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How green hydrogen will make Europe more independent

Hydrogen is an important element in the EU's quest for fossil-free energy sources.

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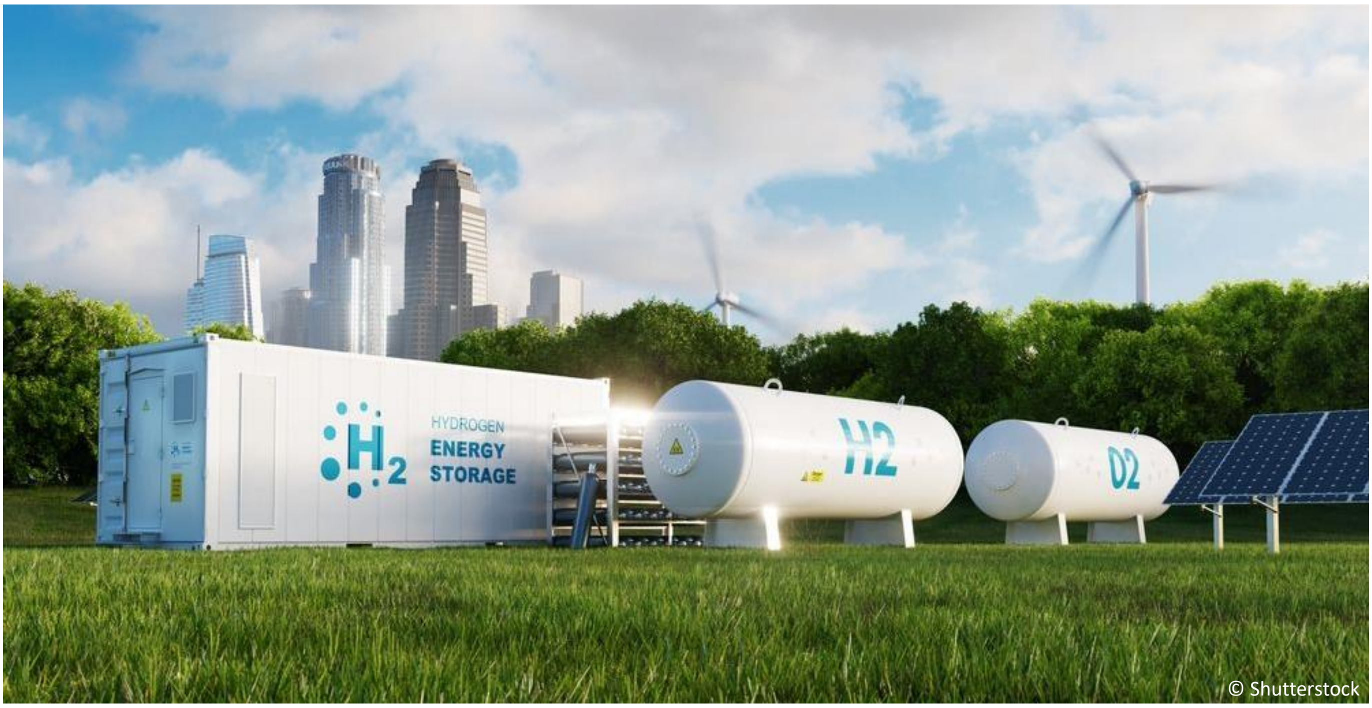

Hydrogen produced from renewable electricity will be a versatile building block on the road to energy independence. Prerequisite: a smart support policy. This will have to remove regulatory barriers and take account of technical strengths and weaknesses.

Key propositions:

- **A Europe-wide hydrogen market** could lay the foundations for a new efficiency-enhancing division of labour in Europe.
- **Adequate availability of renewable electricity** represents the critical bottleneck on the way to a hydrogen-based economy.
- **Political efforts to get the market up and running** should focus primarily on promoting domestic capacity for generating electricity and on developing a hydrogen power infrastructure. The way that hydrogen is utilised will then be decided on the market.
- **Contractual fixing of CO_2 prices** and other forms of risk assumption may help to alleviate demand-side planning uncertainty.

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1 Context

Russia's attack on Ukraine has not only sparked a debate about tighter sanctions against Russia but also boosted efforts to reduce overall dependency on fuel imports and/or to diversify the supply countries. The European Commission provided an interim response on 8 March 2022 with its *REPowerEU* plan[1] which aims among other things to bring about Europe's independence from fossil fuel imports even faster than previously planned.[2] In addition to diversifying the sources of supply of natural gas and increasing energy efficiency, the accelerated roll-out of renewable energies is a cornerstone of the strategy. This refers not only to the use of wind and solar power in electricity production but explicitly also the increased production and use of renewable gases. Hopes rest, in particular, in this regard on "green" hydrogen. That means hydrogen obtained through the electrolytic decomposition of water molecules using only electricity from renewable sources as the source of energy. The hydrogen thereby produced is not only almost climate-neutral but, in principle, can also be used in a variety of ways. In addition to a role as long-term energy storage, thereby helping with the system integration of volatile electricity production from the wind and sun, it will also be available for a wide range of end applications in the heating, transport and mobility sectors. Thus, in many cases, it will act as a direct substitute for natural gas or petroleum products which makes it particularly attractive in the current situation. In contrast to the use of biomass as an alternative energy source, there are also fewer problems associated with land use. Borrowing from the marketing idea of US energy exporters, green hydrogen could thus be described as a "green freedom gas".

Beyond the energy supply considerations, green hydrogen is also of potentially high strategic relevance from an industrial policy perspective as an emerging technology. As a frontrunner in the development of international recycling chains, Europe would secure industrial value creation in segments affected by transformation. In addition, however, as recently outlined in the EU standardisation strategy, the EU could also use the market ramp-up to define global standards (e.g. requirements for safety, cleanliness, sustainability in production and transport) and thus create a level playing field for EU companies in global markets of the future. Due to its fundamentally diverse range of applications, hydrogen is particularly suitable for this sort of overarching industrial policy objective.

