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Opportunities and challenges when importing green hydrogen and synthesis products

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Policy Brief

Opportunities and challenges when importing green hydrogen and synthesis products

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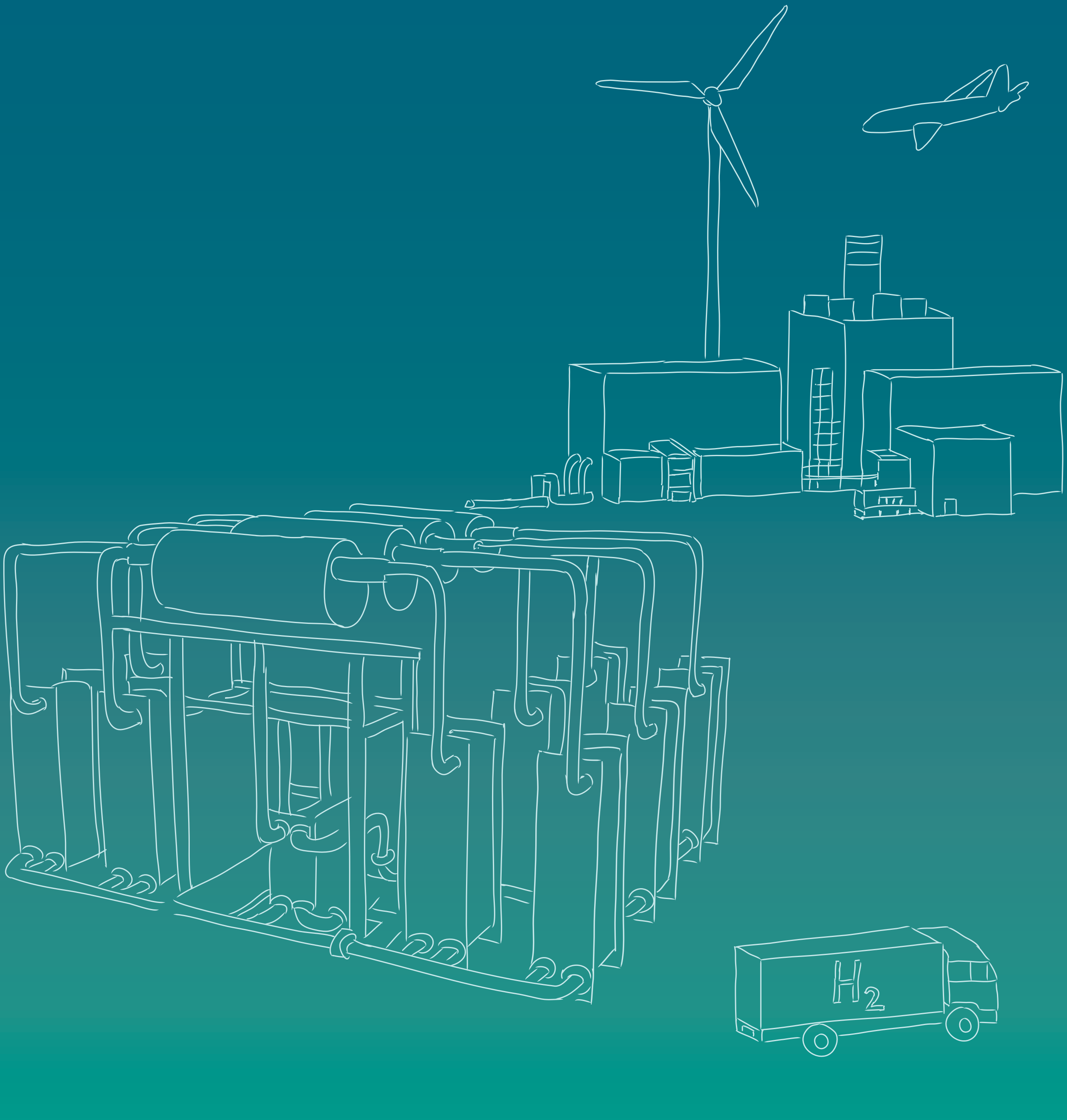
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Summary

Green hydrogen and its synthesis products are regarded as important elements of the energy and climate transition in both Germany's and the European hydrogen strategy. Importing these products is considered an important strategy component. Alongside many aspects that can be classified as relatively certain according to the current state of knowledge, there are still a number of open questions that are addressed in this policy brief and that lead to the following conclusions:

01

Climate neutrality

Green hydrogen and synthesis products are required in the future for greenhouse gas neutrality, especially in certain industrial sectors such as basic chemicals, iron and steel and refineries, as well as international air and sea transport. However, the demand for other applications is still the subject of controversial discussions.
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02

Market

The import market will probably be between 100 billion and 700 billion euros per year in the long term based on current knowledge. This range is determined by the application areas, into which hydrogen and its derived energy sources can penetrate. This will give rise to new import dependencies and risks.
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03

Potentials for renewables

It is very likely that the renewable energy potentials in Germany and the EU will not be sufficient to meet this demand cost-efficiently in terms of availability, economic efficiency and acceptance. Importing green hydrogen and synthesis products is therefore considered necessary.
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04

Import potentials

In techno-economic terms, importing green hydrogen and synthesis products from regions with the right climatic and geographic conditions has already been analyzed comprehensively and is considered feasible. However, it should be noted that constructing the corresponding production and transport capacities will take time and capital.
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05

Import risk

The import risk is reduced if partnerships and long-term relationships can be built with democratic, politically and economically stable countries producing the hydrogen.
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06

Import price

It is still open which hydrogen import price will develop in an international market. Existing analyses probably greatly underestimate the emerging market price, because they are usually oriented on manufacturing costs alone, and neglect other important price components.
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Summary

07

Sustainability

Constructing renewable power generation capacities, the electrolyzers to produce hydrogen and the synthesis plants requires resources like land, water, energy and CO_2 and is associated with corresponding negative environmental effects. In addition, electricity production in potential producing countries is often still based on fossil sources. It is therefore important to develop and apply sustainability criteria, where possible at international level. It is also important to ensure that these countries can achieve their own energy and climate policy goals. Embedding the hydrogen strategy in the national energy strategy and close coordination with industrial policy instruments in the producing countries are essential to avoid conflicts of national goals and resources.

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08

Investors

Investors will only provide sufficient and cheap capital if there is a stable, long-term and secure demand for hydrogen and if bilateral and multilateral agreements address country-specific risks.

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09

Incentive systems

So far, the incentive systems to create attractive market conditions for hydrogen production and transportation are missing for the exporting countries. These include instruments promoting investment and measures to create secure hydrogen demand (e.g. quotas) and instruments to compensate the higher costs (e.g. feed-in tariffs or contracts for difference).

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Governance

The environmental impacts of a hydrogen economy – linked to the low efficiencies from production to use – imply it must be integrated into the governance structures for transforming the energy system via a hierarchical principle. This comprises four stages: (1) The "energy efficiency first" principle to minimize demand, (2) Priority to decarbonizing the electricity sector, (3) Priority use of alternatives based on renewable energy sources with similar services but lower environmental impacts (e.g. direct use of electricity, sustainable biomass/biofuels/biogas taking their limited availability into account), (iv) Use of hydrogen and its synthesis products if the first three stages have been exploited as far as this is reasonable. This four-stage principle, which can be regarded as an extension to the "energy efficiency first" principle, should be implemented in the governance structures for transforming the energy system, both for countries consuming hydrogen and those producing it.

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11

International cooperation

It is possible to meet the complex, societal challenges in the potential producing countries of the Global South, including the impacts of climate change, by properly integrating the import strategy into international cooperation. This requires purposefully building trust to counteract local concerns about continuing to be left behind internationally in the long term in the field of technology and scientific knowledge in spite of local production and export.

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12

Local competencies

Local knowledge carriers should be identified who act at the interface of society and geographical as well as infrastructural issues. For example, local research organizations can be promoted and integrated as intermediaries between politics and society. This should take place in cooperation with existing energy partnerships, NGOs and intergovernmental actors. Capacity-building and integrating the required infrastructure into a regional, social and economic context can encourage the necessary multilateral reliability, local energy supply and economic market attractiveness. In addition to contributing to the global energy transition, creating jobs and expanding local value creation potentials in the producing countries are major drivers for developing a globally networked hydrogen economy. This requires strategies targeting the development of competitive industrial and service sectors along the value chain.

