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The potential of hydrogen for decarbonising EU industry

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The potential of hydrogen for decarbonising EU industry

Given the vast potential for renewable electricity generation, the production of renewable hydrogen, i.e. using renewable electricity for producing hydrogen via water electrolysis, is seen as a promising option for decarbonising EU industry, in particular for hard-to-decarbonise energy-intensive industry sectors.

Transforming the EU's energy system to a hydrogen economy is perceived to provide benefits with respect to job creation, economic growth, innovation and air pollution. The European Commission published its hydrogen strategy in 2020, with the aim of boosting hydrogen use in the EU while fostering the uptake of renewable hydrogen production. Recent activities, such as the launch of the European Clean Hydrogen Alliance and the EU Innovation Fund, the formation of hydrogen valleys and the promotion of important projects of common European interest (IPCEIs), provide promising first steps to fostering a European hydrogen economy.

Nevertheless, important policy gaps need to be addressed to ensure the sustainable realisation of the EU hydrogen strategy targets, in particular with respect to certainty for investors, cost-competitiveness with fossil technologies, regulation of hydrogen infrastructures, certification of renewable and low-carbon hydrogen, as well civil society participation.

This study takes stock of the current situation with respect to the realisation of the EU hydrogen strategy and identifies policy options that address gaps in the current landscape.

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Executive summary

The EU aims to become the first climate-neutral continent by 2050. To this end, it has developed the European Green Deal, which is meant to make the EU the global leader on green technologies, while ensuring economic growth and a just transition. Experts and researchers agree that reaching greenhouse gas (GHG) neutrality will require the decarbonisation of the whole economy. Some sectors are assumed to be harder to decarbonise than others. In these sectors, there is a need for renewable fuels, as full direct electrification is not expected to be feasible. Given the vast potential for renewable electricity generation, **the production and use of renewable hydrogen is seen as a key lever for the decarbonisation of hard-to-decarbonise sectors**. Transforming the EU's energy system to a hydrogen economy is perceived to provide benefits with respect to job creation, economic growth, innovation and reducing air pollution. Accordingly, the European Commission published its hydrogen strategy in 2020 with the aim of **boosting hydrogen use in the industry and transport sectors, while fostering the uptake of renewable hydrogen production**.

The **main objective** of this study was to **take stock of the realisation of the EU hydrogen strategy and to identify policy options that address gaps** in the current landscape. A synthesis of literature review and expert interviews has led to the following **key findings**:

- Low-carbon and renewable hydrogen can be expected to remain a relatively scarce and costly resource during the next decade. Therefore, the **use of hydrogen should be prioritised across sectors, as well as within energy-intensive industries**. There is high uncertainty about the future demand for hydrogen in the transport sector, while its use in the building sector is of minor importance. With respect to industry, it is important to focus on subsectors where hydrogen is a 'no-regret' option, i.e. no decarbonisation option with higher cost-effectiveness is available. This applies in particular to ammonia production and, at least in the medium term, to refineries, due to the current use of fossil hydrogen. In turn, the use of hydrogen for producing steam should not be a priority, since direct electrification may render it superfluous. For the steel industry, building direct reduction plants already allows for a strong reduction of emissions when using natural gas, while a steady switch to renewable hydrogen is possible.
- A **major barrier to the market introduction of renewable hydrogen** in industry is higher costs compared to fossil fuels. This is particularly relevant for energy-intensive industries, because the share of energy costs in gross value added is higher there than in the rest of manufacturing. If the additional costs on the way to a GHG-neutral economy cannot be compensated, then this represents a serious barrier to transformation, because the industries concerned are in international competition. In this regard, carbon contracts for differences, which are envisaged to fund the difference between the production cost and the market value of the delivered product, are a promising option.
- The EU hydrogen strategy plans to **ramp-up renewable hydrogen production** via electrolysis to 10 million tonnes of hydrogen by 2030, with an installed capacity of 40 gigawatt (GW) electrolysers. This massive scaling up of hydrogen and electrolyser capacities needs to be flanked with adequate support policies in research and innovation, as well as with investments. Despite the EU's production targets, the required production capacities to satisfy the expected EU demand for renewable and low-carbon hydrogen will nevertheless exceed the expected production capacities. That means that a substantial share of hydrogen demand has to be imported.
- The role of **low-carbon hydrogen as a bridging fuel** is a highly debatable issue. A switch to a low-carbon hydrogen alternative is technically feasible, since the technology of carbon capture is known and established in many production processes. The

potential advantage of a quite speedy switch could evaporate due to technical, economic and (in particular) societal impediments in respect to storing the excess supply of CO_2, which cannot be utilised due to too low demand for such carbon. Furthermore, excessive installation of carbon capture and storage (CCS) facilities could lead to fossil lock-ins, which should be avoided.

- **Establishing a backbone hydrogen infrastructure** can be expected to be an important step in moving from individual pilot projects to a rollout of hydrogen. While important areas for hydrogen production and use can already be anticipated, the required amounts are still uncertain and the required infrastructure is hard to predict. Building up the infrastructure too early may result in sunk costs, which will ultimately be carried by the end-users. However, long-term planning processes require early action, which means that the necessary provisions must be established very soon, while still leaving the option to navigate the rollout. All energy networks require a joint planning to determine overall optimal pathways as soon as possible.
- Given the current **lack of hydrogen markets** and large-scale networks and the regulatory principle of minimal intervention, there is no urgent need for their regulation. However, the expected benefits of a hydrogen backbone infrastructure call for establishing at least the general principles, in order to avoid a later need for harmonisation of diverse regulations. Such main principles include free access to third parties and overarching principles for remuneration. A promising option is to start with a few regionally focused test cases. Different approaches to regulation, based on the same overarching principles, could be applied for a limited timeframe and compared afterwards. An important prerequisite for shaping the market is a clear certification scheme.
- If the EU wants to form **a hydrogen industry that is globally competitive**, it must ensure the fostering of research, development and innovation as well as commercialisation, across all key technologies – electrolysis in particular. Once electrolyser production reaches an economics of scale regime, continuous improvements of cost and efficiency may occur, but the initial market ramp-up depends heavily on regulatory priorities and the availability of renewable electricity. The EU may leverage its currently favourable technological position to lead the commercialisation of sustainable hydrogen technologies. The important projects of common European interest (IPCEIs) on hydrogen currently being established are a first step to deal with this in a strategic way.
- The realisation of a **hydrogen economy** requires broad societal mobilisation. In terms of key actors, a strong movement supporting the new hydrogen economy in the EU is witnessed, engaging mainly policy-makers and regulators, industries, small and medium-sized enterprises (SMEs) and science. The hydrogen valleys approach, which links all relevant actors in regional clusters, can also contribute substantially to fostering hydrogen use. Nonetheless, weak civil society participation in the design of the new hydrogen economy has been identified. In that sense, it is of high importance that current lead actors take into account that society will play a key role in the adoption of hydrogen technologies. What is needed in the short term is a regulatory framework for a level playing field in a green hydrogen economy.

