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In a Nutshell!

How Important Will Hydrogen be in the Energy System of the Future?

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In a Nutshell!

Hydrogen and its derivatives (e.g. methane, ammonia and methanol) can store energy. They have many different uses, and hydrogen derivatives can also be easily transported over long distances. As both an energy carrier and a feedstock, hydrogen will play a key role in the energy transition and in replacing fossil fuels and achieving net zero.

1. **It's already used today:** Hydrogen obtained from natural gas and coal is already an important feedstock for industry, where it is used e.g. to desulphurise fuels, produce ammonia and as a precursor in the chemical industry. As it has so far hardly been used as a source of energy, demand in this sector is set to grow in years to come.
2. **Transition to zero-emission hydrogen:** Carbon-neutral hydrogen can be produced using renewable energy. But the transition to a green hydrogen economy can also be supported by bridge technologies that use fossil fuels but capture and permanently store as many as possible of the resulting emissions.
3. **Use it when it's the best option:** Initially, there will only be a limited supply of low-emission hydrogen and hydrogen derivatives. So it makes sense to use them in situations where – for technological or economic reasons – it is difficult or impossible to use green electricity directly. This is mainly in primary industry, aviation and shipping, and to compensate for power generation fluctuations in the electricity sector.
4. **The EU's internal energy market:** Renewable hydrogen and its derivatives can be produced especially cheaply in places that are very sunny and windy. A connected, Europe-wide infrastructure of pipelines, tankers and ports will facilitate the necessary imports from Europe and – if necessary – from further afield.

Contents

Background 3
Basic facts and status quo 4
Properties 4
Current uses 4
Production and future uses 6
Production: costs, water usage and emissions 6
Uses: Overall demand and areas of application 12
Hydrogen producing regions and transport options 16
Domestic production and supplementary imports 16
Potential partnerships and associated challenges 17
Transport options and costs 19
Conclusion 22
References 23
Contributors 29

Background

The idea that hydrogen could be an important future energy carrier has been around for some time. Hydrogen has been discussed as an environmentally-friendly alternative to fossil fuels ever since the 1970s oil crisis, and has also featured in the peak oil and climate change debates [1; 2; 3]. But hydrogen was never widely adopted, mainly because oil and gas were too cheap and readily available and the climate policy incentives weren't strong enough.

Now, however, things have changed. Germany and the EU have committed to achieving net zero by 2045 and 2050 respectively. This means that industry and the energy and transport sectors must quickly find alternatives to fossil fuels (coal, oil and natural gas). Renewable electricity has a key role to play, not least because its cost has fallen by between 60 and 90 percent over the last decade [4][1]. However, direct electrification of certain processes is either technologically complex or extremely expensive, if not impossible. In these cases, fossil fuels can be replaced by using hydrogen made with renewable electricity either as an energy carrier or an energy storage medium. Moreover, hydrogen is and will continue to be needed as a feedstock and additive in refineries, the chemical industry, etc.

This means that – together with renewable electricity – renewable or zero-emission hydrogen is set to play a key role in the energy transition and a defossilised economy in Germany, Europe and the rest of the world. Accordingly, **this paper** presents an **overview** of basic aspects of **the hydrogen question** that can ultimately help to establish a hydrogen economy which uses both zero-emission hydrogen and low-emission hydrogen as a transitional solution. The paper begins by discussing hydrogen's **properties** and **current uses**. Next, it looks at the different **methods of producing hydrogen**, including the **costs, water usage and emissions** associated with each process. It then outlines potential future **areas of application** of hydrogen and its derivatives. Following on from this, the final section considers the developments that will be necessary, based on current knowledge, to transition to a defossilised hydrogen economy. This includes a discussion of the **regions** where hydrogen **production** can take place, the **opportunities and challenges** associated with **implementing** hydrogen projects, and the different **transport options**.

1 IRENA calculates that, between 2010 and 2021, the levelised cost of electricity declined by 60% for offshore wind, 68% for onshore wind and 88% for solar PV [4].

Basic facts and status quo

Properties

Hydrogen (atomic symbol H; molecular symbol: H_2) is the first element in the periodic table. Under normal conditions[2], it is a colourless, odourless gas that dissipates quickly because it is much lighter than air. As an energy carrier, hydrogen can be stored in gaseous or liquid form. It has a high energy content for its (low) mass. That said, a given volume of hydrogen contains only one third or so of the energy of an equivalent volume of methane (natural gas), for example [5].[3] Hydrogen can not be liquefied by compression at room temperature – it only liquefies at -253°C. It is non-toxic and non-corrosive. While inert at room temperature, it is highly reactive at higher temperatures. Although hydrogen does not self-ignite, it is flammable at concentrations between 4 and 75 percent in air or when combined with oxygen. Much less energy is needed to ignite hydrogen than to ignite gasoline or methane. This means that it catches fire or explodes far more easily in the presence of an ignition source. As a small molecule, however, hydrogen dissipates quickly and thus has a higher diffusion rate than e.g. methane (natural gas). Working with hydrogen calls for appropriate safety precautions tailored to its specific properties. [6; 7; 8] Hydrogen is not a greenhouse gas. Nevertheless, interactions with other substances in the atmosphere may cause indirect effects that could potentially impact the climate if more hydrogen is used in the future [9; 10].[4]

Current uses

Hydrogen already plays an important role in the economy. In 2021, 94 million tonnes[5] of hydrogen were produced worldwide. Almost all of it was produced from fossil fuels, typically by steam reforming of natural gas. This is a significant figure – the energy content of this amount of hydrogen is roughly equivalent to the energy content of all the natural gas used in the EU [11]. Hydrogen has a variety of uses. To date, it has mainly been used as a precursor and feedstock in industry (see Figure 1) [3].

- In 2021, around 40 percent of global hydrogen use was accounted for by refineries, where its applications include fossil fuel desulphurisation.
- Just over one third was used to produce ammonia (NH_3) and 16 percent to produce methanol.
- Approximately 5 percent was used for the direct reduction of iron ore in the production of green steel.
- The rest was used for other industrial applications such as the production of other chemicals, metals and electronics, or to generate heat.

2 DIN standard 1343 specifies the normal or reference conditions for expressing the properties of gases as a temperature of 0°C and a pressure of 1.01325 bar.

3 This comparison refers to the gaseous forms under reference conditions. Hydrogen contains almost three times as much energy by mass as methane or gasoline (33.33 kWh/kg vs. 13.9 kWh/kg and 12 kWh/kg). However, it has a relatively low energy density by volume (3 kWh/Nm³ vs. 9.97 kWh/Nm³ for methane and 8.880 kWh/Nm³ for gasoline). [5] The fact that you need a larger volume of hydrogen, i.e. more space, to get the same amount of energy has implications for its transport and storage. At higher pressures, the ratio compared to the other energy carriers mentioned above becomes even less favourable.

4 Considering hydrogen's high volatility and its distribution pattern in the atmosphere, inter alia, it is not currently possible to confidently estimate the extent of these effects. Extensive further research is required on this point.

5 In 2021, about 8 million tonnes (264 TWh) were produced in the European Union [3] and about 1.7 million tonnes (approx. 55 TWh) in Germany [12; 13].