The potential of green hydrogen has been known for some time and addressed at European level by the European Hydrogen Strategy. The political climate for building a green hydrogen economy in Europe is currently more favourable than ever. In addition to the war in Ukraine, this is also due to the tightening of EU climate policy proposed in the "Fit for 55" package. Nevertheless, the market launch of green hydrogen still faces technical and regulatory hurdles. Thus, the high fixed costs of electrolysis, and the chemical properties of hydrogen (volatility, reactivity) put pressure on price competitiveness. In most fields of application, hydrogen faces strong climate-neutral competition from the direct use of renewable electricity. In addition, the sluggish roll-out of wind-power capacity and lack of transport infrastructure, also represent external bottlenecks to capacity. The consequences are planning uncertainty and hesitancy on the part of investors. Without further political impetus, a European hydrogen market will not get off the ground. On this basis, the role of green hydrogen in the future decarbonisation of Europe must be carefully considered. In particular, the question arises as to which

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[1] European Commission (2022). REPowerEU: Joint European Action for more affordable, secure and sustainable energy. Communication COM(2022) 108 final

[2] See on this: Reichert, G., Schwind, S., Menner, M. (2022). REPowerEU: Struggling for EU Energy Sovereignty cep**Adhoc** No. 4/2022.

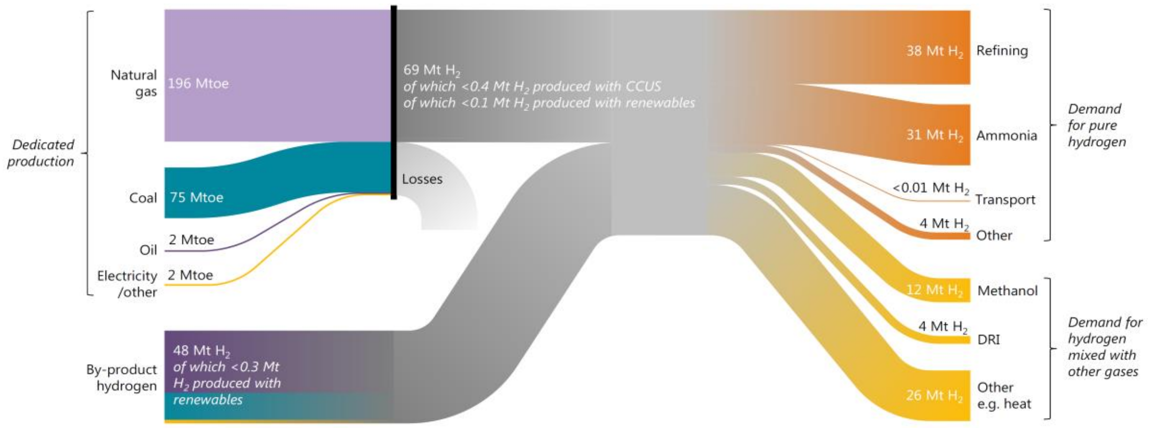
regulatory instruments could be used to accelerate a market ramp-up and which fields of application should the funding framework be concentrating on. This article will provide some food for thought on the subject. It will set out the potential uses of green hydrogen, highlight the current obstacles and discuss possible complementary measures.

2 Potential uses of green hydrogen

2.1 Current fields of application for hydrogen

Hydrogen's current field of application is largely limited to the industrial sector, its predominant use being as a raw material. Two industries are at the centre here: the chemical industry and the petroleum industry. In the chemical industry, pure hydrogen is used together with nitrogen in the production of ammonia and other fertilisers that are derived from it. Hydrogen is used in conjunction with CO_2 to produce the important basic chemical methanol. Other synthetic fuels are produced using similar process routes. In the petroleum industry, hydrogen is used both as a raw material and as an energy source in the processing of crude oil. In various hydrogenation processes, hydrogen is used to remove impurities, particularly from sulphur.[3] By comparison, its use as a fuel in the transport and heating sectors has so far played a subordinate role globally. The production of hydrogen for industrial use is currently still anything but sustainable. It is largely produced as so-called "grey" hydrogen by steam reforming of natural gas, giving rise to CO_2 emissions (see Figure 1). An equally common and equally emission-intensive production method is the gasification of brown coal or black coal ("brown" or "black" hydrogen). The electricity-based production of hydrogen by means of electrolysis is currently still in the start-up phase.

Fig. 1: Current global production and use pathways for hydrogen



Source: IEA (2019).

2.2 Future fields of application

2.2.1 Green hydrogen as an energy store

Using electricity from wind and solar power in hydrogen production means that an energy form, whose supply fluctuates over time, can be converted into a stable and easily storable energy source. The hydrogen that is produced can be stored for long periods in various ways: It can be compressed and stored in pressure tanks or cave storage; it can be cooled down to a liquid aggregate state and stored

[3] IEA (2019). The future of hydrogen. International Energy Agency.

in liquefied gas storage facilities; or it can be adsorbed in certain solid materials. At the same time, it can be converted back into electrical energy at any time, e.g. by using it as fuel in gas-fired power stations or co-generation plants.[4]

In view of the potentially large storage capacity available, green hydrogen may thus play an important role as a system service provider in the European energy system of the future. As the proportion of volatile energy sources grows, so the frequency of temporary power surpluses increases. A storage option must be created as an interim solution for the surpluses that cannot be transferred directly to other sectors and put to worthwhile use. In this situation, the transformation into hydrogen can complement other storage technologies such as battery storage or pumped storage.

Exploiting price fluctuations is profitable: in times of surplus, electricity can be converted for storage at low prices and converted back into electricity when prices are high. In this context, it is also possible to operate as a provider on the electricity balancing market with corresponding remuneration for the grid service. Estimates show that hydrogen's primary advantages are in the long-term storage of electricity (bridging longer-term supply bottlenecks and seasonal variability) and, in terms of costs, it will be superior to alternative technologies such as pumped storage in the medium term.[5] This will depend on the availability of high amounts of surplus renewable energy and improvements in the efficiency of the conversion measures (see Section 3.2) which will have an impact on the contribution to the efficiency of the energy system as a whole. Thus, higher costs will be incurred in the medium term by using power-to-gas as the storage technology but, with ambitious long-term climate targets (greenhouse gas reductions of 95% and more), the systemic costs with hydrogen will be lower than without.[6] Hydrogen storage systems should therefore be seen primarily as an option for the advanced phase of the system transformation towards climate neutrality.