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Technology sovereignty

So far, there are no comprehensive assessments of the technology sovereignty for hydrogen technologies. Initial indications suggest that, from a German and European viewpoint, the reliability of the countries exporting green hydrogen is more likely to pose a risk to technology sovereignty than access to existing technologies. However, in order to arrive at reliable statements, updated analyses are needed that also differentiate technologies to a greater degree. At the same time, it becomes clear that the prospect of importing green hydrogen also requires extending technology sovereignty to include the perspective of developing countries. This is necessary because, for many countries exporting green hydrogen, both the available technology knowledge and the manufacturers of the technologies are located abroad.

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Finally, the authors conclude that too little is understood about the topic of importing green hydrogen in all its complexity, and that the challenges and tasks to be solved in the future are therefore partially underestimated.

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Introduction

Importing green hydrogen and the objective of this policy brief

Setting the political goal of climate neutrality by 2050 in Germany and the EU calls for turning away from fossil fuels completely by 2050. As the path of greenhouse gas reduction from today until 2050 is also relevant for the effects on climate change, this means significantly reducing all greenhouse gas emissions early on.

On the one hand, energy efficiency measures must save fossil fuels and, on the other hand, renewable energies must largely replace them. Since the potential of sustainable biomass is limited and in competition with food crops, primarily renewable electricity and energy carriers based on this are considered suitable substitutes. As far as technically feasible and economical, renewable electricity is used directly, for example, in electric vehicles, heat pumps, and heating networks, or to generate process heat in industry. However, there are a number of applications such as aviation or shipping as well as the basic chemical industry or refineries, where this does not seem possible at present for process engineering reasons or because of the energy densities required. This is where green hydrogen or green synthesis products made from it, such as methanol or methane, come into play. This is why green hydrogen is considered an additional important component of the energy transition, and why German and European climate policy are increasingly focusing on it. In principle, fossil fuels combined with carbon capture, use or storage (CCUS) can continue to be used even in a case of climate neutrality. This is the subject of intensive discussions about "blue" hydrogen, i.e. hydrogen produced using natural gas combined with carbon capture storage (CCS). In general, however, CCS faces serious acceptance issues in Europe. Furthermore, upstream GHG will continue to be emitted from producing and transporting the natural gas.

Most scenarios agree that there is not enough renewable power available in Germany to produce sufficient hydrogen exclusively in Germany or the EU to meet German demand in the long term, and that the hydrogen would be comparatively expensive. [1] shows there are sufficient potentials for a hydrogen economy in Germany as well as in Europe at costs of up to 100 Euro/MWh electricity, and these are sufficient to meet demand, especially when combined with strong energy efficiency measures. This results in higher costs for transforming the energy system, which must be weighed against issues of supply security. Therefore, importing sustainably produced energy sources such as green hydrogen and its synthesis products is currently being discussed. The idea is that regions with advantageous conditions for renewable energy (e.g. high solar irradiation or favorable wind conditions) could produce sustainable energy sources cost-effectively. These so-called green synthetic fuels based on renewable electricity could then be exported to Germany or other countries. Figure 1 shows the individual conversion steps needed from source to application.

The topic of imports is also clearly anchored in the political agenda. The European Commission's hydrogen strategy (see [2]) addresses the issue of importing green hydrogen. One of the goals is cooperation in the field of clean hydrogen with the EU's neighboring countries and regions to contribute to their transition to clean energy and promote sustainable growth and development. Germany's current National Hydrogen Strategy (see [3]) also assumes that the anticipated relevant amounts of green hydrogen will not be able to be produced in Germany alone. From this perspective, Germany will remain a major importer of energy in the future as well, with all the consequences this entails. An important element of the National Hydrogen Strategy is therefore to prepare the import of hydrogen.

Introduction

Meeting the demand for green hydrogen and synthesis products from countries with favorable climatic and geographic conditions is mainly addressed from a techno-economic perspective in completed and ongoing analyses. The interests and concerns of the exporting countries are dealt with only as a marginal issue (see [5], [6], [7], [4]). This is a deficit. Germany's National Hydrogen Strategy, the EU's Hydrogen Strategy, the international agreements on climate protection and the sustainable development goals (SDG) all require a much broader analysis and evaluation. Various studies in this context (see e.g. [8]) as well as Germany's National Hydrogen Strategy point to the need to develop and apply an international sustainability standard for hydrogen production.

The needs of the partner countries must be considered to a greater extent in future strategies. These needs include meeting their own energy demand in a sustainable way, achieving their own climate goals using the economic development opportunities presented by a hydrogen economy, and complying with specific sustainability criteria for the hydrogen economy in the partner countries. In addition, the countries' capacities to construct such capital- and technology-intensive plants must be analyzed (e.g. governance structures, access to capital, geopolitical stability). There is also a lack of knowledge about the opportunities that could result for these countries (e.g. effects on local value creation, capacity-building possibilities), and analyses of acceptance and stakeholders are missing.

So far, an integrative view has not been taken of the global demand for hydrogen and its long-term development in the context of climate neutrality, or of the economic requirements. As a result, there is a lack of understanding about the extent to which potentials must be exploited in the future and what price level can be expected for green hydrogen. This is all essential information for developing an import strategy.

Against this background, this policy brief aims to identify and discuss the aspects of importing hydrogen in the future that go beyond techno-economic issues. In this way, it aims to contribute to outlining the entire path to importing green hydrogen for the energy transition in Germany. The topics of climate neutrality, technical and economic potentials, sustainability, but also capital availability, governance and local impacts are dealt with separately in the following chapters. The state of knowledge and the challenges still to be faced are identified and recommendations made for future research.