In **summary**, recent activities such as the launch of the European Clean Hydrogen Alliance and the EU Innovation Fund, the formation of hydrogen valleys and the promotion of IPCEIs provide promising first steps to fostering a European hydrogen economy. Nevertheless, important policy gaps need to be addressed to ensure the sustainable realisation of the EU hydrogen strategy's targets, in particular with respect to certainty for investors, cost-competitiveness with fossil technologies, regulation of hydrogen infrastructures, certification of renewable and low-carbon hydrogen, as well as civil society participation. Some of these gaps are at least partially covered by the Fit for 55 package. Others will be addressed with the hydrogen and gas market decarbonisation package scheduled for the end of 2021. The opportunity provided by the negotiations on these packages should be used to ensure that the EU is on track to realising the benefits of a hydrogen economy while limiting undesired side-effects.

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BECCS	Bioenergy with carbon capture and storage
CAPEX	Capital expenditures
CBAM	Carbon border tax adjustments
CCfD	Carbon contracts for difference
CCS/CCU	Carbon capture and storage / Carbon capture and utilisation
CO_2	Carbon dioxide
EC	European Commission
ETS	Emissions Trading Scheme
EU	European Union
GHG	Greenhouse gases
GoO	Guarantees of Origin
GW	Gigawatt
H_2	Hydrogen
IF	Innovation Fund
IPCEI	Important projects of common European interest
MENA	Mediterranean countries of Africa and Middle East
NGO	Non-governmental organisation
NIMBY	'Not-in-my-backyard'
OPEX	Operation expenditures
PCI/PMI	Projects of common interest/Projects of mutual interest
PPA	Power purchasing agreement
RED	Renewable Energy Directive
RFNBO	Renewable fuel of non-biological origin
SME	Small and medium-sized enterprises
TSO	Transmission system operator
TWh	Terrawatt hours
TYNDP	Ten-year network development plan

1. Introduction

1.1. A brief overview of the potential of hydrogen for decarbonising EU industry

As announced in its strategic long-term vision in 2018, which is enshrined in the European Climate Law, the EU aims to become the first climate-neutral political entity by 2050. To this end, the EU has developed a new growth strategy, the European Green Deal (European Commission 2019a), which attempts to make the EU the global leader on green technologies, while ensuring economic growth and a just transition. Experts and researchers agree that reaching greenhouse gas (GHG) neutrality will require the decarbonisation of the whole economy. Some sectors are assumed to be harder to decarbonise than others. This applies particularly to the aviation and navigation sectors, but also to heavy industry (among others, the production of steel and basic chemicals). In these sectors, there is a need for renewable fuels, as full electrification is not expected to be feasible.

Given the vast potential for renewable electricity generation, the production of renewable hydrogen, i.e. using renewable electricity for producing hydrogen via water electrolysis, is seen as a promising option. Moreover, hydrogen offers a much larger potential for storing surplus renewable electricity, compared to pumped hydro and batteries. Therefore, the production and use of renewable hydrogen is seen as a key lever for the decarbonisation of the hard-to-decarbonise sectors. Even more, transforming the EU's energy system to a hydrogen economy will provide possible benefits with respect to job creation, economic growth, innovation and air pollution (Fuel Cells and Hydrogen 2019). Accordingly, the European Commission published its hydrogen strategy in 2020, with the aim of boosting hydrogen use in the industry and transport sectors, while fostering the uptake of renewable hydrogen production (European Commission 2020e). In particular, it includes the target to ramp-up electrolysis capacity in the EU to 40 GW by 2030, as well as to a similar magnitude in neighbouring countries exporting to the EU.

1.2. Opportunities and challenges of a hydrogen economy

Today, the production of certain basic chemicals such as ammonia, methanol and petrochemicals relies on the use of fossil hydrogen, produced from natural gas via steam reformation. In these sectors, there is an immediate potential for the replacement with low-carbon or even renewable hydrogen (Bruyn et al. 2020). Meanwhile, the steel industry considers hydrogen-based steelmaking, via the direct reduction route, as the most promising option to produce carbon-neutral steel and is already planning the first industrial-scale plants. In addition, hydrogen can be used for the provision of high-temperature heat in many other industrial sectors, but also for space heating in buildings via heat grids or even small-scale heating.

The potential of hydrogen for decarbonising the EU economy calls for an industrial-scale supply of renewable hydrogen by 2030, and a following increase to reach the scale of today's fossil markets. This comes with great challenges across all elements of the value chain. While the large-scale production of hydrogen requires scaling up today's electrolysis capacities by several orders of magnitude, industrial users, such as steel plants, need to make major investments in hydrogen technologies that in turn require regulatory and/or economic incentives for their amortisation (EPRS 2020b).

A particular challenge in this case, is the need to balance the expansion of demand, production and infrastructure. To foster security of supply, it is useful to consider the options for importing renewable hydrogen and also to open up production to certain non-renewable routes for a limited period. Therefore, the EU hydrogen strategy also considers the use of 'low-carbon hydrogen'

(European Commission 2020e). This is meant to include hydrogen production pathways with substantially lower GHG emissions than fossil hydrogen. This includes the use of natural gas-based production routes combined with the sequestration of carbon, in particular carbon capture and underground storage (blue hydrogen) and pyrolysis (turquoise hydrogen).

Moreover, the hydrogen produced needs to be supplied to synthesis plants and end users. This is likely to require the construction of an EU-wide hydrogen network by combining the partial conversion of the current gas grids with new hydrogen pipelines, where a conversion is not possible (Wang et al. 2020). This needs to be properly reflected in the regulatory framework for both the existing gas infrastructure and the new hydrogen infrastructure.