2.2.2 Use in industry

In the future, hydrogen will still remain an essential raw material for the production of nitrogen fertilisers and thus for maintaining agricultural productivity. Using hydrogen produced from renewable electricity will not only improve the climate balance of fertiliser production. The current threat of a long-term export ban on Russian mineral fertilisers also represents an opportunity for Europe to gain independence by expanding its own production in this sector. One specific challenge facing ammonia production is to find alternative methods for generating not only hydrogen but also the nitrogen that is usually also obtained via the steam reforming process. To this end, technologies are currently being researched to generate nitrogen in its pure form from the decomposition of the mixture of substances in air, also by using electrolysis processes.[7]

In addition, technological development is also opening up new fields for the use of hydrogen in industry. Thus, methanol can be produced from hydrogen in combination with captured CO_2. Apart from its use as a base material in the production of a variety of chemical products (including formaldehyde and acetic acid), methane is very interesting from the perspective of energy

[4] IPP (2019). Potenzialstudie Wasserstoffwirtschaft. IPP ESN Power Engineering.

[5] Schmidt, O., Melchior, S., Hawkes, A., & Staffell, I. (2019). Projecting the future levelized cost of electricity storage technologies. Joule, 3(1), 81-100.

[6] Michalski, J., Altmann, M., Bünger, U., & Weindorf, W. (2019). Wasserstoffstudie Nordrhein-Westfalen. Ministerium für Wirtschaft, Innovation, Digitalisierung und Energie NRW: Düsseldorf, Germany.

[7] Fraunhofer Institut für Keramische Systeme und Technologien (IKTS) (2020).

independence, most notably as a synthetic fuel for the mobility sector (see Section 2.2.4).[8] Converting methanol production, currently based largely on natural gas, to green hydrogen thus creates not only an immediate decarbonisation of this industry sector but also additional scope for the application of stored renewable energy.

In addition to its use as a raw material, hydrogen can also contribute indirectly, as an auxiliary agent in chemical processes, to the decarbonisation of industrial processes. The focus here is particularly on the contribution to new production processes for the steel industry, currently a major emitter of CO_2. The customary, high-carbon method of steel-making, where coke is used to smelt iron ore in blast furnaces, could be replaced by so-called direct reduction processes. In that case, the iron ore is not smelted but reduced to solid sponge iron, for which both natural gas and hydrogen can be used as the reducing agent. The use of green hydrogen can thus significantly improve the CO_2 balance of the process. For the subsequent further processing of the sponge iron into crude steel, however, it must pass through an additional smelting process in electric arc furnaces, which requires large amounts of electricity as an energy source.[9] In addition to the contribution to decarbonisation, the effect on the energy balance of the overall system must therefore always be taken into account when evaluating a switch to H_2-based processes.

2.2.3 Use in the heating of buildings

In its capacity as a fuel, hydrogen can in principle also be used to heat production facilities, homes and other buildings. It can be burned in gas condensing boilers for the local heat supply or used in co-generation units for heat supply via district heating networks. Subject to certain technical limitations, the existing gas grid infrastructure can be used for the necessary transport of green hydrogen to consumers of heating. The use of green hydrogen in the heating sector, however, faces tough competition from other climate-neutral heating technologies. These include, most notably, the direct use of electricity from renewable energy (power-to-heat) in the form of heat pumps and electrode boilers. In principle, efficiencies of almost 100% or even, in the case of heat pumps, far more than 100%, are possible here, which means that power-to-gas technology will remain overshadowed in terms of efficiency in this area of application, even with future increases in efficacy.[10] Added to this is the use of biological energy sources (biomethane, wood pellets) and in the district heating sector of industrial waste heat as further climate-friendly heating alternatives. In this field, green hydrogen is therefore particularly interesting for a transition phase in which the aim is to reduce the CO_2 footprint of the European heating sector as quickly as possible by using the heating technologies currently in existence. This is especially true for countries which currently have a high proportion of gas in the heating mix. Modern gas condensing boilers can tolerate relatively high admixture rates of hydrogen (up to 30% according to the manufacturer Vaillant[11]). With concurrent support for investment in more efficient renewable heating technologies, green hydrogen could thus prepare the ground for a gradual phase-out of fossil-fuelled heating.

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[8] Gulden, J., Sklarow, A., & Luschtinetz, T. (2018). New means of hydrogen storage–the potentials of methanol as energy storage for excessive wind power in North Germany. In E3S Web of Conferences (Vol. 70, p. 01004). EDP Sciences.

[9] Dena (2022). Einsatzgebiete für Power Fuels.

[10] Gerhardt, N., Bard, J., Schmitz, R., Beil, M., Pfennig, M., & Kneiske, T. (2020). Wasserstoff im zukünftigen Energiesystem: Fokus Gebäudewärme. Studie zum Einsatz von H2 im zukünftigen Energiesystem unter besonderer Berücksichtigung der Gebäudewärmeversorgung.

[11] BBB (2022). Neue Heizgeräte versprechen Durchbruch beim Wasserstoff. BundesBauBlatt 1-2/2022.

2.2.4 Use in the mobility sector

Several technologies are potentially available for using green hydrogen as a means of propulsion for vehicles. Most strongly represented in the discussion is fuel cell technology. In the hydrogen fuel cell, energy from the chemical reaction between hydrogen and oxygen is converted into electricity. Fuel cell vehicles use hydrogen as fuel and are propelled by the electricity that is generated. In addition, it is also possible to use hydrogen directly as fuel via hydrogen combustion engines. For this purpose, hydrogen is first compressed or liquefied. Alternatively, green hydrogen can also contribute indirectly to the transport transition as the starting point for the production of climate-neutral synthetic fuels. The possible applications of the technologies, and the competitive situation with battery electric vehicles, differ depending on the mode of transport.