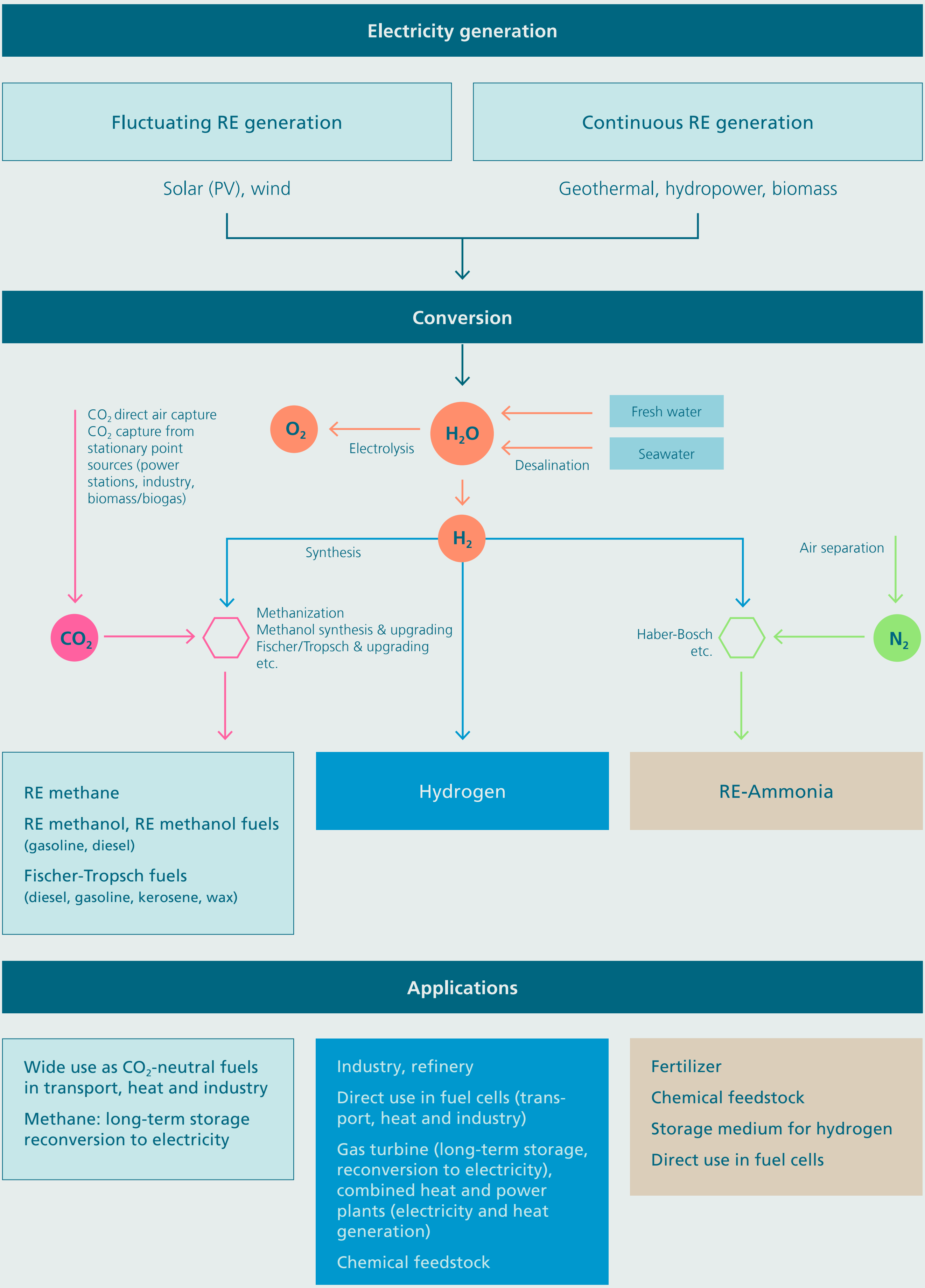

Figure 1: Selected conversion paths to produce green hydrogen and synthesis products based on renewable electricity (as an extension of [4])


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Theses

01

Climate neutrality requires the use of green hydrogen and synthesis products in Germany

Studies aimed at achieving climate neutrality consider the use of green hydrogen and synthesis products essential in parts of the energy-intensive industry and long-distance transport in addition to energy efficiency and sufficiency strategies, CO_2 capture and storage, and the use of advanced biofuels. Technical requirements in the respective application are the main reason for this estimation. Beyond simply supplying heat, industrial process heat applications often require specific chemical process conditions, e.g. a reducing or oxidizing atmosphere as is the case when firing ceramic materials (see [15]). This is a property, which cannot be provided using direct electrification, and requires the use of a material energy carrier such as hydrogen, coal or methane. Chemical feedstocks have an inherently material dimension, often based on carbon. This cannot be replaced by a non-material energy source like electricity. International aviation and shipping also require energy sources with an energy density that can only be provided at present by liquid hydrocarbons and not by hydrogen or batteries. In other applications, such as trucks or industrial process heat, the future role of hydrogen is still uncertain due to the availability of direct electrical alternatives, whereas electric mobility is acknowledged to play a dominant role for passenger cars. The discussion about the future role of hydrogen and its synthesis products in supplying heat to buildings or in storing power is a controversial one. Usually, there are other, more cost-effective options here to reduce greenhouse gases.

A differentiated view must be taken of hydrogen use in energy-intensive industrial processes. On the one hand, hydrogen already plays an important role at present as a raw material (feedstock) in refineries and the chemicals industry. Here, it could be converted to green hydrogen. On the other hand, it could become important in the iron and steel industry in the future, which is a key sector on the way to a climate-neutral world due to its very high energy consumption. In refineries, chemicals, and the iron and steel industry, there are already announcements, demonstration and pilot projects as well as initial implementation projects on a large industrial scale.

Another possible future option for switching to carbon-neutral production is to use green hydrogen to generate the process heat needed in various industry applications such as the glass or paper industry. However, this option is often seen as more of a long-term possibility as it is not economically viable at present.

Green hydrogen can be used in a range of transport applications. The first small series of passenger fuel cell cars are already commercially available. Fuel cell vehicles are already part of normal operations in material handling in forklift trucks, for example. In addition, there are ongoing fleet trials of local and long-distance buses in Germany. There are several activities in the heavy truck segment, especially for medium and heavy-duty trucks, and individual manufacturers have announced the production of small series in the near future. In rail transport as well, there are the first fleet tests or announcements concerning non-electrified track sections.

There are limitations on using hydrogen in transport where very high energy density is required, such as international aviation and shipping. These applications generally have to rely on the synthesis products of hydrogen to reduce their greenhouse gas emissions. Since the volume of transport is growing strongly, especially in air traffic (at least prior to the corona crisis), synthesis products of hydrogen will play an increasing role here. In addition, there are sectors such as long-haul heavy goods traffic where it is not yet clear what role synthesis products will play.

To conclude, relevant amounts of green hydrogen and synthesis products will be required in Germany to achieve climate neutrality, but there are different estimations at present of how much. Further research is needed to determine the economically viable share of green hydrogen and synthesis products in the energy system of the future. Technological innovations can strongly influence this share in the future as well.

Theses

02

There could be a big market for green hydrogen and synthesis products

As already shown, with ambitious climate goals like greenhouse gas neutrality, green hydrogen and its synthesis products have an important role to play, especially in transport and industry. Various studies have dealt with the global potential of hydrogen and synthesis products. [9] estimates the worldwide Power-to-X (PtX) market potentials in a range from 320 to 726 TWh by 2030, and 972 to 6,180 TWh by 2050 (cf. also [10]). This corresponds to a market volume of 45 to 102 billion euros annually in 2030, and 107 to 680 billion euros annually in 2050. In comparison: the oil markets in today's prices amount to approximately 2,000 billion euros annually (cf. [9]). For European companies, [11] expects a turnover of up to 65 billion euros in Europe and an additional 65 billion euros or so on global hydrogen and fuel cell markets.

Depending on the study and scenario, the demand for synthetic fuels in Germany in 2050 is expected to be between 530 TWh and 910 TWh in ambitious climate protection scenarios (see [12], [13], [14]). In comparison: In 2018, the total electricity demand in Germany amounted to 560 TWh (see [66]), and the total final energy consumption was 2,500 TWh (see [67]). This illustrates what efforts will be required in this field in the future.

03

Expansion potentials for renewables in Germany are limiting domestic hydrogen production potentials

Decarbonizing the energy system will ultimately take place to a large extent by generating power based on renewable energies, which substitute fossil energy sources. This power can be used in the energy system either directly or indirectly via hydrogen or synthetic hydrocarbons produced from it. The proportions of these energy sources vary widely in different scenarios. Hydrogen and derived synthetic fuels are characterized by high flexibility of use, but also by higher power demand due to the efficiency of the process chain. The resulting electricity demand in scenarios with a strong use of hydrogen and hydrogen-based synthetic hydrocarbons reaches values of just under 3,000 TWh in studies (see [16]). This requires substantial expansion of renewable electricity generation in Germany, which reached 243 TWh in 2019 (see [17]). The potential in Germany to expand renewable electricity generation is seen as between 700 and 1,100 TWh according to Fraunhofer ISI's internal calculations based on economic viability and acceptance. This implies that the domestic potential of renewable energy is probably not sufficient to meet the total demand for power including hydrogen production. However, in scenarios that strongly emphasize direct power applications, it also means that not insignificant amounts of the electricity required can be covered by domestic potentials (see [1]). According to our own calculations, the capacity expansion potential for renewable power generation in neighboring European countries is much higher at more than 15,000 TWh (see [1]). However, very high exploitation of this potential is expected to be accompanied by higher costs and dwindling acceptance among the population. A possible alternative, therefore, is to produce hydrogen in those regions of the world, which, due to their geographical and climatic conditions, have a naturally high supply of (low-cost) renewable energy sources and less intensively used land areas. Solar technologies in Germany, for instance, always compete with other land uses. In the uninhabited areas of North Africa, there is often no competition for use, and the potential yield of PV is sometimes twice as high.

Despite all the uncertainty concerning future developments, it seems likely that significant amounts of hydrogen will be produced outside Germany and even outside Europe because of lower costs abroad and limited public acceptance at home. This is also emphasized in Germany's national hydrogen strategy and the European hydrogen strategy. However, too little is known about acceptance and the conditions needed for imports to actually take place to the extent considered necessary. The following chapters address the individual problems and open research questions.

