export costs for pipelines consist of the LCOH incurred in the exporting country and the LCOT for transport between the exporting and importing countries. This issue, other methodological aspects, assumptions and framework conditions as well as further conclusions have already been briefly outlined in the previous chapter and can be found in detail in the methodological working paper (Pieton et al. 2024a) and in the set of results slides (Pieton et al. 2024b).

Supply of molecular hydrogen by ship

For the scenario of providing molecular/gaseous hydrogen by ship to feed green hydrogen into the German hydrogen core network, the hydrogen carriers liquid hydrogen (LH₂), ammonia (NH₃) and liquid organic hydrogen carriers (LOHC). Although the energy sources methanol and FTS fuels are also conceivable in principle, their use as hydrogen carriers is rather unlikely, at least in the medium term, since their direct use is more obvious. For the reconversion of shipped LH₂, NH₃ and LOHC into molecular hydrogen is therefore a regasification (LH₂) or reforming (NH₃, LOHC) including product gas processing is taken into account in the calculations to determine the Levelized Cost of Hydrogen (LCOH). To date, the reforming of ammonia has not yet been implemented on a large scale, although various manufacturers do not foresee any major technical obstacles here. LH₂ can be regasified particularly efficiently, comparable to liquefied natural gas (LNG). Hydrogen from LOHC is in turn obtained via a dehydrogenation unit.

The results of the HYPAT model chain (see Chapter 2.3) show that the final hydrogen import costs after conversion back to molecular hydrogen are comparable between ammonia and liquid hydrogen for small export volumes, but are in favour of liquid hydrogen for medium and large export volumes. Thus, liquid hydrogen has the most advantages in the case of larger H₂-Export volumes have decisive advantages over the hydrogen carriers ammonia and LOHC. This could be shown for Brazil (see Figure 10) and for the countries Ukraine, Canada, Morocco and the UAE (see set of results slides, Pieton et al. 2024b).

Figure 10: Import costs for gaseous hydrogen (LCOH) in case of ship import from LH2, NH3 and LOHC from Brazil and a reconversion to molecular hydrogen at the destination Germany for the years 2030 and 2050 and taking into account different export volumes.



Source: Own illustration

In principle, for all export countries examined, there is a cost optimum at which the import costs to Germany are lowest in relation to the quantity: While the marginal costs for hydrogen production increase from an overall energy system perspective, the levelized costs for transport decrease (due to economies of scale, among other things) (see Chapter 2.3). In general, the export country-specific hydrogen import costs increase with the export quantity, since from a certain point onwards the hydrogen production sites can only be supplied with increasingly unfavorable renewable energy potentials and can be developed with a cost-intensive further construction of new electricity or hydrogen transport infrastructures. In contrast, the cost shares for synthesis, storage and shipping decrease with increasing export volumes due to better capacity utilization and economies of scale. This leads to a cost minimum for medium export quantities (between 200-1000 TWh of hydrogen in 2050, depending on the country of production) and can be seen from the "bathtub curve" of the LCOH in Figure 10 for Brazil. It has also been shown for the UAE that cost-optimized LH₂- and NH₃-Exports in 2050 for an export volume of approximately 500 TWh. Further findings and results regarding the other countries examined can be found in the set of results slides of the techno-economic assessment (Pieton et al. 2024b).

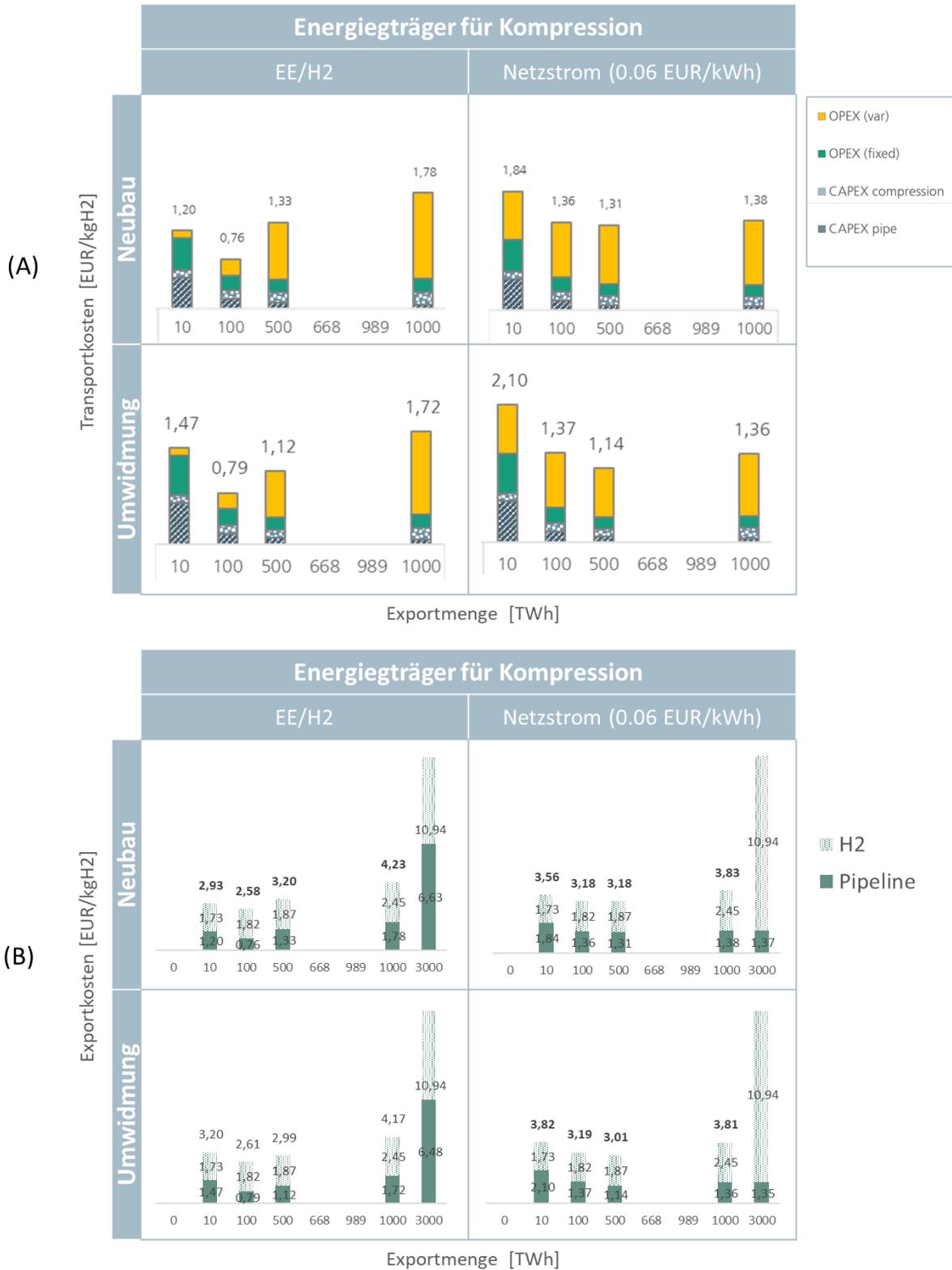
Costs of hydrogen export via pipeline

The project also examined the hydrogen export costs per pipeline for newly built and repurposed pipelines. The conversion of existing natural gas pipelines for H₂- Transport only makes sense if the pipelines can be operated at high capacity over the entire route. However, many existing pipeline sections in the existing gas transport network have only low capacities. In some cases, new pipelines would have to be built to fill these capacity bottlenecks. From a cost perspective, building new pipelines can therefore be cheaper than converting existing pipelines. The argument in favour of building new pipelines is that they can be adapted to the desired export volumes and ultimately operated at higher pressure or higher capacity. With high pipeline-bound H₂-transport volumes, the specific investments for pipelines and compressor stations decrease. Instead, the energy costs for intermediate compression dominate.) Two options for supplying power to the compressors were investigated: 1. Use of regional renewable electricity in the vicinity of the compressor stations in combination with hydrogen from the pipeline; 2. Purchase of grid electricity. In the first case, very high transport capacities can lead to

It may happen that the available low-cost potential is fully exploited and instead part of the transported hydrogen has to be made available for compression. Compressors in the existing natural gas pipeline network, for example, are powered by natural gas. In the second case, if electricity procurement costs are low, the purchase of grid electricity by the compressor stations can counteract an increase in transport costs to a limited extent. As described in the previous chapter, hydrogen production costs (LCOH) increase with increasing export volumes, while transport costs (LCOT) decrease due to capacity utilization and economies of scale (see Figure 11). Details on the methodological approach and further results can be found in (Pieton et al 2024a, Pieton et al. 2024b).

Figure 11 Cost composition for the pipeline export of hydrogen from Morocco to Germany in 2050 depending on export volumes.

(A) Cost shares for transport costs by pipeline (LCOT): Does not include hydrogen production costs. (B) Cost shares for export costs by pipeline: Includes transport costs ("pipeline"/LCOT) and hydrogen production costs ("H₂" / LCOH) in the exporting country.



Source: Own illustration

Conclusion: High pipeline utilization and cheap green compression energy are crucial to keep transportation costs low. In addition, converting an existing natural gas pipeline may not necessarily be more cost-effective than building new pipelines.

It is not possible to make a general assessment as to whether importing to Germany by pipeline or ship is more cost-efficient within an economic pipeline distance, as the energy system of an exporting country can favor both export paths and each must be carefully examined for suitability in each individual case. An analysis of this kind is carried out in Chapter 2.7, whereby the framework conditions set differ from those of the detailed techno-economic analysis (in Chapters 2.3 and 2.4) and must be classified accordingly. Apart from that, importing by ship offers Germany the potential for more flexibility and diversity, while importing by pipeline brings with it strategic partnerships on the one hand and dependencies on the other.

hydrogen derivatives for direct use (LCOPTX)

Among the PtX products (Levelized Cost of Power-to-X - LCOPTX) evaluated without reconversion to molecular hydrogen for direct use as fuel or basic chemical, ammonia is a promising candidate. Compared to the PtX energy sources methanol and Fischer-Tropsch synthesis (FTS) products also considered, the ammonia value chain proves to be more cost-efficient per unit of energy. The processes for the production, storage and transport of ammonia are also already state-of-the-art on a large scale. Imports of ammonia to Germany could be implemented in the near future and ammonia offers additional potential in its additional function as a good hydrogen carrier (see previous chapter). The technological maturity level (TRL) of methanol, however, is on a par with that of ammonia. For the carbon-based energy sources methanol and FTS fuels and under the long-term goal of a closed carbon cycle, access to a greenhouse gas-neutral carbon source is necessary. In addition, industrial point sources are only available at some of the locations analyzed and to a limited extent. In addition, the potential of sustainable biomass, as a potential additional carbon source, is also not sufficient for large export volumes. Therefore, for larger PtX production volumes of methanol and FTS products, CO must be used in most cases, via Direct Air Capture (DAC). This is still associated with very high costs, at least in the near future, and is currently a clear disadvantage of carbon-based PtX products. In the case of ammonia, a final assessment as a fuel is difficult, since with regard to NH₃ slip, NO_x and nitrous oxide formation as well as possible leaks during technical application in the combustion engine and in the fuel cell, there is still insufficient data (see also Chapter 3.6 for the environmental effects of an ammonia economy). The direct cost comparison of ammonia with methanol and FTS products is only of limited use due to the different applications of these energy sources and the additional aspects mentioned. The results must be classified accordingly, but are stored in the set of results slides of the techno-economic assessment (Pieton et al. 2024b) and can be methodically researched in the working paper on the methodology (Pieton et al. 2024a).

2.5 Only a few countries require larger import quantities

As part of the project, extensive analyses were carried out on hydrogen and derivatives demand in industrialized countries that may have a greater need to import hydrogen and derivatives. This was done using a temporally and spatially highly resolved

Modeling of renewable potentials and aggregated green hydrogen and derivatives production compared with supply potentials (see also Franke et al. 2024 and Kleinschmitt et al. 2022).

In the analysis, importing countries were identified based on the delta of renewable potentials (Chapter 2.2) and the projected hydrogen demand for 2050. The net importing countries together with the identified net exporting countries are shown in Figure 12. A meta-analysis of the country-specific literature was then conducted to gain a detailed understanding of hydrogen demand as well as the techno-economic and geopolitical hydrogen landscape. In addition, data from the latest hydrogen atlases were collected and compared with favorable renewable potentials from the HYPAT project (Franke et al. (2024) and Kleinschmitt et al. (2021)). In addition to the meta-analysis, a hydrogen potential calculation at a global level was performed as part of HYPAT. Further information is available in Mendler et al. (2024).

The results show that in the EU it is mainly Germany, the Netherlands, Belgium and Italy that do not have sufficient renewable energy potential that can be exploited cheaply to meet the expected high H₂-Demand through domestic production. In addition, Japan and South Korea in particular are considered future import candidates with high H₂demand is expected to be high in these countries, among other things because they have a strong steel and chemical sector on the one hand and ambitious greenhouse gas reduction targets on the other.

The results of the meta-analysis are presented in Table 1, which shows the differences between hydrogen demand and potential in different scenarios evaluated. These scenarios include: maximum demand minus minimum potential, minimum demand minus maximum potential, median demand minus median potential, average demand minus average potential, maximum demand minus maximum potential, and minimum demand minus minimum potential. Positive values indicate a need for energy imports.

For the European cases, the analysis shows that most scenarios result in an import requirement, except for the scenario where minimum demand is compared to maximum potential. Our evaluation of the six scenarios shows that Japan relies on energy imports in three of the six cases, which is contrary to the widely held assumption that Japan will always be an energy importer. This could be because some scenarios include large offshore wind facilities off the Japanese coast combined with high use of nuclear energy, which could make Japan independent of energy imports in these cases. Likewise, South Korea has a deficit in the same three scenarios, ranging from 21 TWh to 929 TWh. Although it was initially assumed that Indonesia would have a deficit, the meta-analysis shows that Indonesia could potentially become an exporter of hydrogen in most scenarios.

Looking at the difference between the cases presented in Table 1 under deficit conditions, we find that hydrogen demand ranges from 168 TWh in the case of minimum demand and minimum potential to 4,543 TWh in the case of maximum demand and minimum potential. Under minimum demand and maximum potential, all countries have sufficient potential to meet their needs, resulting in a total demand of 0 TWh.

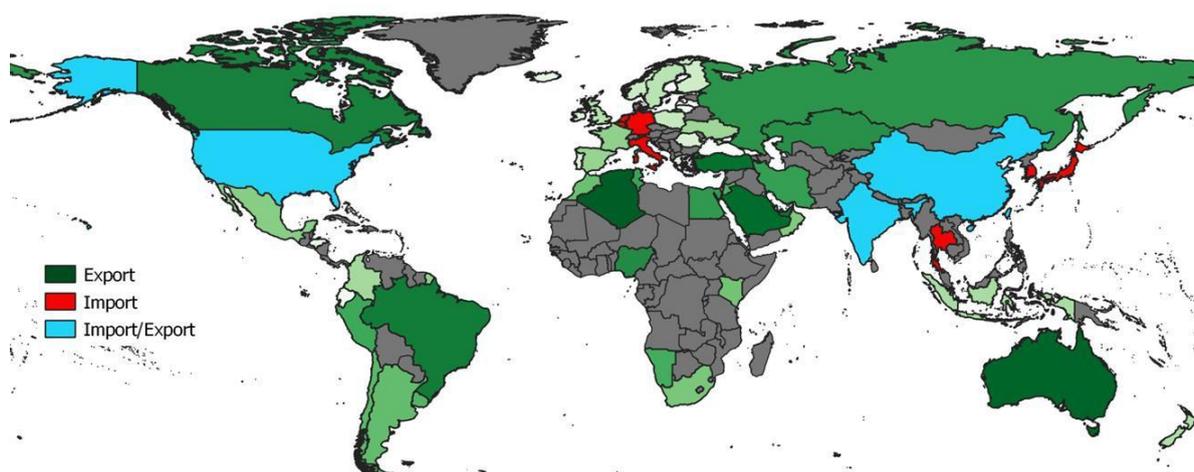
Table 1: Meta-analysis results for the selected deficit countries on H₂import requirements.

D stands for hydrogen demand and P for hydrogen production potential. Max denotes the maximum demand or potential. Min denotes the minimum demand or potential. Med stands for the median.

2050	Difference between demand (D) and potential (P) TWh					
	Max D - Min P	Min D - Max P	Med	mean	Max D - Max P	Min D - Min P
Germany	900	- 321	62	126	595	- 16
Italy	429	- 379	193	98	39	11
Netherlands	242	- 62	111	100	122	58
Belgium	200	- 20	125	97	140	40
Austria	70	- 107	29	15	- 44	8
Czech Republic	72	- 91	43	30	- 30	11
Japan	1161	- 801	- 162	- 72	341	19
South Korea	929	- 523	- 45	- 63	385	21
Indonesia	540	- 1508	- 226	- 356	- 966	- 2
sum	4,543	0	563	466	1,622	168

Figure 12 provides an overview of the identified countries for which a H₂-Import is to be expected. On the other hand, it shows which countries are considered H₂- exporters. In addition, some countries could play both roles in a future global hydrogen market. This applies in particular to the USA, China and India, which despite having sufficient renewable electricity generation potential to cover domestic H₂demand may require imports.

Figure 12: Import demand or export potential of countries (export (green), import (red) and import/export countries uncertain (blue))

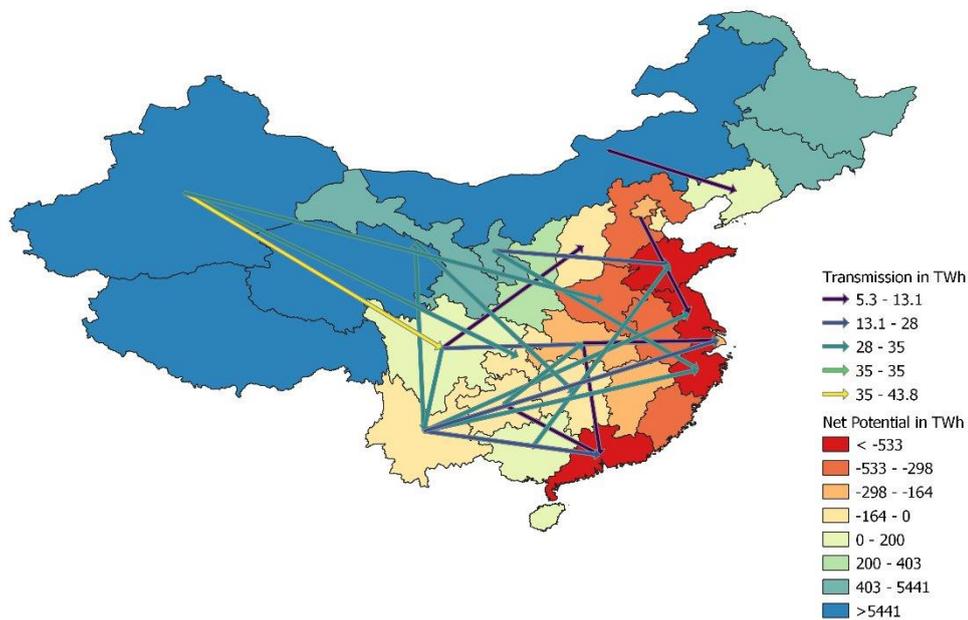


Source: Own illustration

For China, for example, the reason is that the renewable energy potential is largely located in the west of the country and is therefore partly very far away from the potential demand centers in the east of the country along the coast (see Figure 13). In order to supply these with domestic hydrogen, in addition to tapping into the renewable energy potential, either relevant transport costs for the hydrogen to the coastal regions or for the expansion

The eastern provinces have an electricity deficit of over 7,000 TWh. The H₂- import. The decisive factor here will be the strategy that the Chinese government pursues. A similar, but less clear-cut situation also exists for the USA. Here it is likely that they will become more of an exporter. It is also unclear how India will develop in this regard.

Figure 13: China’s net electricity demand (electricity demand in 2050 minus total renewable electricity generation potential at costs < 100 EUR/MWh) divided between the different provinces and existing and planned transmission network capacities for electricity



Source: Own illustration

These results are in some aspects consistent with the results of other studies (Shirizadeh, B. et al. 2023, Hydrogen Council, McKinsey & Company 2022, IRENA 2022, iLF et al. 2023). But for India and China in particular, the studies come to some different conclusions for the reasons stated above. In the updated report by Hydrogen Council, McKinsey & Company (2022), China and India are named as self-sufficient countries because they have extensive renewable energies. Nevertheless, the authors do not rule out the possibility of short-term hydrogen imports from countries with lower production costs such as the Middle East or Australia.

The results of the HYPAT calculation are available in Mendler et al. (2024).

The overall analysis shows that, based on the present analysis, only a small proportion of the hydrogen and derivatives produced is likely to enter international trade, assuming that all countries can also realize their production potential. A number of studies also come to the conclusion that the hydrogen produced

and its derivatives will be used predominantly on national markets (see IRENA 2022, Shirizadeh et al. 2023 and Hydrogen Council, McKinsey & Company 2022). Thus, according to the IRENA (2022) scenario, three quarters will be produced and consumed domestically. This is a significant change from today's oil market, where the majority (about 74%) is traded internationally. But it is similar to today's gas market, where only 33% of gas is traded across borders (see IRENA 2022). Also according to Shirizadeh et al. (2023), global trade will cover about a fifth of total demand between 2030 and 2050.

2.6 The global supply potential curve shows great potential for import diversification for Germany

As described in Chapter 2.2, the global potential of renewable energies, taking into account all restrictions and sustainability criteria, is many times higher than the global total final energy demand forecast for 2050 and is therefore theoretically more than sufficient to cover the increasing demand for green hydrogen and its derivatives. In addition, the potential for cost-effective electricity and hydrogen production from renewable energies is evenly distributed across the world and across numerous countries, which in principle creates very good conditions for the development of diversified hydrogen production, ²-Production and H₂ supply chains.

At the same time, the analysis results presented in Chapters 2.2, 2.3 and 2.4 show that both the production of green hydrogen and its intermediate storage, conversion into derivatives and transport by pipeline and/or ship are influenced by many geographical, technical, economic and sociological conditions and optimization problems.

In order to demonstrate the wide range of future costs (Levelized Cost of Hydrogen, LCOH) of possible hydrogen imports to Germany and to illustrate the various options for diversifying hydrogen supply relationships, a global supply potential curve for green hydrogen was developed within the framework of HyPat.