As a result of the high energy content of hydrogen (in its compressed state), hydrogen-based propulsion systems generally have a greater range than battery-driven vehicles. The refuelling process is also significantly less time-consuming.[12] These advantages are offset, however, by a significantly lower efficiency level than that of battery vehicles A study by Horváth & Partners estimates average figures for this of 25% to 35%, as compared with 70% to 80% in the case of battery electric vehicles.[13] The larger number of conversion stages is partly responsible for this. In addition, conversion losses in the fuel cell itself are significantly higher than in the battery. Consequently, as a result of the additional manufacturing stage, hydrogen-based synthetic fuel production has an even lower efficiency level. Furthermore, production is made even more expensive by the necessary use of rare metals as reaction accelerators. The main advantage of this energy source, however, is the fact that it is available in liquid form and also has other properties that are similar to conventional petroleum-based fuels. It is therefore possible to make direct use of the existing transport and storage infrastructure for liquid fuels. Synthetic fuels can also be added to petrol for combustion engines, or these can be converted, with little effort, to use only synthetic fuels. Where methanol is used as the synthetic fuel, an additional innovative propulsion technology is available in the form of a methanol fuel cell.[14]

As regards the road transport sector, there is a broad consensus that hydrogen-based propulsion systems should focus on long-distance freight transport, and primarily heavy goods transport. In this mobility segment, the fuel cell drive can make the most of its primary advantage of having higher energy density than battery-powered vehicles: greater range ensures economic efficiency. Hydrogen-based synthetic fuels can be used as a complementary option in this segment to decarbonise the existing fleet of lorries in the short term. Different conditions apply to shipping and aviation. Battery electric drives are largely impractical for longer distances. Green hydrogen will thus play a key role in the decarbonisation of these modes of transport. In the shipping sector, various hydrogen technologies are in direct competition. In addition to fuel cells and the development of synthetic marine fuels, direct use via hydrogen combustion engines is also the subject of research. Finally, in the aviation sector, green hydrogen will play a key role in the future as a foundation for the production of synthetic kerosene.[15] In the absence of practicable alternatives, the long-term greenhouse gas reduction targets

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[12] VDI/VDE (2019). Brennstoffzellen- und Batteriefahrzeuge - Bedeutung für die Elektromobilität. VDI/VDE-Studie Mai 2019.

[13] Horváth & Partners (2019). Automobilindustrie 2035 – Prognosen zur Zukunft.

[14] INWL (2018). Potenzialanalyse Methanol als emissionsneutraler Energieträger für Schifffahrt und Energiewirtschaft. Strategiepapier. INWL Institut für nachhaltige Wirtschaft und Logistik.

[15] IPP (2019). Potenzialstudie Wasserstoffwirtschaft. IPP ESN Power Engineering.

for aviation will only be achievable, at least on longer routes, by way of the large-scale substitution of fossil fuel with synthetic kerosene, supplemented by the use of biofuels.

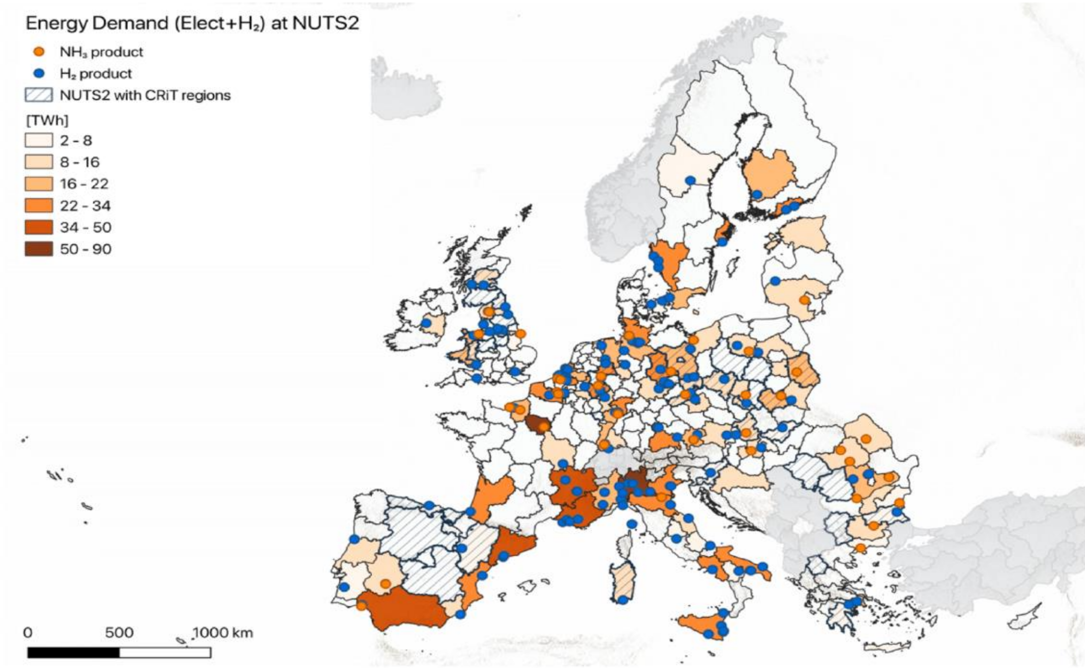
3 Hydrogen production in Europe

3.1 Geographical distribution

There are no official statistics comparing the current level of hydrogen production of countries in the EU. An investigation by Kakoulaki et al (2021), based on data from various industrial databases, recently estimated the distribution of production sites across the entire European continent as being on a small scale. Figure 2 indicates the current production hubs for hydrogen (blue dots) and hydrogen-based ammonia (orange dots) in Europe. The coloured shading of the regional areas (NUTS-2 regions) indicates the estimated electricity demand of the regions, based on a scenario in which the current level of hydrogen production is completely converted to electrolysis.[16] This shows a very high geographical concentration in the EU area. In line with the areas of application described, these are primarily industrial agglomerations. In addition to coastal regions, there are also some urban centres far from the coast where wind power potential tends to be lower. If the regional distribution of hydrogen production remains unchanged in the future, it is likely to mean a growing requirement for capacity in the long-distance grids for the transport of electricity.

[16] Kakoulaki, G., Kougias, I., Taylor, N., Dolci, F., Moya, J., & Jäger-Waldau, A. (2021). Green hydrogen in Europe – A regional assessment: Substituting existing production with electrolysis powered by renewables. Energy Conversion and Management, 228, 113649.