04

Importing green hydrogen and synthesis products is technically and economically attractive

Several studies have looked at the production costs of imported synthetic fuels based on renewable electricity generation (see [4], [18], [4], [19], [20], [21]). Electricity prices, efficiency, investments in the electrolyzers and their full-load hours have the biggest influence on production costs. The electricity costs of renewable installations in countries with favorable climatic conditions, such as North Africa, are much lower than in Germany—with electricity production costs from PV and wind installations of less than 3 €ct/kWh. They are therefore more than 50 percent lower than the costs at German locations. They also have a higher number of full-load hours with more than 4,000 hours per year. The production costs of hydrogen and synthesis products in countries with favorable climatic conditions are therefore significantly lower than production in Germany. Furthermore, the costs for transporting the synthetic fuels from these countries are comparatively low in relation to the production costs. From the supply cost perspective, therefore, it makes sense to import synthetic fuels to Germany.

Technical obstacles do not prevent this, or only occur in specific cases. They still exist, for example, when transporting cryogenic hydrogen, i.e. liquid hydrogen at −253 °C, for which suitable ships still have to be developed and brought to series production, or for transporting synthetic methane, for which retrofitted natural gas pipelines can be used. Another technical requirement that currently exists concerns the need for water in the producing countries, which presents a challenge in some regions and may require working with seawater desalination plants. Manufacturing the synthesis products also requires CO_2. The CO_2 can come from biogenic or stationary sources, e.g. from fossil power plants or industry. As these are not always available, technologies are currently being developed that can capture CO_2 directly from the air. However, this is energy-intensive, requires lots of land and causes additional costs.

Economic assessment shows that hydrogen and its synthesis products based on renewable electricity are currently still two to three times more expensive than hydrogen based on fossil energy carriers (see [7]). This means cost reduction potentials must be exploited and financial incentives should be set for the market introduction and market ramp-up phases. As things stand at present, the costs of synthetic fuels are significantly higher than the costs of today's fossil fuels, even if imported from particularly attractive regions. In addition, from a national economy viewpoint, it should be considered that Germany would relinquish the opportunity for additional domestic value creation by importing hydrogen, and would continue to be heavily dependent on energy imports. This latter point is the subject of the next chapter.

Finally, it should be mentioned that constructing the relevant production plants and transport infrastructures would take several years, and that significant import volumes are only expected from 2030 onwards.

05

Strategies must be developed for the new import dependencies of a hydrogen economy

If it is assumed that relevant amounts of green hydrogen will be imported in the future, it must be asked what this implies for Germany's supply security. At present, Germany is heavily dependent on imported fossil fuels, mainly from non-European countries. In 2019, 60 percent of Germany's primary energy consumption was covered by oil and gas (see [22]). Germany gets its natural gas mainly from Russia, the Netherlands and Norway (see [23]). Oil is primarily obtained from Russia, Norway, Great Britain, Libya and other countries (see [24]). Hard coal is also largely imported from countries like Australia. In some cases, the production of some supplier countries (Netherlands, UK) will decrease strongly over the next 10 to 20 years.

The transformation of the energy system is not only aimed at a sustainable, competitive and efficient energy supply, but also at an affordable and secure one (see [25]). When considering energy supply security, therefore, the EU Energy Union does not restrict itself to import dependency, but includes system stability, critical infrastructures and cybersecurity as well. For instance, in the course of expanding renewable energies, the effect of volatile renewable energies on the stability of the grid is analyzed (see [26], [27]). Nevertheless, import dependency plays a major role in the discussion about supply security. Assessing import risks is based on various factors (see [28], [23]) such as import share, stability of the exporting country, substitutability of the exporting country, number of (potential) exporting countries, transportation risks (transit route, infrastructures), substitutability of the imported energy carrier, and diversification of the supply sources.

As discussed in detail above, in various climate protection scenarios, green hydrogen and synthesis products substitute fossil-based energy carriers in all sectors by 2050, but with different functions and to varying degrees. For the German power grid, for example, hydrogen offers a new flexibility option and contributes to system stability, while in industry green hydrogen will become increasingly important for material use (see [29] and Chapter 01). In the transport sector, depending on the underlying scenario, hydrogen-based fuels will cover up to about 50 percent of the energy demand in 2050 (see [13]). These could significantly reduce the current import ratio in the transport sector of almost 100 percent. As it is not yet clear which countries will deliver hydrogen-based energy carriers to Germany in the future, it is not possible to estimate the risks associated with transport and transit, political stability and the diversity of the supplying countries. Nevertheless, there are already various possibilities for Germany and the EU to build a solid basis for a reliable energy supply. On the one hand, integrating and networking the energy markets in the EU can cushion regional bottlenecks and instabilities. On the other hand, long-term and cooperative relationships that can contribute to supply security can be forged with selected countries by considering socio-economic and sustainable criteria when selecting potential producing countries, and by strengthening international cooperation (see Chapter 11). One of the political tasks ahead is to further develop these approaches and a new sustainable policy for cooperation with future producing countries.

06

It is still open how global supply and demand and an international hydrogen price will develop in future

As discussed in Chapter 04, a number of studies compare the economic attractiveness of importing hydrogen to producing green hydrogen and synthesis products domestically. However, these only analyze individual countries such as Australia, Morocco, Argentina or regions (like North Africa) (see [18], [30], [7], [31]). The potential imports are then analyzed for selected countries like Germany or regions like the EU. What is missing so far is a global overview of the potential supply and the potential demand and the extent to which these match. For a comprehensive analysis, potential producing countries worldwide would have to be identified and analyzed. The first step is to consider natural potentials, such as the availability of resources (wind, solar radiation, water), as well as technical feasibility and costs for plant facilities and infrastructures like power lines and gas pipelines. The second step is to integrate the economic, social, energy and development policy goals and restrictions into the analysis. These include securing the energy supply in the country exporting the hydrogen and meeting the energy and climate policy goals there. Additional aspects should also be included such as industrial structures, know-how of developing production capacities, capital available for investments in plants, training structures and capacities, and environmental aspects. The interests of local actors as well as global actors and stakeholders also influence potential production. All of these aspects ultimately determine the potential for exporting green hydrogen and synthesis products. Many of these aspects also apply to the potential importing country. Energy and climate policy goals, sustainability requirements, actors and stakeholder interests etc. drive the demand for imports. The most important aspects are discussed in more depth in Chapters 05 to 13.