These challenges need to be addressed early enough to harvest the benefits of a hydrogen economy as part of the European Green Deal. The EU is planning to support the production, storage and use of hydrogen with certain policy instruments. This includes investment aid in the upcoming InvestEU programme, which combines several former investment programmes, improved cooperation via IPCEIs, research under the Horizon Europe programme, as well as the EU Innovation Fund and carbon contracts for difference, covering the additional costs of not yet commercially viable projects. Moreover, the EU wishes to ensure a level playing field for industries in international competition via the carbon border adjustment measures. Finally, the EU plans to foster the development of hydrogen markets and infrastructures via appropriate revisions of the TEN-E Regulation and the regulation of its internal gas markets, to be tailored to decarbonised gases (European Commission 2020e).

Based on the potential described above, the realisation of a hydrogen economy in the EU is indeed promising. However, there is high uncertainty about whether these benefits can actually be achieved and how the existing challenges can be overcome. Moreover, systemic effects, including unintended side-effects of a transformation to a hydrogen economy, need to be considered carefully with respect to societal impacts. In particular, the following questions require attention:

- Is the scaling up of production by several orders of magnitude feasible in the given time frame? What does this mean for imports and investment requirements?
- How to prepare for and mitigate implications on the societal level, e.g. local resistance to massive expansion of renewable energy generation capacity, increasing end-user prices or the loss of jobs in certain industries/regions?
- To what extent are bridge technologies needed, e.g. direct reduction of natural gas in the steel industry? If so, should the bridge technologies be included in the same support schemes as the use of renewable hydrogen?
- Is there a risk of a lock-in into carbon-intensive production routes, given that hydrogen may be combined with fossil CO2 in industry processes?
- How to avoid unnecessarily high costs due to profuse use of hydrogen, e.g. in applications where direct electrification is possible, such as steam production?
- Are there safety risks in the use of hydrogen that need more detailed consideration? Are there specific sustainability issues that could arise?
- What are the political and strategic implications if the EU cannot provide competitive renewable hydrogen production or cannot satisfy the internal demand?

This report reflects upon these questions when assessing the design of current and upcoming policies, as well as relevant gaps in the realisation of the EU hydrogen strategy.

1.3. Objectives of the study

The study contributes to three overall objectives:

- **Stocktaking and potential:** The study presents and analyses the state of play regarding the potential of hydrogen for decarbonising EU industry.
- **Current policies and gaps:** The study analyses how the EU is currently performing, including the main opportunities and challenges for implementing the hydrogen strategy as proposed by the European Commission.
- **Policy options:** Based on the specific study results, the study offers and assesses policy options for the creation of a hydrogen ecosystem in the EU that will enable the replacement of fossil fuels in hard-to-decarbonise sectors.

The issues considered under the first objective go beyond the EU industry's production processes and also cover the production of hydrogen and its transport to industrial users. Accordingly, the potential of a hydrogen economy is considered along the whole value chain (sourcing of renewables, production of hydrogen, its transport via networks and other means, hydrogen applications) and a stocktaking of the current status is carried out.

Under the second objective, the study addresses the targets of the European hydrogen strategy and assesses the main challenges for achieving them along the value chain. Furthermore, it analyses which policies are in place to address the main challenges, which impacts can be expected from them and where there are gaps in the current policy landscape.

Under the third objective, policy options for improving the performance of the present policies and closing gaps in the policy landscape are derived along the value chain, in order to seize the opportunities of a hydrogen economy, while limiting potential unintended side-effects.

This study has a strong focus on policy options to foster the use of hydrogen for the decarbonisation of EU industry. To this end, it is necessary to provide both a concise overview of the current status on industry-relevant aspects of the EU hydrogen strategy and to assess key topics related to current and upcoming policies in more detail. The study is structured as follows. In Section 2, the methodology and resources used for the assessment of the key topics is presented. Section 3 provides an overview of the five overarching topics 'Hydrogen use in industry', 'Production of hydrogen', 'Hydrogen infrastructures and markets', 'Actors and regions' and 'EU in international perspective' and policy gaps are identified. Section 4 summarises the main findings from the stocktaking and the assessment of policy gaps. Based on these conclusions, Section 5 presents options to overcome the policy gaps in each of the policy action fields in the EU hydrogen strategy.

2. Methodology and resources used

In this section, the methodology and resources used for the assessment of the key topics is presented. In general, the assessment is based on an in-depth evaluation of the available literature on the key topics. The literature analysis is complemented by expert interviews, which are used to cross-check the findings from the literature and to gain additional input on topics not yet covered by the literature in detail. In the final step, the information is synthesised to identify policy gaps and develop relevant policy options. The steps are described in more detail in the following subsections.

2.1. Literature review

A thorough literature review lies at the core of this study. The study team considered academic literature as well as reports and strategy documents. The different aspects of the study required a wide collection of sources. They can be broadly structured along the following dimensions, whereby each dimension touches on the five overarching topics 'Hydrogen use in industry', 'Production of hydrogen', 'Hydrogen infrastructures and markets', 'Actors and regions' and 'EU in international perspective':

- **Current literature on technical and economic aspects** Scientific and grey literature as well as strategy reports served as the basis for the study. This allowed a review of current technologies of hydrogen production, their market readiness and the implications their use may have in terms of upstream technologies. Furthermore, technologies that generate the demand for hydrogen were summarised briefly to provide an overview of future demand options and quantities. In addition, the literature review covered the latest reports on transport options and the respective infrastructure.
- **Current and planned EU policies:** A thorough review of existing EU policies described the status quo and develops future options. We considered relevant acts and legislation as well as accompanying reports and analyses published by EU bodies along the whole value chain of hydrogen production, transport and consumption.
- **Position of key stakeholders:** Position papers from industry associations, think tanks, research associations and non-governmental organisations provide significant input to enrich the arguments on policy options. We also consider selected national and sectoral strategies, where relevant.

2.2. Expert interviews

In the second step, the findings from the literature review were validated and complemented by five interviews with distinguished experts in fields strongly related to the key topics. In order to cover the different topics in adequate depth, we undertook overlapping interviews with respective experts. The five overarching topics were grouped into the three domains 'Use and production', 'Infrastructure and markets', and 'Actors and international perspective', with two interviewees per domain. The domains can also be broadly linked to the key actions identified by the hydrogen strategy:

- An investment agenda for the EU
- Boosting demand for and scaling-up production
- Designing an enabling and supportive framework: support schemes, market rules and infrastructure
- Promoting research and innovation in hydrogen technologies
- An international perspective

By selecting two experts per topic combination, we ensured that each topic is covered and different viewpoints are reflected. The choice of experts reflected both the key topics to be covered and the representation of views from different groups of actors, in particular policy-makers, industry associations, transmission system operators (TSOs), regional actors and civil society think tanks. Table 1 presents the topics and actions covered by the interviews.