Fig. 2: Current distribution of hydrogen production in Europe



Source: Kakoulaki et al. (2021); dots: location of current production hubs; coloured areas: level of regional electricity demand in the hydrogen scenario; hatched areas: current coal regions (EU Coal Regions in Transition).

3.2 Barriers to roll-out of electrolysis capacities

3.2.1 Technical barriers

A substantial barrier is the cost structure of green hydrogen production. The creation of production capacities requires the construction of a complex system of different components. This also includes, apart from the electrolysis stacks themselves, various devices for heat and mass transfer as well as gas drying and cooling.[17] This results in a high initial investment requirement to expand capacity in electrolysis plants (electrolysers) and thus high capital costs for the subsequent operational phase. From an economic perspective, economies of scale therefore play a decisive role in electrolysis: A high degree of plant utilisation is required to cover fixed capital costs. At the same time, it is hoped that by optimising plant design and mode of operation, it will be possible to reduce unit costs in the future.[18] Such learning effects will require sufficient empirical evidence from practical operations, so that production volume will be important in this respect. Against this background, the supply of electricity from renewable sources represents a critical bottleneck for the economic viability of electrolysers. Currently, in many places, it is primarily surplus electricity from the operation of wind turbines, which would otherwise be restricted (so-called "throwaway electricity), that is used in electrolysers. In order to achieve a sufficient number of operating hours for economic efficiency during the market scale-up, such phases of oversupply on the electricity market would have to occur much more frequently and intensively in the future. The variable costs of operation also present a cost problem. The use of electricity in hydrogen production is linked to energy conversion losses. The result is a high demand

[17] Smolinka, T., Wiebe, N., Sterchele, P., Palzer, A., Lehner, F., Jansen, M., ... & Zimmermann, F. (2018). Industrialisierung der Wasserelektrolyse in Deutschland: Chancen und Herausforderungen für nachhaltigen Wasserstoff für Verkehr. Strom und Wärme.

[18] IEA (2019). The future of hydrogen – seizing today's opportunities. International Energy Agency.

for kilowatt hours of electricity per kilogram of hydrogen produced and thus high electricity purchase costs. This not only exacerbates the scarcity problem but also creates high dependence on electricity price levels, including state electricity price components.

In the areas of storage and transport, the chemical properties of hydrogen pose a challenge. The low weight and - related to this - the high volatility of hydrogen molecules give rise to the risk of high energy losses. The high reactivity also means that attention must be given to the issue of keeping the hydrogen free of impurities. This is especially true if it is mixed with other substances, such as when it is transported in the gas grid. As the fuel cell, for example, places high demands on the purity of the hydrogen used, this can have consequences for the energy efficiency of hydrogen applications.[19] Where hydrogen is incorporated into existing grid infrastructure, there could also be a risk of the hydrogen diffusing into pipeline walls and thereby damaging them. Material compatibility is currently the subject of intensive research.

The development of stand-alone hydrogen grids may offer a possibility for avoiding such risks. This may include the conversion of existing natural gas grids towards a (complete) switch to hydrogen transport and the construction of separate pipelines for hydrogen. According to a recent study by Ready4H2, an alliance of gas distribution network operators in Europe, 96% of the existing gas network in Europe is basically ready to be converted to hydrogen transport. The investigation into the compatibility of individual components, however, has not yet been completed.[20] In addition to the costs of conversion, the variable costs of energy transport may also increase due to the lower energy density of hydrogen if this is not counteracted by increasing the flow rate. Transport by ship may be an alternative depending on the geography. However, in order to increase the density for this purpose, the hydrogen must first either be compressed or cooled down into a liquid aggregate, using large amounts of energy, and therefore, due to the high fixed costs, this transport technology is currently only considered to be economical for distances of more than 10,000 km.[21]

On the user side, there is still a lack of interfaces with future end applications in many cases. This mainly concerns the lack of hydrogen refuelling stations in the mobility sector. It is the classic chicken-and-egg situation: The incentive to invest in the construction of a refuelling station network requires the prospect of sufficient user numbers. In turn, the demand for hydrogen-based mobility is crucially dependent on the availability of a local refuelling infrastructure.

3.2.2 Regulatory barriers

In addition to technical challenges along the value chain, Europe's regulatory landscape is currently still a barrier to economic viability. On the production side, this applies e.g. to the tax burden on purchases of electricity by electrolysers. Unless special rules apply to electrolysers as energy intermediaries, they will have to pay both the levies for the promotion of renewable energies and the grid fees, despite their grid service contribution. The current legal situation in the EU area is inconsistent. Whilst some countries already provide for a (partial) exemption from state electricity price components within certain capacity limits, in other countries electrolysers, operating freely on

[19] ALPIQ (2021). Wasserstoff – Herausforderungen an die Infrastruktur.
[20] Ready4H2 (2021). PART 1: Local gas networks are getting ready to convert. Europe's Local Hydrogen Networks.
[21] Nationaler Wasserstoffrat (2021). Positionspapier zum Wasserstofftransport.

the market, bear the full tax burden. This additionally increases operating costs and prevents the realisation of economies of scale.

On the user side, the basic uncertainty about the regulatory environment is also an important factor. Conversion of production processes or vehicle fleets to hydrogen-based technologies is a fundamental investment decision with long-term implications for the parameters of a company's business model. In view of the disruptive changes to energy policy in the last few years, planning certainty is an issue for businesses. This concerns above all the long-term development of the CO_2 price as an important determinant for the operational viability of such an investment. The same applies at sector level with regard to the question of whether green hydrogen can be credited to sector-related emission reduction targets.