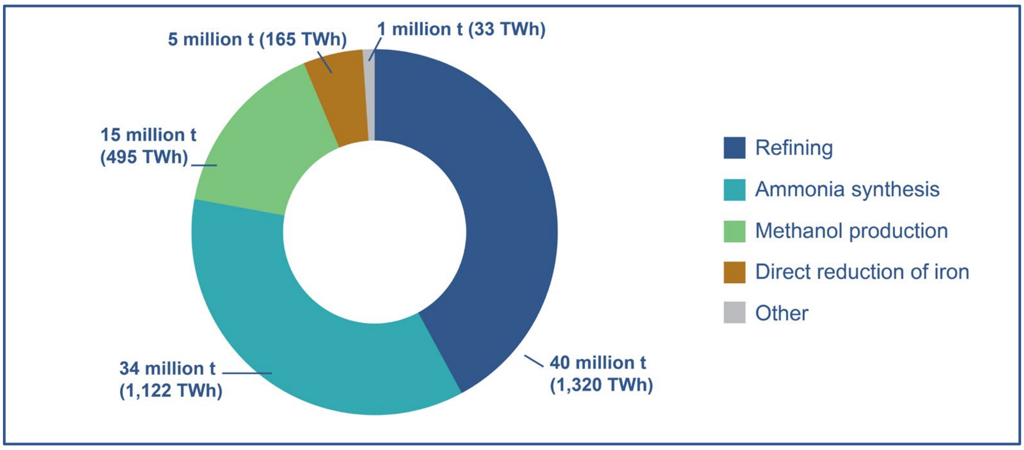

Figure 1: Global hydrogen use (2021) in million tonnes and Terawatt-hours (in brackets) [3]

Hydrogen is an established and currently indispensable feedstock that is used all over the world, especially in refineries, fertiliser production and the chemical industry. Its significance is reflected by the fact that some pure hydrogen pipelines already exist, although they are few and far between. In Germany, they supply major industrial sites in the Ruhr, the central German chemical triangle in Saxony-Anhalt and in Schleswig-Holstein with hydrogen produced from fossil fuels.

Production and future uses

Production: costs, water usage and emissions

While hydrogen is actually a colourless gas, different colours are commonly used to denote hydrogen that has been produced in different ways. Each of these production methods is associated with different production costs, resource consumption and greenhouse gas emissions. The production method also ultimately determines whether the hydrogen can be used in a defossilised economy. Figure 2 provides an overview of the colours used to describe different production methods and the associated direct CO_2 emissions. Figure 3 expands on this by showing the costs and – to illustrate resource consumption – water usage associated with the different production methods.

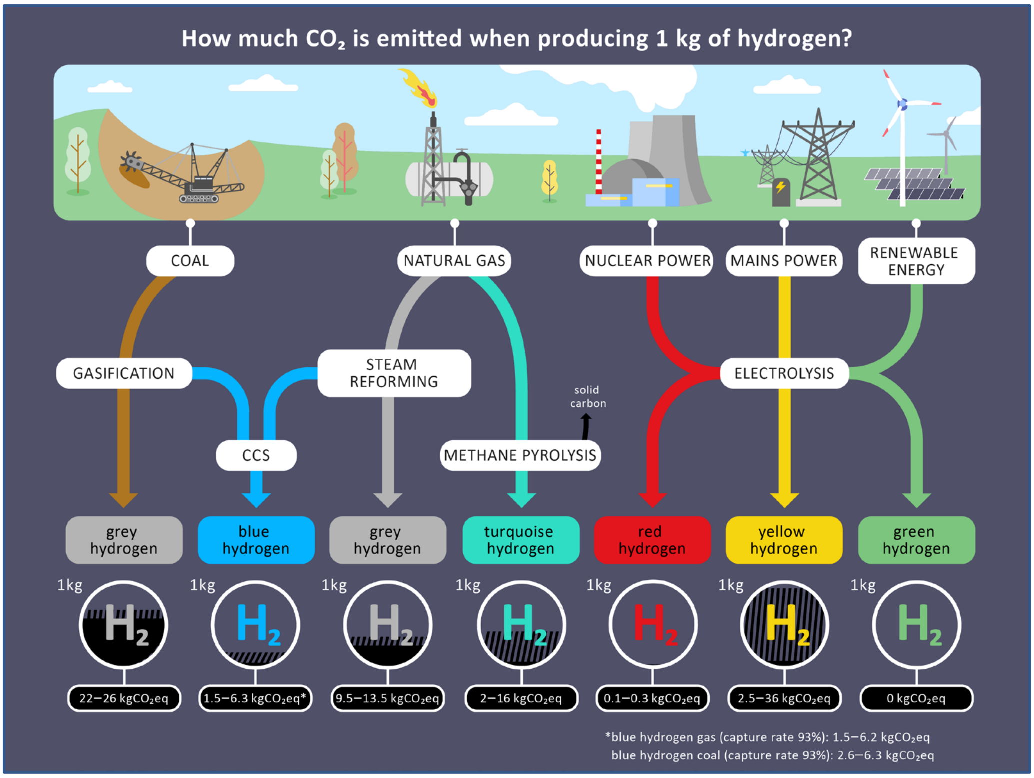

Figure 2: Hydrogen production methods and associated emissions (production process, feedstock and energy supply) in kilograms CO_2-equivalent for 1 kg hydrogen. Upstream and downstream greenhouse gas emissions for individual processes are not included due to the high level of uncertainty about the figures. However, they could be several times higher than the emissions shown in the illustration [3; 14]. (Authors' own illustration based on 15).[6]
Source: Energy Systems of the Future (ESYS), illustration by Joseph & Sebastian.

6 The low emissions associated with red hydrogen come from supplying the nuclear fuel. [15] The illustration does not include white hydrogen, which refers to naturally occurring, geologically formed pure hydrogen gas in the Earth's crust. In theory, this hydrogen could be mined. Natural hydrogen could also be produced in bioreactors through photobiological processes, i.e. using biotechnology-enabled artificial photosynthesis. However, much more research needs to be done into both of these production methods, and the extent of the associated emissions has yet to be clearly determined. Moreover, it currently seems unlikely that they will be able to produce significant quantities of climate-friendly hydrogen. [18; 17; 18].

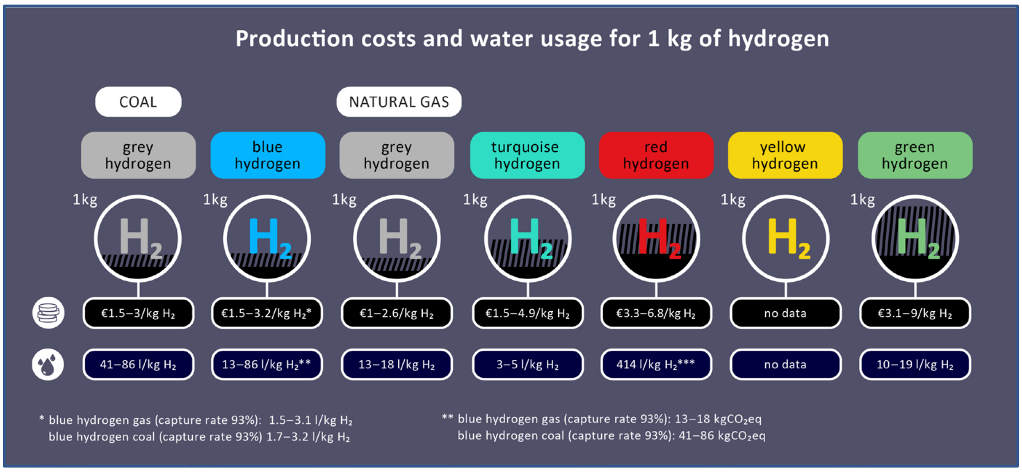

Figure 3: Production costs and water usage for different hydrogen production methods (Authors' own illustration based on 15 and 19)[7]. Source: Energy Systems of the Future (ESYS), illustration by Joseph & Sebastian.

Grey hydrogen

Grey hydrogen is produced directly from natural gas (by steam reforming) or coal[8] (by gasification) and generates high greenhouse gas emissions. In 2021, 62 percent of hydrogen was produced using natural gas and 19 percent using coal [3].

The **cost** of producing grey hydrogen was €1.0–3.0/kg in 2021 [15][9]. This means that producing hydrogen from fossil fuels is still cheaper than the alternative methods.[10] However, factors including rising carbon prices and falling production asset and electricity costs are likely to tip the balance in favour of blue and eventually green hydrogen in years to come (see sections on blue and green hydrogen).