Table 1 – Topics and actions covered by the expert interviews

Domain	Use and production	Infrastructure and markets	Actors and international perspective
Topics	Hydrogen use in industry and other sectors Production and import of hydrogen	Hydrogen infrastructures and markets	Actors and regions EU in international perspective
Hydrogen strategy key action addressed	An investment agenda for the EU Boosting demand for and scaling up production	An investment agenda for the EU Designing an enabling and supportive framework: support schemes, market rules and infrastructure	Promoting research and innovation in hydrogen technologies The international dimension
Experts interviewed	Policy experts on European support schemes and investment aid	Regulatory experts for EU-wide regulation of gas infrastructure and markets. Policy, technical and regulatory experts from gas TSOs	Policy expert from the industry association Hydrogen Europe Expert on hydrogen valleys from the New Energy Coalition

The interviews were semi-structured, following specific guidelines, but adapted flexibly to the interviewee's answers. All interviews covered the following overarching areas, tailored to the individual focus topics:

- Introduction
- Current and future developments
- Opportunities and challenges
- Socio-economic impacts
- Policy options

2.3. Synthesis and derivation of policy options

In each of the five policy action fields of the EU hydrogen strategy, we investigated certain aspects of the future hydrogen economy, evaluated existing policies and developed policy options to fill respective gaps. Under each of the five policy action fields, three options were developed, one with a high level of control at EU level, one with overarching principles for Member States (Member States) at EU level and one with a high level of control at the Member States level. The policy options were compared on the basis of their performance against similar criteria:

- Cost and benefits
- Feasibility and effectiveness
- Ecological sustainability
- Risks and uncertainties
- Coherence with EU objectives
- Other impacts (ethical, social and regulatory).

This allows policy-makers to respond to future policies, which will likely be discussed along these criteria. An evaluation of these criteria including a semi-quantitative assessment for each of the policy options can be found in the annex.

3. Synthesis of the research work and findings

In this section, the available literature on the role of hydrogen for decarbonising EU industry is summarised and enriched by findings based on expert interviews. The results are synthesised under the following topics:

- Hydrogen use in industry and other sectors
- Production and import of hydrogen
- Hydrogen infrastructures and markets
- Actors and regions
- EU in international perspective

3.1. Hydrogen use in industry and other sectors

The EU hydrogen strategy outlines a strategy for decarbonising industrial processes that requires ambitious transformations (European Commission 2020e). For this, the EC proposes a two-stage approach in which renewable hydrogen is used in the first stage (2020-2024) where carbon-intensive hydrogen has been used so far, e.g. in refineries and in the production of ammonia. In the second stage (2025-2030), the use for new areas, e.g. in steel production, is to be pushed through targeted demand-side measures.

3.1.1. Technical aspects that influence the market ramp-up of hydrogen

Overall, there is a broad consensus in the literature that hydrogen is a technically feasible and promising decarbonisation option for industry. For instance, a study for the European Parliament stresses the importance of hydrogen for the process industry (Bruyn et al. 2020). While today hydrogen is mainly used in the chemical industry, particularly for ammonia generation (for fertilisers) and for hydrocracking, in the future it could also replace natural gas or coal as feedstock for novel industrial processes. For the steel and chemical industries, hydrogen production with renewable energies could be the most important technology for CO_2-neutral production by 2050 (Neuwirth and Fleiter 2020; EPRS 2021c). In the heat sector, hydrogen could take on a limited role for high-temperature applications, alongside more efficient direct electrification (Bruyn et al. 2020).

There is less consensus for the use of hydrogen in other end-use sectors. For example, the German Advisory Council on the Environment SRU assumes that hydrogen will remain a valuable and scarce energy carrier for the foreseeable future and therefore recommends that it only be used where there are no more efficient alternatives, e.g. not in passenger cars or in building heating systems (SRU 2021). Guidehouse (2020), on the other hand, sees relevant options for its use in buildings. The following sections therefore focus on the industrial sector.

The use of hydrogen in industrial applications can be divided into three different categories (Agora Energiewende and AFRY Management Consulting 2021). Firstly, as a chemical feedstock for the synthesis of products in which it is a molecular component: Essential processes here are ammonia and methanol production. Secondly, as a chemical reactant, where it participates in chemical reactions but it is not a molecular component of the final product, e.g. in steel production by means of direct reduction, where the hydrogen is used to reduce the oxygen in the iron ore. Thirdly, as a fuel for heat generation e.g., in high-temperature furnaces.

Steel industry

In the steel industry, direct reduction with 100 % renewable hydrogen is seen as a long-term GHG-neutral solution. Hydrogen is used here as a chemical reactant for the reduction of iron ore. However, direct reduction iron (DRI) plants can also be operated with natural gas; in this case, the necessary hydrogen is produced from the natural gas. This process is state of the art and already enables significant GHG reductions, compared to the stock of today's blast furnace-based steel plants in Europe, at around 50-60 % (without CCS, Scope 1) (IREES 2021). Therefore, natural gas DRI can be seen as a bridging technology for the decarbonisation of the steel industry. With CCS, higher emission reductions are possible with natural gas DRI, up to 85 % according to EPRS (2021a), but the sense of building a CO2 capture infrastructure for these additional emission reductions is doubtful if the long-term solution is to be 100 % use of hydrogen in the DRI.[1]

Basic chemistry (especially ammonia and olefins)

In contrast to the steel industry, the technological field in the chemical industry is still somewhat undeveloped. One main driver of hydrogen demand is the need for feedstock for the production of plastics (made from olefins), for which hydrogen and carbon molecules are needed. Both are currently provided by fossil naphtha. Converting the production process to renewable hydrogen requires that additional carbon sources are integrated into the olefin production process. Theoretically, more (especially chemical) recycling can significantly reduce the demand for hydrogen and carbon, but research and especially the large-scale implementation of these technologies is still in its infancy (Solis and Silveira 2020). In addition, the use of CCS is a potentially cheaper option, which could also generate negative emissions in combination with sustainable biomass (so-called BECCS, cf. (European Commission 2018)).[2] Another important driver is the ammonia industry, where hydrogen is currently produced from natural gas using steam methane reforming. On the premise that ammonia will continue to be produced in significant quantities in the EU in the future, the scenarios consistently project considerable hydrogen requirements for 2050. Moreover, ammonia can also be used as a carrier medium for renewable hydrogen and can therefore take on an additional functions in a hydrogen ecosystem.