This supply potential curve shows, according to the merit order principle (marginal costs), how much hydrogen could theoretically be imported into Germany in 2050 and at what cost⁴. The supply potential curve is derived as follows:

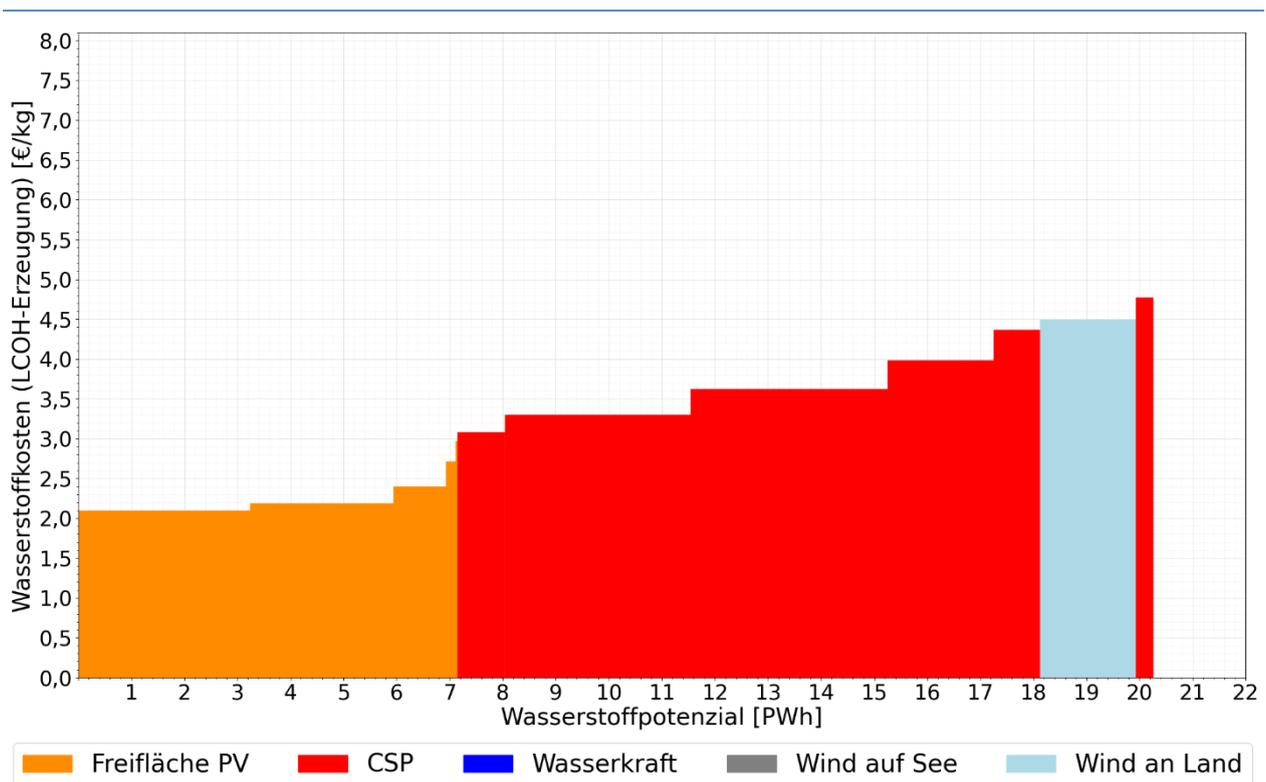
Based on the potential analyses of the Renewable Potential Calculator 2.0 of the Enertile model and the forecasts of final energy and primary energy consumption for all 193 countries in the world (see Chapter 2.2) as well as the multi-criteria country analyses in Breitschopf et al. 2022, the 48 countries with the highest renewable energy potentials are selected for representation in the global supply potential curve. In the multi-criteria analysis, various indicators were collected that are essential for the production of sustainable hydrogen, such as renewable potentials, water resources, installed renewable capacities, available energy infrastructure and various economic factors, such as WACC etc. Only potentials with LCOE (Levelized Cost of Energy) of a maximum of 100 EUR/MWh are considered. Together, these 48 countries have a renewable electricity generation potential of 890 PWh, which is more than nine times the forecast for 2050 based on IEA scenarios.

⁴ The analysis is based on the assumption that the necessary expansion of production capacities and infrastructure will have been completed by 2050, but does not take into account the influences of the expected international competition on available hydrogen quantities and market price formation.

final energy demand and a share of around 57% of the total global potential in this LCOE segment (IEA 2023c). The export potential of a country is the amount of renewable energy that exceeds the primary energy demand forecast for 2050 and would therefore in principle be available for export-oriented hydrogen production. This assumption is in line with the goal of the national hydrogen strategy (Federal Government (2024)), according to which possible hydrogen imports to Germany should not make it more difficult or more expensive to cover and decarbonize the domestic energy needs of potential export countries.

Using the methodology developed in Mendler et al. (2024) for the simplified calculation of the LCOH based on the country- and region-specific full load hours and LCOE of the global renewable energy potentials calculated in Enertile, individual merit order curves of the hydrogen production potentials available for export, of different sizes and costs, can be created for each individual country (see Figure 14 for Brazil).

Figure 14: After primary energy demand has been met, remaining available Hydrogen production potentials and costs (LCOH) of Brazil in 2050 (moderate scenario with country-specific WACC and consideration of all renewable energy potentials up to 100 euros/MWh



Source: Own illustration

In addition to the hydrogen production costs (LCOH), in the next step the cost share associated with hydrogen transport (Levelized Cost of Transport, LCOT) and the cost share associated with intermediate storage and conversion into hydrogen derivatives are also shown separately in the supply potential curve.

Since only eight of the 48 countries selected for HYPAT have been included in the Toolbox *H2ProSim* were analyzed in detail (see Chapter 2.4), these detailed analyses form the basis for the simplified calculation of the transport costs and the costs arising in the case of ship transport.

other capital and operating costs for the hydrogen storage and conversion processes.

The estimate of the costs of hydrogen transport by pipeline is based on the following calculations: Using the pipeline route optimization methodology developed in Weißenburger et al. (2024) for the HyPriM market model, various pipeline routes are determined through comprehensive GIS and cost analyses. This includes both national transport (from potential hydrogen electrolysis sites to existing or future export terminals) and international pipeline transport from countries for which there is a potential H₂-Pipeline connection to Germany would be theoretically conceivable. will be used both for domestic transport (from potential hydrogen electrolysis sites to existing or future export terminals) and for international pipeline transport from countries for which a potential H₂-Pipeline connection to Germany would theoretically be conceivable, various optimal pipeline routes were determined. Due to the large number of possible electrolysis sites spread across the country, the geographical center of the countries is chosen as the starting point of the pipeline routes and the average pipeline length weighted across all possible routes is calculated. The international pipeline transport of hydrogen was limited to 5,000 km for this analysis. According to the technical and economic comparison described in Wietschel et al. (2021), pipeline transport is only economically attractive up to this upper limit; everything beyond that is considered ship transport.

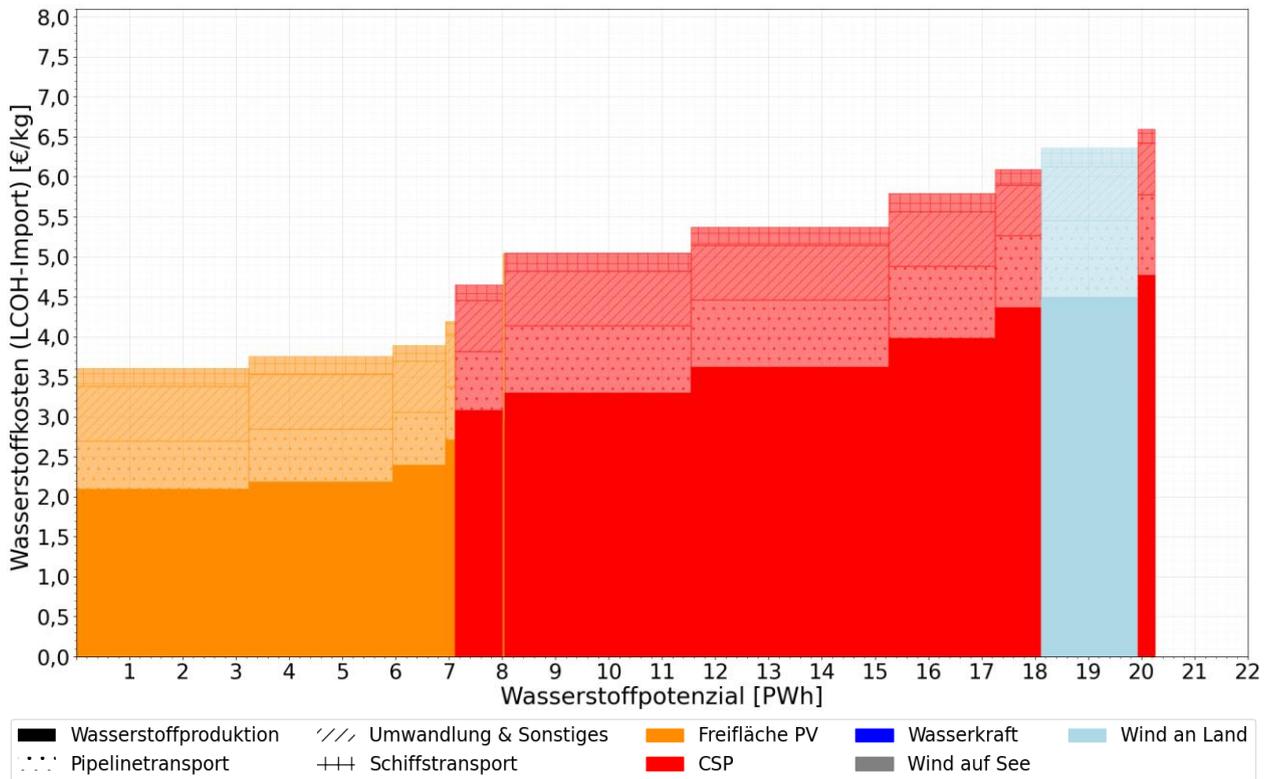
Applying the country-specific WACC and assuming that the compressor stations of the pipelines are operated with locally generated electricity from renewable energies at LCOE of 30 to 100 euros/MWh (= upper limit of the considered renewable energy potentials), the distance-dependent capital and operating costs of pipeline transport are calculated in the HyTra tool for different transport volume levels (2030: 1 to 200 TWh/a, 2050: 10 to 1,000 TWh/a).and then added to the already determined LCOH of the various hydrogen supply potentials of the selected countries.

The costs of shipping result, on the one hand, from the construction and operation of the industrial and port facilities required for the hydrogen conversion processes and, on the other hand, from the investment requirements for the necessary tankers and their use. The detailed models described in Chapters 2.2 and 2.4 show that, with otherwise similar assumptions for specific investment and operating costs, the country-specific WACC, in addition to economies of scale, have the greatest influence on the LCOT of shipping.

The example of the potential analyses for Brazil shows that the costs for domestic and international transport (pipeline and ship), storage and conversion processes increase the costs of importing Brazilian green hydrogen to Germany by around a third (see Figure 15).

⁵ The upper limits for export potentials are set country-specifically according to maximum renewable energy potentials. For more information, see the methodology paper on techno-economic assessment (Pieton et al 2024a).

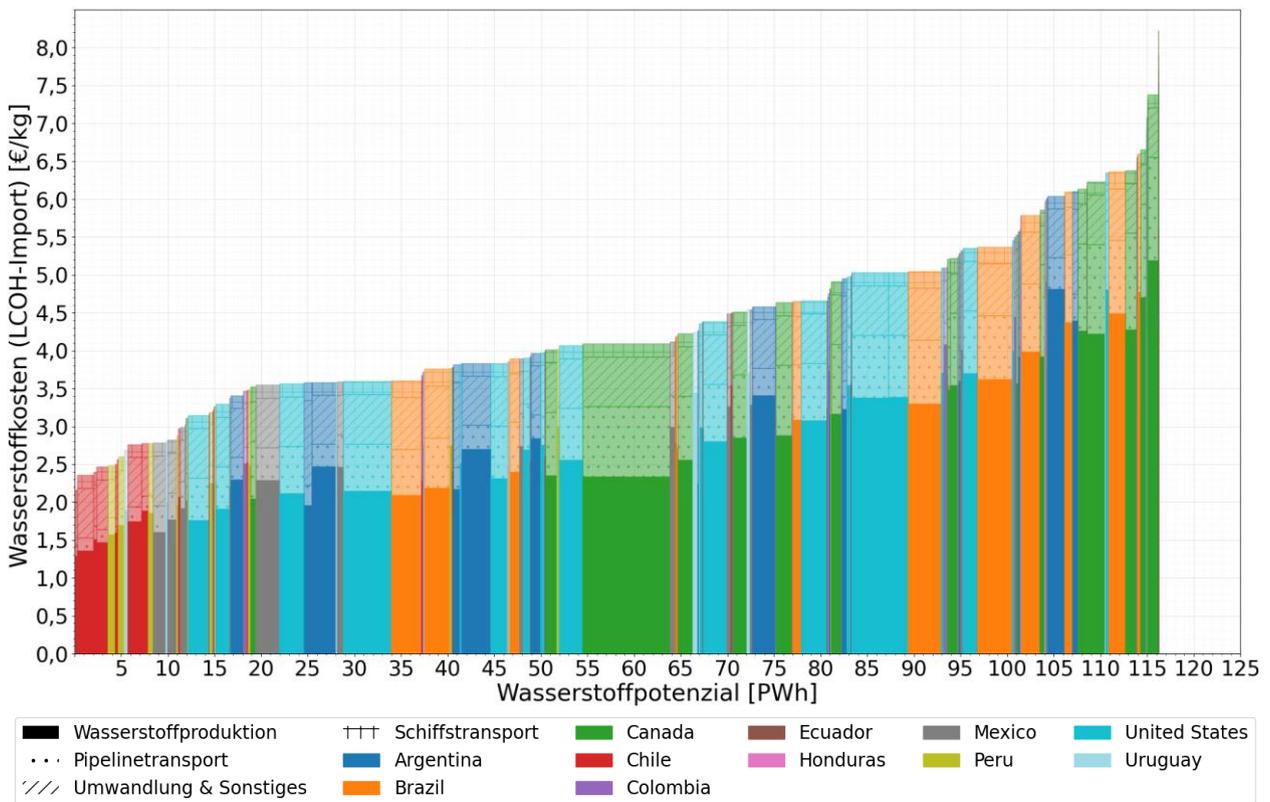
Figure 15: Hydrogen import potential and costs (LCOH) of Brazil for the year 2050 at Conversion into NH₃ for shipping and with reconversion into molecular hydrogen at the import hub in Germany (moderate scenario with country-specific WACC and consideration of all renewable energy potentials up to 100 euros/MWh)



Source: Own illustration

The findings and data obtained from the detailed analysis are used to determine the costs of shipping by LH₂, ammonia (NH₃) or LOHC from the potential export terminals of the hydrogen production countries selected for the global supply potential curve to Germany. Other existing but less relevant cost factors, such as the geographical conditions in the export countries (especially geological conditions and water availability), are not taken into account in the calculation of the LCOH for the global supply potential curve for reasons of simplification. Figure 16 shows the analysis results for the countries of North and South America considered using the example of the ammonia route, which is described as the most cost-effective option for shipping in Chapter 2.4.

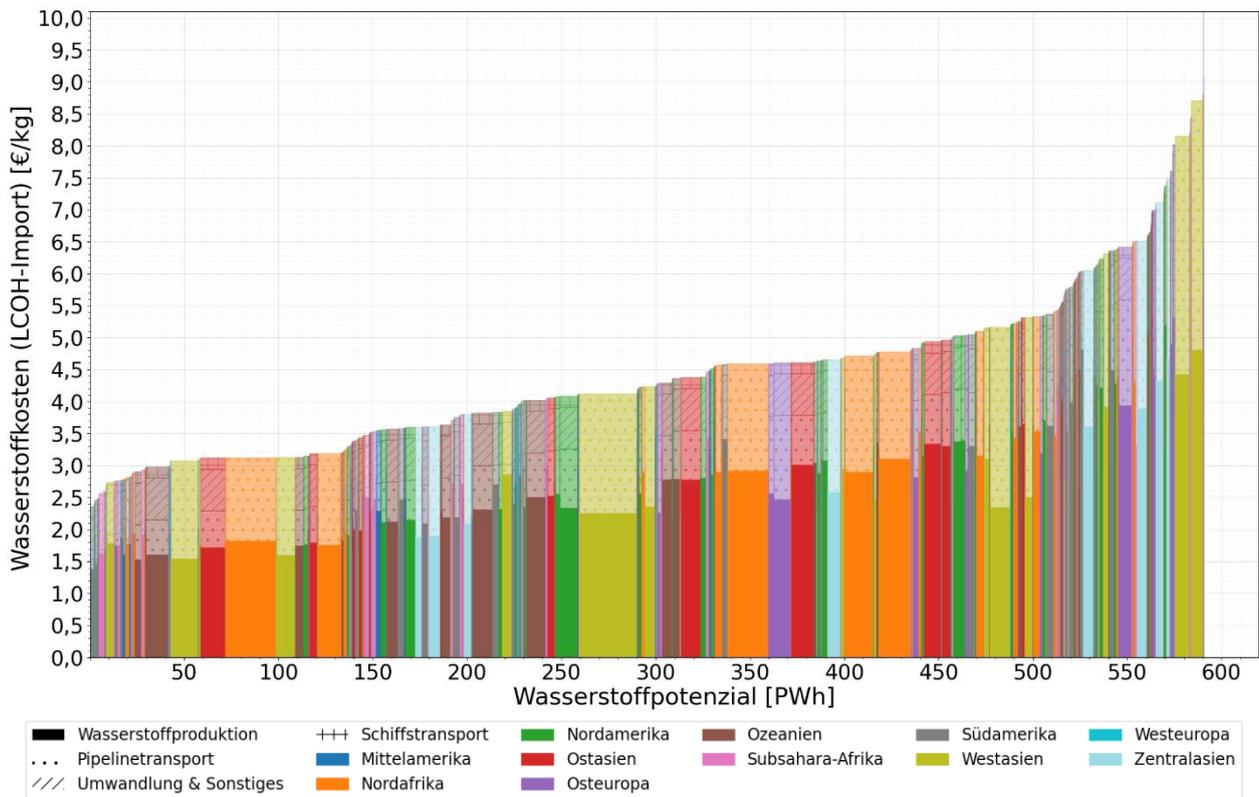
Figure 16: Supply potential curve for selected countries in North and South America for the Year 2050 (shipping with NH₃-Route including reconversion into molecular hydrogen at the import hub in Germany; moderate scenario with country-specific WACC and consideration of all renewable energy potentials up to 100 euros/MWh)



Source: Own illustration

The global supply potential curve for green hydrogen from the perspective of Germany as an importer is shown with its most important cost components in Figure 17. Following Pieton et al. (2023), the calculation of the transport costs shown in the global supply potential curve is based on the premise that for distances of up to 5,000 km, both ship and pipeline connections are possible for international transport (the variant with lower LCOT is shown) and above 5,000 km only ship transport is possible. For reasons of clarity, Figure 17 does not show all 48 selected countries individually, but summarizes them by world region.

Figure 17: Global potential curve for hydrogen supply for 48 selected countries in the Earth for the year 2050 (H₂Pipeline transport or ship transport with NH₃-Route including reconversion into molecular hydrogen at the import hub in Germany; moderate scenario with country-specific WACC and consideration of all renewable energy potentials up to 100 euros/MWh



Source: Own illustration

The analysis results shown in Figure 17 clearly show that the global potential for hydrogen exports exceeds the hydrogen demand forecast for 2050 by several times. In addition, since only countries are taken into account whose total renewable electricity generation potential exceeds their primary energy demand forecast for 2050 and the latter includes domestic H₂-Demand is already covered⁶, the reported hydrogen supply potential is essentially only exceeded by the H₂-Demand from those countries that will continue to rely on hydrogen imports in the future. In the cost range of around 2.5 - 3.0 EUR/kg alone, the global supply potential curve for green hydrogen at the German border in 2050 includes an import potential of almost 50 PWh/year. This is significantly more than the maximum import demand determined for the import countries considered in Chapter 2.5 combined. In the range of 3.0 - 4.0 EUR/kg, a further 200 PWh/year of hydrogen import potential can be tapped from numerous regions and countries around the world. The small difference in hydrogen import costs between the regions is an indication of how competitive the future hydrogen market can be.

⁶ Of the hydrogen production potential determined for each country, the cheapest quantities are used to cover domestic needs, are therefore not available for export and are therefore not included in the hydrogen supply potential curve (principle: “National energy transition first”).

Consideration of the entire value chain when importing green hydrogen to Germany also shows that the influence of the transport and conversion processes on the total costs (LCOH) is considerable, depending on the distance. Countries with higher hydrogen production costs but low WACC and short transport distances can therefore become at least as important partner countries for Germany in the future as countries with very low production costs, but which have higher WACC and/or are significantly further away. The analysis results thus show the variety of options for the long-term diversification of Germany's hydrogen imports and provide an indication of the forward-looking development of the necessary infrastructure and trade relations between potential export and import countries for green hydrogen.

2.7 Wholesale prices for hydrogen in Germany will remain comparatively high in the long term.

The previous chapters have shown that the potentially high global demand for hydrogen can be met by the sufficiently available - comparatively cheap - global supply potential of renewable energies. Furthermore, for the focus countries considered, it was shown how this hydrogen can be transported to Germany from an advantageous techno-economic point of view. In this chapter, the supply, demand and transport of green hydrogen are considered from a market perspective. For this purpose, a possible future hydrogen market for Europe and the MENA region is examined, with particular attention being paid to the distinction between hydrogen supply costs, which include the costs of production and possibly necessary transport to the target country, and the resulting market prices there. In addition, the long-term price elasticity of hydrogen demand in Germany is examined in more detail.

The hydrogen market model HyPriM was used for the market analysis⁷ used. The model analyzes possible trade flows and market prices. Market prices are collected on the basis of marginal costs on a full cost basis and thus assume the emergence of a perfect market, which will only emerge in a few years (see Wietschel et al. 2022a). Full costs are chosen because the operating marginal costs will not provide an incentive for market development in a market that is still in the process of being developed and is also characterized by low marginal costs. The marginal costs are collected on the basis of an energy system model to minimize the total system costs for a given demand to be met, which focuses on the hydrogen system. The model was developed with a country-specific resolution of 55 countries in Europe, North Africa and Southwest Asia for the period from 2030 to 2050. The results presented later are limited to the EU and neighboring countries.