The **water usage** associated with the production of grey hydrogen from natural gas is around 13–18 l/kg H_2. [19]

Blue hydrogen

Like grey hydrogen, blue hydrogen is produced from natural gas or coal. However, the resulting CO_2 emissions are captured at the production facility and stored underground (Carbon Capture and Storage, CCS) or used to produce a new product (Carbon Capture and Utilisation, CCU). Together, all the commercial CCS facilities currently operational around the globe are able to capture about 42.5 million tonnes of CO_2 a year [20].[11]

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7 Further information on how the figures compare is provided in the sections on the different production methods.

8 A further distinction is sometimes drawn between brown hydrogen (produced from lignite) and black hydrogen (produced from bituminous coal).

9 This range is based on gas prices of €10–45/MWh. The cost of producing grey hydrogen rises to €4.6–7.4/kg H_2 for gas prices of €80–145/MWh (German wholesale prices in June 2022) and €2.7–3.9/kg H_2 for gas prices of €50–65/MWh (German wholesale prices in Q1/23) [15].

10 By way of comparison, blue hydrogen (produced from natural gas but with CCS or CCU) cost €1.5–3.2/kg, while green hydrogen produced by electrolysis using renewable energy cost €3.1–9.0/kg H_2 [15].

11 At present, CO_2 injection is mainly used for enhanced oil recovery, especially in North America. Injecting CO_2 forces more oil out of the well, increasing its oil yield. [20] If all the captured CO_2 were stored and all the existing CCS facilities used exclusively to produce blue hydrogen, current capacity would be enough to produce 4.3–4.74 million tonnes (142–156 TWh) of blue hydrogen a year. That is equal to roughly 4.5–5% of current total global hydrogen demand (2021: 94 million t/3,102 TWh [3]).

In 2021, the average cost of producing blue hydrogen was €1.5–3.2/kg [15]. The **cost** depends on whether gas or coal is used as a feedstock. The costs associated with capturing the CO_2 mean that the overall cost of producing blue hydrogen is higher than for grey hydrogen. [12] However, blue hydrogen could become cheaper than grey hydrogen if the carbon price rises, since its lower CO_2 emissions would mean that a lower carbon price would be payable.

Although low-carbon, blue hydrogen is not a zero-carbon solution. This is because the CO_2 can not be fully captured, either for technical reasons or because it is not economically viable to do so (see also Figure 2). It is also associated with high **water usage**. Depending on the feedstock source, around 13 to 18 litres of water are needed to produce one kilogram of hydrogen from natural gas with CCS. This rises to 41–86 l/kg for the production of hydrogen from coal with CCS. [19]

Green hydrogen
Green hydrogen is produced by using renewable electricity to split water into its component hydrogen and oxygen in a process known as electrolysis. [13] The production of green hydrogen is a net zero process. [14] [21]

At present, the **cost** of producing hydrogen by electrolysis with renewable electricity is higher than the cost of producing grey or blue hydrogen. In 2021, the cost of producing green hydrogen was €3.1–9.0/kg [15]. If the upper and lower cost figures are compared, it can be seen that green hydrogen is roughly two to three times as expensive as grey and blue hydrogen, depending on the electricity and feedstock costs. Nevertheless, various studies predict that green hydrogen will become cheaper than hydrogen produced from fossil fuels in the medium to long term. This is because the cost of renewable energy is likely to fall further, while the cost of electrolysers will also probably come down. At the same time, carbon pricing will make it more expensive to use fossil fuels. It is important to remember this last point when comparing blue and green hydrogen, since it is not possible to capture and store or reuse all of the CO_2 emitted during the production of blue hydrogen. For technical reasons, there will always be some residual emissions, and these will result in additional costs due to carbon pricing. [3; 22; 23; 24]

At roughly 10-19 l/kg, green hydrogen production requires a similar amount of **water** to grey or blue hydrogen produced from natural gas. However, green hydrogen uses less water than grey or blue hydrogen produced from coal. [19]

Red hydrogen
Hydrogen produced by electrolysis can use electricity from various different sources. The term “red hydrogen” is used when the electrolysers are powered by nuclear power or waste heat from nuclear power plants. Hydrogen produced in this way is occasionally also referred to as pink, purple or yellow hydrogen. This production method generates virtually no CO_2 emissions [15] [15], making red hydrogen a largely net zero solution.

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12 The IEA puts the cost at \$53/t CO_2 for a 60% capture rate and \$80/t CO_2 for a 90% capture rate [35].

13 Four different methods are currently used: alkaline water electrolysis (AEL), anion exchange membrane electrolysis (AEM), polymer electrolyte membrane electrolysis (PEM) and solid oxide electrolysis cell electrolysis (SOEC).

14 If the emissions generated across the entire life cycle of the necessary assets are taken into account, then even green hydrogen is not actually a net zero solution. This approach counts the emissions generated upstream and downstream of the hydrogen production process itself. These include the emissions from the manufacture of the electrolysers and the assets used to produce the necessary renewable electricity. [21]

15 The production of hydrogen using nuclear power does not generate any CO_2 in itself. However, taking uranium as an example, low-level emissions of 0.1–0.3 kg CO_2-eq./kg H_2 arise from the extraction and processing of the fuel needed to produce the nuclear power. [15]

From a policy and legal perspective, nuclear power has been classified as a sustainable transition technology by the EU since summer 2023. However, this is a controversial decision among both the scientific community and the public, not least because of the particular risks associated with accidents and the largely unresolved question of how to permanently dispose of nuclear waste. [16] [18; 26; 27]. The nuclear phase-out in Germany means that no red hydrogen will be produced there in years to come. In principle, however, it could be imported – some countries such as the US and the UK have included red hydrogen in their national strategies, while others such as France are committed to a high percentage of nuclear power in their electricity supply [28].

In 2021, the **cost** of red hydrogen was €3.3–6.8/kg H_2, making it slightly cheaper than green hydrogen but much more expensive than grey and blue hydrogen [15].

Because water is needed to cool nuclear reactors, the **water usage** associated with this production method is 414 l/kg, several times higher than the other methods [19]. [17]

Yellow hydrogen

Yellow hydrogen is hydrogen produced by electrolysis using mains electricity. However, with Germany's current electricity mix, the emissions from producing hydrogen in this way would be far higher than the emissions from conventional steam reforming. For hydrogen produced with mains electricity to have lower emissions than grey hydrogen produced from natural gas, the electricity mix's emission intensity would need to be more than halved. That said, in countries like Norway and Sweden, where almost all of the electricity supply comes from renewable sources or renewables and nuclear power, the production of yellow hydrogen would generate almost no CO_2 emissions. [18] [15; 30; 21]

It is not possible to provide general **cost** and **water usage** figures for yellow hydrogen. This is because, as with the emission figures (see footnote 18), they are strongly determined by the electricity mix, i.e. the energy sources used and the associated water usage and cost structures.

Turquoise hydrogen

Turquoise hydrogen is produced by using heat to split methane in a process known as pyrolysis. Provided that the solid carbon produced in the reaction is used to make very long-lived products or stored underground, the emissions associated with some methods of turquoise hydrogen production can be very low[19]. [15; 31; 32]

Until now, hydrogen has only been produced as a by-product of methane pyrolysis. The main product of this process is carbon, primarily in the form of carbon black. Depending on its grade,

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16 In a Complementary Delegated Act of July 2023, the EU incorporated nuclear and gas energy activities into the EU Taxonomy. The EU Taxonomy clarifies which economic activities are environmentally sustainable and describes these activities in detail. Both nuclear and gas are now legally classified as sustainable transition technologies, provided that certain requirements are fulfilled (e.g. they must meet specific safety and environmental requirements and must not impair the expansion of renewables). [25] This classification is controversial within the scientific community, for a number of reasons. These include the fact that only a few countries have places where high-level radioactive waste can be permanently disposed of, the sites for these repositories are often still unspecified, nuclear power is considered a high-risk technology, and the lengthy intermediate and final disposal of nuclear waste is extremely resource-intensive. Due to the (potential) long-term impacts of using nuclear power, there are various actors who do not regard red hydrogen as sustainable [18; 26; 27].