Refineries

The role of refineries in the market ramp-up for a hydrogen ecosystem in the EU is unclear. Hydrogen is currently used in refineries to reduce the sulphur content in oil products to meet certain environmental standards, and to upgrade low-grade heavy oil. In Europe, refineries account for about 45 % of hydrogen demand; if methanol production is included, which usually also takes place at refinery sites, the figure is 50 % (Hydrogen Europe 2020a). Part of the refineries' hydrogen demand is covered by production from by-products of the refinery process (Noussan et al. 2021) assuming that this share is about one third globally. But refineries differ. For Germany, the country with the highest refinery capacities in the EU, the share is 78 % (dena 2018). Moreover, the scenarios consistently project a sharp decline in demand for refinery capacities by 2050. So if renewable hydrogen is to be used at refinery sites, the question at which sites this should be done is relevant, so that no sunk investments arise. Many refinery sites already produce methanol. This raw material, if produced from renewable hydrogen, could play a central role in the transformation of commodity chemistry, e.g. in the production of plastics via the methanol-to-olefin route. Some refineries could thus become methanol producers in the medium- to long-term. For the use of hydrogen in refineries, a medium- to long-term strategy for the refinery in question is therefore a reasonable prerequisite.

Other sectors (especially relevant for heat)

In other industrial sectors, hydrogen is primarily a potential fuel for heat generation. About 40 % of today's industrial natural gas consumption in the EU is used for heat below 100°C, and another 25 % for heat between 100°C and 500°C (Agora Energiewende and AFRY Management Consulting 2021).

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[1] In principle, DRI plants can be operated with both energy sources, i.e. hydrogen can also be used in natural gas-fuelled DRI plants, with modifications in principle up to 100 %. Thus, it is not necessary to build a new plant to switch from natural gas to hydrogen, because this can be done step by step

[2] Biomass directly provides carbon and hydrogen as a feedstock. However, the availability of biomass is a limiting factor.

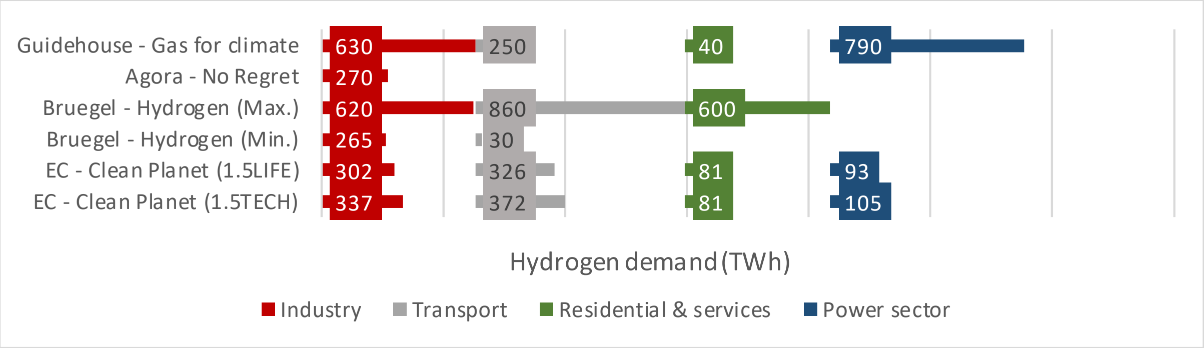
Heat below 100°C can be produced with common heat pumps, requiring significantly less electricity compared to the hydrogen option. In addition, heat above 100°C can also be supplied with high-temperature heat pumps, whereby temperatures of up to 150°C are achievable in the medium-term, and even up to 200°C in the long-term (Arpagaus 2019).

3.1.2. Projections of hydrogen demand

In 2018, the European Commission (EC) published a document entitled 'A Clean Planet for all', which presents and analyses options for a long-term climate policy in the European Union (EU) (European Commission 2018). Eight different scenarios with different technology focus were developed for this purpose, whereby two of the developed scenarios achieve net-zero emissions, thus reaching the ambition level of the current European climate policy. These two scenarios projected a hydrogen demand of 800-900 TWh in 2050 (see Figure 1 for the sector split). Recent studies show partly higher, and partly lower values. For example, McWilliams and Zachmann (2021) estimate a demand corridor for 2050 that lies between 295 and 2080 TWh and (Guidehouse 2020) estimate 1710 TWh. Agora Energiewende and AFRY Management Consulting (2021) estimate the hydrogen demand needed to decarbonise certain industrial sectors and identify a demand of 270 TWh, which could be considered as 'no-regret potential'. The projections for hydrogen demand in 2050 are therefore subject to high uncertainties and are strongly influenced by the scenario philosophy of the respective studies.

Figure 1 shows the estimated hydrogen demand of the studies mentioned above, differentiated by sector. It can be seen that there are huge differences between the sectors, both in absolute and relative terms. For example, the gap between the maximum and the minimum estimate for the industry sector is about 365 TWh, whereas the same gap is 830 and 560 TWh for sectors Transport and Residential respectively. In addition, in the industry sector, the four lower values are between 270 and 340 TWh; the two higher values are between 620 and 630 TWh.

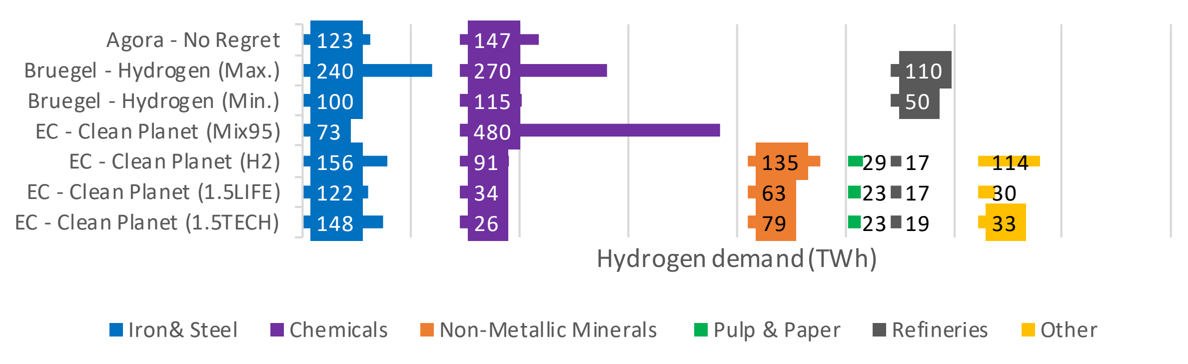
Figure 1 – Hydrogen demand for 2050 differentiated by sector in different studies



Source: Own representation based on European Commission (2018), McWilliams and Zachmann (2021), Agora Energiewende and AFRY Management Consulting (2021), Guidehouse (2020).