3.3 Cost development

The efficiency of the fuel as compared with climate-friendly alternatives is not the only thing that is decisive for the long-term economic success of green hydrogen. Production costs must also reach a competitive level compared to other forms of hydrogen production. Depending on specific assumptions about electrolysis technology, utilisation rates and production sites, various figures have been circulating on the cost per kg of producing hydrogen. The consensus is that green hydrogen cannot yet compete with hydrogen from fossil sources in terms of cost. At the same time, a significant catching-up process is predicted in the near future, due to a combination of several factors: Leaps forward in the productivity of electrolysis, rising CO_2 prices, increases in the cost of natural gas. Greenpeace (2020) believes that green hydrogen will be price-competitive on its own by 2050 at the latest, and as early as 2030 if there is a significant drop in the price for electrolysers, which it considers a possibility.[22] BloombergNEF (2020) also believes that price parity is possible as early as 2030, assuming an optimistic development in the cost of capital.[23] Other sources are more cautious in this respect, predicting that price competitiveness will not be achieved until around 2050.[24] Of crucial importance in all simulations are the expected developments in the utilisation rates of the electrolysis plants. Thus, it is clear that this can in no way be regarded as a no-policy scenario. The increase in demand can only bring about the envisaged economies of scale if the current political obstacles to the development of a market for green hydrogen are overcome. Thus, the main question in this regard is which instruments make sense for the development of a European market.

[22] Greenpeace (2020). Kurzstudie blauer Wasserstoff – Perspektiven und Grenzen eines neuen Technologiepfads. Greenpeace Energy.

[23] BloombergNEF (2020). Hydrogen Economy Outlook – Key Messages. Bloomberg Finance L.P.

[24] E.g.: Agora Energiewende (2019). Klimaneutrale Industrie: Ausführliche Darstellung der Schlüsseltechnologien für die Branchen Stahl, Chemie und Zement. Agora Energiewende.

4 Support for hydrogen markets in the EU

4.1 EU Hydrogen Strategy

In July 2020, the European Union (EU) published its "Hydrogen Strategy for a Climate Neutral Europe".[25] It provides a roadmap for building and expanding value chains based on the production of "green" hydrogen. According to the EU definition, hydrogen is considered green if it is produced through the electrolysis of water provided that the electrical energy used as input stems from renewable sources. The roadmap outlines a three-phase path. In the short-term phase up to 2024, the focus is on the production of green hydrogen for existing areas of application. These are largely limited to the chemical industry. At the same time, however, new areas of application are to be promoted. For this purpose, electrolysers with a total capacity of 6 GW are being installed capable of producing up to a million tonnes of green hydrogen per year. In the medium term (2025-2030), the roll-out of electrolysers will be accelerated with hydrogen taking over new areas of application including as the source of energy for energy-intensive industries (e.g. steel) and various transport applications. In 2030, the total capacity of the electrolysers is expected to reach 40 GW, with an effective annual production of up to 10 million tonnes of hydrogen. In the long term, i.e. from 2030 onwards, the use of green hydrogen should be widespread in all areas of application where it is technically feasible and has cost advantages over alternative green technologies.

In order to support timely implementation, several measures have been designed at EU level that are divided into four pillars. The first pillar involves the promotion of investment with funds from *InvestEU* as financial support and the *European Alliance for Clean Hydrogen* as a platform for stakeholders to coordinate an investment agenda. The second pillar consists of measures to scale up the supply of hydrogen and the demand for hydrogen-based applications, including fiscal incentives such as a programme of state guaranteed carbon prices (carbon contracts for difference). The third pillar includes measures to create a supportive framework for market growth including the planning of physical infrastructure for hydrogen-based value chains and the revision of market rules to facilitate access to end-user markets for hydrogen. The fourth pillar aims to promote innovation by funding pilot and demonstration projects from EU regional funds. Finally, national measures will be complemented by plans to increase cooperation with partners outside the EU on issues such as regulation and infrastructure.

Although these measures are designed at EU level, their implementation requires the active participation of legislators and private actors in all Member States. Figure 3 illustrates the relationship between the measures at European and national level. This concerns all four pillars of the EU strategy. The actual level of investment support for hydrogen projects will depend on the willingness of Member States to contribute part of their EU budget to InvestEU, and on the implementation of their own financing instruments at national level. The EU-wide effectiveness of regulatory support measures for the introduction of hydrogen production will require the timely transposition of the relevant EU directives into national law. The roll-out of EU-wide hydrogen infrastructure must be given sufficient priority in national infrastructure planning. The success of pilot projects depends on the strength of networks between public and private actors in the Member States as well as on the willingness for cross-border cooperation.

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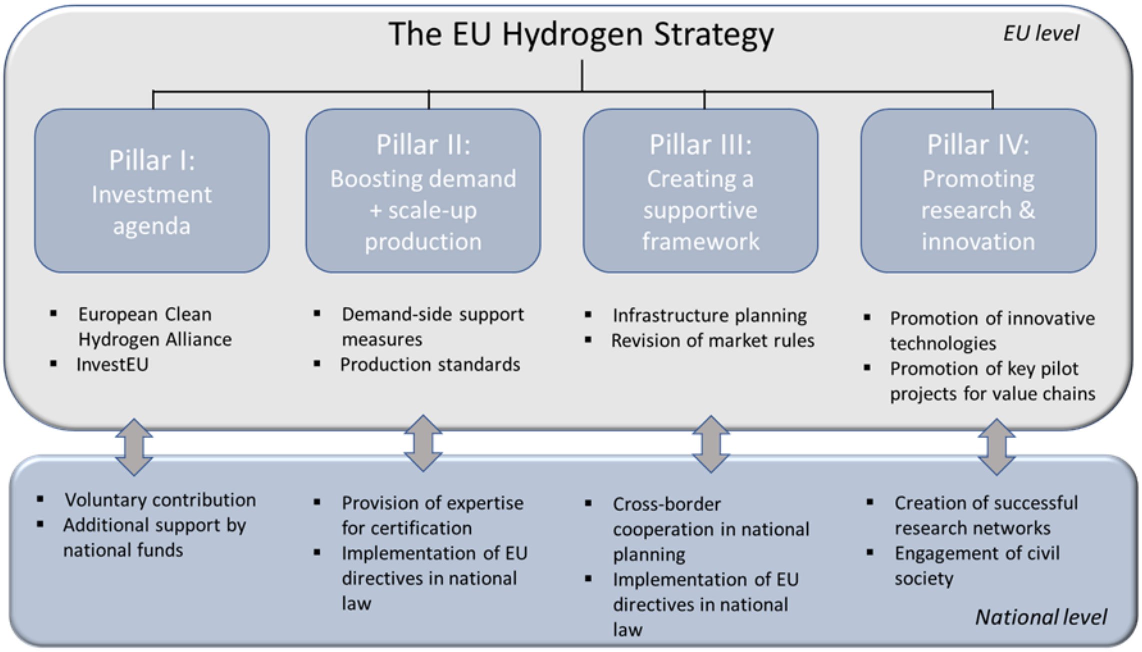
[25] See on this: Reichert, G., Menner, M. (2020). EU Hydrogen Strategy. cep**PolicyBrief** 14/2020.