17 The 414 l/kg H_2 figure cited by the Hydrogen Council in [19] seems rather high, and no details are provided as to how it was arrived at. The IAEA reports nuclear power plant cooling water usage of 1.9–4.2 l/kWh electricity [29]. If this is added to the water usage for electrolysis (assuming 65% electrolysis efficiency), it gives a total water usage figure of 107–225 l/kg H_2.

18 In 2022, the emission intensity of Germany's electricity mix was 442 g CO_2-eq./kWh excluding upstream emissions and 498 g CO_2-eq./kWh with upstream emissions [30]. This is equivalent to 23 and 26 kg CO_2-eq. per kilogram of yellow hydrogen respectively [authors' own calculation based on 15]. The global electricity mix figure of 460 g CO_2-eq./kWh (including upstream emissions) equates to 24 kg CO_2-eq./kg H_2 for yellow hydrogen production. On the other hand, the production of yellow hydrogen in Sweden, which has one of the lowest emission intensities in the world for mains electricity (10 g CO_2-eq./kWh), would generate just 0.5 kg CO_2-eq. per kilogram. [15] A global electricity mix with an emission intensity of under 172 g CO_2-eq./kWh would make yellow hydrogen less emission-intensive than steam methane reforming [authors' own calculation based on 15].

19 Emissions can arise in connection with the necessary process energy, which may take the form of electricity (in the Kværner process) or high-temperature heat. Emissions are also generated if natural gas is used as a methane source.

this carbon black may be used in various industrial applications, for example to make tyres, paints and fibres [33]. The hydrogen by-product is produced very cheaply, but is only available in relatively small quantities due to the limited size of the market for industrial carbon black. Further research could increase production by making it possible to produce types of carbon black that cannot be produced using current methods. But even then, turquoise hydrogen could only cover a tiny fraction of today's global hydrogen production. [33; 34]

It is doubtful whether it would be economically viable to use methane pyrolysis to produce hydrogen as the main product. The process would still produce carbon, but in quantities that would not always find a market. In these cases, there would be no additional revenue from the sale of carbon black, and there would be an additional cost for the safe disposal of the significant quantities of surplus carbon black unless new applications were developed for it. [31; 32; 35].

Failure to sell the carbon co-product as industrial carbon black would result in **costs** of €1.5–4.9/kg H_2, excluding the disposal cost of the surplus carbon. [33] [20] The large-scale production of turquoise hydrogen becomes more attractive when natural gas prices are low. However, since the process requires significant quantities of electricity or natural gas, the economic viability of turquoise hydrogen declines as gas prices rise.

Water usage for methane pyrolysis is very low – modern systems use no more than 5 l/kg hydrogen [35].

Alternative ways of classifying hydrogen

The European Commission uses different terminology to describe the different hydrogen production methods [36]:

- **Electricity-based hydrogen**: hydrogen produced through the electrolysis of water, regardless of the electricity source (green, yellow and red hydrogen).
- **Renewable hydrogen**: hydrogen produced from renewable sources, i.e. through the electrolysis of water using renewable electricity (green hydrogen) or the biochemical conversion of biomass.
- **Fossil-based hydrogen**: hydrogen produced using fossil fuels such as gas and coal as feedstock (grey hydrogen).
- **Fossil-based hydrogen with carbon capture**: hydrogen produced using fossil fuels as feedstock. The emissions or carbon content from the production process are (albeit not fully) captured and stored (Carbon Capture and Storage – CCS) or used for industrial purposes, locking them up for long range (Carbon Capture and Utilisation – CCU) (blue and turquoise hydrogen).

20 Calculated by converting the values in [35] to the natural gas price range used in [15].

Another way of classifying hydrogen is by the emissions associated with its production. This classification method is not tied to individual technologies or the associated regulations. However, it does require a system for verifying the different production methods' CO_2/greenhouse gas emissions. One example of this approach is found in the Inflation Reduction Act (IRA), a major federal investment programme in the US that includes measures to enable a significant expansion of clean energy and the hydrogen economy. Direct support is provided in the shape of variable tax credits per kilogram of hydrogen produced – the lower the CO_2 emissions, the higher the credits. [37; 38]

Hydrogen derivatives

The development of a hydrogen economy is not confined to the use of pure hydrogen. Hydrogen can also be used to make other products such as ammonia, methane, methanol and liquid hydrocarbons. These are referred to as (hydrogen) derivatives. Derivatives are important because they enable a wider range of applications and transport options for hydrogen. The production of derivatives from hydrogen produced with (typically renewable) electricity is known as Power-to-X (PtX). The somewhat more specific term Power-to-Gas (PtG) can be used for the production of gaseous derivatives, whereas Power-to-Liquid (PtL) refers to the production of liquid derivatives.

Uses: Overall demand and areas of application

Hydrogen comes into its own as an alternative to fossil fuels where it is difficult or impossible to use direct electrical power either for technical or economic reasons [35; 39; 40]. Fossil fuels, feedstocks and raw materials will need to be replaced by zero-emission alternatives if Germany is to achieve net zero by 2045 (see Figure 4). In areas such as manufacturing industry and the electricity and heating sectors, new technologies will be required to enable sustainable, net zero economic processes and environmentally-friendly lifestyles while at the same time strengthening regional and national competitiveness through innovation and new industries.

Since low-emission and zero-emission hydrogen is still only available in very limited quantities, it is not yet widely used. But studies predict that demand will rise rapidly as a consequence of efforts to transform the energy, transport and industrial sectors, for example [41]. As a result, many international, national and regional policy actors are now developing strategies and roadmaps to ramp up the zero-emission hydrogen market so that it is able to meet future demand [28; 42].

The IEA forecasts that annual global demand for hydrogen and its derivatives will reach 530 million tonnes by 2050[21]. This is equivalent to an energy content of 17,660 Terawatt-hours [43; 44][22]. By way of comparison, global demand in 2021 was approximately 94 million tonnes (3,100 Terawatt-hours) [3]. Demand is also set to grow strongly in Germany. In 2019, it was around 1.7 million tonnes (56 Terawatt-hours) [45], most of which was produced from fossil fuels. By 2045, it is forecast to grow to between 3 and 21 million tonnes a year (100 to 700 Terawatt-hours) for pure hydrogen, and between 7.5 and 34 million tonnes (250 to 1,100 Terawatt-hours) if the demand for producing hydrogen derivatives is included [41]. Moreover, all of this demand will have to be met by zero-emission hydrogen. For the EU, the scenarios forecast that annual hydrogen demand will increase to between 6 and 51 million tonnes (200 to 1,700 Terawatt-hours) by 2050. It should be noted that some of the basic assumptions underpinning these forecasts are different to those used in the scenarios for Germany. [44]

21 Some of the scenarios used as the basis for the following global and German hydrogen demand figures assume that net zero will be achieved by 2050. However, Germany has set itself the target of achieving net zero by 2045. Consequently, wherever possible the figures for Germany relate to this date.

22 Long-term forecasts are subject to numerous uncertainties. They are also strongly influenced by the assumptions made in different studies. These include things like the balance between direct electrification and hydrogen use, and the extent of energy efficiency improvements and consumption reduction. Moreover, since scenario studies often describe multiple potential development pathways, the range of hydrogen demand figures is correspondingly wide. This applies to both the global demand figures and the figures for Germany and the EU. A literature review by the JRC cites scenarios for global hydrogen demand in 2050 that range from 2,500-23,500 TWh [44].