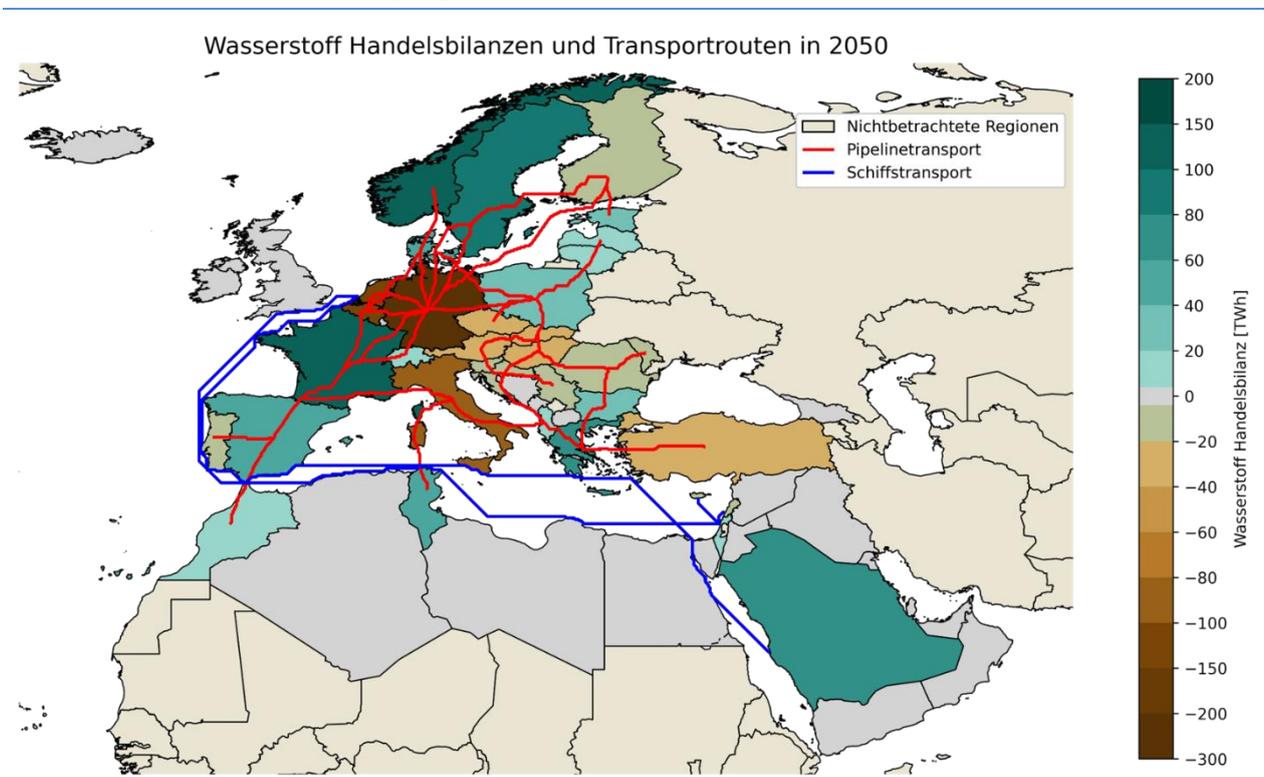
It is assumed that the countries will first use the cheap domestic renewable electricity generation options in the country itself. The remaining renewable energy potentials after covering the national electricity demand (based on Franke et al. 2024 & Mendler et al. 2024b) are summarized into country-specific hydrogen supply potential curves for possible export. These are compared with price-inelastic country-specific hydrogen demands taking into account various transport options. The approach builds on the findings from the previous HYPAT work and is based in particular on the modeling work of the

⁷ More information about HyPriM (HydrugsPriceModel) under www.hyprim.eu

Focus export countries. Due to the expanded spatial scope, the resolution was reduced and additional simplifications were made. Detailed information on the methodology and the underlying scenario assumptions are described in more detail in (Weißenburger et al. 2024). To analyze Germany's price-elastic hydrogen demand, existing energy system and demand models are used on a uniform data basis to calculate and investigate hydrogen demand at a range of possible predefined hydrogen wholesale prices. Further details on the methodology can be found in (Weißenburger et al. 2024b).

The results for the hydrogen market are presented below. A (supra-)regional hydrogen market can develop in the EU. With a hydrogen demand of 1,608 TWh in 2050, which comes from an ambitious climate protection scenario by (Fleiter et al. 2024), about 50% of European demand will be met within the countries themselves. The remaining share is traded internationally, with 84% of it being produced within Europe and only 16% being imported from other regions. See Figure 18.

Figure 18: Hydrogen trade flows in the EU and neighbouring countries in 2050 at a Realization of the Hydrogen Backbone at New Construction Costs



Source: Own illustration

In particular, Germany (-285 TWh), the Netherlands (-125 TWh), Belgium (-109 TWh) and Italy (-93 TWh) have negative export balances for green hydrogen. In contrast, France (+144 TWh), Norway (+127 TWh), Sweden (+82 TWh) and Greece (+69 TWh) have the largest export surpluses within Europe.

Hydrogen is imported from the MENA region via pipelines from Morocco to Spain and from Tunisia to Italy. However, the planned infrastructures of the European Hydrogen Backbone (EHB) (see European Hydrogen Backbone Initiative 2022), which are assumed to be realized, will not be expanded further, as countries such as Spain, Portugal and France are not able to compete with the hydrogen from Morocco and Tunisia in terms of supply costs.

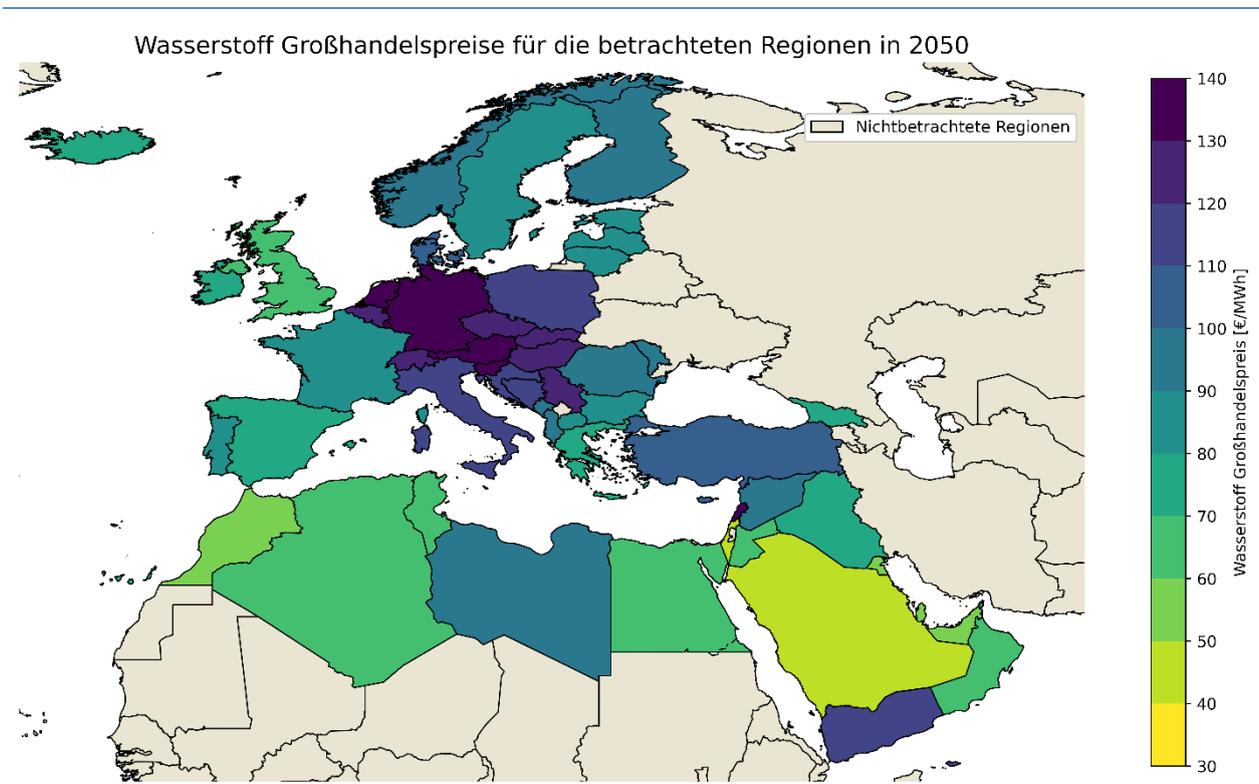
If the EHB is not implemented, the assumed H₂- Demand no need for a pipeline to the MENA region. A connection is only possible with a higher H₂-Inquiry required.

Ship imports represent a flexible and economically viable addition to transport via pipeline, and are particularly useful for long transport distances. In the market analysis carried out, ship imports contribute to making supply in the importing countries more flexible in the long term. In 2050, the model results show significant hydrogen flows by ship from Saudi Arabia to the Netherlands, with a volume of 49 TWh per year (see Figure 18). The advantages and disadvantages of ship transport are discussed in more detail for transport from selected focus countries in Chapters 2.3 and 2.4.

Germany sources hydrogen from various regions, with France (23%), Sweden (20%) and Norway (19%) being the main suppliers. Only 9% of hydrogen demand is produced directly in Germany and less than 1% comes from the MENA region (Morocco).

The determined wholesale prices, which here correspond to the marginal costs on a full cost basis (Wietschel et al. 2021), do not include domestic distribution network costs and vary greatly between regions. In Europe, they range from EUR 70/MWh in the UK to EUR 139/MWh in the Netherlands in 2050 (see Figure 19). Net export countries such as Spain and the UK benefit from lower prices, while higher prices can be observed in Central Europe.

Figure 19: Hydrogen prices in the EU and neighboring countries in 2050 if of the Hydrogen Backbone to new construction costs



Source: Own illustration

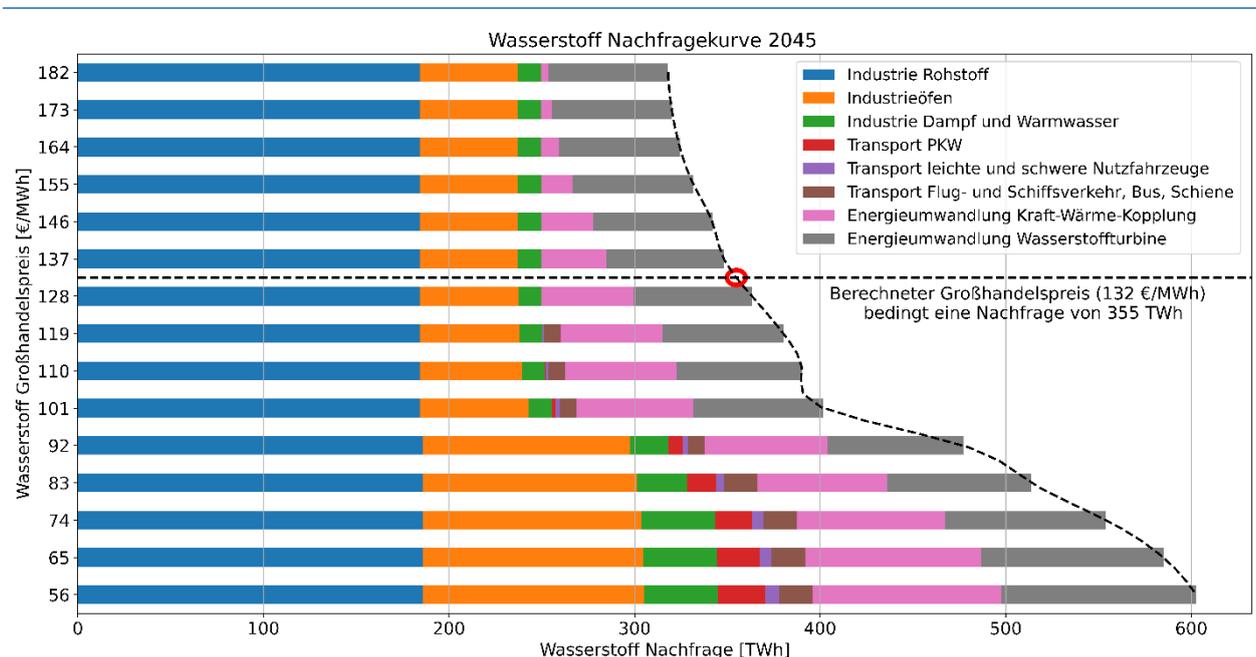
Interesting ^{becomes} it, if the wholesale prices, with the average Provisioning costs within countries can be compared, which are usually

comparable studies. In Germany, whose hydrogen mix comes from 13 different countries (with only 9% domestic production), the average supply cost of hydrogen in 2050 is EUR 97/MWh, of which EUR 16/MWh is for transport to Germany. The wholesale price, on the other hand, is EUR 132/MWh, which is EUR 36/MWh higher.

This deviation is particularly small in net export countries such as Spain and Great Britain, where the low-cost renewable energy potential is not fully exploited. In Spain, where 89% of the hydrogen mix comes from domestic production, the wholesale price of EUR 74/MWh is only EUR 9/MWh above the average supply costs of EUR 65/MWh.

The study also analyzes the long-term price sensitivity of hydrogen demand in Germany in more detail. A key finding is that hydrogen demand in all sectors is dependent on price. However, the elasticity varies in the individual sectors (see Figure 20). Industry (assuming no migration) and the conversion sector in particular still show a basic demand for hydrogen even at the highest prices examined. When prices fall sharply, this demand increases. The transport sector's direct need for hydrogen is rather low. It has no basic demand at high prices. Demand is rather low when the price falls below EUR 119/MWh. However, this analysis makes no statements about synthetic fuels, which can also be hydrogen-based.

Figure 20: Price-dependent hydrogen demand in Germany in 2045 at the target greenhouse gas neutrality)



Source: Own illustration

If both analyses are combined, Germany has a hydrogen demand of around 355 TWh at the calculated wholesale price of 132 EUR/MWh. The largest customer group is industry, with the main demand coming from the material H₂-Use and the use of H₂ in industrial furnaces. At this wholesale price, the conversion sector is mainly focused on power plants to cover peak loads, while there is no direct demand for hydrogen in the transport sector.

In conclusion, the present analyses illustrate the opportunities and challenges of a future supply of green hydrogen in the EU. The large difference between supply costs and wholesale prices, especially in import-dependent countries such as Germany, makes it clear that examining pricing is essential in order to estimate competitiveness in this market and possible effects. Despite the sufficient intra-European renewable energy potential to cover the H₂-Demand, the MENA region will play a complementary role in supplying Europe with green hydrogen when the backbone connections are implemented and can thus lead to the diversification of market participants. This is also to be seen as positive for reasons of risk hedging. In addition, ship imports from more distant regions with low H₂-production costs, such as Saudi Arabia, represent a flexible and economically viable addition to the European energy supply. Stakeholders should be aware that prices in countries that are heavily dependent on imports, such as Germany, are likely to be higher than the pure supply costs that have often been reported to date. In the EU, they are at the top alongside the Netherlands, which raises questions about the competitiveness of hydrogen-based products in Germany. Furthermore, the analyses show that at these wholesale prices, hydrogen will very likely only be able to prevail in applications where other options are lacking. Large-scale use of hydrogen in building heating and in road transport is therefore unlikely.

However, there are some limitations to be considered. In market modelling, H₂- Synthesis products on the supply and demand side have not yet been considered, which can further influence the development of the hydrogen market. However, a sharp increase in hydrogen demand was investigated as a sensitivity in Weißenburger et al. 2024.

The consideration is limited exclusively to green hydrogen. However, the use of blue hydrogen with possibly lower supply costs could play a decisive role as a bridging technology for a successful and timely market ramp-up of the hydrogen economy. The costs and availability of water have been neglected in hydrogen production.

In the analysis, the focus was expanded from direct country connections to the market, thereby increasing the resulting complexity. However, the borders of the EU-MENA region under consideration were cut off. In reality, countries such as Saudi Arabia could also supply their hydrogen to Asia instead of Europe. This would create competitive situations that are not taken into account in the present analysis. However, the proportion of hydrogen traded across continents in this study was small, so the impact should be minimal. In the future, the integrated hydrogen market should also be considered beyond the region, ideally globally. In addition, for a better coupling of supply and demand, hydrogen demand curves such as those presented here for Germany could be extended to the other countries and integrated directly into the market analysis.

2.8 The development of a market for hydrogen and derivatives imports is not a sure-fire success.

The construction of a hydrogen infrastructure is a huge task in terms of its dimensions. In order to cover 10% of the final energy demand with hydrogen and its derivatives, around 3,500 GW of electrolysis capacity are required (if one only uses

electrolysers for production). Furthermore, if the demand is to be met with green hydrogen, around 4,500 GW of renewable electricity production capacity would be needed. Currently, the total installed renewable electricity production worldwide is 3,100 GW (the share of renewables in global final energy consumption is 12.6% in 2021). This means that the installed renewable capacity would have to be increased by around 130% in order to be able to cover the demand for green hydrogen and its derivatives alone, without including renewables, for example, to replace existing fossil plants. Furthermore, direct air capture plants would have to be built for carbon-containing hydrogen derivatives, which can also only be operated with renewables if greenhouse gas neutrality is to be achieved. These plants are not yet commercially available. And corresponding synthesis plants would also have to be built.

These figures make it clear, among other things, that there is a high capital requirement for financing, that skilled workers must be available for this and that the approval and construction times must be appropriate.

As the IEA shows in its current review (IEA 2024), the number of announced low-emission hydrogen production projects has recently increased significantly, mainly through new electrolysis projects. However, only 7% of this potential production has at least made a final investment decision. The number of electrolyzer manufacturers who have announced ambitious expansion plans is also increasing rapidly. However, only 0.7 GW of electrolysis capacity is currently installed worldwide (IEA 2023b). Annual low-emission hydrogen production could reach 49 million tonnes in 2030 if all announced projects are realised (IEA 2024). For this to happen, however, the sector would have to grow at an unprecedented annual growth rate of over 90% from 2024 to 2030, which is well above the growth recorded by photovoltaics during its fastest growth phases. Several projects have been delayed and cancelled, putting a large proportion of the announced projects at risk (IEA 2024).

The short-term challenges are:

- The interests and policies of potential export countries are not always export-oriented and possible investments are hampered by a lack of planning security.
- Equipment and financing costs are rising and banks are becoming more skeptical.
- Clear commitments to creating production capacities on the one hand and purchase assurances on the part of users on the other hand are rare.
- Regulation varies internationally, which slows down cross-border projects.
- Approval procedures are delayed.
- Various geopolitical crises are creating new uncertainties.
- It is still unclear what effect the current hydrogen policy in the EU and other major demand countries will have on the global market ramp-up.
- There is only a rudimentary coherence of international policies within the framework of IEA, IRENA, OECD, G7 or G20.
- Technical development, including large-scale electrolysis and synthesis plants, is behind schedule, as is the development of an international storage and transport infrastructure.
- The pre-financing of the international transport infrastructure is not clear.

- It is not clear in what form hydrogen is transported and to what extent which derivatives are used.
- There are risks that today's investments, e.g. in ammonia infrastructure, could become stranded assets due to future changes in conditions.
- The current multiple uncertainties (including energy and raw material prices, supply disruptions, geopolitical unrest...) are unsettling investors.

2.9 The export region and the import criteria influence the acceptance of hydrogen imports in Germany.

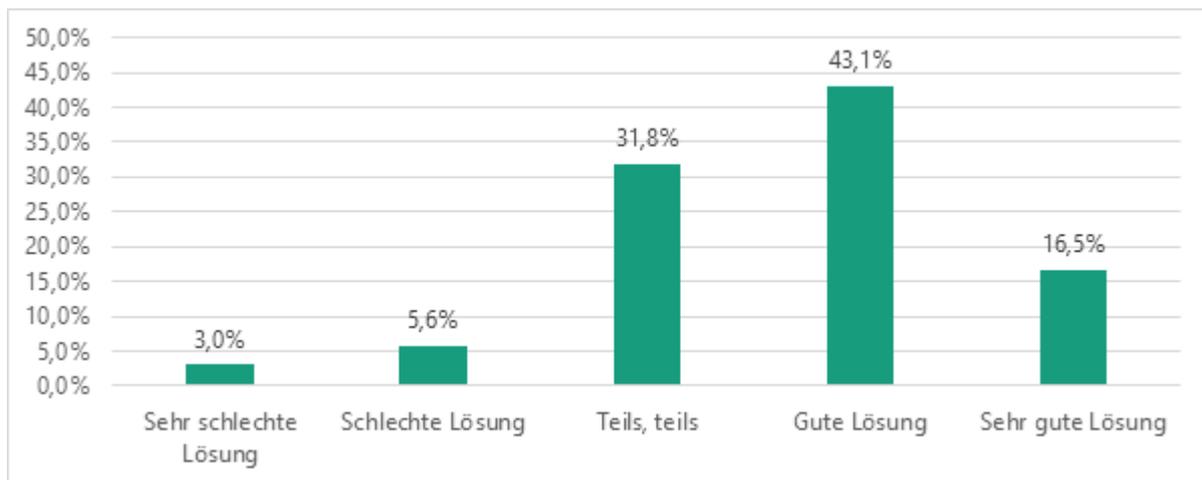
As already shown in Chapter 2.5, for example, the import of hydrogen, especially green hydrogen, will be crucial to achieving the climate goals of greenhouse gas neutrality in Germany. However, the success of a global hydrogen economy does not only depend on technological progress or economic competitiveness. Social acceptance of hydrogen technologies and imports is also crucial for successful implementation. A lack of or low public approval can significantly hinder the development and implementation of hydrogen projects, as has already happened with other energy technologies, such as carbon capture and storage. carbon (CCS) or nuclear power (see e.g. Wüstenhagen et al. 2007; Oltra et al. 2017).

Research on hydrogen imports has so far focused mainly on identifying suitable import countries and quantities. However, the social dimensions of these trade relations have so far been largely unexplored. Initial studies suggest that social justice in the exporting countries could be a decisive factor for the acceptance of the new hydrogen trade (Altenburg et al. 2023).

In this context, HYPAT analyzed both the perspective of the exporting countries (see Chapter 3) and the acceptance of hydrogen imports among the German population. The data for analyzing the social acceptance of hydrogen imports among the German population were collected via a representative online survey between August and September 2023. Participants were recruited via the panel of a market research institute and were representative of the entire German population in terms of gender, age, education and region.

The HYPAT study shows an overall high level of acceptance of green hydrogen among the German population (see Figure 21), while the level of awareness of hydrogen technologies among the population remains low. The survey results also show that the general acceptance of hydrogen depends heavily on the type of production: Green hydrogen produced using electricity from renewable energies such as wind power and photovoltaics receives by far the highest level of approval. Despite the generally positive attitude towards green hydrogen, the study shows that many people know little about hydrogen and its production. 30% of respondents say they know nothing about hydrogen or its possible uses, and around 60% of respondents rate their knowledge as limited.

Figure 21: "What do you think about the use of green hydrogen as a solution for Energy and environmental problems in Germany?"



Source: Scherrer et al. 2024

Interestingly, the study shows that although the focus of the survey was on regions outside Europe, respondents prefer European hydrogen imports (North America as an export region ranks second). This is in line with recent model calculations that emphasize Europe's self-sufficiency potential in hydrogen and point to a growing importance of derivatives (such as ammonia or methanol) in world trade (Wietschel et al., 2024). Support for imports from North Africa and the Gulf States (e.g. MENA region) was lower than for Europe and North America, but was supported by about half of respondents if a strategy with social standards verified by the importing country and import relations with several countries is pursued. About half of respondents support imports from this region under these conditions. For imports from all export regions examined, respondents' approval was higher if they came from several countries in a region and with social standards verified by Germany.

The results of the study were published as a HYPAT Working Paper by Scherrer et al. 2024 ("The acceptance of hydrogen imports in the German population").

In addition, building on the finding that some exporting countries are open to H₂-Production routes with Carbon Capture and Storage (CCS), the acceptance of CCS technologies was examined in more detail in another population survey in order to obtain information on the acceptance of such a trading path in Germany. For this purpose, an online survey was carried out with around 1,000 German private individuals.

The survey shows moderate to low levels of knowledge on the topic, which translates into a general attitude of neither approval nor rejection towards the use of CCS in Germany and in countries of the Global South. However, there is a tendency to perceive the technology as expensive and limited in its (positive) climate and environmental impact. The survey results indicate that the German population does not yet have a solid opinion on CCS and that this will be further reinforced by further information, for example in the course of media reports on German projects.² partnerships and growing experience with blue hydrogen.

3 Results from the perspective of export countries

3.1 Hydrogen can lead to a triple win for exporting countries – but the effect is not guaranteed.

From the perspective of exporting countries, the export of green hydrogen and derivatives can fundamentally promote the national energy transition, domestic decarbonization and local value creation. Synergies arise not only in terms of electricity generation and infrastructure as well as hydrogen use, but also in terms of building the capacity of skilled workers (see also 3.5). However, the extent to which this triple win can be implemented is highly context-dependent.

Within the framework of HYPAT, therefore, based on the catalogue of criteria developed in HYPAT (Breitschopf et al. 2022), in addition to comprehensive modeling work, qualitative-empirical studies were carried out on countries in Africa (Algeria, Kenya, Namibia, South Africa) and Latin America (Argentina, Brazil, Costa Rica and Uruguay). In addition, two other countries within pipeline distance to Europe, Turkey and Ukraine (along with Algeria), were included in the study. These potential and acceptance studies of predominantly middle-income countries were supplemented by analyses of Australia, another potential export partner for Germany.