Figure 2 shows the estimated hydrogen demand of the studies mentioned above differentiated for industrial sectors. For the EC - Clean Planet Study, in addition to the two (1.5) scenarios listed above, the Mix95 scenario is also shown. The 1.5 scenarios were developed with the PRIMES model, Mix95 was developed with the Forecast model.

Figure 2 – Hydrogen demand for 2050 differentiated by industrial sectors in different studies



Source: Own representation based on European Commission (2018), McWilliams and Zachmann (2021), Agora Energiewende and AFRY Management Consulting (2021), Guidehouse (2020).

For the demand of the steel industry, the range between minimum and maximum estimate is the smallest; five of the seven estimated values lie in a corridor between 100 and 150 TWh. In scenario Mix95, a lower demand is estimated; a key driver for this is an increase in the recycling (EAF) route. For the chemical industry, the ranges between maximum and minimum are somewhat larger, as the values from the EC-Clean Planet 1.5 scenarios are quite low at around 30 TWh. In the case of 1.5LIFE, this is probably due to the scenario philosophy, which focuses on circular economy and lifestyle changes that reduce the demand; in 1.5TECH, it is due to the balance limit, as the electricity demand (about 100 TWh) is also used for the production of hydrogen, but is not differentiated. In Mix95, a scenario for the same target (95 % reduction) from the same study, the demand is projected to be around 480 TWh; here the chemical industry's feedstock demand is only very slightly reduced. In „Agora - No Regret', the demand is projected at around 150 TWh, which is mainly due to the fact that hydrogen demand for plastic production is also reduced there through chemical and mechanical recycling, as well as through bio-based materials and (25 %) sustainable naphtha imports. Refineries play a minor role in all three EC scenarios and none in „Agora - No Regret'; only in the Bruegel scenarios refineries still have significant shares in 2050. Other sectors, such as 'non-metallic minerals' or 'pulp & paper' are only considered in the EC scenarios. In this sector, hydrogen plays a role primarily for the provision of (high-temperature) heat.

Figure 3 shows a regional breakdown of the hydrogen demand for 2050 as estimated in the Agora-No Regret study (Agora Energiewende and AFRY Management Consulting 2021).

Figure 3 – Industrial hydrogen demand for 2050, broken down regionally

The figure shows that the focus of demand is in the Benelux countries and western Germany. Other areas with particularly high demand are in Eastern Europe, the Northern Balkans and Southern Italy. This illustrates the tension between demand and production. For example, the supply of renewable energy is particularly high in southern Spain, while the demand there is present but rather low in comparison.

Source: (Agora Energiewende and AFRY Management Consulting 2021).

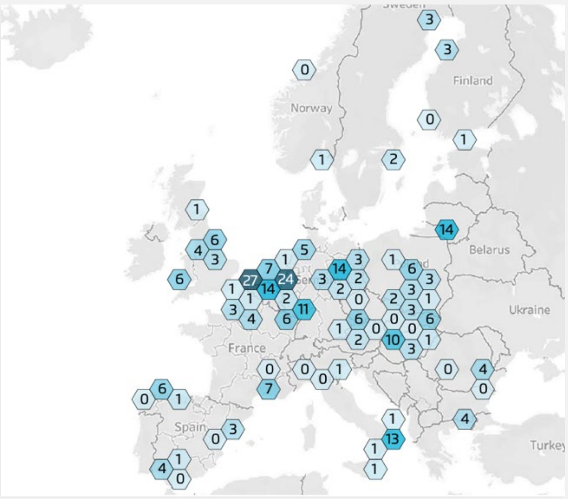
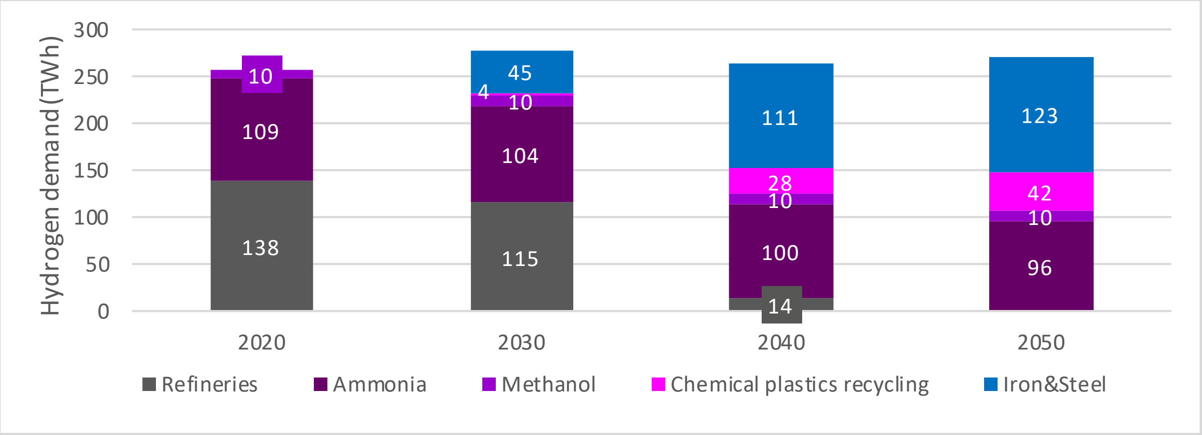


Figure 4 shows the projection of industrial hydrogen demand from study Agora - No Regret over time. It can be seen that the total demand does not increase significantly; the demand for methanol production remains constant and the demand for ammonia production falls slightly over time. Between 2020 and 2030, additional demand is built up for the chemical plastics recycling and iron and steel sectors. Between 2030 and 2040, the strongest changes take place; demand in refineries almost disappears by 2040 and is more or less compensated by an increase in demand mainly in the iron and steel sector, but also in chemical plastics recycling.