Fig. 3: Structure of the EU Hydrogen Strategy



Source: Wolf & Zander (2021)[26]

4.2 The role of hydrogen in the "Fit for 55" legislative proposals

The European Commission's extensive package of legislative proposals on climate policy from July 2021 ("Fit-for-55") provides impetus for rolling out production of green hydrogen in various areas. This starts with fundamentally tougher climate policy targets expressed for example through a steeper reduction of the cap in emissions allowance trading (**Emissions Trading Directive**), stricter CO_2 limits for countries in the non-ETS sectors (**Burden Sharing Regulation**) and tougher targets for increasing the share of renewable energies in final energy consumption at sector level (**Renewable Energy Directive**). The draft amendment of the latter Directive also defines concrete requirements for setting hydrogen off against renewables targets. Energy from renewable fuels of non-biogenic origin is only supposed to be set off against national renewables targets if the resulting greenhouse gas savings are at least 70% [Art 29a (1)]. The draft also makes it clear that fuels produced using green electricity will only be eligible as renewable fuels under certain conditions. The criteria soon to be developed for this purpose in a delegated act are to be extended from the transport sector to all areas of application. Based on current information, this includes tough requirements for the eligibility of the renewable electricity used by electrolysers (largely restricted to new plants) and for the distance in terms of time and location between electricity production and its use in electrolysis.[27]

Specific funding requirements for the development of user-side infrastructure in the transport sector are contained in the **draft Regulation on the development of infrastructure for alternative fuels**. This states that, up until 2030, Member States should ensure that a network of publicly accessible hydrogen refuelling stations is established in which the refuelling stations are no more than 150 km apart and at least one refuelling station is set up in every urban node [Art. 6 (1)]. Electronic payment facilities must

[26] Wolf, A., Zander, N. (2021). Green Hydrogen in Europe: Do Strategies Meet Expectations?. Intereconomics, 56(6), 316-323.

[27] Erneuerbare Energien Hamburg (2021). Grüne Wasserstoffwirtschaft – Appell an die EU für einen erfolgreichen Marktstart! Positionspapier – Stand 04.11.2021-

be provided [Art. 7]. In the aviation sector, the draft ReFuelEUAviation Regulation provides for the explicit promotion of the use of synthetic fuels. Fuel suppliers would thus be obliged to ensure that every aviation fuel offered at an EU airport contains a minimum proportion of synthetic fuel [Art. 4]. Airports would also be obliged to provide the necessary infrastructure for synthetic fuel refuelling [Art. 6]. The minimum amount is still to be defined in the ongoing procedure.

4.3 The EU legislative package on hydrogen and decarbonised gas

In December 2021, the European Commission proposed a specific package for the regulation of future renewable gas markets.[28] The proposals, consisting of a directive and a regulation, will help decarbonise the gas sector and build an infrastructure for alternative gases which, in addition to bio-based fuels, will explicitly include hydrogen-based solutions. The Commission sees the package as complementary to the "Fit for 55" proposals in the area of renewable energy and emissions trading.

The proposed **Regulation on internal markets for renewable and natural gases and for hydrogen** is a recast of Regulation (EC) No. 715/2009 on conditions for access to the natural gas transmission networks. The main objective is to create an EU internal market for natural gas, similar to the existing market for natural gas, which enables fair cross-border trade and thus takes account of the varying natural conditions in the Member States regarding the production of green hydrogen. In order to advance cross-border planning and operation of the pipeline infrastructure, a European network of Hydrogen Network Operators (ENNOH) will be set up [Art. 40]. Its area of responsibility will include the preparation of ten-year plans for network development and of monitoring reports on the quality of the hydrogen, as well as the advancement of cooperation with the gas network operators [Art. 42]. A range of privileges is envisaged to promote the transport of renewable and low-carbon gases. Thus, tariff reductions of 75% will apply to network charges for entry points from generation plants as well as entry and exit points to and from storage facilities. Also, cross-border tariffs for trading in these gases will be abolished [Art. 16]. In addition, transmission system operators will be obliged to guarantee binding capacity for the access of renewable and low-carbon gases [Art. 18]. Also, from as early as 2025, they will have to accept the inclusion of gases with up to 5% hydrogen content, at the network interconnection points between the Member States [Art. 20].

The supplementary **Directive on common rules for the internal markets in renewable and natural gases and in hydrogen**, a revised version of Directive 2009/73/EC concerning common rules for the internal market in natural gas, places important emphasis on competition issues. It provides for a certification obligation for renewable gases [Art. 8]. Member States must develop a regulatory system for the hydrogen grids built in the future that guarantees non-discriminatory access for third parties and transparent calculation of tariffs [Art. 31]. In addition to the usual vertical unbundling, horizontal unbundling is also planned for the operation of hydrogen networks: Network operators that are part of an undertaking which also operates electricity or natural gas networks, must be independent at least in terms of their legal form [Art. 63]. This requires them to have an independent organisation as well as their own capital resources. Cross-subsidisation of the development of hydrogen networks via gas transport is thus strictly limited, which could lead to expensive parallel administrative structures in the future.

[28] European Commission (2021). Hydrogen and Decarbonised Gas Package.

5 Possible measures for an accelerated market ramp-up

Against the backdrop of the current crisis situation, the question arises as to which complementary measures could accelerate the switch to a green hydrogen economy. European coordination is crucial to this and there is also a need for action at national and regional level.