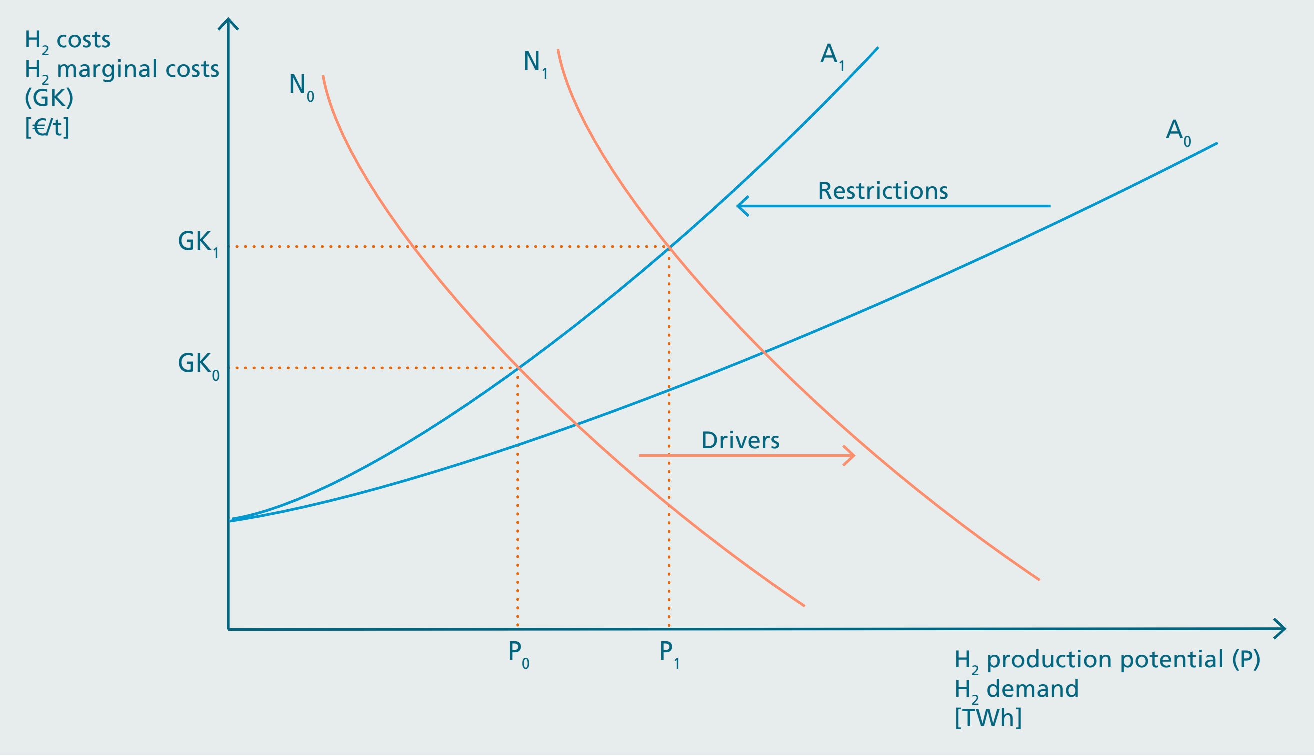


Figure 2: Methodology to determine hydrogen supply and demand and possible pricing derived from marginal costs (Index 0 without drivers and obstacles, Index 1 including these)

A comparison purely in terms of quantities helps to gain an idea of whether supply and demand can be matched. However, this is followed by another question that is difficult to answer. How will the prices for green hydrogen and synthesis products develop in future? The economic analyses conducted so far are almost without exception based on the costs for production and transportation. However, it is not possible to derive market prices directly from these. Market prices are based on marginal costs plus surcharges for taxes, profit, risk premiums, sales, warranty, R&D expenditure etc. or even scarcity prices (see crude oil) or prices based on other energy sources (such as natural gas).

Chapter 08 examines the connection between market attractiveness, risks and costs of capital in more detail. Figure 2 illustrates the connections. There will be restrictions that limit the supply of green hydrogen, and drivers that increase the overall global demand for it. Today's mainly production cost-based analyses entail the risk of significantly underestimating the actual market price and deriving incorrect policy recommendations as a result. This is why analyses of production costs are needed for a realistic future perspective in order to add the derivation of potential market prices, comparable to today's trade with energy carriers and raw materials.

07

Sustainability criteria must be developed and complied with in the potential producing countries

As can be read in the German government's National Hydrogen Strategy (see [3]), from the perspective of the German government, only hydrogen produced using renewable energies is sustainable in the long term—so-called "green" hydrogen. It is therefore the German government's goal to use green hydrogen, to support its rapid market ramp-up and to establish the corresponding value chains. It is also being discussed whether CO_2-neutral hydrogen should be used, at least in a transitional period, for reasons of economic efficiency (e.g. "blue" (see [68]) or "turquoise" (see [69]) hydrogen). This can be used transitionally in Germany due to the country's integration into European energy supply infrastructure.

Globally, there are very different definitions of "green hydrogen", including some that allow the use of nuclear energy as CO_2-free (see [32]). Other definitions, such as the Green Hydrogen Standard of the TÜV SÜD, are based on limits for the reduction of CO_2 emissions (see [33]).

One of the policy measures in Germany's National Hydrogen Strategy makes the following reference to pilot projects in partner countries:

"[...] attention will be paid to ensuring that importing green hydrogen or energy sources based on it to Germany takes place on top of domestic energy production in the respective partner countries and does not impede the supply of renewable energy, which is inadequate in many cases, in the developing countries. Also, the sustainable supply of water in arid regions of these countries must not be impaired by the production of hydrogen. The aim is to achieve sustainable production along the entire supply chain."

Producing hydrogen requires large amounts of electricity, and therefore also large areas of land to generate renewable power. In the "Greenhouse gas neutrality" path of its roadmap published in 2019, the German Chemical Industry Association (VCI) assumes that 628 TWh electricity will be required annually until 2030 for the chemical industry alone (see [34]). The world's largest PV plant at present, the Bhadla (see [70]), has had a capacity of 2.2 gigawatt since December 2019. This plant covers an area of 45 square kilometers. Assuming a daily production of 5.5 kWh per square kilometer, about seven of these plants with an area of more than 300 square kilometers would be needed just for the German chemical industry. Depending on spacing regulations, the area required for wind turbines would be even larger. In addition, land is needed for the electrolyzer facilities, transport infrastructure, and other things. If green synthesis products are also produced from hydrogen on-site, areas with favorable climatic conditions for renewables often lack stationary point sources or biomass sources able to meet the necessary carbon demand. CO_2 would then have to be captured directly from the air, which also entails a significant demand for land and energy due to low plant efficiency. These dimensions show that constructing additional renewable energy capacities here can only be done together with expanding the power supply for the local population.

In many of the potential hydrogen producing countries, such as those from the MENA region or Australia, for example, power generation is often still based on fossil energy sources. Developing renewable power generation to export green hydrogen must not result in the perpetuation of fossil sources or countries not being able to meet their own energy and climate policy goals.

Many of the possible hydrogen producing countries already have large installed hydropower capacities (e.g. Egypt, Turkey). The sustainability of large hydropower plants is controversial, and water consumption is another problem. The electrolyzers used to produce hydrogen require water that may be in short supply depending on local conditions and where distribution issues may arise, for example, to supply the local population with drinking water or to produce food. Seawater desalination plants are often used to obtain water. In addition to their high energy consumption and CO_2 emissions, these plants also produce large amounts of residues, above all large quantities of brine with highly concentrated salts, biocides, anti-scaling agents, anti-foaming agents and metals (see [35]).

In the future, it will therefore be important to provide proof of origin for the electricity needed for electrolysis, but also for the water required and, if necessary, for the carbon sources. From the viewpoint of the acceptance of importing green hydrogen into Germany, sustainability issues along the entire value chain are of great importance to avoid the mistakes that were made with biofuels, for example. More than a decade ago, the discussion about the sustainability of biofuels (palm oil) from Malaysia or Brazil and indirect changes in land use halted the spread of a global biofuel economy. In terms of an extended sustainability discussion, it is important to consider the social consequences in the producing countries, see also the section on the possible positive aspects due to the creation of local value added.

Consequently, it should be an important political priority in the next few years to develop a sustainability standard that is as international as possible, and this should be integrated into global climate negotiations. Germany and the EU could take a lead role here. Strong state institutions in the future producing countries are an important factor for improving environmental and social standards, and this aspect should be part of developing a strategy. A comprehensive sustainability standard must have positive effects on at least six of the global sustainability goals, specifically: SDG 6 (clean water), SDG 7 (affordable and clean energy), SDG 8 (decent work and economic growth), SDG 9 (industry, innovation and infrastructure), SDG 12 (responsible consumption and production) and SDG 13 (climate action).

08

An economically attractive market must be created for investors

The production as well as the energetic and material utilization of hydrogen require extensive investments in facilities to supply electricity and water, in conversion plants, and in application technologies. Mobilizing large amounts of capital is necessary for this. For private investors, the expected return on investment is decisive, while for external lenders (financial intermediaries), minimizing the default risk plays a major role (see [36]). A high risk drives up financing costs (see [37]), which in turn are reflected in the specific production costs (see Chapter 06 on the challenge of pricing green hydrogen). Furthermore, there is limited venture capital available. The goal is therefore to shape market conditions so they are attractive to a large number of investors and to have enough low-cost capital available.