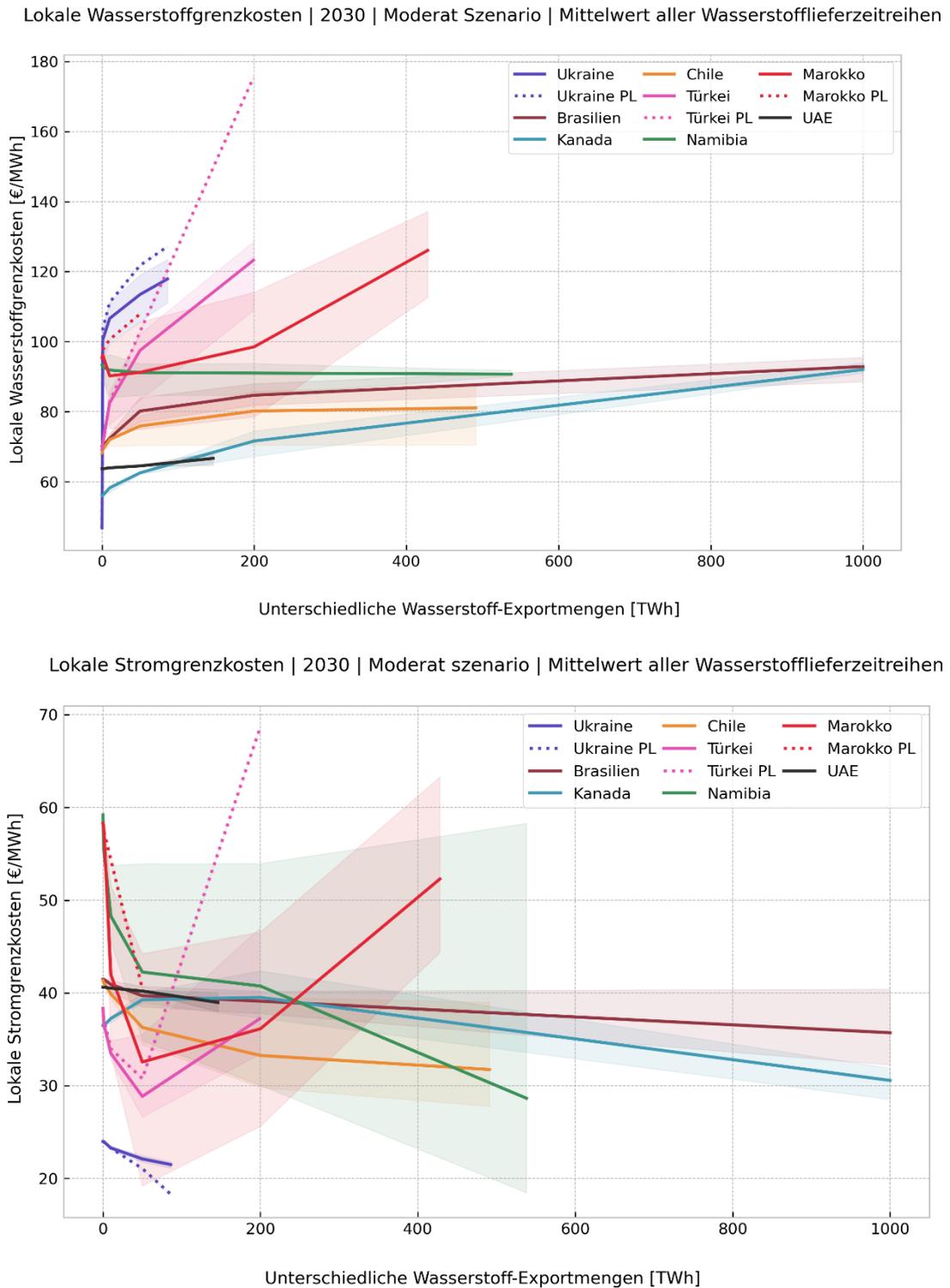
The results can be summarized, very briefly, as follows:

What the national energy transition As far as renewable energies are concerned, the expansion of renewable energies in the context of an export-oriented hydrogen economy can have a positive impact on the domestic electricity system (see Figure 22). As a model study has shown, with increasing export volumes of green hydrogen and derivatives in integrated projects, the domestic electricity mix changes significantly in favor of renewable energy due to the development of new renewable energy potential. This can have a positive effect on domestic electricity prices. However, this only applies as long as the favorable renewable energy potential is not exhausted or no high investments in energy infrastructure are necessary for system integration.

In countries that already have extremely low electricity costs from non-fossil fuels (such as Ukraine in the case of nuclear energy), the expansion of renewable energies can potentially lead to an increase in local electricity prices.

Increasing export volumes can also have a negative impact on the *domestic* hydrogen prices (not import costs/prices) will be affected if poorer renewable energy potentials have to be used due to increasing use. The construction of a national hydrogen network is also associated with high system costs, which can only be sustained if domestic demand is correspondingly high.

Figure 22: Local (a) marginal electricity and (b) hydrogen costs with increasing export volumes



Source: Own illustration

Figure 22 illustrates this relationship for selected countries under study. Rising hydrogen costs as export volumes increase are accompanied by falling electricity costs resulting from the overproduction of cheap renewable electricity from newly installed renewable energies.

In addition to these synergies between hydrogen exports and the national energy transition, there are also benefits in terms of domestic hydrogen demand. These are

important than the fact that the potential positive effects are considered to be small in relation to a pure hydrogen economy: It is still uncertain at what prices companies in industrialized countries are prepared to purchase low-emission hydrogen and what returns can therefore be achieved. The direct employment effects of export-oriented hydrogen projects are high in the construction phase, but this is not the case in the operational phase. Whether technological learning takes place to a relevant extent also depends heavily on the willingness of international investors to share knowledge and expertise.

The potential of a green hydrogen economy for **domestic decarbonization** of heavy industry and long-distance and heavy goods traffic was investigated in HYPAT using in-depth country studies. In addition to researching published and "grey" literature, this work is based primarily on qualitative-empirical methods such as semi-structured expert interviews and two visioning workshops (with South Africa and Brazil), with the direct involvement of various stakeholder groups from politics, industry, research and development in the potential export countries mentioned above. A research stay also took place in six of the countries; in the case of Argentina and Uruguay, intensive field research was carried out over three months. By involving five scientists from the countries under investigation, this study also made a significant contribution to transformative research because the results could be directly used by policy makers and other stakeholders in their work.

The potential for forward linkages is linked to the extent to which sectors of use are under pressure to reduce their greenhouse gas emissions due to national regulations or international agreements. One important industrial sector that should be mentioned here and plays a role in practically all countries is the refinery industry, in whose processes hydrogen - previously from fossil sources - has traditionally played an important role. Here, the use of low-emission hydrogen can help reduce greenhouse gases. Other industrial sectors in which hydrogen can play an important role in protecting the climate are industries that require high levels of process heat that cannot be generated using electricity. First and foremost here is metal production and processing (iron, steel, aluminum, copper). All of the countries examined in depth have a more or less important metal industry, some of which process raw metals into end products such as reinforcement or roofing sheets. The recycling of metals also plays an important role. The metal industry plays a key role, especially in Brazil, as one of the world's largest steel exporters. Green hydrogen is one of several decarbonization routes that the country is considering for this sector. Tax incentives, technology import facilitations and import tariffs on foreign (especially Chinese) steel products are intended to minimize the price difference between green and conventionally produced steel and thus increase international competitiveness.

Green hydrogen can not only contribute to the decarbonization of existing industries, but also drive re- and neo-industrialization in potential export countries. In Namibia, for example, the construction of a pig iron production facility based on the DRI-EAF route is planned (see Altenburg and Kantel, 2024). Furthermore, many countries want to use green hydrogen to replace imports, especially with regard to nitrogen fertilizers. As the second largest importer of nitrogen fertilizers, Brazil has concrete plans to revitalize the corresponding industry; with great potential for green hydrogen. In Kenya, there is already a project that is financially and technically supported by the BMZ PtX Development Fund (Oyan et al. 2024). Many of the countries are also relying on the

'Renewable/Hydrogen pull effect', the attraction of foreign direct investment or relocation of foreign companies.

In some of the countries studied, the potential of hydrogen is seen primarily in the conversion of parts of the transport system to low-emission drives. This is especially true for smaller emerging countries such as Costa Rica (see Stamm, 2024) and Uruguay. The focus is primarily on heavy-duty transport in agriculture and industry and, in some cases, long-distance buses. Potential for synthetic fuels is also seen in the propulsion of ships (e-ammonia, e-methanol) and, in the medium term, for aviation (e-SAF). With regard to the latter, countries that have biogenic carbon can particularly benefit. This applies to all the countries studied in Latin America. Domestic production of e-SAF can play a significant role, especially for Brazil as a regional hub for international air traffic.

The results show that hydrogen demand in exporting countries is often limited. Many of the countries studied (e.g. Costa Rica, Namibia, Uruguay) do not have a large industry whose decarbonization generates significant demand. In addition, the political incentive for decarbonization in the form of CO₂-pricing or national carbon markets. Therefore, the domestic market is in most cases ruled out as an initial driver of the hydrogen economy. In addition, the variation of possible technology paths that is characteristic of the formation phase of new socio-technical systems continues to prevail. The open question of which derivative or technology path will prevail in the long term contributes to great uncertainty among private actors and hinders the decarbonization potential of green hydrogen in the producing countries (see also 3.2).

Opportunities for industrialisation and local value creation arise not only in sectors in which hydrogen can be used as a raw material and fuel. New economic linkages are also possible in other backward and forward sectors. The extent to which this potential can be exploited depends primarily on the diversification of the economies. Turkey, Brazil, South Africa and Argentina have diversified economies and relatively strong industrial sectors that offer starting points for linkages to a developing hydrogen economy. For example, local production of wind power plants or parts thereof, as in the case of Brazil, can increase domestic value creation. However, entry into a highly concentrated supply market is difficult and is therefore limited to the production of locally specific or insufficiently transportable components (such as wind towers). Value creation can also be achieved in a developed service sector, for example in identifying optimal locations (*siting*) or specialized transport and assembly services. Countries with experience in the development of renewable energy (such as Uruguay) have comparative advantages in this regard that should not be underestimated, especially when it comes to setting up pioneering projects. Countries with sufficiently large innovation capacities, such as Argentina, Brazil, South Africa and Turkey, are already showing signs of developing new niche technologies. These include, for example, small-scale electrolyzers for the domestic market (Argentina and Brazil), innovative hydrogen carriers (Turkey), and low-emission mining vehicles (South Africa) (see e.g. Stamm et al. 2023 and Oyan 2024).

However, the interviews did not provide any indication that most countries are capable of developing technologies beyond demonstration projects or for export in the short or medium term. The technical challenges are too complex and the international competition from suppliers from Europe and China is too tough. In addition, there is a lack of skilled workers and financial support for scaling these projects.

Table 2 compares the countries studied with regard to the main industrial development pathways. A detailed description of these pathways can be found in Altenburg and Strohmaier (under review). In addition, UNIDO/IRENA/IDOS (2023) contains a detailed description of policy instruments available to potential export countries in the Global South in this regard.

Table 2: Industrial development pathways according to national strategies and programmes (see Altenburg and Strohmaier 2024, under review).

complexity VW's activity	country	H ₂ product tion route	export	local decarbonization rung		Construction technological niches		Renew- able Energy & hydrogen pull
				In- dus- trie	Trans- port	local finished supply	Innova- tions	
			(1)	(2a)	(2b)	(3a)	(3b)	(4)
high	Türkiye		○	●	○	○	●	—
	Brazılı		●	●	○	○	—	○
moderate	Costa Rica		○	○	●	○	○	○
	South Africa		●	○	○	○	●	—
	Argentine nienz		●	○	○	●	○	—
	Uruguay		●	○	○	○	—	—
small amount	Kenya		○	●	○	—	—	○
	Namibia		●	—	○	○	—	○
	Algeria		●	○	—	—	—	—

¹program (instead of national strategy)

²National Strategy suspended under current government

: green; : blue; : other production routes (eg nuclear, pyrolysis, natural H₂)

: strongly persecuted, : relevant, —: not relevant/addressed

Chapter 3.2 specifically addresses the importance of existing industrial capacities for the development of local component manufacturing, based on a complexity study of selected countries in the MENA region.

3.2 The industrial conditions for producing components of the hydrogen value chain in exporting countries vary greatly

The HYPAT project investigated the economic complexity of green hydrogen production technologies and the industrial prerequisites

different countries for the local production of parts of the value chain. For this purpose, a list of 36 "Green H₂Products" that are relevant for the production of green hydrogen and includes technology components of solar PV, wind turbines, batteries and electrolyzers. The results were published as an article in the scientific journal "Renewable and Sustainable Energy Reviews" (Müller & Eichhammer 2023).

The know-how required to manufacture these components is analyzed using international trade data from 1995 to 2019 using the methods of economic complexity and product space (see Hidalgo et al. 2007, Hidalgo & Hausmann 2009). The methods are based on the concept of revealed comparative advantage (RCA). An RCA value greater than one indicates that the export share of a particular product in a country's national export basket is above the global average. Based on this, the country-specific "Economic Complexity Index" (ECI) and the product-specific "Product Complexity Index" (PCI) can be calculated.

- **HeightECI**Values show that a country exports a wide variety of products with a comparative advantage, especially those that are exported by only a few other countries. The country in question therefore has a diversified and complex industrial structure.
- **HeightPCI**-values mean that the product is exported only by a few countries that have a complex industrial structure, indicating a high level of specialized knowledge and skills to produce this product.

In order to examine how well different countries are positioned for the production of the products relevant to the green hydrogen value chain, the "Green Complexity Index" (GCI) is also calculated. This combines the theory of product complexity with the concept of selected green products, in this case the 36 "Green H₂Products".

- The higher the GCI value, the better the industrial conditions for producing a large number of the relevant components.

A final central concept of the analysis is the proximity between two products based on the probability of joint export, which serves as a measure of shared relevant industrial know-how. The visualization of the network representing the interconnection between the products is called "Product Space".

The analysis of the complexity of the identified "Green H₂Products" and "Close to Green H₂ Products" shows that they tend to have higher PCI values compared to other traded goods, which indicates a higher need for industrial know-how. Looking at the distribution of the products across the four quartiles of the mean PCI values (see Table 3), none of the 36 "Green H₂Products" are in the lowest quartile, while 21 products are in the highest quartile. Overall, more than half of the products potentially relevant for green hydrogen production are statistically among the historically most complex 25% of all traded goods, while only 5.6% are below average in complexity. Of the 470 "Close to Green H₂Products" the distribution is similar: 53.0% of these products are in the highest quartile, while 36.1%, 10.0% and 0.8% fall into the following quartiles, respectively.

A key finding is that the technology components examined are comparatively complex to manufacture.

Table 3: Relative complexity of the different product groups by classification into the quartiles of the mean PCI values of all products from 1995 to 2019 (Müller & Eichhammer 2023)

	Q1	Q2	Q3	Q4
Number of "Green H₂Products"	0	2	13	21
Number of "Close to Green H₂Products"	4	47	170	249
number of all products	1,149	1,148	1,149	1,149
Share of "Green H₂Products"	0.0%	5.6%	36.1%	58.3%
Share of "Close to Green H₂Products"	0.8%	10.0%	36.2%	53.0%
share of all products	25.0%	25.0%	25.0%	25.0%

μμ

The "Green H₂Product Space" shows an uneven distribution of connections: some products, such as heat exchangers, are strongly interconnected with other products, while others have only a few connections. The 434 products identified that are highly close to at least one of the 36 "Green H₂Products" mainly come from the fields of electronics, mechanical engineering, vehicles, chemicals and metals. These components of the hydrogen value chain thus offer an opportunity for diversification of the industry through know-how transfer in these areas. At the same time, countries with already developed industries in these areas can more easily set up local development and production of hydrogen technology components. Components of the hydrogen value chain represent an opportunity for green diversification.

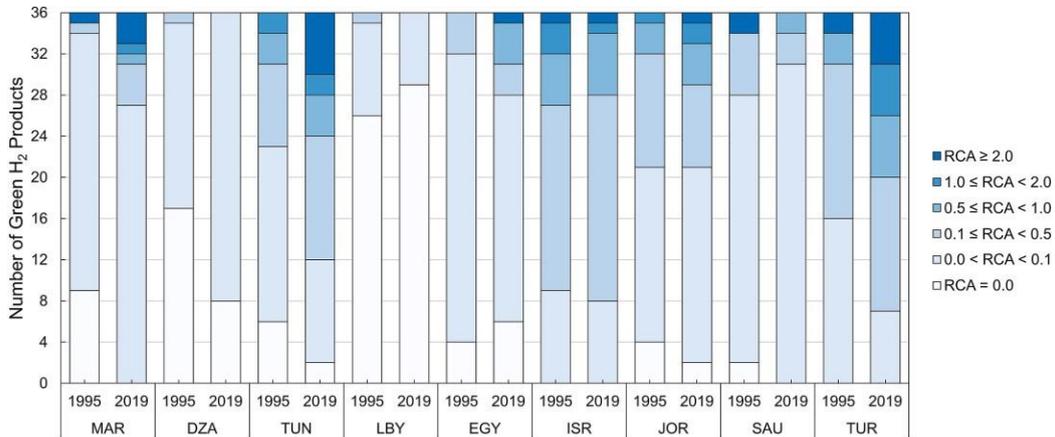
The analysis of the Economic Complexity Index (ECI) values of 107 countries in 2019 shows that economic complexity tends to increase with gross domestic product (GDP) per capita. Countries such as Japan, Germany and Switzerland have the highest ECI values and are therefore particularly well positioned industrially. Some emerging countries such as India and Mexico have above-average ECI values for their GDP per capita, which indicates greater industrial diversification and higher know-how. Countries with high ECI values usually also have higher GCI values and are thus better positioned in the field of green hydrogen technologies. There are exceptions, however: While Germany, Japan and Switzerland are close together at the top in terms of ECI values, Germany is far behind in terms of "Green H₂ Products" than Japan and especially Switzerland. In addition to Germany, China stands out in particular, which has a unique development in the area of "Green H₂Products". While China only had three of the 36 identified "Green H₂Products", in 2019 it had already reached 31.

It can therefore be concluded that there are large differences between countries with regard to industrial conditions and their development over time.

A detailed analysis of nine MENA countries (see Figure 23) shows that Turkey and Tunisia already possess industrial know-how in various components of green hydrogen technology and perform only slightly worse than potential European competitors, while Algeria, Libya and Saudi Arabia have the lowest scores in terms of calculated hydrogen-related green complexity. These results are supported by statistical tests showing that countries with a higher share of natural resources in gross domestic product have significantly lower scores in economic and green complexity. This phenomenon is known as the "resource curse" and describes the paradox that countries with rich natural resources often have worse economic development and growth rates than resource-poor countries.

Thus, fossil exporters have a below-average economic complexity, especially with regard to the identified "Green H₂Products".

Figure 23: Number of "green H₂products" within a certain RCA threshold with colours ranging from light blue (RCA = 0) to dark blue (RCA ≥2) for nine different MENA countries in 1995 and 2019



Source Müller et al. 2023

3.3 Hydrogen projects have a high potential for conflict during implementation

In the countries for which in-depth studies were carried out, hydrogen projects are usually available in the form of pre-feasibility or feasibility studies, which is why potential conflicts have hardly come to light yet. The available experiences and statements from interviewees imply that conflicts only become virulent when planning goes beyond political declarations of intent and "siting" begins, i.e. when concrete considerations are made as to where projects could be implemented. Only then can possible interventions in the natural balance and subsequent effects on the local population be measured and potential conflicts assessed. This ties in with different dimensions in studies on technology acceptance in transition processes, in which a distinction is often made between social acceptance (at the general population level), market acceptance (for scaling technology markets) and local acceptance. In particular, local acceptance challenges and associated conflicts usually emerge during the phases of concrete implementation processes (Wüstenhagen et al. 2007).

An example of this is the conflict over the hydrogen project in Tambores in **Uruguay**. A joint venture between the German company Enertrag and SEG Ingeniería from Uruguay is developing a project to produce hydrogen and derivatives (e-methanol) in this location. A capacity of 350 MW is planned to produce 15,000 tons of hydrogen annually on site. The population of the region does not feel sufficiently informed and is particularly concerned about the water reserves in the region. The project envisages extracting the water for electrolysis from the Guaraní aquifer. This is a gigantic water reservoir under parts of Argentina, Paraguay, Brazil and Uruguay. Several of the experts interviewed do not see any fundamental threat to the availability of water in the region, for example for irrigation agriculture. However, it is not yet possible to conclusively clarify how rapid and large-scale water extraction in one place will affect the water supply in the immediate vicinity. Several residents of

Tambores have filed a complaint with the country's Constitutional Court. Most of those interviewed agree that inadequate and late communication between the project management and the local population is the main reason for the escalating conflict.

The issue of communication was also evident in other countries, for example in **Namibia**. There has been criticism of the lack of disclosure and public consultation, as well as the failure to comply with transparency rules in hydrogen investments. If strict transparency rules are not applied, direct involvement in deals with large investors can create opportunities for legal (e.g. consulting fees) or illegal (bribes) advantages, and politically connected individuals and firms can gain privileged access to secondary sources of income. The principle of "prior and informed consent" (*prior and informed consent*) should be applied whenever investment projects have potentially far-reaching impacts on local communities. However, in a public letter to then Namibian President Hage Geingob, an alliance of local NGOs lamented the "lack of adequate public consultations and oversight" (Economic & Social Justice Trust, 2023).

Even if deals are transparent and all policy actors behave in a fully welfare-oriented manner, this does not automatically mean that the national (or local) population benefits on a large scale. For example, in Namibia, there may be fewer employment and socio-economic spillovers than hoped for in the national strategy, projects may be less profitable than expected – given all the technological and pricing uncertainties – and information asymmetries between large investors and Namibian decision-makers may lead to unfavourable risk-benefit-sharing arrangements.

Local conflicts over land, exacerbated by historical injustices from the colonial era, represent another significant sociopolitical challenge in countries such as Namibia - but also Kenya and South Africa. Ancestral land claims are of great importance to many Namibian communities, complicating efforts to resolve disputes (Altmann and Kantel 2024). Water conflicts may also develop into a significant potential conflict in the future in some of the countries studied. As arid countries already struggling with water scarcity, several regions in Namibia, including the capital Windhoek, and also the northern regions in Kenya, have problems accessing drinking water. The production of green hydrogen requires large amounts of fresh water for electrolysis. The additional water demand should be met as fully as possible by seawater desalination plants so that these can be built as part of the hydrogen investment projects. The Hyphen megaproject in Namibia includes seawater desalination. Here, desalination plants are designed to produce more than is needed for electrolyzers, allowing surplus freshwater to be provided to local communities (*oversizing*). This can certainly be seen as a measure for conflict management or prevention. However, there are environmental risks if the residues from desalination (brine) are not treated appropriately.

Costa Rica is one of the countries examined in which no conflict lines are evident, as no siting has yet taken place, so it is unclear which regions are likely to be affected. Since the high-potential regions for solar energy are in the western coastal region and those for wind in the mountain regions, the following conflict lines are to be expected: Large solar energy plants near the beaches on the Pacific could compete directly with tourism. Wind plants in the high altitudes of the mountains compete with nature conservation and

Here too, this is partly due to tourism, as some of the most visited national parks are located in the mountains (Stamm and Kantel 2024).