Figure 4 – Hydrogen demand over time differentiated by industrial sectors



Source: Own representation based on Agora Energiewende and AFRY Management Consulting 2021)

Quintessence from the projections

The (absolute) corridor of demand projections for hydrogen in industry is lower compared to the other sectors (cf. Figure 1). This may indicate that the studies have somewhat more consensus on the needs of industry compared to the needs of the other sectors. However, the corridors of the demand projections already differ quite significantly between the industries in some cases, e.g. for refineries. The demand projections for the iron & steel sector differ the least and, in addition, all studies estimate a significant demand for the chemical industry. Presumably, these two industrial sectors are particularly relevant for building a hydrogen ecosystem in the EU in the medium to long term. Nevertheless, choices for specific technological pathways will play a crucial role in determining how high the demand will be in 2050, but more importantly, how the demand will evolve over time. This inevitably raises the question of whether some kind of technological prioritisation (within the industry) is necessary to allocate the still scarce hydrogen volumes at the beginning of the market ramp-up.

The European Parliamentary Research Service EPRS (2021c) proposes to decarbonise existing hydrogen production first e.g., in the chemical sector, when ramping-up the market for renewable hydrogen. The Rocky Mountain Institute (2020) analysed hydrogen as a decarbonisation option for industry and considered the steel industry as a primary sector for hydrogen use, unless carbon capture and storage (CCS) is a viable and scalable technology. Agora Energiewende and AFRY Management Consulting (2021) analysed the hydrogen demand required for the decarbonisation of specific industrial sectors, which can be understood as an expected (no-regret) minimum level of hydrogen demand. For that, the industrial sectors chemicals, refineries and iron & steel are taken into account. No prioritisation is made between the industrial sectors; from the time course of the projections, it can be seen that the demand in refineries drops sharply from 2030 onwards, so that it only plays a minor role in 2040, while the demand of the other two sectors, especially the iron and steel sector, increases steadily from 2020 to 2050.

Table 2 collects estimates of hydrogen demand for various sectors and categorises them in three dimensions. It provides an overview of the order of magnitude of the estimated requirements, and represents a starting point for a hierarchisation with regard to higher-level political goals.

Table 2 – Estimation of hydrogen demand for 2050 from some studies (categorised)

Category	Definition	Sectors	Min. (TWh)	Max. (TWh)
No-regret sectors	Applications that can be decarbonised by hydrogen and otherwise only by either CCS and/or biomass. Applications that cannot be fully decarbonised through electrification.	Ammonia	96 (1)	480 (2)
		Olefins *	42+10 (1)	
		Refineries **	n.a.	n.a.
		Steel	73 (2)	123 (1)
		∑ Industry	270	570
		Aviation	0 (3)	340 (3)
		Shipping	20(3)	120 (3)
		∑ Transport	20	460
No-lock-in sectors	Applications that can in principle be decarbonised by renewable hydrogen, but also by using renewable electricity. However, it is currently unclear which of the options is the more cost-effective and whether one of the two options will prevail.	High-temperature heat	145 (2)	
		Heavy-duty vehicles	10 (3)	200 (3)
Game-changing sectors	Applications that can be decarbonised more efficiently through the use of renewable electricity. However, other factors may lead to hydrogen use here.	Passenger cars	0 (3)	200 (3)
		Space heating	0 (3)	600 (3)

*Part of basic chemistry, incl. methanol. **on the way to RES.

Sources: (1) Agora Energiewende and AFRY Management Consulting (2021), (2) European Commission (2018), Scenario Mix 95, (3) McWilliams, B. and G. Zachmann (2021).

Key messages about the future hydrogen demand in industry

The steel and basic chemicals sectors are seen in the scenarios as major consumers of hydrogen in the medium- to long-term. In the steel sector, considerable GHG reductions can already be achieved along the way through the use of natural gas. In basic chemicals, the demand is accounted for by the production of ammonia and olefins (for plastics). In ammonia production, hydrogen is already produced from fossil sources; here renewable hydrogen can therefore be used directly to reduce GHG emissions.

In olefin production, the situation is more complex. Hydrogen would be used here in combination with captured CO2 as a feedstock substitute for the (fossil) naphtha, which would require new production facilities. First, BECCS approaches might be a competitor to hydrogen routes. Second, the role of recycling of plastics, which can have a very large impact on hydrogen demand, is unclear.

In the refining sector, demand is expected to decline in the medium- to long-term as demand for fossil fuels falls. In the future, however, refineries could grow into the basic chemicals sector as methanol producers. When using renewable hydrogen in refineries, long-term strategies are therefore recommended in order to avoid sunk investments.

Key messages about the future hydrogen demand of the transport sector

In the aviation and navigation sectors, full decarbonisation via direct electrification is expected to be practically impossible in the next decades. So a need for zero-carbon fuels will remain in these sectors also in the longer term. Since the potentials of sustainable biofuels are limited, synthetic fuels produced from hydrogen can be considered a no-regret option here. The use of hydrogen in heavy-duty vehicles competes with other options such as electrification of trucks and the preferred option is not clear, suggesting that scenarios with both high and low hydrogen demand in this sector should be considered. For light-duty transport, battery-electric vehicles have clear advantages over hydrogen-fuelled vehicles, so that no substantial use of hydrogen in this sector is to be expected.

Key policy instruments for fostering a reasonable use of hydrogen in the transport sector are the Alternative Fuels Infrastructure Directive (AFID), the TEN-T Regulation as well as the provisions of the ETS Regulation on aviation and navigation. Moreover, the current Renewable Energy Directive (RED II) contains important provisions for hydrogen-based fuels to count under the renewable energy target of the transport sector. An additional option is a quota for hydrogen-based fuels, which should be focused on aviation and navigation, as long as the preferred option in the other sectors is unclear.

3.1.3. Policy gaps

The market take-up of hydrogen in industry is closely linked to the issue of decarbonisation of industry, as hydrogen is an important decarbonisation option in energy-intensive industry. To support EU industry in its decarbonisation efforts, a number of measures have already been implemented focusing on the promotion of research and pilot projects (e.g. under Horizon 2020), thus reducing barriers in the area of research and development. The first main measure to achieve the strategic goals of the hydrogen strategy was the establishment of a stakeholder networking platform, the European Clean Hydrogen Alliance. The main objective of the Alliance is to build an investment pipeline, with an estimated volume of up to €430 billion by 2030. The Alliance organises six thematic roundtables. The demand side is represented through the topics of hydrogen for mobility, residential applications and industrial processes (European Commission 2021d), (European Commission 2021g).