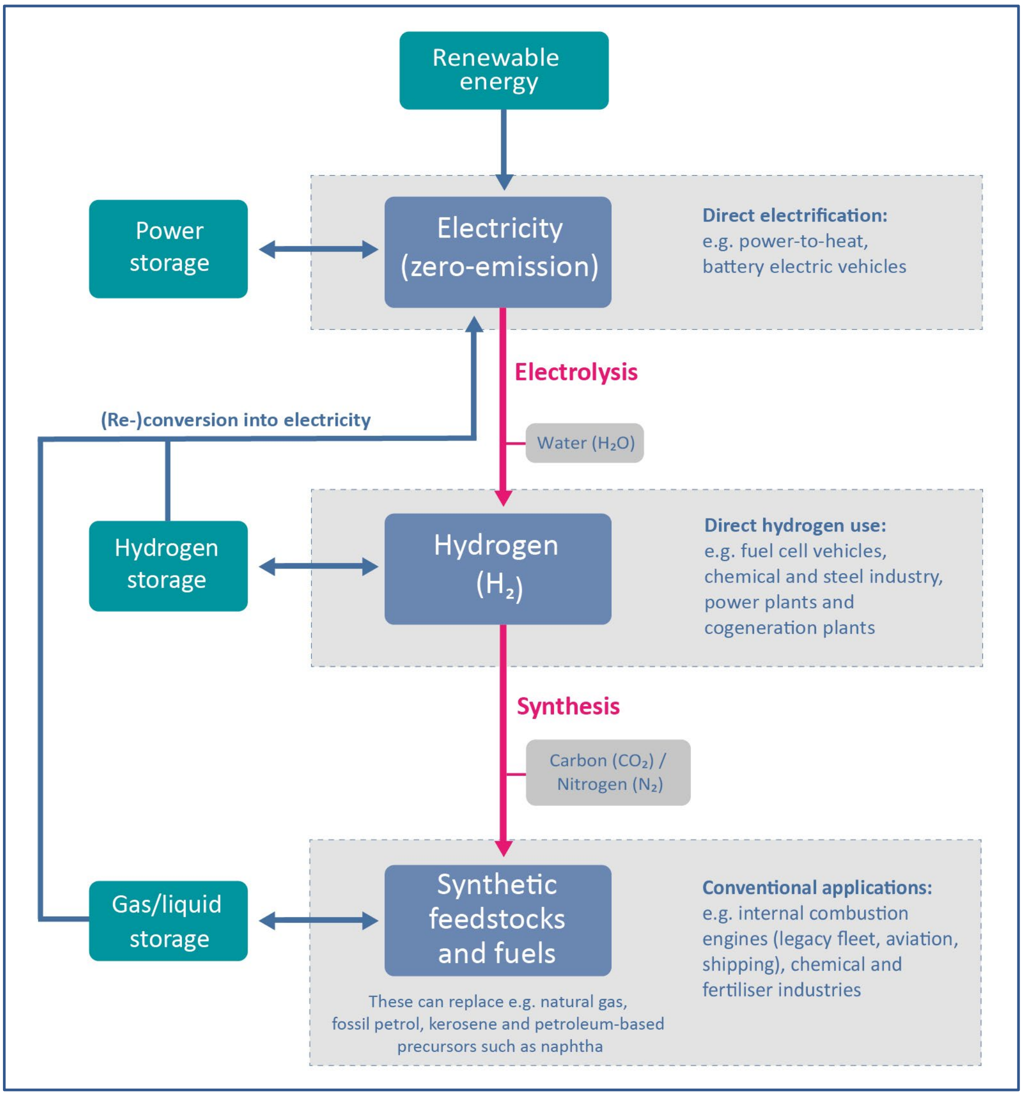

Figure 4: Defossilisation options using electricity (direct electrification) or renewable hydrogen/synthetic materials and fuels made with renewable hydrogen. Source: authors' own illustration.

Industry

Over the coming years, it will be necessary to replace the coal, oil and gas that are currently widely used in industry as energy carriers and to produce feedstocks. Zero-emission hydrogen and its derivatives will play a key part in the transition to net zero production processes [46].

The steel industry, for example, will need to transition from the traditional, coal-based blast furnace route to direct reduction with hydrogen. [23] Similarly, the chemical industry will gradually need to replace the fossil fuels like natural gas and oil that it currently uses as feedstocks and as an energy source. [24] Refineries and the fertiliser industry mainly use hydrogen as a feedstock – synthetic fuels and fertilisers like ammonia (NH_3) contain hydrogen, for example. The glass industry uses hydrogen as an energy source to achieve the necessary high melting temperatures. At present, this process heat is still mainly generated by burning natural gas. [48; 49; 50]

23 The steel industry's traditional blast furnace route still emits 1.7 t CO_2 per tonne of raw steel. Switching to direct reduction with hydrogen could reduce these emissions by 97% [47].

24 Major reinvestments are due in the steel and chemical industries over the next few years. In order to prevent long-term lock-in to fossil fuels or costly future retrofits of assets that have not yet paid for themselves, these investments must be in low-emission technologies that will help to meet the climate targets. This is vital, since assets like blast furnaces in the steel industry and glass melting furnaces in the glass industry usually operate continuously for several decades.

Transport

The best drive type for significantly reducing transport-related greenhouse gas emissions varies by transport mode (e.g. cars, HGVs, aviation or shipping).

In many areas of application, especially **cars**, battery electric drives are usually the cheapest and most efficient drive type in terms of electricity consumption. If a similar hydrogen-powered fuel cell car and electric car drive the same route, the fuel cell car needs around two-and-a-half times as much electricity to produce the necessary hydrogen as the electric car needs to charge its battery. An internal combustion engine vehicle using green hydrogen-based synthetic fuel needs around five times as much electricity as an electric vehicle due to the extra production steps involved in making the fuel [51].

While the trend for **heavy goods vehicles** is also towards battery electric drives, other technologies do exist. It remains to be seen whether the future market will be dominated by one drive type or whether multiple drive types will coexist. There are some situations where, for economic or technical reasons, electric drives are not the best solution. This may be because they are too heavy, because the large batteries severely limit the vehicle's payload, or because their range is too limited. Fuel cell drives and internal combustion engines powered by hydrogen or synthetic fuel can have a role to play in these cases. [52]

Aviation and **shipping** are other potential areas of application for alternative fuels or different fuel cell types. This is because battery electric drives are currently only suitable for small aircraft and boats. Particularly promising fuels include synthetic ammonia (NH_3) and methanol (CH_3OH) for ocean-going vessels, and synthetic kerosene for aircraft.

Electricity sector

A net zero, predominantly renewables-based energy system must be able to safely negotiate fluctuations in the amount of electricity fed into the grid in different weather conditions and seasons and at different times of day. Storage systems are thus vital for balancing electricity supply and demand. Hydrogen and its derivatives such as ammonia, methanol and synthetic methane could be used as a storage medium if they are produced with renewable electricity at times when there is a plentiful supply of renewable energy. At a later point in time, they can then be burned in gas turbines or converted into electricity in fuel cells, in a process known as "reconversion". This can help to manage everything from short-term supply dips to "dunkelflautes" lasting several days ("dunkelflautes" are times when there is very little sunshine and wind). [51]

As well as providing a backup at times when not enough renewable energy is being generated, hydrogen can also be used to store "excess electricity" when the amount of power being generated outstrips demand. Until now, generators have been "curtailed" at these times in order to maintain a stable grid voltage. This "unused" energy could be used to produce hydrogen, which would store it in molecular form. [25] However, it is not currently economically viable to produce hydrogen exclusively with excess electricity. This is because the electrolyser capacity utilisation would not be high enough, making electrolysers too expensive to buy and operate. [26]

Buildings

25 In 2021, 5.8 TWh of renewable electricity were curtailed in Germany to manage grid congestion [53]. Assuming that PEM electrolysis can achieve efficiencies of around 60% [53], this energy could have been used to produce approximately 107,000 tonnes of hydrogen. This is enough to cover about 23 days of Germany's current annual hydrogen demand of 55 TWh [12].