5.1 Measures to strengthen production

- Administrative help with the expansion of wind power: A stable supply of sufficient amounts of renewable electricity is a precondition for adequate utilisation of the increased electrolysis capacity and thus improved efficiency through economies of scale. In view of the competitive situation with the direct use of electricity, this requires even more ambitious target paths for the roll-out of renewable capacity, most notably in the case of wind power. In addition to rolling out capacity in existing locations, focus should also be on regions with high wind power potential but where development of electricity production has so far been lacking. This would enhance the division of labour with regard to electricity production in Europe and reduce vulnerability to local fluctuations in electricity generation. Long planning and approval procedures continue to represent a practical obstacle to the expansion of capacity in many areas. Here it is important to ensure that the potential for streamlining is fully exploited, such as by shortening review processes through standards and presumptions and reducing the number of appeal tribunals.
- **More flexible requirements for the purchase of electricity:** The European Commission's current plans, for enabling green hydrogen to be set off against sectoral targets (see Section 4.2), could, in view of the sluggish rate of renewables development, prove to be a major stumbling block for the roll-out of electrolysis capacities in Europe. Requiring electricity to be purchased only from renewables capacities created with electrolysers would generally lead to planning uncertainty, and in many cases also to a delay in realisation. The shortness of the time delay permitted between generation and use of the electricity could increase the production costs for electrolysers as a result of the necessary capacity adjustments. Here, the nature of the power-to-gas technology should be addressed by granting installations more flexibility, at least in the market launch phase.
- **Smart siting policy for electrolysers:** The huge importance of economies of scale in the production of green hydrogen supports the idea of concentrating electrolysis capacities in locations with high regional renewables capacities in order to be able to guarantee a sufficient number of full-load hours. The distance to the industrial centres in Europe, i.e. the future large-scale consumers of hydrogen, can then be covered largely via transport in converted gas pipelines and a new hydrogen grid. This could not only provide the basis for a new form of industrial division of labour in Europe but also prove to be a wise move in terms of cohesion policy, enabling both producer and consumer regions to participate equally in the emerging value chains.
- **Developing a sustainable EU import strategy:** Full exploitation of internal EU generation potential should be a priority in the development of hydrogen markets. In view of the natural capacity limits of wind and solar power, a broad-based hydrogen economy will additionally also require imports from regions outside Europe in the future. For the EU, coordinated action at this point offers the opportunity to exercise market power and define standards for a future global hydrogen economy. Countries with globally favourable electricity production costs are

natural partners in this respect. For assessing long-term economic viability, however, other criteria such as geographical proximity (transport costs) as well as political stability and sustainability issues in the production region are also important.

5.2 Measures to strengthen use and transport

- **Reducing investment risks through carbon contracts for difference:** Switching to the use of green hydrogen in the industrial sector also requires extensive and long-term investment on the part of the user. In view of ongoing regulatory adjustments and fluctuating CO_2 prices, planning uncertainty is a major obstacle here. A state guaranteed fixed CO_2 price enables investors to better calculate future cost savings from CO_2 avoidance as an essential component of the return on investment. Over an agreed period of time, the state compensates the difference between the contractually fixed price and the prevailing market price in emissions allowance trading. In view of the expected long-term price increases in allowance trading, the contract duration can be limited in time thereby minimising government budget risks.
- **Consistent roll-out of a transnational hydrogen infrastructure:** In order to maximise the growth and employment effects of a European hydrogen economy, the emerging potential for a new European division of labour should be used, both in terms of production and use of the hydrogen produced. This will require the capacity for cross-border transport over long distances. The rapid development of a non-discriminatory Europe-wide transport infrastructure should therefore be given top priority in the design of a future internal hydrogen market. To shorten planning and approval processes and to save construction costs, the conversion of existing gas networks should be permitted where technically possible. In the interests of affordable transport costs in the start-up phase, barriers to financing arising from unbundling requirements should be kept to a minimum without ignoring the risk of provider concentration.

6 Conclusion

It has become clear that green hydrogen can play an important role in the transformation of the European energy system thanks to its versatility and the fact that it can be used to complement electricity production from renewable sources. However, technical limitations and competition with more efficient climate-neutral technologies set limits on its function as an all-purpose tool. In the future, it will be important to channel its use rationally, into areas in which the specific advantages of green hydrogen can be used to their best effect. This includes areas where it can be used as a raw material, as a reducing agent and as a fuel in sectors where battery technology is inappropriate. In sectoral terms, use is therefore likely to focus on the industrial sector, long-term energy storage and on certain segments of the transport sector (air and sea transport, long-distance goods transport).

For a sustainable market launch, the timing of support should follow a clear roadmap. During the current start-up phase, the rapid scale-up of electrolysis capacities will take priority. This primarily requires a steeper expansion curve for wind energy in the vicinity of the electrolysers, alongside the development of pipeline capacity for long-distance transport. The use and/or conversion of gas pipelines in the direction of current European centres of consumption may be a good place to start in this regard. Initially, commercial applications will primarily be those in which the use of hydrogen is already inherent in the technology (e.g. production of fertilisers, methanol) or in which conversions (within limits) can be carried out without high conversion costs (e.g. as an admixture in gas condensing boilers). The economies of scale achieved and the experience gained can then be used in the medium term to diversify the fields of application. The development of an import economy, on the other hand, should be regarded as a long-term aim which will become more relevant once EU-wide generation capacities for wind power have been largely exhausted. The necessary groundwork must nevertheless be laid now, in the form of a sustainable EU import strategy.

From an economic perspective, the development of an EU-wide hydrogen market gives rise to new potential for the intra-European division of labour with regard to production and consumption. Not only could this advance the integration of the European energy system but also help to increase the energy efficiency and competitiveness of the European industrial sector. With this in mind, the EU Commission has already made some proposals to remove existing regulatory hurdles. Behind this is the awareness that the combination of economies of scale in production, planning uncertainty in investments, and the chicken-and-egg problem in infrastructure development, make government stimulus necessary. Continual monitoring of the regulatory situation and complementary measures at national and local level will be necessary to provide green hydrogen with a level playing field in the competition between fuel sources. In such a fair competitive environment between the technologies, the extent to which hydrogen really can rise to become the “green freedom gas" will then rest on entrepreneurial rather than political decision-making.

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