The potential conflicts related to the hydrogen transition are in **South Africa** particularly diverse and severe. The country is suffering from both an employment and an energy crisis. Statistics South Africa estimates the overall unemployment rate for the first quarter of 2024 at 32.9% and youth unemployment at 45.5%. In addition, the country has been suffering from an energy crisis for several years, with constant power outages leading to significant economic losses and business closures. The biggest challenge for the future is the closure of coal-fired power plants, only partially as part of a conscious energy transformation strategy. Many power plants have simply reached their maximum lifespan. Mining will also be affected here. South Africa currently uses three quarters of the coal mined domestically, in power generation and coal liquefaction. To avoid an exacerbation of latent conflicts, hydrogen projects must create a relevant number of sustainable jobs and they must be designed in such a way that the population also realizes that the domestic energy shortage will not be further exacerbated. To achieve this, renewable energy plants would have to be planned beyond the direct needs of hydrogen production and excess electricity would have to be fed into the grid. Foreign investors should be encouraged to invest in the repair and maintenance of the electricity grids. As in the case of Namibia, the situation in South Africa is similar with the water supply. Parts of the country suffer from permanent or seasonal water shortages. Large H₂-Plants must be preceded by desalination plants for seawater. Here too, *oversizing*, for example to supply agriculture with clean water, a way to prevent and resolve conflicts.

In the case of **Kenya** a few years ago, a qualitative survey found broad support for renewable energy projects, coupled with the hope of being able to reduce the very high electricity prices. Kenya also emphasizes the potential of supporting its agricultural sector through hydrogen production or the production of nitrogen fertilizers, and thus counteracting food shortages. The interviews identified a number of potential conflict points that could prevent a rapid ramp-up of the hydrogen economy. As in Namibia and South Africa, access to land is a contentious issue. Clarifying the associated legal issues is time-consuming. This particularly affects systems that rely on large-scale use of PV, because this requires large areas of land. Balancing the interests of investors in renewable energies / hydrogen and the local population is seen as a major challenge. Water use is another potential conflict point. Kenya is an arid or semi-arid country, at least in large parts of the country, and suffers from water stress at least at certain times. Seawater desalination is a necessary step to avoid conflicts of use. Plans for large-scale desalination plants have been in place for years, but they have not yet been implemented. Another point of conflict identified for Kenya is the possible competition for the use of the additional electricity generation capacity that needs to be created. In recent years, Kenya has made significant progress in supplying the population with reliable electricity. However, 25% of the population is still not connected to the grid. It cannot be ruled out that a massive expansion of renewable energies will lead to conflicts over the use of electricity between hydrogen production and use in households. In addition, irrigation agriculture is also expanding, which can lead to additional conflicts over use (Oyan / Kantel 2024).

A key challenge in **Brazil**, which could be exacerbated or mitigated by the establishment of a green hydrogen economy, is the great heterogeneity between the regions. The country is currently characterized by a wealthy south with large cities and industry, a less wealthy but economically emerging northeast with great potential for renewable energies, and rainforest regions in the northwest.

In the past, the differences between these regions and the people living there have led to struggles over indigenous rights, settlements and resources in the Amazon and beyond. One respondent also described the social divide between the ethnic groups living in the large wealthy cities and the smaller settlements in the north as visible (interview with the University of Rio).

Politically, the country has recently undergone a transition from a government with a more conservative and private profit-oriented approach to a new leadership that is perceived as more socially and environmentally focused. Nevertheless, political perspectives on both sides remain within the wider government structure and society and it cannot be taken for granted that this changed focus will remain stable in the future. This could particularly impact the green aspect of a developing hydrogen economy.

The documents and interviews focused mainly on potential conflicts that could arise in the energy sector related to land use. The expansion of energy infrastructure, depending on location and scale, could lead to land use conflicts with the natural environment in previously undeveloped areas, as well as with individuals and communities in already inhabited areas. In the past, conflicts related to the latter dimension have been reported for the general population in certain regions, as well as for indigenous communities. In the energy sector, conflicts in the past have mainly concerned hydroelectric power plants. Some hydroelectric power plants in the rainforest area were contested for decades before they were built.

Four other important points could be considered for the future acceptance of a hydrogen economy in the Northeast. *First* respondents mentioned that the electricity grid would need to be expanded to accommodate new renewable energies and/or transport enough energy to the hydrogen production sites. This fact was mentioned neutrally in the interviews. However, it remains to be seen where and in what capacity or extent such expansions will be necessary in the northeast and other parts of the country and what impact this will have on the acceptance of hydrogen. Some respondents expected fewer conflicts locally than in other countries, as the existing grid connections could enable the production of green hydrogen with green grid electricity, instead of, for example, large solar plants and the necessary grid extensions having to be built entirely additionally (BHA interview, AHK interview).

Secondly respondents mentioned the need for desalination plants. On the one hand, they were seen as key to avoiding conflicts with already scarce freshwater sources and to increasing acceptance, but on the other hand, it is not yet clear what should be done with the residual products from desalination, such as brine. Corresponding developments must be monitored in order to protect the local population and the coastal environment.

Third Hydrogen plants, including electrolysers, must be built. Interviews and documents highlighted the potential for this development in or near existing port facilities and industrial areas. The exact placement and

However, the necessary extensions are still unclear and would particularly affect local acceptance.

Fourth the interviews showed that many stakeholders consider the Northeast to be sparsely populated and therefore do not expect major acceptance problems. However, recent developments and acceptance studies on wind energy in the region have shown that new energy projects can lead to challenges for local communities, for example for local fishermen who specifically depend on the natural coastal environment. In addition, acceptance among indigenous peoples living in the region may vary due to their way of life. Recent press releases provide initial indications that indigenous people are being consulted when planning new projects. However, it remains important to monitor developments as projects move from the planning phase to the actual construction phase and operation and as the impacts of implementation on the ground become more concrete (*Fundação Nacional dos Povos Indígenas*).

In Algeria Low-carbon hydrogen has only recently been on the political agenda. Just a few weeks ago, the Algerian hydrogen strategy was adopted and published. A number of international partnerships to develop the technology have been concluded, including with Germany and Italy. In principle, the country has excellent natural conditions for the production of green hydrogen and the export of the energy carrier to Central Europe. The country has one of the highest levels of solar radiation in the world. It also has a well-developed gas infrastructure that connects it to Europe and which could be used alternatively to transport hydrogen or hydrogen derivatives in the future. Given the country's declining gas production and increasing energy consumption, hydrogen could help increase Algeria's energy security, diversify its energy mix, decarbonise carbon-intensive sectors and meet the country's commitments to combat climate change. However, the potential investments in a hydrogen economy give rise to several economic, technical and, above all, political challenges. There is a widespread lack of industrial development and diversification and a strong private sector. Institutional and market reforms are needed to increase transparency, encourage market entry and create a level playing field for domestic and international investors along the hydrogen value chain. Most importantly, the transition from a fossil fuel-based economy to a new model with uncertain profitability seems to be a risky decision for the various centers of power in Algeria, such as the economic elites and the state-owned oil and gas companies (Aboushady and Jaroudi 2024).

3.4 The national H₂-Market ramp-up is largely shaped by transnational factors.

The hydrogen economy is a new large-scale technical system that requires coordination between national and international processes in many respects. Especially with regard to **technology availability** From the perspective of most export countries, dependence on foreign countries is very high. In addition to established technologies (such as in the production of renewables), innovative processes (such as electrolysis) are necessary, the development of which has so far been limited to industrial nations such as Germany, the USA and China. Therefore, within the framework of HYPAT, cost-optimal transformation paths of the hydrogen economy were examined for a variety of scenarios using a new, global and multi-regional cost optimization model. The focus of the analysis was on examining the long-term

establishing production technologies as well as the resulting international Trade structures. The results show, on the one hand, that the speed of technological progress in electrolyzers is a key factor in the cost degression of green hydrogen. On the other hand, they point to the importance of spillover effects between different regions, e.g. between industrialized and developing countries. Spillover effects occur when one region benefits from the experience gained by another region in using a technology and thereby achieves lower costs itself. This phenomenon is well documented in the literature and is also of great importance for the hydrogen economy, as economically less developed producing countries are likely to need support in setting up hydrogen production. In scenarios without spillover effects, regions with good renewable potential but weaker economic development, such as Latin America or Africa, do not establish themselves as exporters because they lack the necessary access to low-cost electrolyzers and these regions do not achieve competitive production costs through their own research and development. Instead, Asia is becoming the dominant exporter. In the more realistic scenario with spillover effects, however, the Middle East, Africa and Latin America play an important role as exporters, as confirmed by the rest of the literature.

The results of the model analyses thus clearly underline the availability of the technology for the potential export countries and are also reflected in the qualitative-empirical potential studies on developing and emerging countries.

None of the countries included in the in-depth studies are in a position to drive forward the hydrogen ramp-up on their own. Rather, cooperation with players in other countries and, in some cases, regions of the world is required. Some of the countries examined have the technological know-how to build large solar and wind farms that can supply electrolyzers with renewable energy. In a few cases, this can be done on the basis of technology developed in-house, but the systems are often purchased from abroad. All of the countries examined would have to purchase electrolyzers from international suppliers because they are not yet able to develop their own systems above the laboratory scale. In principle, there are a large number of suppliers of electrolyzers from various supplier countries, for example Norway, China or Germany. However, the costs for electrolyzers, including the balance of plant, are still very high. This is particularly true for small units. Whether and how quickly there will be a cost degression depends, among other things, on how quickly the hydrogen ramp-up takes place globally. Related to this is the question of which production model the suppliers are pursuing. So far, electrolyzers have been manufactured to meet specific customer demands. Series production and technological advances that save raw materials could significantly reduce unit costs.

In addition to the availability of technology, financing is also a significant hurdle for many countries, which can only be overcome with international support and foreign direct investment. In some of the countries examined (such as Costa Rica or Uruguay), hydrogen projects are still in the pre-feasibility phase or feasibility studies, discussions or negotiations with international project developers and investors about specific projects are ongoing. Whether they will actually be implemented is still very uncertain (with the exception of Namibia). Final investment decisions (*Final Investment Decisions*, FID) are still pending. Whether and when FID will be met did not become clearer over the investigation period.

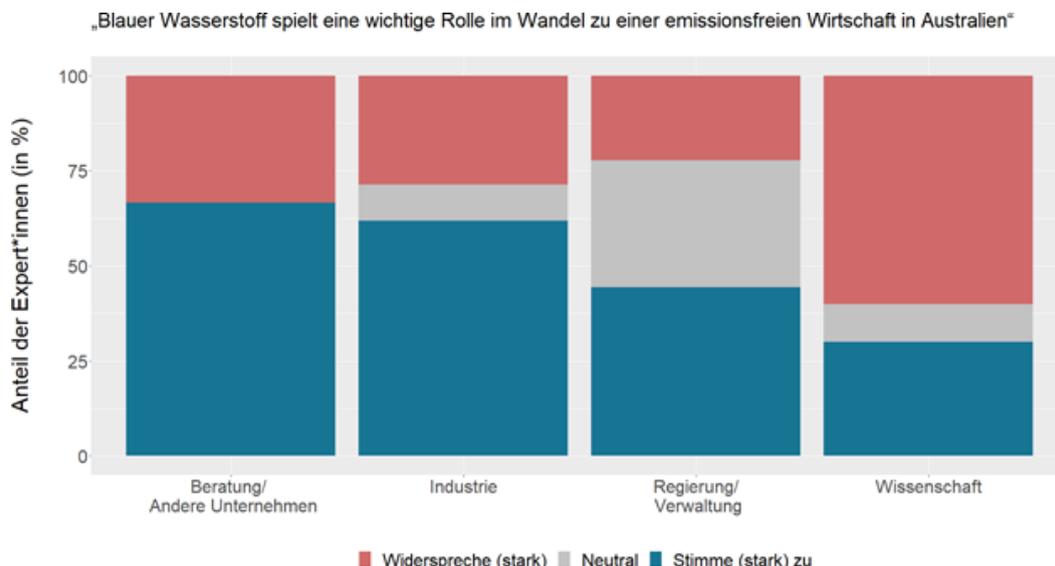
According to the experts interviewed, a whole series of market uncertainties are preventing positive decisions. The question of when and how large quantities of hydrogen and/or derivatives (ammonia, methanol) can be traded internationally safely and cost-efficiently has not yet been answered.

A further uncertainty is seen in the prices that buyers on the major markets are willing to pay, especially if costs are incurred for conversion to derivatives and possibly reconversion to elemental hydrogen.

In particular, the role of alternative production routes, especially blue hydrogen, in the market ramp-up is unclear. In the in-depth studies on developing and emerging countries, it became clear that most countries are focusing on green hydrogen because the signals from Germany and Europe have long shown a clear preference for this. However, five of the countries studied in more detail also state in their national strategies that they are open to blue hydrogen from natural gas or coal and other production routes (see Figure 24). The countries are "color agnostic" in particular for domestic use, which can lead to the emergence of "H2 tandem markets" with different hydrogen colors for domestic and foreign demand. Countries such as Brazil and Argentina also want to specifically use their comparative resource advantages and combine the development of existing natural gas sources with new sales opportunities.

The ambivalence regarding production routes is also reflected in the study on Australia. Using an expert survey, the expectations of various stakeholders regarding the ramp-up and export of hydrogen were recorded and compared, focusing on the most important hurdles and policy instruments. The study included interviews with 47 high-ranking experts from industry, other companies, science, politics and administration. The expert survey showed that the role of blue hydrogen in the energy transition there is still controversial among stakeholder groups. As shown in Figure 24, agreement with the statement that blue hydrogen plays an important role on the way to a zero-emission economy is highest among representatives of the private sector. In contrast, experts from science are the most skeptical, while people from government and administration position themselves in between.

Figure 24: Perceived importance of blue hydrogen by stakeholder group

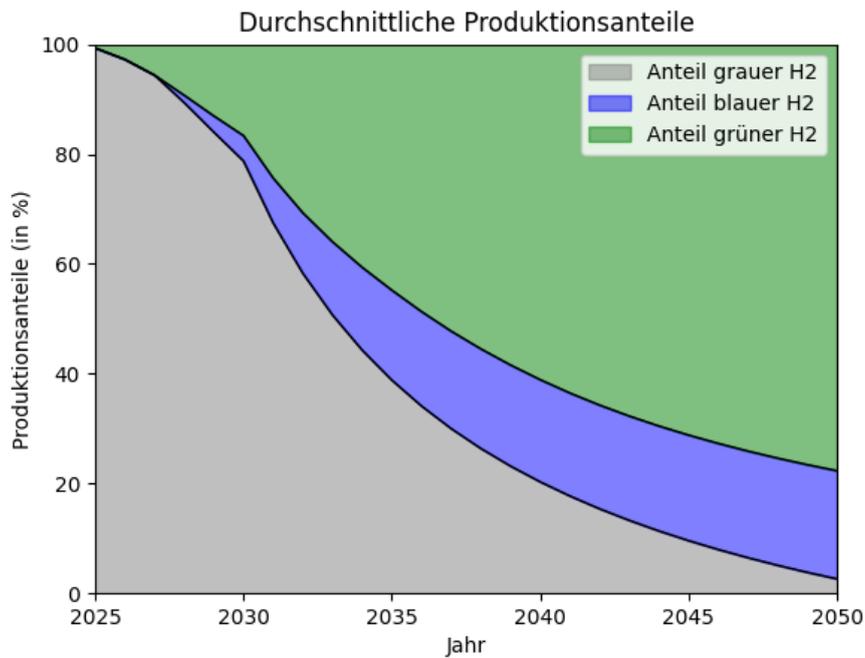


Source: Own illustration

The model analysis also showed that green hydrogen is the dominant production technology in most of the scenarios examined and that this dominance is relatively robust to changes in important techno-economic parameters (see Figure 25). Nevertheless, blue hydrogen is particularly attractive in regions of the world with favorable

Gas prices are a cost-effective alternative. In realistic to optimistic scenarios, it therefore functions as a bridging technology. In scenarios with high prices for renewable energy and slow technological development of electrolyzers, blue hydrogen can even be the cost-optimal production technology in the long term. As shown in Figure 25, blue hydrogen represents around 20% of global hydrogen production on average across all scenarios considered in 2050.

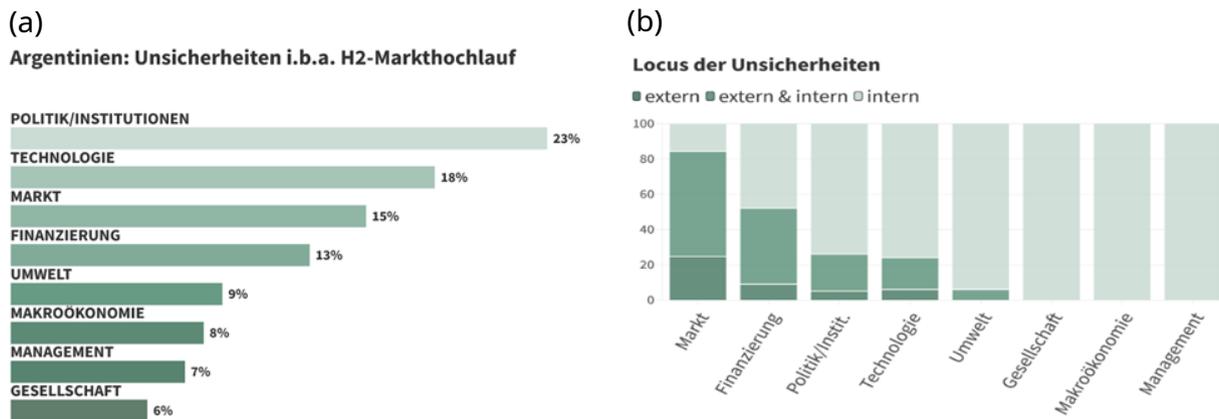
Figure 25: Average share of different production technologies



Source: Own illustration

What political factors As far as the green hydrogen market is concerned, a study on Argentina and Uruguay with regard to uncertainties in the market ramp-up of green hydrogen - in the context of which 75 stakeholders were surveyed, among others - highlights the challenges at the political and institutional level. In Argentina in particular, the change of government in November 2023 has led to great uncertainty among actors, which increases the imponderables at the technology, market and financing levels (see Figure 26(a)). Changing political orientations and faulty or unstable institutions strongly influence the decision-making behavior of domestic and foreign investors.

Figure 26: Uncertainties in the market ramp-up of green hydrogen in Argentina.



Source: Own illustration

As Figure 26 (b) also shows, many of the uncertainties mentioned above are perceived as external. In particular, a large proportion of respondents see the demand and financing of the market ramp-up clearly in international hands.

In addition, a comprehensive regulatory framework and a consistent, harmonized certification system in all countries studied are assessed as a key measure – and previously missing element – in building a national and global hydrogen economy.

Hydrogen diplomacy is considered particularly important: for example, the expert survey in Australia shows that existing relationships in the form of energy partnerships, economic agreements, trade relations and corporate cooperation, in addition to a high willingness to pay, are the most important criteria when choosing importing countries. These results are also reflected in the other in-depth country studies.

The Federal Constitutional Court's ruling of November 2023 on the Climate and Transformation Fund (KTF) has not only contributed to political uncertainty at the international level from the perspective of the exporting countries, but has also significantly limited the Federal Government's scope for supporting the market ramp-up with public funds.

3.5 Diverse interactions between national energy transitions and international hydrogen cooperation must be taken into account.

As part of HYPAT, possible interactions between national energy transitions and the development of an (at least partially) export-oriented hydrogen economy were also investigated and important aspects of these interactions were highlighted. The global goal of entering the hydrogen economy must always be kept in mind: Green hydrogen should contribute to a reduction in global CO₂ emissions. To do this, it must be ensured that green hydrogen actually and from a broad perspective (largely) reduces CO₂-neutral production. This also means that emission reductions in countries that import green hydrogen for their energy transition must not be at the expense of the energy transition in the exporting countries,

This means that it must be ensured that the energy transition in the exporting countries is not hindered but supported. This is also a requirement that is reflected in the German National Hydrogen Strategy.

Clarifying the role of hydrogen in the respective national energy transition is still in its early stages in many countries. Being more aware of the opportunities and risks is a first step towards taking these into account in the further design of the political and regulatory framework. Opportunities must be actively exploited and risks actively managed - proactive policy is essential for both.

Basic recommendations that can be derived from HYPAT results include the following aspects:

It must be avoided that hydrogen projects, especially if they are intended for export, lead to a displacement or postponement of already planned energy transition projects or to dwindling acceptance of the energy transition strategy in the country itself. It must also be avoided that local greenhouse gas emissions increase as a result of an export-oriented hydrogen economy, e.g. if the additional electricity demand is covered by fossil fuels through the use of grid electricity.

The development of capacities and training programs for renewable energies must take into account the needs for local energy transitions and the entry into the hydrogen economy equally. One area must not be at the expense of the other. The same applies to the development of resources for administrative and approval processes or for the political management and regulation of the sector.

The entry into the hydrogen economy can have significant impacts on the local electricity system. These can often only be estimated through specific grid and water operation simulations. It may be useful to require such simulations when planning export-oriented hydrogen projects in order to systematically analyze the impacts on the local electricity system.

Negative impacts on the local grid infrastructure can initially be avoided by using isolated solutions when planning export-oriented hydrogen projects. In the medium to long term, however, hydrogen production and use should be integrated into the local energy system and therefore explicitly addressed and incorporated into grid expansion planning.

The options for using green hydrogen must be assessed realistically. In many countries, corresponding analyses and considerations are already part of the process of formulating national hydrogen strategies. Since the market for green hydrogen and hydrogen-based green products is still emerging, these analyses must be continuously updated and adapted.

In international cooperation to promote entry into the hydrogen economy (so-called "international hydrogen cooperation"), the interactions outlined in this paper should be taken into account. This is also anchored in the National Hydrogen Strategy, which states that the production of green hydrogen in developing countries should be used as a stimulus to promote the rapid development of generation capacities for renewable energies in these countries, which in turn also benefit the local markets (Federal Government, 2020).

Only a limited number of aspects could be taken into account in this study. In addition, the country-specific interviews could only highlight the topics and

do not claim to be complete. In particular, the country-specific analyses of the interactions should be continued and deepened and the results should be incorporated into the development of national hydrogen and energy transition strategies and their updates. These interactions must not be ignored in the international discussion on sustainability criteria and certification. This increases the complexity, but helps to ensure that the transition to a green hydrogen economy is truly sustainable and, from a global perspective, actually contributes to significant greenhouse gas emission reductions.

Detailed information on this can be found in Vespermann et al. (2023).