26 In 2021, there were 139 hours when the electricity price on the day-ahead market (wholesale electricity price) was negative, reflecting an oversupply of electricity. In 2022, this fell to just 69 hours [55]. Neither of these figures are high enough to support a sustainable business model [57; 58]. However, the use of excess electricity to produce hydrogen could become viable in the future if renewables are significantly expanded, the regulatory framework is modified and rebates are offered to customers using excess electricity. [56].

Whether and to what extent hydrogen should be used to heat buildings is a matter of some controversy. This is partly due to the fact that electrically powered heat pumps use electricity between 4 and 7 times more efficiently. [32; 51; 61] Moreover, zero-emission hydrogen will initially only be available in limited quantities. Adding hydrogen to the gas grid would limit its availability for other applications outside of the heating sector. In addition, doing so would only achieve a very small reduction in CO_2 emissions per kilowatt-hour of electricity produced. The climate benefits would thus be minimal.

Heating is the main potential application of hydrogen in the buildings sector. A number of different technical solutions exist. For example, a certain percentage of hydrogen could be added to the existing gas infrastructure and burned together with natural gas.[27] Before hydrogen is transported via the existing gas grid, it will be necessary to check whether the relevant grid sections need to be retrofitted to cope with hydrogen's specific physical properties.[28] [62; 63] In addition, it would be necessary to upgrade or replace the heat generators and meters in buildings [60]. One alternative would be to heat buildings with pure hydrogen using condensing boilers or fuel cells. However, this would mean supplying hydrogen directly to households or district heating plants. If the current gas distribution network was fully converted to hydrogen, it would only be able to transport about 80 percent of the energy that can currently be transported with natural gas.[29]

Hydrogen can be a viable option in places where it is not possible to install heat pumps, as a means of powering district heating plants, or as a storage medium for locally produced excess electricity. The cost effectiveness and achievable emission reductions should be assessed on a case-by-case basis for each application or location.

27 Until 2021, the maximum hydrogen blending ratio for the gas grid was 10 vol. %. Since then, hydrogen blending has had to comply with combustion parameters tailored to the specific area of application/components used. For example, the maximum amount of hydrogen that can be added to existing gas turbines is 1 vol. %, whereas it is 20 vol. % for domestic gas pipes. However, because hydrogen has a lower volumetric energy density than methane, adding e.g. 20 vol. % hydrogen would only reduce CO_2 emissions by less than 7% [59; 60].

28 Hydrogen can cause problems such as material embrittlement in components and pipes. This has implications for compressor station design, for example.

29 Hydrogen only has about one third of the energy density of methane. However, this much lower energy density is to a large extent compensated by the fact that hydrogen has a higher flow speed due to its lower density and viscosity.

Hydrogen producing regions and transport options

Domestic production and supplementary imports

A significant expansion of renewables will undoubtedly be key to achieving a successful transition away from coal, oil and gas. But it will also be necessary to build new production facilities for renewable hydrogen and its derivatives and a network for transporting them. Hydrogen and its derivatives can be transported over long distances with acceptable losses and at a reasonable, economically viable cost. It is therefore likely that they will take over the role and importance of oil and gas in the energy market. Since hydrogen production does not depend on the presence of local deposits, more countries, regions and actors will be able to engage in hydrogen trading than is the case for oil and natural gas. This means that, in the future, Germany will be part of a European production system and transport network that will in turn be connected to the global trading system. As a result, it will be less dependent on individual supplier countries.

It is still too early to say what proportion of hydrogen and its derivatives will be produced in Germany and Europe and how much will be imported from other countries. The balance will be influenced by policy and commercial decisions within the emerging hydrogen economy.

Germany’s federal government aims to establish a domestic electrolyser capacity of 10 gigawatts by 2030 [64]. This could produce roughly 850,000 tonnes (28 Terawatt-hours) of green hydrogen a year [65]. There are several reasons why, in the medium to long term, Germany will probably only be able to meet part of its hydrogen demand through domestic production:

- The **energy yield** from solar PV and wind, for example, is higher in other countries and regions than in Germany (see Figure 5). This means it is cheaper to produce renewable energy there, which in turn affects the cost of hydrogen produced by electrolysis. As a result, it may sometimes be cheaper to import this hydrogen.
- In some regions, the level of imports may also be influenced by the **limited space available** for the necessary renewable energy installations, or by the fact that not enough space has been designated for this purpose.
- The **availability of skilled professionals** can also have an influence on the number of renewable energy installations and electrolysers. A shortage of skilled professionals would make it impossible to achieve the ambitious targets for new installations in Germany and potentially also the rest of Europe by the middle of this century. This could lead to a higher percentage of imports.

It can thus be assumed that, in order to meet the strong growth in demand, Germany will import significant quantities of hydrogen and its derivatives (e.g. ammonia and methanol) from European and non-European countries [30]. [12] Germany will thus form part of a European network of reciprocal import and export relationships and – like almost every other European country today – will almost certainly continue to import energy. [31]

30 An ESYS working group calculated that imports will meet 76% of demand for green hydrogen and its derivatives in 2030 and around 61% in 2045 [66]. Other net zero energy system studies [67;68;69;70] report that imports will meet 50% or more of demand for hydrogen and its derivatives in 2030 (2030: approx. 50–90%) and 75–90% in 2045. The latter figure is lower in the ESYS calculations because they optimise demand and assume a greater role for sector coupling. This means that more renewable excess electricity is used for electrolysis, allowing more hydrogen to be produced in Germany. One point on which the studies unanimously agree is that pure hydrogen will tend to be produced domestically, while hydrogen derivatives such as ammonia and synfuels will tend to be imported. [39;66]

31 In 2021, for example, Germany met around 70% of its total primary energy demand through imports.[11] The 64% figure cited in the source was adjusted by assigning nuclear power to imports, since the nuclear fuel originates from abroad. This differs from Eurostat’s definition of nuclear power as a domestic energy source.

Potential partnerships and associated challenges

Until now, almost all hydrogen production has been fossil fuel based. Consequently, it will be necessary to develop new value chains for zero-emission hydrogen and hydrogen derivatives. Moreover, the growing demand for these products will call for new and wider supply relationships. [72] It will be especially important to forge trade partnerships with countries and parts of the world where the conditions for producing renewable energy are better than in Germany. In other words, places with more sunshine, high hydropower potential or more frequent and stronger winds.

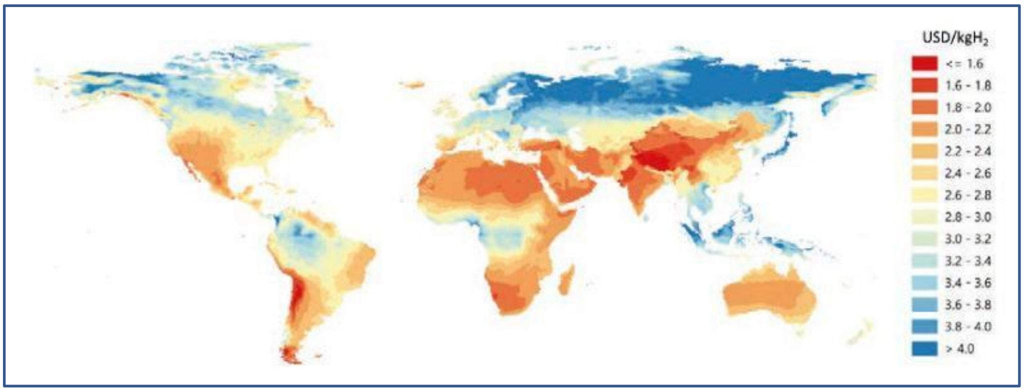

Figure 5: Long-term forecast of renewable hydrogen production costs [32] [35]