Looking at the risks, certain analogies can be drawn to the expansion of renewable energies, but differences are also expected. There are differences, for example, resulting from country risks that are partially reflected in the capital costs of external investors via counterparty contracts. With regard to the production of hydrogen, for example, part of this will take place in countries with high risks. The financing costs in developing countries are sometimes twice as high as in industrial nations; this discrepancy is especially evident in projects with high initial investments (derisking renewable energy investment, see [38]). Analogies can be drawn with regard to the long-term development of the market and the investors. Over time, the financing costs for renewable energies have fallen significantly (compare [71], [72]). The main reasons for this are declining risks at country level and developments on the capital market, especially in the eurozone. In addition, declining technology risks and learning effects among investors play a role (see [39]). Effective policy measures to promote the expansion of renewable energies have also made a significant contribution to reducing the investment risk (see [40], [41]). From a global perspective, private investors such as households, companies, and project developers now contribute about two thirds of renewable energy financing, and private financial intermediaries and development banks about one third, while the importance of institutional investors is still low at five percent (low expected returns due to risk aversion). Development banks are attributed an important role as enablers during the early phase of expansion (see [41]), as they reduce the extent of potential credit defaults through grants and low-interest loans, and thus increase the attractiveness for other investors (leverage effect).

It was decisive for the expansion of renewable energies and thus also for investments and financing that various bundles of policy instruments created secure demand (guaranteed purchase of electricity), which influenced the risks involved and thus the financing costs (see [42]). If policy measures such as premiums, quotas or certificates in the countries importing hydrogen generated a similarly reliable demand as has partly been accomplished in the expansion of renewable energies (shifting demand to the right in Figure 2), this would reduce the market risk and make the market more attractive to investors. If, in addition, corresponding guarantees from the importing countries reduced the existing country or counterparty risk in the exporting countries, and if development banks served the capital market as enablers, investment risks could be reduced and the supply of hydrogen increased (shifting supply to the right in Figure 2), so that the market as a whole could grow significantly.

09

Incentive systems for hydrogen production are largely missing and must be introduced

Under the current framework conditions, producing hydrogen abroad and the associated hydrogen imports are not competitive (see Chapter 04). In addition, the lack of sales markets and unclear legal boundary conditions, for example with regard to certification as green hydrogen, are hindering competitiveness. This is why different incentive systems are being discussed to make the production of hydrogen abroad and its import attractive.

- *Investment support*: Germany's National Hydrogen Strategy plans the construction of hydrogen production facilities in Germany with a capacity of 5 gigawatt by 2030, and an additional 5 gigawatt by 2035 (see [3]). At European level, the EU's Hydrogen Strategy aims at an electrolysis capacity of more than 40 gigawatt by 2030, which is to be supported within so-called IPCEI projects (see [2]).

- *Regulatory framework conditions in the producing country*: The regulatory framework in the producing country has to be designed so that it does not impede the production of green hydrogen. This concerns, for example, extra charges for power through state-induced price components, but also regulations on plant operation.

- *CO_2 pricing*: Designing CO_2 pricing to reflect costs more accurately and expanding emissions trading or CO_2 pricing to other sectors and countries creates incentives for electricity from renewable energies and therefore for green hydrogen (or acts as a cost burden on fossil competitors).

- *Feed-in tariffs*: At EU level, feed-in tariffs are seen as a major support instrument for hydrogen production. In this way, producers of green hydrogen can become competitive with existing producers of gray hydrogen at an early stage. It is unclear to what extent producers in countries outside the EU can or should also be paid feed-in tariffs for green hydrogen exported to the EU.

- *Contract for differences*: In addition to the producers of hydrogen, incentives are also needed for potential consumers in order to create a (global) hydrogen market. "Contracts for differences" are being discussed as an incentive here. They aim to compensate the cost differences to consumers between existing production processes and processes modified to use hydrogen, if CO_2 pricing is not sufficient for this.

- *Quotas*: Quotas are an instrument to increase the use of hydrogen in the transport sector and partly in the heating sector. Quotas are fulfilled by the suppliers of fuels. They are suitable in areas not subject to international competition. The costs of meeting the quota are passed on in the form of higher fuel costs. Due to the flexibility in meeting quotas, there is much higher uncertainty for hydrogen producers than with "Contracts for differences" regarding the development of market demand.

- *Proof of origin for green hydrogen*: When importing green hydrogen, quality and origin are of major importance to ensure that the use of hydrogen contributes to sustainability (see the discussion in Chapter 07 on sustainability). In countries of hydrogen origin, certification can create an incentive to trigger additional investment in renewable energies due to hydrogen exports. Care must be taken to ensure that this does not take place at the expense of the local energy supply, or that it creates incentives for additional fossil energy generation.

The lack of economic viability for producing and using hydrogen as a decarbonization option means that additional incentives are needed, and the current framework conditions must be adapted. This is also very important for the discussion in Chapter 08 about incentives for investors. This should consider their integration into existing instruments, especially the EU emissions trading scheme, in order to guarantee efficient and effective climate protection. Further research is required concerning the coordination of appropriate instruments in order to make a contribution to climate protection and to incentivize the most suitable options.

10

The hydrogen economy must be integrated into the overarching governance structures for transforming the energy system

As discussed in Chapter 07, generating electricity to produce hydrogen in Europe and in developing countries is linked with environmental impacts that are enhanced by the low efficiencies in the entire chain from producing to using the hydrogen and synthetic energy sources. Although these impacts are not easy to quantify and internalize in renewable power generation, they provide arguments for a hierarchy principle that minimizes the necessary RE capacities—even if costs continue to fall. This implies that the development of the hydrogen economy must be integrated into the general governance structures for transforming the energy system via a hierarchical principle. This *hierarchical principle* should—analogous to the energy efficiency first principle—minimize the cost of hydrogen production, even if the costs for renewables, electrolysis and the production of synthetic energy sources continue to fall. This principle applies to the entire system of supplying and consuming energy, i.e. it covers both producing and consuming countries, and comprises the following four stages:

- The *"energy efficiency first" principle* recently introduced into European policy must be a strong guiding principle when expanding energy supply and therefore the RE capacities in a country. This refers to both PtX import and export regions. This also applies to the direct use of renewable energies to decarbonize the power sector and the demand sectors as well as to RE capacities used to produce the hydrogen itself.

- The second stage in the hierarchical principle is *priority for renewable energies in the continued expansion of the electricity sector* (or if substituting fossil power capacities is necessary). Fossil fuels should be phased out as quickly as possible to make room for clean power generation. This second stage is especially relevant for potential hydrogen producing countries that have not yet decarbonized their own power sector.

- The third stage of the hierarchical principle gives priority to *alternatives based on renewable energy sources that provide similar services but with less environmental impact*. These include the direct use of electricity in particular and sustainable biomass/biofuels/biogas, taking into account their limited availability in the countries consuming and producing hydrogen.

- Applications where none of the above three apply must use hydrogen and synthesis products. As mentioned in Chapter 02, this still opens up a global market of 100 to 700 billion euros worldwide for the hydrogen economy.

This four-stage principle, which can be regarded as an extension to the "energy efficiency first" principle, must be implemented in the governance structures for transforming the energy system for both the countries consuming hydrogen and for those producing it. This is an important prerequisite for their sustainable development.

11

Integration into international cooperation should take place

The selection of producing countries will include African states both North and South of the Sahara, among others (see Chapter 04). As is the case for many regions in the Global South, these states are increasingly caught up in a spiral of climate change impacts that are hard to control, such as uncontrolled urbanization due to declining livelihoods in rural areas (see [46]). The resulting increase in energy demand in urban centers has been discussed for several decades, but is still hardly being met, as is the case in Nigeria, for example (see [47], [48] and Chapter 07 as well). Among other reasons, this is because many states have faced far-reaching (development) political and social problems since their independence in the 1950s and 1960s (above all in the domain of state and nation-building) (see [49], [50]).

The desired security of supply (see Chapter 05) is therefore rooted in a large area of conflicting interests. However, based on carefully planned international cooperation, Germany can work towards translating its own dependency (imports of hydrogen, see Chapter 05) into the necessary bilateral and multilateral reliability and infrastructural resilience (production and maintenance). Germany has helped to formulate the task of international cooperation on climate protection and for global energy supply within international agreements (see discussion in Chapter 07). The relevant Paris Agreement of 2015 explicitly mentions support for developing countries via technology transfer and joint technology development:

"*Taking full account of the specific needs and special situations of the least developed countries with regard to funding and transfer of technology […]*" (see [51]).