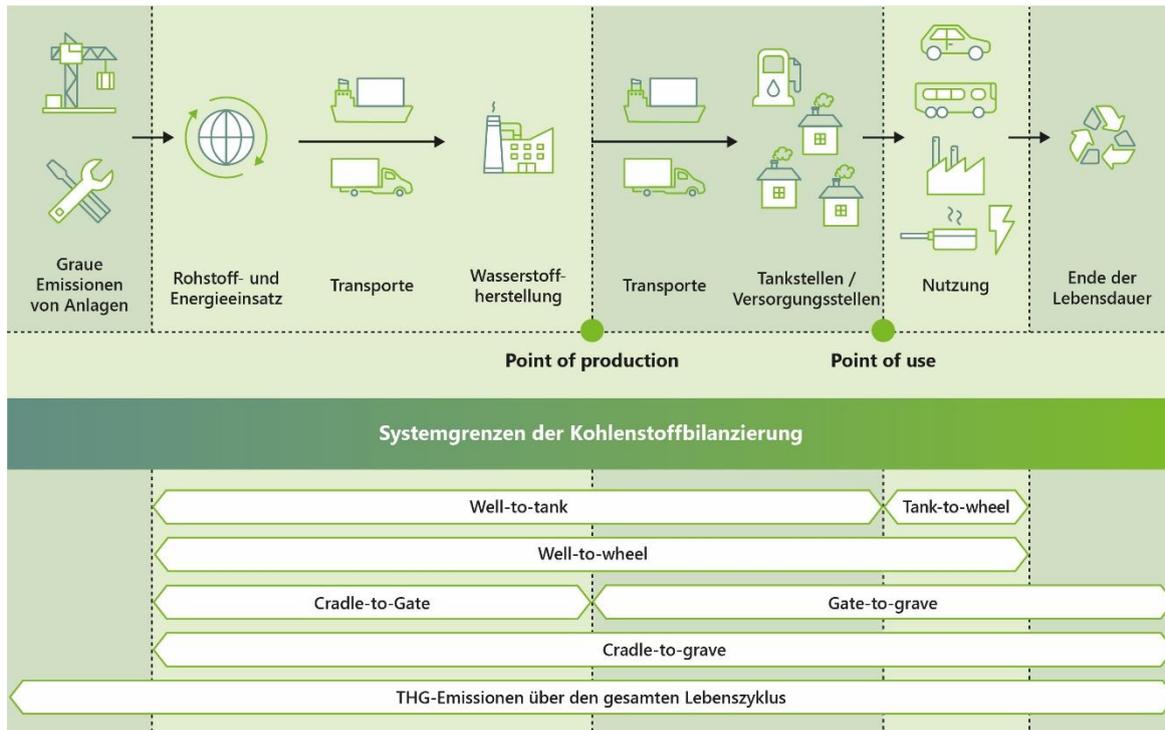
3.6 From a sustainability perspective, a number of points need to be considered.

The topic of the sustainability of hydrogen and its derivatives is widely discussed and is very important for acceptance, among other things. Various national and international regulatory activities are currently taking place. This topic is addressed on the basis of literature reviews and our own analyses.

As part of HYPAT, the project partners started early on to write a background paper on the sustainability aspects of green hydrogen and synthesis products (see Thomann et al. 2022).

In addition to energy sources, HYPAT also considers other criteria such as water requirements, land use, CO₂ sources and social concerns, analogous to the Sustainable Development Goals (SDGs) of Agenda 2030. In addition to the production processes for hydrogen and synthesis products, upstream and downstream processes are also examined. Upstream processes include, for example, the extraction of raw materials, but also the production and construction of the necessary infrastructure such as electrolysis plants or the construction of tankers for transporting the products. Downstream processes include, among other things, emissions from the use of the products and the dismantling of the production plants. HYPAT therefore aims to consider the entire life cycle of hydrogen and synthesis products, see Figure 27.

Figure 27: Limits of consideration for the production of hydrogen and synthesis products



Source Velazquez Abad et al. (2020)

Only renewable energies can be used to generate electricity for sustainable green hydrogen, as stipulated in the National Hydrogen Strategy. It must be ensured that

- 1) the generation plants used have a low negative environmental impact. For example, the destruction of biotopes (large hydroelectric power plants) or damage to marine mammals (offshore wind turbines built without soundproofing measures) would be unacceptable
- 2) the renewable electricity is generally generated in plants specifically built for hydrogen production
- 3) that the energy transition is supported in the partner countries and that hydrogen projects are implemented in a socially acceptable manner.

From a sustainability perspective, electrolysis is seen as the only option for producing green and sustainable hydrogen in the medium and long term. According to the National Hydrogen Strategy (NWS), the electricity must come from renewable energies (RE), and the use of fossil fuels or nuclear energy must be ruled out. It must be ensured that the RE generation plants used have a low negative environmental impact. The RE plants required for hydrogen production must be built in addition (as close as possible in terms of time and geography to hydrogen production). This criterion of "additionality" is considered an important prerequisite for supporting the energy transition of a producing country. This also includes access for the population to electricity supplies in the producing countries.

Other relevant environmental impacts are the water and land requirements. Water availability should be high for hydrogen production sites; no plants should be built in designated protected areas. The preservation of biological

Diversity must be taken into account. From a social perspective, there must be no negative impact on the population, e.g. with regard to energy and drinking water supplies, nutritional situation or health. The aim should be to create a win-win situation in which qualified jobs are created in the exporting countries in compliance with the core labor standards of the International Labor Organization (ILO) and acceptance in exporting countries remains high, although the importing countries demand strict proof of sustainable hydrogen.

Of the synthetic products, ammonia is particularly problematic from an environmental perspective due to its toxicity, its high eutrophication and acidification potential, and its formation of fine dust. For this reason, and against the background of existing international reduction agreements, the use of ammonia should be reviewed through a holistic ecological assessment.

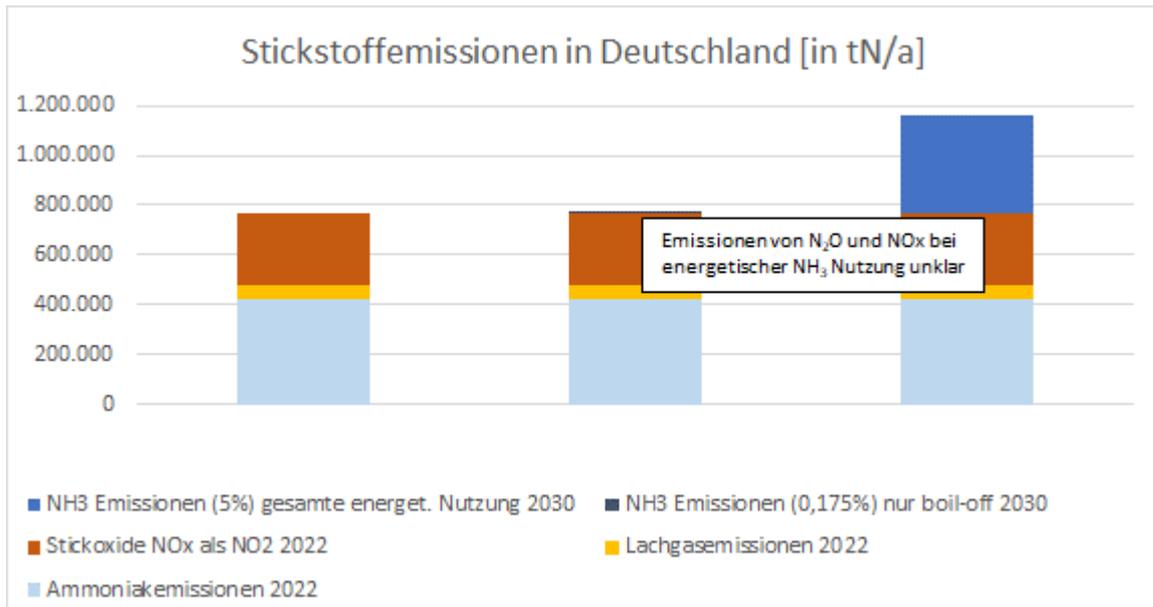
Environmental effects of the ammonia industry unclear

Even in low concentrations, ammonia is irritating and in higher concentrations it is corrosive to mucous membranes, especially those of the eyes and respiratory tract. However, due to the pungent smell, fatal poisonings are rare. Ammonia is highly toxic to aquatic organisms (water hazard class 2). The aquatic toxicity of ammonium salts is about two orders of magnitude lower. As an air pollutant, ammonia forms secondary inorganic aerosols (SIA) and is thus a source of fine dust. Ammonia emissions therefore contribute to the tens of thousands of deaths per year in Germany due to fine dust.

Currently, the data on nitrogen oxide and nitrous oxide emissions when using ammonia as an energy or hydrogen carrier is very poor, as Tomos et al. (2024) report. This means that in many life cycle assessments only the greenhouse gas potential is calculated as an impact category. For example, Bicer et al. Dincer (2018) found that ammonia as a ship fuel saves 67% of greenhouse gas emissions. Chalaris et al., (2022) examine green and blue ammonia and see reductions in GWP emissions of up to 83% and 57% respectively compared to conventional fuels. However, they also point out the uncertainties within the life cycle assessment model, since there are no existing ammonia ship engines with primary data and nitrous oxide may be produced during combustion. Wolfram et al. (2022) discuss this issue and point out that the byproducts of ammonia combustion (such as nitrates and nitrous oxide) have the potential to outweigh any positive environmental impacts of ammonia combustion compared to traditional fossil fuels.

Bertagni et al. (2024) come to the same conclusion, focusing in their study on the global nitrogen cycle. They point out that a large-scale ammonia economy (with 30 EJ/a) emits 65 million tonnes of nitrogen per year at a loss rate of 5%, which would correspond to 50% of current fertilizer production. The authors call for cautious action in the new ammonia economy. Assuming that half of the hydrogen reaches Germany as ammonia in 2030 and the loss rate of 5%, ammonia emissions for Germany would double, see Figure 28 below. This would mean that the NH₃-Emissions on a scale similar to that of around 1990 at the time of forest dieback (UBA, 2002).

Figure 28: Nitrogen emissions in Germany



Source: Own illustration

Studies on the use of ammonia in comparison to other energy sources are completely meaningless if impact categories are not considered that are relevant for NH₃ are highly relevant. These are mainly the acidification potential with 1.88 kg SO₂ equivalents per kg and the eutrophication potential (EP) with 0.33 PO₄-equivalents per kg. The fact that ammonia has a GWP of 0 is only one side of the coin; more important and much more useful are analyses of the acidification and eutrophication effects during the production, transport and use of ammonia.

4 Results and Conclusions for German Policy

4.1 Germany should cooperate with importing nations inside and outside the EU

Globally, only a few countries are dependent on large import quantities of hydrogen and its derivatives (see Chapter 2.5). Germany is heavily dependent on other countries and their actions when it comes to its imports. Within the EU, it is one of the few future importing countries when it comes to both hydrogen and its derivatives. International cooperation between importing nations is necessary to increase the market power of the demand side and to benefit from economies of scale.

Currently, potential import countries for hydrogen and derivatives have different requirements, including sustainability. Different requirements or limits on the part of consumers (e.g. only green hydrogen and no blue) can shrink the market. This increases the risk that market power will arise on the supply side and be used strategically to set higher prices.

Cross-border coordination on certification and standards in the hydrogen sector can prevent market fragmentation, ensure market liquidity and support the development of an international market. Harmonized certification is also an important tool for reducing uncertainty in export countries. For example, a consistent, harmonized certification system was rated as the most important policy measure for building a hydrogen economy in a large-scale expert survey in Australia as part of HYPAT.

In addition, scaling and cost advantages can be achieved through international cooperation. Many countries only achieve the lowest hydrogen export costs when export volumes exceed a critical level (~100 TWh/year in 2050). Within Europe and globally, it is therefore advisable to establish international trade alliances so that hydrogen reaches the critical trade volume for economical transport and overcomes the disadvantage of high costs for small quantities.

For further details, see Wietschel et al. (2024).

4.2 Germany should advocate for support and cooperation mechanisms between European countries with export potential and import needs.

There is high but unevenly distributed renewable energy potential within Europe. The development of hydrogen partnerships within Europe/the EU opens up opportunities to actively diversify hydrogen supply chains to Germany. However, investments and funding have so far been heavily focused on individual countries (especially Germany and France). Germany should therefore advocate the following at EU level and among the member states:

- Establish higher EU subsidies for hydrogen projects, both in terms of production and (priority) applications: To offset the current trend that

As investments in renewable hydrogen tend to be made in countries with high fiscal capacity rather than high renewable potential, the introduction of consolidated, large-scale financing schemes at EU level would be helpful, both to support hydrogen production and hydrogen use. This could notably take the form of the planned auctions of renewable hydrogen (on the supply side) and contracts for carbon differences (CCfD) (on the demand side). This could also include dedicated auctions for structurally disadvantaged regions.

- Cross-border auctions for green H₂ Another way to channel investments to Member States and regions with a high renewable energy potential but relatively limited tax capacity could be cross-border auctions for renewable hydrogen. The upcoming revision of the EU Governance Regulation, which already contains the Renewable Energy Financing Mechanism for cross-border financing of electricity from renewable energy sources, could introduce a corresponding system for renewable hydrogen. Among other things, Member States could hold cross-border auctions with other EU Member States to promote their national RFNBO⁸ quotas to be met.
- Establish national expansion targets for electricity from renewable energies in all EU countries: It is also important that – in parallel with investments in renewable hydrogen – accelerate investments in renewable energy in general. To ensure this, the EU could introduce a system of national targets for electricity generation from renewable energy, including annual interim targets consistent with the EU's path to climate neutrality by 2050. As a first step, such a harmonised target system could remain voluntary and serve as a basis for granting exemptions from additionality requirements to those countries that meet or exceed their interim renewable energy targets.
- Development of bilateral or regional hydrogen partnerships between H₂- Surplus and H₂-deficit countries in the EU (forming a "Hydrogen Alliance"): The establishment of bilateral or regional hydrogen partnerships could help deepen intra-European cooperation, in particular between potential surplus and deficit countries. First, such partnerships could facilitate knowledge sharing and mutual learning. Second, such partnerships could serve as a basis for agreeing a sharing between importing and exporting countries in counting the use of RFNBOs towards the fulfilment of renewable energy targets. Such agreements would enable Member States with a high renewable energy potential to contribute to the EU-wide hydrogen deployment while supporting the fulfilment of their national quota.

For further details see Quitzow et al. (2023).

⁸ RFNBO: Renewable Fuels of Non-Biological Origin.

4.3 Export countries and the development of international transport capacities should be actively supported.

Capital costs make up a large proportion of the costs for hydrogen or PtX projects (see Chapter 2.3). In addition, high investments are required for infrastructure construction, meaning that the infrastructure, which is initially in deficit, must be pre-financed. In some developing regions, such as the MENA region, development costs are also rising, e.g. due to political instability. Investors in export countries therefore need access to favorable financing conditions in order to be able to exploit the good renewable energy potential in a financially lucrative way.

One solution is to use innovative financial instruments (e.g. debt-for-nature swaps, Global Environment Facility, Green Climate Fund) to finance the energy transition and H₂- projects. Furthermore, non-financial cooperation can also increase the chances of success of H₂- projects. This may include measures such as:

- training programs in the field of vocational education,
- Strengthening capabilities for technology foresight and technology assessment,
- Support in the development and updating of hydrogen strategies,
- shed light on local use and export ambitions or
- Science and technology cooperation involving German research institutions.

Such support should be used to actively exploit opportunities in the producing countries from the development of an international hydrogen market. For example, the expansion of renewable energy plants connected to the grid can, under certain assumptions (existing transmission infrastructure, good renewable energy locations near export ports), reduce the local electricity price. On the other hand, the export of green hydrogen and derivatives in the producing countries must not be at the expense of the local energy transition, e.g. by taking green electricity from the grid (if capacities are limited or there are no surpluses), competition for good locations, dwindling public acceptance of renewable energies, and so on.

Creating international transport capacity requires time and pre-financing. Export infrastructures (especially existing pipelines) may not be fully utilized at the beginning. Pre-financing of initially under-used transport infrastructure is crucial to increase exports. If the existing pipeline infrastructure is suitable in terms of quantity and size, repurposing could be the cost-optimal solution and requires further analysis.

The construction or conversion of underground hydrogen storage facilities in the exporting country should begin at an early stage. Underground hydrogen storage facilities can play a key role in the cost-effective export of H₂ and PtX. The size, proximity to export points or renewable energy sources and the degree of technical readiness are crucial. The potential of underground storage facilities from salt caverns, aquifers and depleted gas fields should be used as best as possible to reduce the prices for hydrogen export, especially for large volumes. The conversion or new construction of underground storage facilities is very time-consuming. It is therefore advisable to start converting or building new storage facilities as soon as possible so that they can be put into operation by 2050 at the latest (HYPAT Podcast 2024, Pieton et al. 2024b).

4.4 The respective specifics (application and infrastructure) of H₂ and derivatives and prioritize applications in no-regret sectors.

Liquid and gaseous hydrogen and its derivatives (eKerosene, ammonia, methanol, Fischer-Tropsch crude) vary in terms of their areas of application and infrastructure requirements. For derivatives and liquid hydrogen (LH₂) will probably create a global market, as already exists for fossil products. Gaseous hydrogen may lead to large-scale local markets. In addition, the use of LH₂ and hydrogen derivatives, which act as hydrogen transport vehicles, are always associated with conversion losses. Therefore, an import strategy should consider the various energy or hydrogen carriers individually. The development of ammonia as H₂-carrier and PtX product should be promoted, as this represents the most realistic technology path and the most cost-effective PtX product (with or without reconversion) in the short and medium term. Although there is still a need for research into its environmental effects (see Chapter 3.6), ammonia can be considered a safe choice for future energy exporting countries due to its versatility. However, the development of LH₂- Technologies are being accelerated. LH₂ is currently still subject to the restriction that the necessary technologies (ship, liquefaction) are not available in the required number and size. LH₂ However, it can be used extremely flexibly in different fields of application and thus markets and is expected to play an important role in the hydrogen market in the medium to long term.

Since hydrogen and derivatives will remain scarce in the short to medium term and will remain expensive in Germany in the longer term (see Chapter 2.7), the areas of application for hydrogen and derivatives should be carefully considered. Against this background, available quantities should be allocated primarily to the no-regret sectors (steel industry, chemicals, international aviation and shipping, refineries, energy generation). Funding programs should also initially focus more on the no-regret sectors. However, the focus on no-regret applications also presents certain risks. Since these usually represent a few large stakeholders (steel industry, chemical parks), a delay in the development of these consumers can represent a complete delay in the ramp-up of the hydrogen market. Diversity should therefore also be presented on the application side and applications should be promoted as long as the willingness to pay is realistic in the medium term (see Chapter 2.7 for price-elastic demand). In a market ramp-up phase, a broadening of the application does not necessarily have to lead to a price increase due to scarcity, but can also trigger strong developments on the supply side.

In addition, further consideration of the possible (partial) relocation of value creation seems necessary. As the evaluations in the project have shown, many exporting countries want to tap into higher shares of value creation. Imports of intermediate products such as sponge iron or end products (e.g. ammonia, aromatics, olefins) could be cheaper than hydrogen imports themselves. Such a partial relocation of value creation could entail challenges for the domestic economy.

5 Summary and Conclusions

In the future, green hydrogen will play a central role in the transformation of industry, the transport sector and the energy industry towards sustainability and climate neutrality. However, Germany will have to import a large part of the green hydrogen and synthesis products, as renewable energy sources are only available to a limited extent in this country on the one hand and there is high demand on the other.

Against this background, the aim of the project was to develop a global hydrogen potential atlas. For this purpose, possible partner countries for Germany for the cooperative development of a future green hydrogen economy were comprehensively identified for the first time, including the importance of the production regions for a secure, economical and ecologically sustainable supply. For the detailed survey of the global techno-economic potential and the analysis of the hydrogen chains, coupled energy system models were developed and used that map the production and infrastructures, including international transport options and demand, in detail.

The analyses included the needs of the partner countries. The latter include the sustainable coverage of their own energy demand, the achievement of their own climate targets and compliance with specific sustainability criteria for the hydrogen economy in the partner countries. Furthermore, the countries' abilities to build such capital and technology-intensive plants were analysed. The opportunities arising for these countries were also identified and acceptance and stakeholder analyses were carried out.

The resulting supply of hydrogen and synthesis products was then compared with the global demand of the importing countries. Emphasis was placed on analyzing how hydrogen markets will establish themselves in the future and what market prices for hydrogen can be expected in the future. On the basis of the analyses, policy recommendations were made for the development of a sustainable import strategy for Germany.

To achieve the goal, an interdisciplinary approach was pursued with an interlinking of qualitative and quantitative-empirical research and cooperation between technical, political, social and economic scientists. This was supplemented by a transdisciplinary approach with a dialogue with stakeholders from politics, industry and research. The main results and conclusions are presented below.

The global demand for green hydrogen and its derivatives will increase significantly, especially if ambitious greenhouse gas reduction targets are set. The range of global hydrogen demand in 2050 is between 4 and 11% of global final energy demand in ambitious greenhouse gas scenarios. For Germany, it is higher (approx. 20% of final energy demand) due to the industrial structure, in particular due to the relevant role of the steel and chemical sectors as potential consumers.

The global supply potential of green hydrogen is sufficient to meet global demand, even when taking into account severe constraints such as water scarcity. This extensive supply potential offers Germany good opportunities to diversify its imports and thus hedge against risks. However, analyses have shown that, particularly in the short to medium term, broader diversification will increase import costs because economies of scale in the production and construction of transport infrastructures

play a role that should not be underestimated. Many countries only reach the lowest hydrogen export costs once they reach a critical export volume (~100 TWh/year in 2050). A political balance is required here to determine an appropriate level of diversification that makes sense in terms of affordability and security of supply.

Although the potential exists and despite a wide range of political support and industrial initiatives, the international market ramp-up for hydrogen and derivatives is only progressing slowly and the necessary investments are not being made to the extent required. The current multiple uncertainties (including energy and raw material prices, supply disruptions, geopolitical unrest, complex and inconsistent international regulations, uncertainties due to alternative technology paths, uncertain purchase quantities and prices, future division of value chains and possible relocations, financing of the high initial investments) play an important role.

Costs for importing hydrogen to Europe are expected to be between EUR 3.5 and 6.5 per kg in 2030 and EUR 2.5 to 3.5 per kg in 2050. Globally, there is a high potential for the cost range (the supply curve is relatively flat), which is good for selecting possible export countries and indicates stable prices in the long term. However, only a few regions offer very favorable potential; ie no statement should be made about possible global prices on the basis of the isolated analysis of regions.

However, the expected wholesale prices, which compare supply potential with demand potential, are comparatively high for Germany in the long term at around EUR 4/kg in 2050. It has already been assumed that a perfectly competitive market will have been established by then. Within the EU, but also worldwide, Germany must expect the highest hydrogen prices, which will worsen the competitiveness of German industry, especially in industrial applications that will depend on green hydrogen to reduce greenhouse gases in the future. Countries such as the United States or Canada, which have large and inexpensive resources for producing green hydrogen and have considerable market shares in today's industrial applications in which hydrogen can play an important role in the future, could have relevant competitive advantages by integrating segments of the green hydrogen value chain in production and industrial applications. From a German perspective, this creates the dangerous situation of relocation or an international reorganization of value chains, especially in areas that are subject to strong international competition. Politicians are called upon to develop support for the relevant industrial sectors in the weighing process. In international comparison, Germany has very good industrial conditions for the production of components of the hydrogen value chain, which puts Germany in a good competitive position in this regard.

The import prices and competitive situation, together with the short and medium-term shortage of supply, should lead to the use of hydrogen being focused on sectors where there are hardly any other sensible options (steel and basic chemicals, international air and sea transport, refineries and in power generation as a storage option). In order to use hydrogen and derivatives on a larger scale in other areas such as building heating or road transport, the prices would have to be very low, but this is not currently the case. Hydrogen and derivatives can also be introduced here through political support or appropriate regulations. However, this is not economically effective because the CO₂-Avoidance costs are relatively high here compared to other applications (see Wietschel et al. (2022b) and Ueckerdt et al. (2021)).

When importing hydrogen from geographically close countries, pipeline import is often cheaper, but ship import can also be economically competitive in certain constellations. This offers more flexibility and diversity, whereas pipeline import promotes strategic partnerships but also brings with it dependencies.