If projects are designed fairly, importing from regions with these local conditions (see Figure 5) can bring **benefits** for both EU and non-EU exporting partners and for Germany as an importing country [39; 73; 74]:

- Imported zero-emission hydrogen may be **cheaper** because the electricity needed to produce it can be generated at lower cost in the export regions and/or because the more constant supply of renewable energy allows for better electrolyser capacity utilisation [24; 56].
- European and German companies could benefit from exporting hydrogen technology. They could tap into **sales opportunities** in an emerging technology market that will play an important future role and in which demand is set to grow strongly. [33] [75]
- The **exporting countries** could also benefit from the expansion of renewables and the installation and in some cases production of, for example, electrolysers in their own country. As well as earning export revenue, they could also benefit from the employment of local people to install the relevant equipment. In addition, the production facilities could help to establish new industries that add local value and improve employment and education opportunities for the local population.
- A targeted expansion of renewables could also contribute to a more **sustainable energy supply** in the exporting countries and regions. Moreover, well-managed projects could improve local people's access to electricity in areas where this is currently lacking.
- Switching to green hydrogen production would provide countries that rely heavily on fossil resource exports with a way of **transitioning to a climate-friendlier economic model**.

32 Rightholder's note: This map is without prejudice to the status of or sovereignty over any territory, to the delimitation of international frontiers and boundaries and to the name of any territory, city or area. Electrolyser CAPEX = USD 450/kWe, efficiency (LHV) = 74%; solar PV CAPEX and onshore wind CAPEX = between USD 400–1 000/kW and USD 900–2 500/kW depending on the region; discount rate = 8%. Source: IEA analysis based on wind data from Rife et al. (2014), NCAR Global Climate Four-Dimensional Data Assimilation (CFDDA) Hourly 40 km Reanalysis and solar data from renewables.ninja (2019).

33 In 2022, around 60% of global electrolyser production capacity was located in the EU. European and German companies are strongly positioned in this field. However, global competition between electrolyser manufacturers is intensifying with the emergence of suppliers in China and the US, for example.

- Renewable installations and electrolysers can in principle be built and expanded almost anywhere. This makes it possible to establish a **wider supplier network** than for fossil fuels, offering customers and suppliers of hydrogen and its derivatives more opportunities to form partnerships. This in turn creates mores stable sales prospects for suppliers and greater security of supply for customers.

However, as well as potential benefits, building import and export relationships also entails a number of **challenges** [39; 72; 76; 77; 78]:

- The exporting countries must be able to produce enough renewable electricity to meet both domestic demand and export demand. Exports to other countries must not jeopardise the **defossilisation** of their own energy systems. They may use the hydrogen they produce to meet their **own demand** first, i.e. to support the transformation of their own energy supply or for local derivative production. This could mean that very little is left over for exports.
- It is important to ensure that the development of hydrogen export infrastructure does not cause a hike in **local energy prices**. This could happen if customers in industrialised and emerging economies in regions like Europe and Asia are willing and able to pay more than the local price. If this happens, then rather than large sectors of the population benefitting directly or indirectly from energy carrier exports, the necessary development of countries in the Global South could actually be inhibited.
- One general point to bear in mind when implementing major export projects is to avoid reinforcing or replicating **long-term structural dependencies** – sometimes referred to as post-colonial structures – that are detrimental to countries in the Global South. One negative example of this is when large-scale facilities only or mainly produce energy products for industrialised nations, with very little real net output in the local economy.
- Fairly designed projects must also observe **social and environmental standards**. This means, for example, that the production and transport of hydrogen and its derivatives must not cause damage to water, soil or habitats. Working conditions must not be hazardous to health, and as many local people as possible should benefit both financially and educationally from involvement in the project.
- Some of the countries with the most wind and sunshine are **politically unstable** or **difficult to invest in**. A lack of legal certainty, unstable government institutions, corruption, border conflicts and competition for natural resources between ethnic groups can lead to higher default risks or risk premiums for implementing hydrogen projects.
- Geopolitical or **geostrategic factors** can also influence investment and funding decisions. Political, economic or defence alliances, ethnic and cultural allegiances or strategies to secure or expand a country’s sphere of influence can affect decisions about whether or not to invest in particular countries or regions.

Some of these challenges are more than just barriers to the development of a functioning hydrogen market. They also mean that it is currently difficult to estimate the quantities and prices of hydrogen in the future global market.

Transport options and costs

The desired quantities of hydrogen and hydrogen derivatives must be transported from their production sites to the import terminals and distribution points and then on to the end customers and storage facilities. This calls for a European infrastructure network of pipelines, tankers and ports, much of which has yet to be built. However, it will be possible to continue using some of the existing fossil fuel and feedstock infrastructure (e.g. gas pipelines or ammonia and methanol road tankers). Retrofits may be necessary, for instance because the products being transported have a different density, must be transported at a different temperature, or affect the materials around them in different ways.

In principle, hydrogen and its derivatives can be transported by different modes of transport and, in some cases, in different phases. They can be transported as gases and/or liquids by pipeline or by ship, rail and road. How economical it is to transport them often depends on the amount involved – the quantities transported over long distances are typically much larger than the quantities distributed to individual end users.

For long-range transport, the cheapest solution for **shorter to medium distances** of up to 4,000 kilometres is to transport hydrogen gas in large pipelines. This applies to imports from Europe and neighbouring countries. However, enough hydrogen must be available to ensure sufficient utilisation of the pipeline's capacity.[34] If modified natural gas pipelines are used instead of new hydrogen pipelines, the lower investment costs mean that the pipelines can be operated economically over longer distances of up to about 8,000 kilometres. The timescale for modifying existing pipelines is also significantly shorter than for building new ones (3–5 years compared to 8–10 years). This is chiefly due to simpler pipeline licensing and laying procedures. [39]

Tankers are necessary for transporting products over **longer distances** or if they can only be transported **by sea**[35]. In this case, pure hydrogen must first be liquefied by cooling it to -253 degrees Celsius. But there are not yet any tankers capable of transporting liquid hydrogen on a commercial scale. The alternative is to ship hydrogen derivatives (see Figure 6) for direct use in the importing country, for instance ammonia for use in fertiliser production.

However, additional energy and feedstocks (nitrogen for ammonia, carbon dioxide for methanol, methane, etc.) are needed to liquefy hydrogen or convert it into its derivatives. This ultimately reduces the **energy efficiency** of the transport chain: as the amount of energy used for production, preparing the product for transport and transporting it increases, the amount of energy that the end product can contain decreases for a given initial energy input. One reason that the transport chain's energy efficiency is important is that it affects the associated resource consumption. For instance, a more efficient transport chain would require a smaller number of renewable energy installations to generate the electricity for producing the hydrogen. [39]

34 As well as an adequate number of electrolysers for producing hydrogen, export countries will also need to install the necessary (additional) renewable electricity capacity. Roughly 85 TWh of renewable electricity is needed for a pipeline with a diameter of approximately 1,000 millimetres (transport capacity of 6,000-7,000 tonnes of hydrogen per day at 60% capacity utilisation, i.e. about 50 TWh hydrogen a year). This is equivalent to a combined wind and solar output (at 2,500 full-load hours) in the region of 35 GW, which is more or less the same as the capacity of all the wind and solar installations in Spain in 2020 (approx. 40 GW). [39]

35 Initially, these would use fossil fuels, just like today's ocean tankers. However, it is possible that propulsion systems which use small amounts of the tanker's cargo as a power source could be developed. Research is being carried out into hydrogen fuel cells and engines that burn hydrogen, ammonia or methanol, for example. But because tankers transport such large quantities of green hydrogen and its derivatives, there are still climate benefits to importing these products on ships with fossil-powered propulsion systems. For instance, one tonne of ammonia produced from grey hydrogen in Germany generates about 1.8 tonnes of CO_2 emissions. But one tonne of renewable ammonia transported to Germany over a distance of 10,000 km in a tanker using heavy fuel oil only generates about 50 kg of CO_2 emissions. [39]