Building on the discussion of local value creation (see Chapter 12), Germany has the opportunity to create structural and "systemic" trust (see [52]) in partner countries for hydrogen exports. With regard to the characteristic features of trust, such as interaction and reciprocity (ibid.), the aim should be to counteract the local feeling that can be derived from discourses of being kept at the periphery of technological and scientific knowledge and of resource-based neocolonialism (see [53], [54], [55]). Related large-scale infrastructure projects in the field of renewable energies, such as Desertec for example, have failed partly due to these tensions in North-South relations (see [56]).

Importing hydrogen should be based, among other things, on empirically sound findings about development cooperation. In the case of infrastructure projects, sub-areas such as the local development and adaptation of smaller everyday technologies (see [57], [58], [59]) should also be placed in relation to national innovation systems (see [60], [61]). It would be negligent to leave this complexity of technologies, institutions and stakeholders out of the hydrogen topic and only to consider the mutually dependent import/export relations when problems resulting from this escalate.

Local actors who are able to build trust in implementing the necessary technological and socio-economic infrastructures (see Chapter 12) should be identified using situation and stakeholder analyses. It is essential to integrate local carriers of knowledge about historical-geographic, climatological, economic, sociocultural and technological aspects if partner countries are to be reciprocally involved when working towards the SDGs. This is also necessary to prevent expensive bottlenecks through trustworthy capacity building (see Chapter 12), and to increase the economic attractiveness of the market to investors (see Chapters 06 and 08). Local research institutions can play a role here as intermediaries between society and politics. Local universities possess relevant knowledge, for instance, but its transfer is sometimes pushed into the background due to a lack of infrastructures and corresponding day-to-day efforts in capacity building (see [62]). Supporting local research on energy issues not only builds trust, but also can properly integrate the H_2 infrastructure into a regional, social, and economic context (see Chapters 07, 10 and 12).

At the same time, strategy development should consider already ongoing international activities in the context of energy partnerships and multilateral cooperation, such as

"International Partnership for Hydrogen and Fuel Cells in the Economy (IPHE)". Complex political, economic and cultural contexts should also be taken into account. Morocco, for example, acts as an "African", "Maghrebi", "Arabian" and international player. With regard to the energy transition, it is important to consider conflicting goals and unnecessary redundancies at an early stage. The systemic consideration of NGOs, intergovernmental organizations and transnational partnerships can integrate stakeholders that have not yet been identified, as these can have both a supportive and a hindering effect (see [63]). In addition to bilateral and multilateral dialogs between Morocco and other states (for example PAREMA), these also include the African Union (AU, see [64]), UNECA and the League of Arab States (LAS with reference to IRENA & RCREEE) (among others, see 3.4. in [65]).

12

Local economic competencies are required for successful implementation

A global hydrogen economy, which is developed by the users and producers of hydrogen and synthetic energy sources or chemicals working together, requires the development of new and the enhancement of existing local economic competencies. This is the only way to ensure that a globally networked green hydrogen economy not only contributes to the global energy transition, but also to sustainable and innovative economic development in the producing countries as well. This is a major driver for establishing new energy technologies, especially in emerging economies and developing countries, as creating jobs and expanding local value creation potentials in sustainable sectors are key elements of national development strategies.

In the context of developing an internationally networked hydrogen economy, local value creation may concern the direct production of hydrogen and the associated supply of materials and services. However, it may also involve the upstream and downstream components of value chains, such as expanding and developing supplier industries and locally required transport or storage infrastructure. In addition, it can encompass components for energy generation (i.e. renewable energy technologies) and any downstream chemical synthesis and transformation processes, and application technologies.

Assuming an ambitious scenario for a European hydrogen industry, a recent study by E4tech (see [43]) estimates that developing a hydrogen and fuel cell economy in Europe could have potential economic effects of up to 3.5 billion euros and create 38,500 direct jobs and more than 70,000 indirect ones (i.e. full-time equivalents) by 2030. By 2050, the hydrogen economy could reach a volume ranging from 100 billion euros worldwide, which is equivalent to today's steel market, up to almost 700 billion euros, about one third of today's oil market. The size of the market depends on where alternatives are available in the form of direct electricity use, such as freight transport (see [9]).

Organizing the global value chains for hydrogen is still in its infancy, with only a few active players so far. Against this background, there is significant potential for local value creation in possible producing countries worldwide. Currently, numerous emerging economies and developing countries are not only working on strategies to use different hydrogen application technologies in the transport sector or industry, for example, but are also actively assessing the possibilities for local value creation due to establishing a local hydrogen economy (see [44], [45]).

The following local competencies are especially relevant for realizing an international trading system in the context of a hydrogen economy, and must be taken into account when developing a strategy:

- Existing local industrial value chains support the emergence of hydrogen value chains.

- The producing countries must have already implemented successful policies to develop renewable energies, with the goal of developing a local economic base here too, parallel to a green hydrogen economy. Not all the technologies needed to produce hydrogen have to be manufactured in the producing countries, but it is in their interests to keep as much of the value chain as possible up to the final product in their countries.

- Since investments in research are needed to reduce the costs of hydrogen and increase the longevity of the products, local research networks must be competitive and, where necessary, further developed through international research cooperation and energy partnerships in order to keep up with global competition.

- The development and implementation of global quality and safety standards for the production of green hydrogen represent a key element that calls for intensive international cooperation.

- Embedding the hydrogen strategy in the national energy strategy and close coordination with industrial policy instruments in the producing countries are essential to avoid conflicts of goals and resources (compare Chapter 07).

13

Technology sovereignty must be critically analyzed and ensured for countries importing and exporting hydrogen

Calls for technology sovereignty in Europe were becoming louder even before the current Corona crisis. Growing geopolitical uncertainties and the threat of global trade conflicts are questioning the optimism of recent decades concerning the interdependence of our economies. This is triggering a discussion about how independent a state or a federation of states must and can be with regard to critical technologies. A definition of technology sovereignty and ways to determine the criticality of technologies have recently been presented by Fraunhofer ISI (see [73]). Technology sovereignty refers to the ability of a state or a federation of states to provide the technologies it deems critical for its welfare, competitiveness and ability to act, and to be able to develop these or source them from other economic areas without one-sided structural dependency. Technology sovereignty should be addressed in particular for those technologies and their value chains that are essential for economic competitiveness, meeting key societal needs such as energy supply and sovereign tasks. Chapters 02 and 03 clearly show that hydrogen technologies meet these criteria. It is therefore foreseeable that hydrogen strategies will be increasingly assessed from the viewpoint of technology sovereignty (TS) in the future.

The factors needed to produce technology sovereignty are distinguished in [73] between a state's already existing own competencies and resources or the possibility to develop these itself if needed, and access to resources, competencies and upstream services of third parties. Constraints on technology sovereignty are to be feared if there is no security of supply from third parties for critical resources or competencies that a state or a federation of states cannot provide or develop itself.

In the discussion up to now, technology sovereignty has mainly been addressed from the viewpoint of important industrial nations and regions. From a German and European perspective, therefore, the first question is how to assess the availability of the technologies needed to establish a hydrogen economy. There are additional questions here about importing green hydrogen. The second question concerns the reliability of imports from the exporting countries, which was already raised in Chapter 05. From the perspective of the compatibility of a hydrogen strategy with the development prospects of the countries producing green hydrogen, the third question concerns how these countries assess the technology sovereignty of a corresponding hydrogen strategy for themselves, and what consequences result from this.

So far, there are no comprehensive assessments of the technology sovereignty of hydrogen technologies. [73] refers to patent analyses as a starting point to assess the availability of technology expertise. Initial information can be obtained from previous patent analyses, in which hydrogen production, storage and distribution technologies formed a subset of the green technologies examined (see [76] and [82]. For the mid-2010s, these data indicate a visible position of Germany (a good 10 percent share of global patents) and for the EU as a whole (roughly 40 percent patent share). Other important players were primarily Japan and the US, while China as a whole took a less prominent position and even showed negative patent specialization in this field. It remains to be seen what picture will result once these data have been updated. Looking at, e.g. the members of the Hydrogen Council, suggests that German and European companies play a prominent role here as well (see [74]). From a German and European point of view, therefore, the starting situation is likely to be quite favorable with regard to the domestic availability of hydrogen technologies. However, a more reliable statement would require updated analyses that also differentiate technologies to a greater extent.