For long transport distances, liquid hydrogen (LH₂) and ammonia are among the most economically attractive options when imported by ship. It turns out that ammonia is a cost-efficient and technologically advanced energy source that, in addition to its direct use, also has great potential as a hydrogen carrier. The pure transport costs usually only play a minor role and existing infrastructure can be used in some cases. It should be noted that the production, transport and use of ammonia is associated with a not insignificant environmental impact and further analyses are necessary in this regard.

If the energy source has to be converted back into hydrogen, LH offers²often have advantages over ammonia and LOHC (Liquid Organic Hydrogen Carriers). However, it should be noted that there is currently no significant production and transport infrastructure for LH₂ and this option is therefore only likely to become relevant after 2030. This creates a situation where the further expansion of ammonia supply chains currently appears to be expedient, but these long-term investments may later prove to be uneconomical. This is currently leading to market uncertainty and thus to a reluctance to invest.

The EU can essentially supply itself economically with hydrogen, while it is dependent on imports for derivatives, both in terms of the quantities required and for economic reasons. Germany should therefore actively support export countries and the development of international transport capacities. Clarifying how an infrastructure that is initially in deficit will be pre-financed is particularly important. Within the EU, high levels of investment are currently taking place in countries that have a high demand for hydrogen, but less so in countries with favorable production potential. This is where the focus should be correctly set in the future.

Furthermore, only a few countries require large import quantities of hydrogen and its derivatives and global trade is therefore expected to account for only a third of total demand between 2030 and 2050. In the EU, these are Germany (with the greatest demand), the Netherlands, Belgium and Italy. Spain, France, Denmark, Great Britain and Poland in particular are suitable for supplying the EU countries that cannot supply themselves. A well-developed European hydrogen pipeline infrastructure is therefore in Germany's interest.

Germany should cooperate with importing nations inside and outside the EU, among other things to build up buyer power. If the few importing countries compete, among other things due to different requirements regarding sustainability, the markets could become smaller, which in turn could lead to higher prices. Worldwide, Japan and South Korea in particular will need imports in the future. The situation in China is not clear because it depends on political decisions there, among other things.

Germany should continue to advocate for support and cooperation mechanisms between European countries with export potential and import requirements. If one looks at current activities to develop hydrogen production and infrastructure in addition to the technical and economic potential, it is noticeable that France is rather restrictive in terms of transit and the development of its own production capacities compared to the other potential export countries. This is a particular challenge for Germany.

Challenge, as France is also a potential transit country. German politicians should develop a strategy for this.

If we look at acceptance, the population survey in Germany has shown that there is a high level of acceptance of green hydrogen, while knowledge about hydrogen technologies is still low. In addition, the export region and import criteria influence the acceptance of hydrogen imports on the demand side in Germany.

As export regions, sunny regions, possibly in combination with good wind potential to achieve high full load hours in hydrogen production, offer the cheapest production costs. From this point of view, regions such as southern Chile, the MENA region, the Midwest of the USA and Australia are suitable.

When selecting export regions, the volume potential for export must always be taken into account, as meeting domestic demand for electricity and, in the future, for hydrogen used domestically plays a role in whether there is any relevant export potential at all. But it is also a market question, as the prices that buyers are willing to pay determine whether domestic use or exports are made. The influence of government regulation and the existence of an export infrastructure must be taken into account.

Since many potential export countries offer similarly attractive conditions in the form of favorable potential for renewable energies, other aspects are coming to the fore in hydrogen production and export. Capital costs in particular have a major influence on profitability, because building an export and transport infrastructure for green hydrogen and its derivatives is capital intensive. Many developing and emerging countries in particular have difficulty accessing cheap capital. Future export countries should therefore be given access to low-cost financing and national funds. Oil and gas countries sometimes have a competitive advantage in terms of the cheap capital available.

Furthermore, the possibility of storing hydrogen underground in order to achieve the highest possible plant utilization is of great relevance. An additional factor is whether export ports exist and whether these are located close to hydrogen production and storage.

Among these techno-economic aspects, the countries examined in detail are particularly Morocco, the United Arab Emirates, Canada, Brazil and Chile interesting. However, the analyses also show that only detailed and comprehensive system analyses are able to identify favourable export countries and that a sole focus on favourable renewable energy potential, as found in many studies, falls short.

In addition to the techno-economic criteria, other criteria are also important when evaluating potential export countries. Geopolitical interests as well as the assessment of human rights and democratic aspects are also relevant topics. Under these criteria, some countries, e.g. from the Middle East, are classified as critical. Here there is a conflict of objectives with the most cost-effective procurement of imports. In addition, water availability, national policy priorities and the national regulatory framework play a role. In addition, the industrial conditions for the production of components of the hydrogen value chain in export countries vary greatly. An analysis of nine MENA countries showed that Turkey and Tunisia already have industrial know-how on various components of green hydrogen technology and perform only slightly worse than potential European competitors. In contrast, Algeria, Libya and Saudi Arabia perform worse here. In general, it can be shown that countries with a higher share of natural resources such as oil and gas are the most important exporters.

Gross domestic product shows significantly lower values in the production of products that have a high level of complexity.

External factors are also relevant for exports, some of which can represent obstacles. For example, technology availability and access are key bottlenecks for the establishment and expansion of a national hydrogen economy in the exporting countries. In addition, a secure sales market must be identifiable. In this context, clear (national and international) regulations and stringent sustainability requirements along the entire value chain are also needed. It must be noted that the implementation of hydrogen projects in the exporting countries has the potential to cause social conflict in terms of acceptance and, where appropriate, a lack of socio-economic spillover effects. The issue of water scarcity and the avoidance of water conflicts in certain regions must be taken into account. The local population should also benefit from settlement projects. It must continue to be avoided that hydrogen projects for export lead to the displacement or postponement of already planned energy transition projects or to dwindling acceptance of the energy transition strategy in the country itself. It must also be prevented that local greenhouse gas emissions increase as a result of an export-oriented hydrogen economy, e.g. B. if the additional electricity demand is covered by fossil fuels through the use of grid power.

Ideally, green hydrogen offers exporting countries the opportunity for a triple win, consisting of value creation and employment effects through the export of a new and promising raw material, the decarbonization of the domestic economy and the development and expansion of technological skills. In addition, hydrogen exports could accelerate the energy transition in the exporting countries and reduce energy prices in the exporting country (reduction in domestic hydrogen or electricity prices). Many potential producing countries are not committed to green hydrogen, but are also open to blue hydrogen for their own consumption, while they focus on demand for exports. This aspect underlines the importance of cooperation between demand countries in order to avoid market fragmentation according to hydrogen colors and different sustainability standards, because illiquid markets could lead to higher prices.

For mutually beneficial cooperation, it is important to actively exploit opportunities in the producing countries, for example through vocational training programs, access to capital or support in the development and updating of hydrogen strategies for local use and export. From the perspective of the exporting countries, existing relationships in the form of energy partnerships, economic agreements, trade relations and corporate cooperation, in addition to a high willingness to pay, are the most important criteria when choosing importing countries.

Finally, it can be noted that the current uncertainties in both the exporting and importing countries remain high and that the hydrogen ramp-up is therefore at risk. Therefore, on the one hand, the political frameworks mentioned are needed and, on the other hand, further detailed analyses of their effects are needed.

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Wietschel et al. (2022a): War in Ukraine: Impacts on the European and German import strategy for hydrogen and synthesis products. HYPAT Impulspapier. Karlsruhe: Fraunhofer ISI (ed.).

Wolfram, P.; Kyle, P.; Zhang, X; Gkantonas, S.; Smith, S. (2022): Using ammonia as a shipping fuel could disrupt the nitrogen cycle. *Nat Energy* 7(12):1112–4h
Wüstenhagen, Rolf; Wolsink, Maarten; Bürer, Mary Jean (2007): Social acceptance of renewable energy innovation: An introduction to the concept. In: *Energy Policy* 35 (5), pp. 2683-2691. DOI: 10.1016/j.enpol.2006.12.001.

Wietschel et al. (2022b): Long-term environmental balance and future potential of alternative drive technologies. Study on the German innovation system | No. 9-2022. Commissioned by the Expert Commission for Research and Innovation (EFI).

Wietschel, M.; Weißenburger, B.; Wachsmuth, J.; Müller, VP (2024): What do we know about imports of green hydrogen and its derivatives and what can be derived from this for a German import strategy? HYPATAT Impulspapier 02/2024. Karlsruhe: Fraunhofer ISI (ed.).

Appendix 1: In the global supply potential curve states considered

Table 4: List of selected countries for the global supply potential curve of possible hydrogen imports by Germany in 2050

Western Europe	Eastern Europe	North Africa	sub-Saharan Africa	West Asia
Finland	Greece	Egypt	Kenya	Georgia
France	Latvia	Algeria	Namibia	Iran
Ireland	Lithuania	Morocco	Nigeria	Jordan
Iceland	Poland	Tunisia	South Africa	Qatar
Norway	Romania			Kuwait
Portugal	Russian federation			Oman
Sweden	Ukraine			Saudi Arabia
Spain				Türkiye
United kingdom				United Arab Emirates

Central/East Asia	North America	Central America	South America	Oceania
Kazakhstan	Canada	Honduras	Chile	Australia
China	United States	Mexico	Peru	New Zealand
			Uruguay	
			Colombia	
			Argentina	
			Brazil	
			Ecuador	

Appendix 2: Overview of project publications

The most important publications from the project are briefly presented below:

- **Too much or too little governance? – Hydrogen Support Systems of the EU and the US**

- Wachsmuth, J.; Quitzow, R.; Thiel, Z.; Eicke, L.; Zabanova, Y.: Too much or too little governance? – Hydrogen Support Systems of the EU and the US. Journal paper, submitted.
- Achieving climate targets in hard-to-abate sectors such as energy-intensive industries, aviation and maritime requires a resilient uptake of hydrogen supply in spite of deep market uncertainties. However, hydrogen will contribute to decarbonization only when production achieves a sufficiently high reduction of greenhouse gas emissions. Furthermore, limited public funding calls for an efficient allocation of support. Hence, public hydrogen support policy needs to address this conundrum of environmental effectiveness, economic efficiency and a resilient market uptake with a suitably designed instrument mix. This policy analysis applies corresponding qualitative assessment criteria for the design of such support systems to the most relevant deployment policies in the European Union, including but not limited to the Hydrogen Bank, and the United States, in particular the Inflation Reduction Act and the Bipartisan Infrastructure Law. We find that the EU support system for hydrogen uptake is more stringent than the US support system regarding environmental effectiveness and economic efficiency but entails higher risks for a rapid market uptake due to higher complexity and limited focus on domestic supply chains. The EU could benefit from more emphasis on domestic manufacturing, while the US should consider establishing a governance mechanism that allows the long-term transition to netzero emissions.

- **Towards a Green H₂Economy: Kenya Country Report**

- Oyan, E.; Kantel A.; Stamm, A.; Strohmaier, R.; Dütschke, E.; Scherrer, A.; Boie, I.; Müller, V.; Aboushady, N.; Altenburg, T. (2024): Towards a Green H₂Economy: Kenya Country Report (Hypat Working Paper) (in the process of publication)
- The development of a green hydrogen economy, as part of Kenya's climate and energy vision to move to 100% clean energy by 2030, is currently still in its incipient stage. In September 2023, Kenya published the executive summary of its first Green Hydrogen Strategy and Roadmap, identifying three areas of application for green H₂ within the country's economy: As a feedstock in the chemical industry, eg to produce ammonia and methanol; as a fuel to decarbonize the transport sector and as a means of energy storage to provide baseload power in the electricity sector.

The domestic fertilizer production industry is defined as “low-hanging fruit” for the country and has been given high-priority as currently all nitrogen fertilizer used in Kenya is imported. In addition to benefits to the agricultural sector and therewith food security, Kenya's Green Hydrogen Strategy and Roadmap identifies benefits across two other dimensions for the successful establishment of a domestic green hydrogen economy, namely improved balance of payment and green industrialization and decarbonization. The country's green hydrogen development is currently driven by its government and public institutions, but enjoys strong support from the EU as well as from some private sector associations representing both national and international business stakeholders.

While the Republic of Kenya offers several competitive advantages for producing green hydrogen derivatives, we remain skeptical that the country's current trajectory will result in significant socio-economic benefits for the majority of the population as several factors pose challenges in ramping up the nascent green hydrogen market in Kenya. High renewable energy prices may increase the production cost of green hydrogen. The efforts of the Kenyan government to increase the installed capacity of geothermal power do not seem to help bringing the energy prices down. This challenge currently results in limited incentives for domestic and regional heavy industries (eg cement and iron and steel) to use and produce green hydrogen. Therefore, the potential growth of the off-take market for Kenyan green hydrogen remains – both domestically and internationally- limited.

The success of Kenya's incipient green hydrogen economy in the coming years will - to a large extent - depend on the implementation and successful operation of some currently starting or ongoing commercial pilot projects aiming to demonstrate feasibility and incite not only interest but also financial investment from the (international) private business.

- **Towards a Green H₂Economy: Algeria Country Report**

- Aboushady, N.; Jaroudi, I.; Boie, I.; Dütschke, E.; Kantel, A.; Müller, V.; Scherrer, A.; Laasmi, M.; Altenburg, T.; Oyan, E.; Stamm, A.; Strohmaier, R.; Thoms, K. (2024): Towards a Green H₂Economy: Algeria Country Report. HYPAT Working Paper 11/2024. Karlsruhe: Fraunhofer ISI (Ed.)
- Hydrogen is a promising environmentally friendly alternative to fossil-fuel-based energy carriers if it is green hydrogen (GH₂), which is produced using renewable energy sources. Green hydrogen has been identified as a key element of the European as well as the global energy transition. Furthermore, it is at the top of Germany's agenda for international cooperation, due to the huge demand for GH₂ projected in the future. This report provides a socio-economic analysis of Algeria as one of the potentially strategic partners of Germany in the field of hydrogen supply. The analysis focuses on Algeria's overall conditions, opportunities, and challenges and is complemented by an investigation of the potential societal acceptance of hydrogen production and use (both locally and for export). Algeria is endowed with huge renewable energy and GH₂potentials. The country enjoys one of the highest solar irradiances worldwide. It also has a relatively well-developed gas infrastructure connecting it to Europe, which could be used alternatively for the transport of hydrogen or hydrogen derivatives in the future. At present, (green) hydrogen does not seem to be at the top of Algeria's policymakers' agenda. The country is a latecomer to the race for hydrogen investments in the MENA region. The Algerian government has just recently published its National Hydrogen Development Strategy and signed a limited number of cooperation agreements with Germany, Italy, and other international partners for the eventual exploration of hydrogen production opportunities. In light of the country's slowdown in gas production and increasing energy consumption, hydrogen could contribute to increasing Algeria's energy security, diversifying its energy mix, decarbonizing carbon-intensive sectors, and helping to realize the country's commitments to fight climate change. However, several economic, technical, and, above all, politico-economic challenges arise from the potential investment in a hydrogen economy. Industrial development and diversification and a strong private sector are largely lacking. Institutional and market reforms are necessary to increase transparency, encourage market entry, and level the playing field for domestic as well as international investors along the hydrogen value chain. Most importantly, the shift from a fossil fuel-based economy to a new model with uncertainties regarding rent creation appears to be

a risky choice for the different centers of power in Algeria, such as the business elites, state-owned oil, and gas enterprises.

- **Towards a Green H₂Economy: Türkiye Country Report**

- Oyan, E.; Boie, I; Dütschke, E.; Kantel A.; Müller, V.; Scherrer, A.; Aboushady, N.; Altenburg, T.; Stamm, A.; Strohmaier, R. et al. (2024): Towards a Green H₂Economy: Türkiye Country Report. HYPAT Working Paper 10/2024.
- The ramp-up of the green hydrogen market is becoming a pivotal focus in the global transition towards sustainable energy. Green hydrogen, produced through the electrolysis of water using renewable energy sources, is heralded as a key solution for decarbonizing sectors that are traditionally hard to abate, including heavy industry, transportation, and power generation. As countries worldwide strive to meet ambitious climate targets and reduce their reliance on fossil fuels, the development of a robust green hydrogen infrastructure is emerging as a cornerstone of future energy systems.

The global green hydrogen market is expected to grow exponentially in the coming decades, driven by declining costs of renewable energy and electrolysis technologies, as well as increasing policy support and investment. Countries are investing heavily in research and development (R&D) to improve the efficiency and reduce the costs of hydrogen production, storage, and distribution. International collaborations and partnerships are also playing a crucial role in advancing the hydrogen economy, facilitating technology transfer, and establishing global supply chains.

Türkiye, with its strategic geographical location and dynamic economic landscape, is well positioned to become a major player in the green hydrogen market. The country's proximity to both European and Asian markets provides significant opportunities for export and collaboration. Additionally, Türkiye's existing energy infrastructure and industrial base offer a strong foundation for developing a robust green hydrogen economy.

This country report aims to provide a comprehensive analysis of the green hydrogen market ramp-up in Türkiye. Through an in-depth examination of policy frameworks, stakeholders, opportunities and challenges, this report seeks to shed light on the evolving landscape of green hydrogen production in Türkiye. Lastly, the report makes some recommendations and identifies strategies to unlock Türkiye's full potential in the global hydrogen economy, with a focus on international cooperation.

- **Water Supply for Electrolysis Plants**

- Mandler F., Ranzmeyer O., Grimm G., Binninger S., Merseburg S., Holst M., Voglstätter C. (2024): Water Supply for Electrolysis Plants. HYPAT Working Paper 09/2024. Freiburg: Fraunhofer ISE, 2024.[HYPAT website](#).
- This working paper outlines a comprehensive framework for evaluating the Levelized Cost of Water (LCOW) for electrolysis and Power-to-X (PtX) production models under the HYPAT project. The report employs a water cost calculation methodology that integrates technological and geographical parameters to quantify water supply costs. Key variables influencing these costs include water discharge, transport distance, and altitude. The methodology involves analyzing groundwater potential using "Baseline Water Stress" (BWS) indicators, assessing financial and energy demands of seawater desalination, and considering expenses and energy requirements for water transmission based on distance and topography. The study highlights the necessity of localized water availability

assessments, especially in water-stressed regions, to ensure sustainable hydrogen supply chains. Results indicate that LCOW varies significantly with geographical conditions and infrastructure, affecting hydrogen production costs. The LCOW for the water supply system ranges from 0.012 to 0.245 € per kilogram of hydrogen (€/kgH₂), which is very low compared to other hydrogen production costs like electricity and electrolysis investment. This research underscores the critical role of efficient water management in transitioning to a sustainable hydrogen economy, offering valuable insights for future infrastructure planning and investment strategies.

- **In-depth techno-economic assessment of hydrogen and PtX export supply chains**

- Pieton, N. et al. (2024), slide set, 2024; [HYPAT website](#).
- This work assesses the PtX export potential of selected countries to Germany and gives an H₂ and PtX price range for 8 selected countries: Ukraine, Morocco, Namibia, UAE, Brazil, Turkey, Chile, and Canada. A detailed model supply chain was developed that is integrated into the national energy system and includes hydrogen and PtX production in the national energy system such as the electricity grid and underground storage. In addition, the model results show the impact of exports on the domestic energy system, such as the local development of electricity and H₂ prices. We evaluated (1) the effects of the domestic energy system on H₂ and PtX exports and (2) the effects of exports on the domestic energy system: (1) The energy system changes depending on export quantity and PtX product. (2) The energy system of the exporting country can benefit from exports under the right conditions.

The HYPAT model chain is a first step to mapping the complete export supply chain, and further studies are needed. We recommend conducting more detailed techno-economic assessments, pushing LH₂ development to build a trade alliance, and supporting the development of a sustainable export economy in the targeted country.

- **In-depth techno-economic assessment of hydrogen and PtX export supply chains - Annex**

- Pieton, N. et al. (2024), Slide set, 2024; HYPAT website.
- **Towards a Green H₂ Economy: Costa Rica Country Report**
 - Stamm, A.; Kantel A.; Sagner, L.; Dütschke, E.; Scherrer, A.; Boie, I.; Müller, V.; Aboushady, N.; Altenburg, T.; Oyan, E.; Strohmaier, R.; Thoms, K. et al. (2024): Towards a Green H₂ Economy: Costa Rica Country Report. HYPAT Working Paper 02/2024. Karlsruhe: Fraunhofer ISI (Ed.)
 - The future of Costa Rica's green hydrogen (GH₂) economy is uncertain despite significant natural and human-made advantages. The country has a history of pioneering environmental initiatives and nearly 100% renewable energy, positioning it well for GH₂ development. Recent momentum includes a GH₂ strategy approved by the Ministry of Environment and Energy (MINAE) and a presidential decree favoring hydrogen investments. However, the government's reluctance to invest public funds and uncertainties at both national and international levels pose challenges. Private sector pioneers and international cooperation, particularly with Germany, are crucial in advancing the GH₂ sector. Experts foresee a phased development, focusing initially on research and pilot projects, with significant scaling and exports of hydrogen derivatives expected post-2030. Continued support from Germany in pilot projects and capacity building is vital, and Costa Rica could become a regional knowledge hub for the hydrogen economy.

- **National energy demand projections using LEAP and Excel**
 - Müller, VP; Pieton, N.; Lenivova, V.; Abdel-Khalek, H.; Sinha, MFA (2023): National energy demand projections using LEAP and Excel - A brief user's guide. HYPAT. Karlsruhe: Fraunhofer ISI (ed.)
 - This document serves as a manual for national sectoral energy demand projections with LEAP and the seven developed excel templates.
- **Global optimization of capacity ratios between electrolyser and renewable electricity source to minimize levelized cost of green hydrogen**
 - Mendler, F.; Fragoso Garcia, J.; Kleinschmitt, C.; Voglstätter, C. (2024): Global optimization of capacity ratios between electrolyzer and renewable electricity source to minimize levelized cost of green hydrogen. International Journal of Hydrogen Energy. Volume 82, September 11, 2024, Pages 986-993
 - This paper presents a novel and effective approach for calculating Levelized Cost of Hydrogen production across the globe, without requiring timely resolved modeling or data. We select characteristic production patterns of photovoltaic and wind turbine power generation based on location qualities indicated by full load hours. These representative patterns are applied worldwide on similar locations to evaluate the proportion of electricity that electrolyzers can use if they have a smaller capacity than the renewable electricity source. Hence, the ratio of capacities is optimized to minimize hydrogen costs. The findings from various worldwide locations reveal that decreasing electrolyzer capacity is economically beneficial across all locations for boosting full load hours and curbing investments, particularly in locations with lower electricity generation. Validation using precise electricity production time series in specific locations revealed minimal errors in the methodology, although the quality of the results is impacted by the seasonality index differences between representative and exact location.
- **The long term price elastic demand of hydrogen - A multi-model analysis for Germany.**
 - Weissenburger, B.; Wietschel, M.; Lux, B.; Rehfeldt, M. (2024): The long term price elastic demand of hydrogen - A multi-model analysis for Germany. Energy Strategy Reviews. Volume 54, July 2024, 101432
 - Hydrogen and its derivatives are important components to achieve climate policy goals, especially in terms of greenhouse gas neutrality. There is an ongoing controversial debate about the applications in which hydrogen and its derivatives should be used and to what extent. Typically, the estimation of hydrogen demand relies on scenario-based analyzes with varying underlying assumptions and targets. This study establishes a new framework consisting of existing energy system simulation and optimization models to assess the long-term price-elastic demand of hydrogen. The aim of this work is to shift towards an analysis of the hydrogen demand that is primarily driven by its price. This is done for the case of Germany because of the expected high hydrogen demand for the years 2025– 2045. 15 wholesale price pathways were established, with final prices in 2045 between 56 EUR/MWh and 182 EUR/MWh. The results suggest that – if climate targets are to be achieved - even with high hydrogen prices (252 EUR/MWh in 2030 and 182 EUR/MWh in 2045) a significant hydrogen demand in the industry sector and the energy conversion sector is expected to emerge (318 TWh). Furthermore, the energy conversion sector has a large share of price sensitive hydrogen demand and therefore its demand strongly increases with lower prices. The road transportation sector will only play a small role in terms of hydrogen demand, if prices are low. In the decentralized heating for buildings no

relevant demand will be seen over the considered price ranges, whereas the centralized supply of heat via heat grids increases as prices fall.