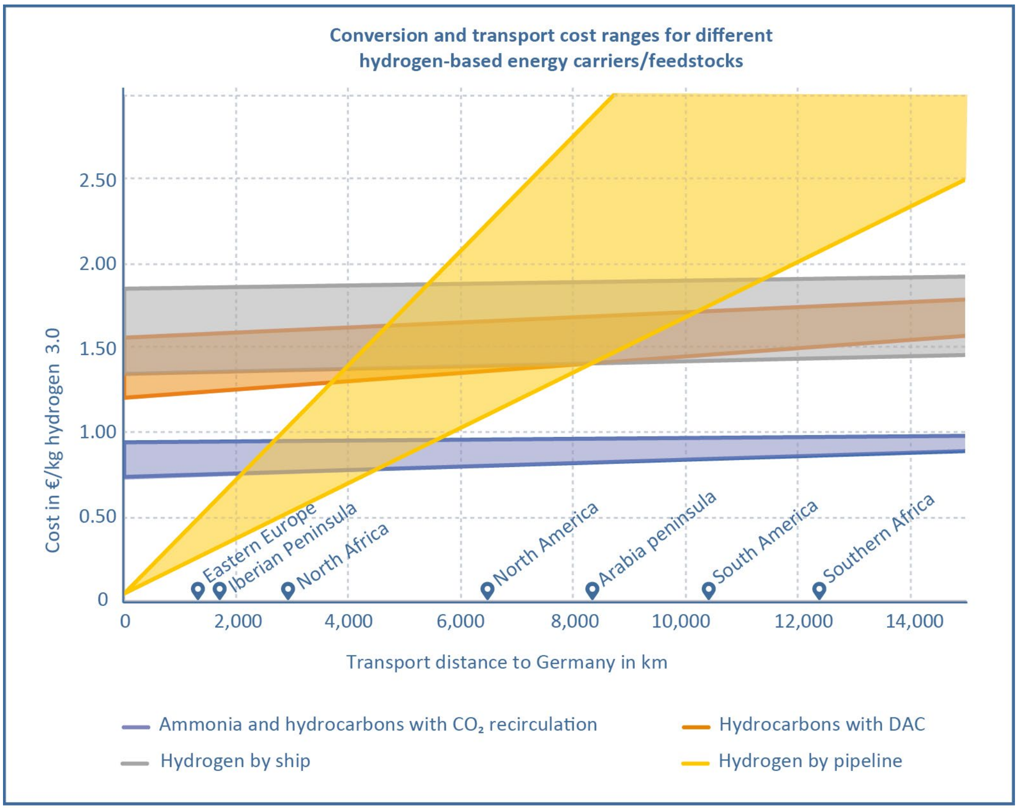

Figure 6: Conversion and transport cost ranges for different hydrogen-based energy carriers/feedstocks by transport distance. The costs relate to the total amount of hydrogen to be supplied in the exporting country. Depending on the process chain, this includes not only the transported hydrogen but also e.g. the hydrogen used to make the product, plus transport losses. It includes the costs associated with the compression or liquefaction of the hydrogen and the synthesis of hydrogen derivatives (ammonia, methane, methanol, synthetic Fischer-Tropsch products)[36]. However, the data does not include the cost of producing the hydrogen itself. DAC = Direct Air Capture, i.e. the extraction of CO_2 from the air. Source: authors' own illustration adapted from [39].

But there are other ways of importing hydrogen apart from in its pure form or as a derivative. One alternative is to bind it to a carrier material (i.e. a particular molecule) prior to transport and release it again for use afterwards. Suitable carriers include ammonia and liquid organic hydrogen carriers (LOHCs). However, releasing the hydrogen from the carrier material requires significant amounts of energy. Moreover, in the case of LOHCs, the carrier material for the next loading cycle must be returned to the original tanking location or transported to the new tanking location. This entails additional logistics costs. One further challenge is that the potential environmental hazards posed by carrier materials in the event of an accident have yet to be fully investigated. Furthermore, a number of issues still need to be resolved with regard to licensing the transport of large quantities of these materials. [39; 79]

In addition to the production conditions and costs in the exporting country (see Figure 5), the overall cost is also affected by the distance the imported hydrogen or hydrogen derivatives have to be transported and the purpose they will be used for in the importing country. Depending on whether the product that will be used in the importing country is pure hydrogen or a derivative, additional conversion stages may be necessary after transport. These, too, will add to the cost (see Figure 6). Importing hydrogen mainly from Europe and neighbouring regions is thus the most cost-effective solution. For more distant regions, the conversion and transport costs can outweigh the savings from the lower levelised cost of hydrogen, making imports from these regions uneconomical. The picture is different for hydrogen derivatives

36 The transport distances shown for the different example regions are based on shipping routes. The distances for pipelines may differ. Fischer-Tropsch products are produced by Fischer-Tropsch synthesis. This industrial-scale process converts syngas (a mixture of hydrogen and carbon monoxide) into liquid hydrocarbons such as olefins and paraffins.

like ammonia, methanol or hydrocarbons. When these products are imported from distant parts of the globe, they can still be cheaper than pure hydrogen produced in Germany – and that is even before it has been converted into the desired derivatives. The cost benefits can thus make it worthwhile to import these products. [39]

Regardless of how it is transported to the importing country, the hydrogen or imported hydrogen derivative will still need to be brought from the import terminal to the end user via a **distribution network**. The smaller quantities involved mean that smaller pipelines or trains, trucks and inland waterways can be used for this purpose. Existing systems such as the gas grid, storage systems and road tankers can be used for this onward transport in some cases (e.g. for methanol, ammonia and LOHCs). However, it is not currently possible to say exactly what the future distribution network will look like. This is because it will depend heavily on the industries, areas of application and locations where hydrogen is used and the quantities of hydrogen required. [80]

Conclusion

This overview shows that hydrogen will have an important role in the energy system of the future. Together with renewable energy, renewable or zero-emission hydrogen will play a key part in the energy transition and in achieving net zero – not just in Germany, but in Europe and the rest of the world:

- Hydrogen and its derivatives can replace the natural gas and oil that are currently used, helping to defossilise economic activity, transport and energy use.
- The development of leading-edge hydrogen technologies can strengthen German and European competitiveness.
- Because hydrogen and its derivatives are easily stored and transported, they can increase security of supply in the energy sector.
- Far more countries and regions can engage in hydrogen trading than is the case for oil, gas and coal. Doing so helps to strengthen their energy supply and adds value for the local population. It also allows countries to diversify their supply sources more easily, reducing the risk of supply dependencies and shortages.

To leverage this potential, it will be vital to actively drive the development of the hydrogen economy in Germany, Europe and the rest of the world. Economic viability should not be the sole consideration when establishing the necessary energy installations, production and processing facilities, storage systems, transport infrastructure and trading structures. It will also be important to observe labour and environmental standards and ensure fair distribution of the economic benefits among the project partners. In international projects, planning and implementation cannot be limited to German interests, i.e. the interests of all parties involved must be taken into account. This will include coordination within the EU and European bodies.

Only limited amounts of zero-emission or renewable hydrogen will be available in the short to medium term. It will therefore be necessary to prioritise the areas where hydrogen and its derivatives are used. Costly misinvestments in infrastructure must be prevented when developing the regulatory framework and establishing market incentive mechanisms, funding programmes and other measures. A rapid and dynamic transition from fossil fuels to zero-emission hydrogen will ultimately call for a focus on the most promising and effective applications. These can provide valuable momentum and use cases to spur the further development of an integrated European, globally connected green hydrogen economy.

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