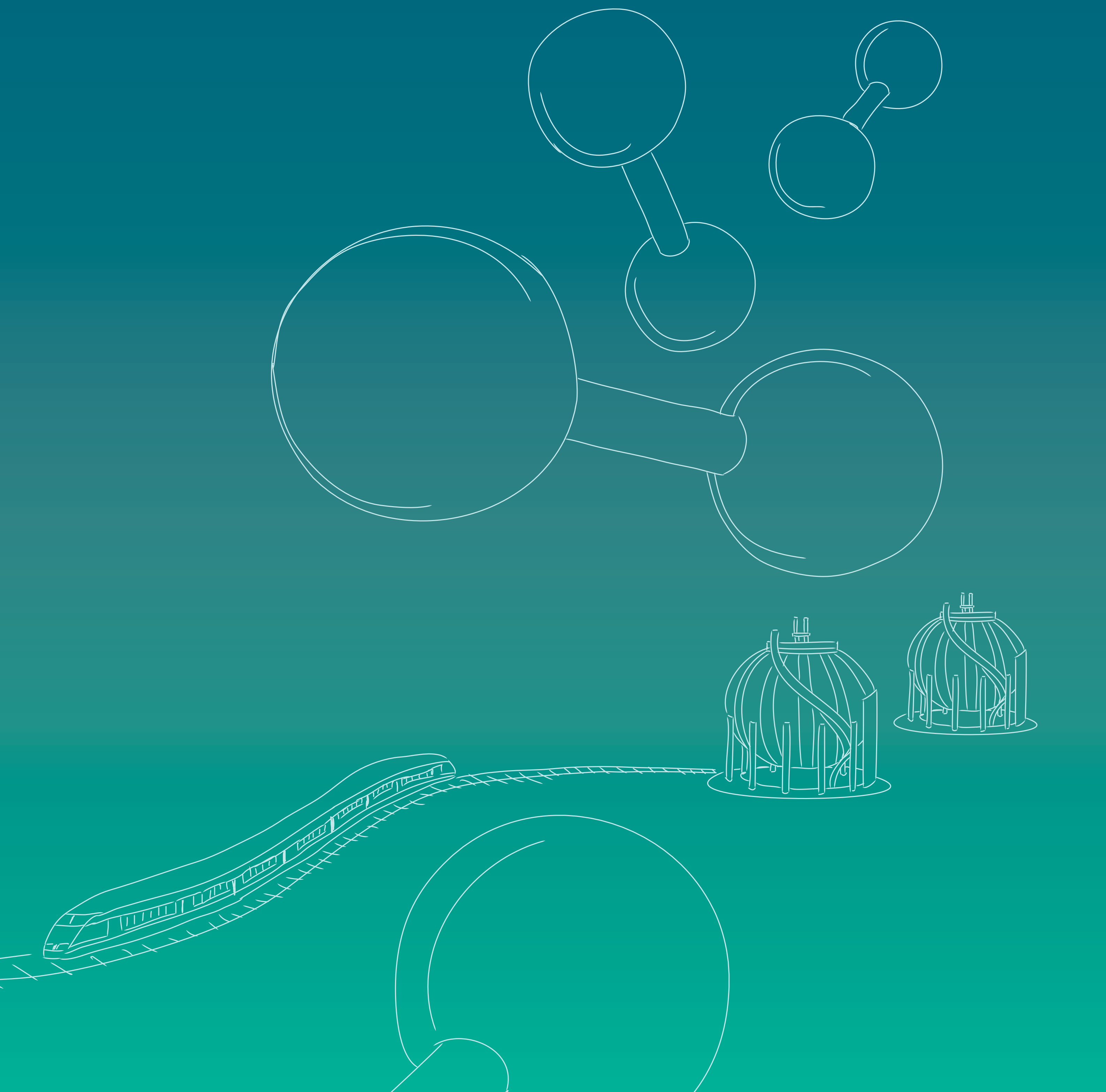
To assess technology sovereignty with regard to hydrogen technologies that are not available domestically, the choice of different countries, but also their reliability are important for the risk of dependency. Indications of a concentration in patent applications for technologies for producing, storing and transporting hydrogen can be derived from the above-mentioned data for Japan and the US as the two countries, in which the most knowledge is likely to be available, in addition to the EU. However, so far, there has been no differentiated analysis of the trade relations in these technologies, which is also important for this question.

With regard to the second question concerning reliability, a number of dimensions must be considered when assessing the reliability of countries from which green hydrogen is to be imported to Germany or the EU (see Chapter 05). In addition, [73] refers to the importance of countries complying with the WTO regime and of general country indicators such as the World Bank's Worldwide Governance Indicators (compare [75]). The index based on these indicators is also used by the EU to assess critical raw materials. For example, Germany has an index value of 1.46 for the indicators analyzed in 2019, and is therefore slightly better than Japan (1.32) and the US (1.13). This index can also be used as a first indication of the reliability of the potential countries exporting green hydrogen. If applied, e.g. to the countries being discussed as the starting points for a hydrogen strategy in Africa, significantly lower index values result for the nine countries considered, which range between –0.89 and 0.16 (see [75]).

With regard to the third question outlined above, from the viewpoint of many countries exporting green hydrogen, both the available technology knowledge and the manufacturers of the technology are located abroad. The distribution of patents across different countries, mainly the EU, Japan and the US, does indicate a certain heterogeneity in the origin of the knowledge. On the other hand, it should be noted that restrictions in technology availability may also result from the link with financing. This could occur especially if financing countries link their financial commitments to expectations about the choice of country of the technology provider. In-depth empirical studies are needed here, as is further development of the concept of technology sovereignty in its application to developing countries.

Overall, the comments make it clear that, from a German and European viewpoint, a risk to technology sovereignty is more likely to occur with regard to the reliability of the countries exporting green hydrogen than with regard to access to existing technologies. In order to arrive at reliable statements, however, updated analyses are required that differentiate technologies to a greater extent. At the same time, it is clear that the prospect of importing green hydrogen also requires extending technology sovereignty to include the perspective of developing countries. That these countries are expected to be dependent on foreign technologies and financing underlines the urgency of the issue addressed in Chapters 10 and 12 of linking an import strategy for green hydrogen with a strategy of technological and economic cooperation with the developing countries producing green hydrogen. Successfully improving the social and political stability of potential supplier countries would not only be key with regard to international sustainability goals, but would also increase the technology sovereignty of a hydrogen strategy from Germany's point of view. However, it falls short to indicate that investments in constructing hydrogen production capacity and the relevant exports to the EU would automatically strengthen a positive development outcome in the corresponding export countries. The resource curse, which describes the problematic relationship between a wealth of resources and positive economic development (see [79], [80], [78]),) is now also being discussed in the context of renewable energies (compare [81]). When discussing increased international R&D cooperation with producing countries and the development of future-oriented competencies, it would therefore be important to explicitly consider the extent to which these knowledge and production interconnections between consuming and producing countries also have stabilizing effects on governance in the producing countries.

Finally, the analysis of technology sovereignty in the context of importing green hydrogen also requires adapting the analysis concept itself. Especially with regard to the mentioned link to the financing of development strategies, it becomes clear that foreign policy aspects play a role here as well. In the future, one challenge to the technology sovereignty of Germany and Europe when importing green hydrogen could also result from the activities of players like China, for example, if these were to influence the technology sovereignty of green hydrogen producers in Africa not only by technology provisions, but also by integration strategies such as the Belt&Road initiative. Similar to the discussion about the criticality of raw materials (see [82]), it can therefore be expected that technology and market-related dimensions will increasingly merge with development and foreign policy dimensions in the future determination of technology sovereignty when importing green hydrogen.



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