- **What do we know about imports of green hydrogen and its derivatives and what can we derive from this for a German import strategy?**

- Wietschel, M.; Weißenburger, B.; Wachsmuth, J.; Müller, VP (2024): What do we know about imports of green hydrogen and its derivatives and what can be derived from this for a German import strategy? HYPAT Impulse Paper No. 1/2024. Karlsruhe: Fraunhofer ISI (ed.)
- In the revision of the national hydrogen strategy, the federal government has decided to build 10 gigawatts of electrolysis capacity in Germany by 2030. According to the federal government's assessment, based on an evaluation of the current scenarios, around 50% to 70% (45 TWh to 90 TWh) of the demand forecast for 2030 of 95 TWh to 130 TWh will be covered by imports from abroad (in the form of hydrogen and hydrogen derivatives). The government wants to define what an import strategy should look like in more detail in a hydrogen import strategy for hydrogen and its derivatives, which is currently being developed. A number of current studies have dealt with the costs of production and transport as well as export prices and international trade flows for hydrogen and/or its derivatives. The aim of this discussion paper is to work out the key findings from these studies and, based on them, to then make recommendations for action for a German import strategy.

- **Green hydrogen in Namibia: opportunities and risks.**

- Altenburg, T.; Kantel, A. (2024): Green hydrogen in Namibia: opportunities and risks. Bonn: German Institute of Development and Sustainability (IDOS), Discussion paper.
- Namibia is a highly competitive location for solar and wind energy, which can be used to produce green hydrogen and derivatives that are essential for decarbonizing the global economy. Its government therefore has high hopes for this entire industrial complex, as do several European countries interested in importing green hydrogen and derivatives from Namibia. This Discussion Paper assesses the related opportunities and risks and offers policy recommendations with a view to maximizing the societal benefits for Namibians.

Scaling up renewables projects is a no regret option for Namibia, as there is demand for domestic electrification, clean electricity could be exported to South Africa, and using renewable to produce hydrogen and derivatives for export offers prospects for foreign exchange earnings and economic growth. Here, the most immediate opportunities lie in exporting green ammonia, yet other market opportunities may open up, including the export of sustainable aviation fuel, hot-briquetted iron and green fertilizer. At the same time, international investors are hesitant to implement their planned investments due to uncertainties regarding international offtake agreements and other risk factors, eg relating to shipping capacities and financial guarantees. These calls for a gradual scaling-up of hydrogen and ammonia investments, accompanied by continuous technology and market foresight, and carefully designed risk-sharing agreements with international investors.

Hydrogen investments come with political and environmental risks. Politically, the sheer size of the planned projects creates incentives for socially exclusive rent-seeking deals. Unless strict transparency rules are applied, directly participating in deals with large investors

may create opportunities for legal or extra-legal enrichment. Hence, it is essential to have full transparency for tenders and contracts. Even if all deals were fully transparent, this would not guarantee widespread benefits for the Namibian people. We predict fewer employment and other socio-economic spillovers than anticipated in the country's current strategy. Also, projects may be less profitable than expected, and information asymmetries between large investors and Namibian policymakers may translate into unfavorable risk and benefit-sharing agreements. To ensure widely shared benefits, options for a pro-poor use of revenues from hydrogen projects should be explored to achieve socio-economic spillovers from financial investments in green hydrogen. These include direct dividend payments to citizens, earmarking of public revenues for development funds, mandatory oversizing of electricity generation and desalination to serve local communities, and coownership of energy projects.

- **Assessing worldwide future potentials of renewable electricity generation: Installable capacity, full load hours and costs.**

- Franke, K.; Fragoso Garcia, J.; Kleinschmitt, C.; Sensfuß, F. (2024): Assessing worldwide future potentials of renewable electricity generation: Installable capacity, full load hours and costs. *Renewable energy*. Volume 226, May 2024, 120376.
- Several studies calculate the potential of renewable energies throughout the world. However, these studies vary in the underlying assumptions and do not consider several technologies within a uniform methodology, which affects comparability. In this paper, we calculate the worldwide potentials of ground-mounted photovoltaic (PV), concentrated solar power (CSP), and wind onshore and offshore on a 6.5 by 6.5 km grid. The results consist of installable capacity, generated electricity, and specific cost of electricity generation. Our methodology combines high-resolution data for land uses, slope, and hourly weather data with a thorough analysis of different factors for wind power, like hub heights and rotor diameters, and solar power plants, like tilt angle, and temperature-related loss of efficiency. The results show that the summed-up potential capacity of ground-mounted PV surpasses the amount of CSP, wind onshore and offshore combined with 450 TW. Given the cost-potential curve, ground-mounted PV reaches 560,000 TWh at costs below 20 EUR/MWh, which is twice the projected worldwide primary energy supply of the World Energy Outlook 2022 for the year 2050 with 205,557 TWh. The calculated results can function as input factors for energy system models, which are an important tool to analyze the energy transition.

- **Interactions between national energy transitions and international hydrogen cooperation.**

- Vespermann, D.; Thielmann, S. (2023): Interactions between national energy transitions and international hydrogen cooperation. HYPAT Working Paper 06/2023. Karlsruhe: Fraunhofer ISI (ed.).
- The aim of this working paper is to compile possible interactions between the national energy transitions and the development of an (at least partially) export-oriented hydrogen economy and to highlight important aspects of these interactions. The interviews with the local knowledge holders showed that the interviewees are not always aware of all interactions. If they are aware of specific interactions, the local political and regulatory framework is often not yet designed to adequately address these interactions. The clarification of the role of hydrogen in the respective national energy transition is still in its early stages in many countries. A greater awareness of the opportunities and

Being aware of risks is a first step towards taking these into account in the further design of the political and regulatory framework. Opportunities must be actively exploited and risks actively managed - proactive policy is essential for both.

- **Mobilizing Europe's Full Hydrogen Potential: Entry Points for Action by the EU and its Member States.**
 - Quitzow, R.; Triki, A.; Wachsmuth, J.; Fragoso Garcia, J.; Kramer, N.; Lux, B.; Nunez, A. (2023): Mobilizing Europe's Full Hydrogen Potential: Entry-Points for Action by the EU and its Member States. HYPAT Discussion Paper No 5/2023. Karlsruhe: Fraunhofer ISI (Ed.)
 - This policy paper takes stock of ongoing hydrogen policy developments in Europe, placing particular attention on how the European Union (EU) can most effectively mobilize its domestic hydrogen potential. While the paper acknowledges that hydrogen imports from countries outside the EU are likely to play a significant role, it departs from the premise that the large [1] scale mobilization of cost-competitive domestic resources is an essential element for ensuring the EU's energy security and industrial leadership in the sector. It begins with an overview of future renewable energy demand in Europe within the context of decarbonization, on the one hand, and potentials for renewable hydrogen production and their distribution across the EU, on the other. It then contrasts this with hydrogen-related targets and announced investments in the Member States. Against this background, the paper provides a review of key EU-level policies, focusing on the promotion of hydrogen production and use. Questions related to infrastructure for storage and transport of hydrogen are beyond the scope of the paper and are not considered. Building on the policy review, the final section proposes five recommendations for further development of EU hydrogen policy and funding schemes.
- **Research Networks - Imports of Hydrogen and Derivatives - What can systems analysis contribute?**
 - Workshop, 2023, HYAPT website
 - The two-day conference "Networking Energy Research – 1st Symposium of Energy Research Networks" took place in Berlin on June 13 and 14. For the first time, members of all nine networks as well as experts from the fields of energy transition and society as well as resource efficiency came together. In addition to important political contributions to the reorientation of energy research, the focus of the event was on interdisciplinary workshops and cross-network collaboration. The Fraunhofer Institutes ISI, IEE, ISE and IEG as well as the IDOS led an interactive workshop on the topic "Imports of hydrogen and derivatives - What can system analysis contribute?" based on results and findings from the two major atlas studies "HyPat - Global H2 Potential Atlas" and "DeV-KopSys2 - Decarbonization of transport - feedback loops in the energy system - global to regional".
- **Economic complexity of green hydrogen production technologies - a trade data-based analysis of country-specific industrial preconditions.**
 - Müller, VP; Eichhammer, W. (2023): Economic complexity of green hydrogen production technologies - a trade data-based analysis of country-specific industrial preconditions. Renewable and Sustainable Energy Reviews, Volume 182, August 2023, 113304
 - Countries with high energy demand but limited renewable energy potential are planning to meet part of their future energy needs by importing green hydrogen. For potential

exporting countries, in addition to sufficient renewable resources, industrial preconditions are also relevant for the successful implementation of green hydrogen production value chains. A list of 36 “Green H2 Products” needed for stand-alone hydrogen production plants was defined and their economic complexity was analyzed using international trade data from 1995 to 2019. These products were found to be comparatively complex to produce and represent an opportunity for countries to enter new areas of the product space through green diversification. Large differences were revealed between countries in terms of industrial preconditions and their evolution over time. A detailed analysis of nine MENA countries showed that Turkey and Tunisia already possess industrial know-how in various green hydrogen technology components and perform only slightly worse than potential European competitors, while Algeria, Libya, and Saudi Arabia score the lowest in terms of calculated hydrogen -related green complexity. These findings are supported by statistical tests showing that countries with a higher share of natural resource rents in their gross domestic product score significantly lower on economic and green complexity. The results thus provide new perspectives for assessing the capabilities of potential hydrogen-producing countries, which may prove useful for policymakers and investors. Simultaneously, this paper contributes to the theory of economic complexity by applying its methods to a new subset of products and using a dataset with long-term coverage.

- **Berlin Dialogue Forum Import of Hydrogen and Synthesis Products in a Changing World**

- IN-PERSON EVENT BERLIN DIALOGUE FORUM, 20, June 2022, Workshop, 2022, HYAPT website

- **Ukrainian Hydrogen Export Potential: Opportunities and Challenges in the Light of the Ongoing War**

- Sukurova, N.; Wietschel, M.; Fragoso Garcia, J.; Müller, VP; Franke, K.; Kantel, A.; Graf, M.; Jalbout, E.; Pieton, N.; Abdel-Khalek, H.; Bergup, E.; Weise, F. (2021): Ukrainian Hydrogen Export Potential: Opportunities and Challenges in the Light of the Ongoing War. HYPAT Working Paper 04/2023. Karlsruhe: Fraunhofer ISI (ed.).

- Against the background of the ongoing war of aggression, the working paper analyzes the opportunities and challenges of Ukraine in the topic of hydrogen and Power-to-X products. The main findings are:

Despite the ongoing war, the EU remains interested in Ukraine as a potential future supplier of hydrogen, to meet European energy demand and support Ukraine's recovery.

Ukraine must adopt European standards for hydrogen and comply with European legislation for hydrogen exports to the EU.

Green steel could become an important export product in the future, generating additional revenues and enabling local value creation in the country.

Ukraine as well as the relevant transit countries have well-established infrastructure for exporting hydrogen and Power-to-X products to Western Europe via pipelines and seaports, but the repurposing of this infrastructure needs to be further investigated.

Important energy infrastructures and land for potential renewable energy (RE) deployment are currently occupied by the Russian military. Apart from that, the war's uncertain duration and outcome increase the risks of investing in developing the large RE potential in Ukraine. As a result, low-cost RE might only be sufficient to cover domestic demand.

Opportunities and obstacles: The development of a hydrogen economy can bring sociopolitical advantages, such as new jobs. Nevertheless, large-scale hydrogen production in Ukraine might be limited due to water scarcity and competitive water use for the agricultural sector and could imply higher energy costs for households.

- **Green Hydrogen: Implications for International Cooperation With Special Reference to South Africa.**

- Discussion paper, 2023, [Green hydrogen: implications for international cooperation: with special reference to South Africa \(HYPAT.de\)](#)
- Green hydrogen – produced with renewable energy – is indispensable for the decarbonization of economies, especially concerning “hard-to-abate” activities such as the production of steel, cement and fertilizers as well as maritime transport and aviation. The demand for green hydrogen is therefore booming. Currently, green hydrogen is far more expensive than fossil fuel [1] based alternatives, but major initiatives are underway to develop a global green hydrogen market and bring costs down. Green hydrogen is expected to become cost-competitive in the mid-2030s. Given their endowment with solar and wind energy, many countries in the Global South are well positioned to produce low-cost green hydrogen and are therefore attracting investments. Whether and to what extent these investments will create value and employment for – and improve environmental conditions in – the host economies depends on policies. This discussion paper analyzes the potential industrial development spillovers of green hydrogen production, distinguishing seven clusters of upstream and downstream industries that might receive a stimulus from green hydrogen. Yet, it also underlines that there is no automatism. Unless accompanied by industrial and innovation policies, and unless there are explicit provisions for using revenues for a Just Transition, hydrogen investments may lead to the formation of socially exclusive enclaves. The paper consists of two parts. Part A provides basic information on the emerging green hydrogen market and its technological ramifications, the opportunities for countries with abundant resources for renewable energy, how national policies can maximize the effects in terms of sustainable national development and how this can be supported by international cooperation. Part B delves into the specific case of South Africa, which is one of the countries that has an advanced hydrogen roadmap and hosts several German and international development projects. The country case shows how a national hydrogen strategy can be tailored to specific country conditions and how international cooperation can support its design and implementation.

- **Positioning Germany in an International Hydrogen Economy: A Policy Review.**

- Quitzow, R., Almudena Nunez, AM (2023): Positioning Germany in an International Hydrogen Economy: A Policy Review. HYPAT Working Paper 03/2023
- Germany, the European Union member state with the largest fiscal space and its leading manufacturer of industrial goods, is pursuing an ambitious hydrogen strategy aiming at establishing itself as a major technology provider and importer of green hydrogen. The success of its hydrogen strategy represents not only a key element in realizing the European vision of climate neutrality but also a central driver of an emerging global hydrogen economy. This article provides a detailed review of German policy, highlighting its prominent international dimension and its implications for the development of a global renewable hydrogen economy. It provides an overview of the strategy's central goals and how these have evolved since the launch of the strategy in 2020. It then highlights the strategy's institutional underpinning and discusses its implications for strategy implementation. Next, it moves on to provide an overview of the strategy's main areas

intervention and highlights corresponding policy instruments. For this, we draw on a detailed assessment of 160 hydrogen policy instruments, which have been systematically analyzed and coded. This was complemented by information gathered in six interviews with government officials and staff of key implementing agencies. The article places particular emphasis on the strategy's international dimension. While less significant in financial terms than domestic hydrogen-related spending, it represents a defining feature of the German hydrogen strategy, setting it apart from other strategies in the EU. The article closes with a reflection on the key implications of the German approach for the development of a hydrogen economy in Europe and globally. It emphasizes the importance of systematic policy assessment as a basis for understanding how policies are driving not only decarbonization but also the sustainability and resilience of a hydrogen economy.

- **HYPAT - The Hydrogen Podcast**

- Podcast, 2023-2024, [HYPAT - The Hydrogen Podcast](#)
- The HYPAT podcast brings together information on the topic of hydrogen in the context of the energy transition and presents the relevant hydrogen studies as well as the latest results from the HYPAT project. This podcast is moderated by Dr: Andrea Herbst, Natalia Pieton and Viktor Paul Müller.
- # 1_Hydrogen imports, Wietschel, M.
- # 2_A hydrogen world?, Eckstein, J.; Riemer, M.
- # 3_What do developing countries in the global South gain from this?, Strohmaier, R.; Stamm, A.
- # 4_What is so important about sustainable green hydrogen?, Thomann, J.; Riemer, M.
- # 5_The human factor: The role of actors and acceptance in building a global green hydrogen economy, Kantel, A.
- # 6_Hydrogen transport – A chicken and egg problem?, Ragwitz, M.
- # 7_A policy review of Germany's International Hydrogen Economy, Almudena Nunez, A. M.; Quitzow, R.
- # 8_Modelling of renewable energy systems, Neumann, F.
- # 9_Storing hydrogen underground? Alms, K.; Graf, M.
- # 10_International hydrogen partnerships and local energy transitions, Vespermann, D.

- **Export Potentials of Green Hydrogen – Methodology for a Techno-Economic Assessment.**

- Pieton, N.; Abdel-Khalek, H.; Fragoso, J.; Franke, K.; Jalbout, E.; Graf, M.; Holst, M.; Kleinschmitt, C.; Müller, VP; Mendler, F.; Ranzmeyer, O.; Drechsler, B.; Lenivova, V.; Nolden, C.; Voglstätter, C.; Wietschel, M.; Bergup, E.; Sinha, MFA (2024): Export Potentials of Green Hydrogen – Methodology for a Techno-Economic Assessment. HYPAT Working Paper 02/2023. Karlsruhe: Fraunhofer ISI (ed.).
- This working paper describes the quantitative and model-based methodology used in HYPAT to assess hydrogen and Power-to-X (PtX) export potentials in the eight countries Brazil, Ukraine, Namibia, Canada, Morocco, United Arab Emirates, Turkey, and Chile . The

Results of the techno-economic assessment are used as a basis for a global hydrogen and PtX atlas and as an indication of hydrogen and PtX price development.

- **Price-elastic hydrogen demand in Germany – methodology and results.**
 - Wietschel, M.; Weißenburger, B.; Rehfeldt, M.; Lux, B.; Zheng, L.; Meier, J. (2023): Price-elastic hydrogen demand in Germany – methodology and results. HYPAT Working Paper 01/2023. Karlsruhe: Fraunhofer ISI (ed.).
 - The aim of this working paper is to develop and apply a method for the creation of a long-term price-elastic demand for hydrogen for Germany up to 2045. The aim is to analyze which applications are characterized by high price elasticity and which are characterized by low price elasticity. This can then be used to calculate hydrogen demand depending on assumed price developments.
- **Future hydrogen demand: A cross-sectoral, global meta-analysis.**
 - Riemer, M.; Zheng, L.; Pieton, N.; Eckstein, J.; Kunze, R.; Wietschel, M. (2022): Future hydrogen demand: A cross-sectoral, multiregional meta-analysis. HYPAT Working Paper 04/2022. Karlsruhe: Fraunhofer ISI (ed.).
 - Hydrogen and synthesis products are considered of high importance in future energy systems and therefore play an increasing role in climate change mitigation strategies. This working paper provides an overview of scenarios for the future development of hydrogen demand from a global perspective. The results show the range of possible developments in total as well as for the sectors industry, buildings and transport. Next to worldwide demand, results for the EU and China are disclosed. The bandwidths of hydrogen demand have been determined based on over 40 recently published energy system and hydrogen scenarios. The focus is on scenarios with ambitious reduction targets for greenhouse gas (GHG) emissions. In the following, these scenarios are referred to as "focus scenarios". In addition, the projected hydrogen demand is compared to the bandwidth of over 300 mitigation scenarios from the 6th Assessment Report of the Intergovernmental Panel on Climate Change (IPCC), referred to as "IPCC scenarios
- **Global potential of renewable energies.**
 - Kleinschmitt, C.; Fragoso Garcia, J.; Franke, K.; Teza, D.; Seidel, L.; Ebner, A.; Baier, M. (2022): Worldwide potentials of renewable energies. HYPAT Working Paper 03/2022. Karlsruhe
 - This report presents the global potentials of the renewable energy technologies mentioned and their specific costs, which were determined within the HYPAT project. These results are used in HYPAT as a basis for detailed modelling of selected countries and for further calculation of global hydrogen potentials.
- **Hydrogen and hydrogen derivatives: export countries.**
 - Breitschopf, B.; Thomann, J.; Fragoso Garcia, J.; Kleinschmitt, C.; Hettesheimer, T.; Neuner, F.; Wittmann, F.; Roth, F.; Pieton, N.; Lenivova, V.; Thiel, Z.; Strohmaier, R.; Stamm, A.; Lorych, L. (2022): Import of hydrogen and hydrogen derivatives: export countries. HYPAT Working Paper 02/2022. Karlsruhe: Fraunhofer ISI (ed.).
 - The aim of this study is to develop and apply an analysis grid to evaluate possible hydrogen production and export countries. This grid is based on

the requirements of sustainability in the broadest sense, i.e. economic, ecological and social sustainability.

- **War in Ukraine: Impact on European and German import strategy of hydrogen and synthesis products.**

- Martin Wietschel et al. (2022). War in Ukraine: Impact on the European and German import strategy for hydrogen and synthesis products. HYPAT stimulus paper.
- The war between Russia and Ukraine has led many sides to realise that the previously held certainty that close trade relations lead to a stable energy supply needs to be questioned. In order to increase our resilience, key strategic assumptions must be put to the test. The future topic of hydrogen is particularly affected by this. Strategic decisions are pending here that will have long-term economic and political consequences. This discussion paper addresses individual aspects, discusses approaches for a possible reassessment and raises open questions.

discussion paper.

- **Background paper on sustainable green hydrogen and synthesis products.**

- Thomann, J.; Edenhofer, L.; Hank, C.; Lorych, L.; Marscheider-Weidemann, F.; Stamm, A.; Thiel, Z.; Weise, F. (2022): Background paper on sustainable green hydrogen and synthesis products. HYPAT Working Paper 01/2022. Karlsruhe: Fraunhofer ISI (ed.).
- There is currently a lot of debate about the sustainability of green hydrogen and its synthesis products. This working paper takes up the discussion and serves as a basis for developing a common understanding of the sustainability of hydrogen and its synthesis products in the HYPAT research project. The criteria developed in this document serve as background information for potential considerations, economic calculations and model calculations within HYPATT. They are the result of literature research, participation in workshops, interviews and, above all, discussions within the HYPAT work package "Sustainability criteria for green hydrogen"). The paper also takes into account the various points of view from these discussions. Since these results are not without significance for the further development of the green hydrogen economy, the publication of this paper is intended to make them available to a wider user group.

- **Import of hydrogen and hydrogen derivatives: from costs to prices.**

- Wietschel, M., Eckstein, J.; Riemer, M.; Zheng, L.; Lux, B; Neuner, F.; Breitschopf, B.; Pieton, N.; Nolden, C.; Pfluger, B.; Thiel, Z.; Löschel, A. (2021): Import of hydrogen and hydrogen derivatives: from costs to prices. HYPAT Working Paper 01/2021. Karlsruhe: Fraunhofer ISI (ed.)
- This working paper aims to highlight the various challenges in collecting market developments and price scenarios for hydrogen and derivatives and to develop a methodical approach for determining prices. The focus is on hydrogen. Its derivatives such as methanol or ammonia are also considered, although the transport costs for these are significantly lower over longer distances than for hydrogen. Furthermore, a well-developed pipeline supply on a relevant scale is easily conceivable for hydrogen, while the derivatives ammonia and methanol of fossil origin are already transported over longer distances.

be transported by ships. The transport infrastructures for these derivatives already exist, whereas they still need to be built for hydrogen.

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