Further measures relate to research and development and the promotion of investments. Here, the creation of a new 'Important Project of Common European Interest (IPCEI)' for the field of hydrogen technologies is a central component (European Commission 2020e). Calls for expressions of interest to participate in the Hydrogen IPCEI have already started in the participating Member States, and the first decisions on approved Hydrogen IPCEI projects are expected towards the end of 2021. In Germany alone, a total of over 200 project outlines have been submitted, 62 of which have been selected for funding, for which a total of over 8 billion euros is available. In the field of industry, the main projects are for the hydrogen-based production of chemicals (including methanol) and steel (German Ministry for Economic Affairs and Energy 2021). In addition, the instruments Next Generation EU, InnovFin, InvestEU and the EU Innovation Fund (EU IF) are to be used for the market ramp-up of renewable hydrogen, with the EU IF in particular targeting the energy-intensive industry. Currently, more than a quarter of the projects that have entered the second stage of the two-stage selection process deal with the use or production of hydrogen (European Commission 2021f). Furthermore, the EU hydrogen strategy proclaims the development of a pilot project for a 'Carbon Contracts for Difference' programme, in particular to support low-carbon and circular production of steel and chemical raw materials.

However, there remain important barriers in the area of costs, labelling/certification and lead markets, which are addressed below.

Cost

A major barrier to the market introduction of renewable hydrogen in industry is higher costs compared to fossil fuels. This is particularly relevant for energy-intensive industries, because the share of energy costs in gross value added is higher there than in the rest of manufacturing (Fleiter 2013). For example, Bruyn et al. (2020) highlight that currently 'carbon-neutral energy is often 2 or 3 times more expensive than fossil-sourced energy'. However, they also note that even if industrial energy costs were to double, 'the carbon neutral economy would only result in price increases of 2-11 % in the most energy-intensive sectors such as refineries, cement, fertilisers and iron and steel'. Therefore, Bruyn et al. (2020) do not consider it likely that a transition to a carbon-neutral economy will wipe out the European base of energy-intensive industries, as companies have 30 years to adjust to these price increases. Thus, possible price increases from a carbon-neutral economy would be moderate, and moreover, there is a plannable and longer-term time horizon to pass on these price increases to the market, or to reduce them through economies of scale. However, the main purpose of private sector companies is to maximise profits. If the additional costs on the way to a GHG-neutral economy cannot be passed on or compensated, then this represents a serious barrier to transformation, because the industries concerned are in international competition. Commodity prices are usually indexed (e.g. on stock exchanges). Increased costs without the possibility of compensation/pass-on could thus lead to a kind of 'first-mover-disadvantage'.

Lead markets

In response to the Paris Climate Agreement adopted in 2016, numerous companies have formulated the goal of becoming GHG neutral in the coming decades, also at Scope 3 level (Mace 2020). This means that emissions from upstream supply chains will increasingly come into focus and demand for energy-intensive goods produced with low or neutral GHG emissions will have to increase in the coming decades. Lead markets can accelerate this process by creating new structures in value chains. However, these do not yet exist.

Labelling/Certification

The technical nature of products from energy-intensive industries is independent of whether the production route was GHG neutral or not (e.g. green steel is basically the same as grey steel). This makes it difficult to identify the GHG intensity of an energy-intensive product as an additional product specification. Linked to this, it becomes more difficult to pass on additional costs for low-GHG or GHG-neutral goods in the market, e.g. to develop lead markets.

3.1.4. Implications for future policy options

Costs

Policy-makers have recently become aware that higher operating costs (OPEX) are a major barrier to widespread market introduction of many low-carbon technologies in the energy-intensive industry. The EU Innovation Fund addresses this: it provides revenues from the ETS to finance low-carbon technologies in industry, while operating costs are also eligible. A similar approach can be found in the Netherlands, where the revenues from the Sustainable Energy Surcharge (ODE) are used to finance a support programme for the deployment of low-carbon technologies (SDE++). Here, the difference between the cost price of the technologies (the 'base amount') and the market value of the product the technologies deliver (the 'market price') can be funded (Anderson 2021). In Germany, a pilot programme for carbon contracts for differences (CCfDs) is currently being developed, and a first paper on key points has been published (German Ministry of the Environment, Nature Conservation and Nuclear Safety 2021). The EU hydrogen strategy also envisages a pilot programme.

Key instruments for refinancing operating cost subsidies could be CO2 prices or climate levies on end products. In the case of the CO2 price on end products, for example, a charge can be levied on the basis of the CO2 content of end products; in the case of the climate levy on end products, for example, charges can be levied by weight on selected materials (e.g. steel, plastic, aluminium, cement, etc.). A major strength of CO2 prices or climate levies on final products is that there is no carbon leakage risk, as the levy would also apply to importers, i.e. imported and domestically produced materials/products would be treated equally. A weakness of the CO2 price on end products, however, is that this instrument is hardly feasible in the long-term without product-specific (in principle global) tracking of emissions, which makes it difficult to apply in complicated value chains. The climate levy, on the other hand, could be limited to the most relevant products, which is an opportunity, as the administrative burden is minimised, but also represents a risk, because it can lead to unequal treatment of materials and thus to possibly unwanted material substitutions if the scope of the levy is set too low. For example, if steel is subject to a climate levy, but aluminium is not.

Lead markets

Currently, there are no dedicated policy instruments at EU level to create lead markets for products from energy-intensive industry with low GHG emissions. (Agora Energiewende und Wuppertal Institut 2019) investigate, among others, the following instruments for this area: sustainable public procurement, quota for low CO2 materials. In sustainable procurement, for example, countries could commit to high sustainability criteria in construction. A quota for low-carbon materials could be implemented, for example, by obliging manufacturers of consumer goods to use defined proportions of low-carbon materials. Both instruments can create secure sales markets and thus increase planning security for investments in long-lasting production facilities. In this way, the hydrogen ramp-up can be indirectly flanked, e.g. by increasing the demand for steel from hydrogen-fired DRI plants. However, a quota for low-carbon materials has weaknesses in terms of administrative burden, and there is also a risk of creating trade barriers. In addition, according to Agora Energiewende and Wuppertal Institut (2019), it could be subject to the requirements of the WTO Agreement on Technical Barriers to Trade (so-called TBT Agreement). So there is a risk of trade barriers. The strengths of sustainable procurement lie in the fact that important signals are sent to citizens and business and, in addition, there is the possibility here for policy-makers to act directly, since sustainability criteria can in principle be used in all areas of public procurement.

Key conclusions on the use of hydrogen

- There is a broad consensus that hydrogen is a technically feasible and promising decarbonisation option for industry.
- Operating cost subsidies are promising for the start of the market ramp-up of hydrogen use in industry.
- Hydrogen use and CCS (e.g. BECCS) do not have to be competitors, they can also complement each other.
- Labelling systems for energy-intensive products produced with low or zero greenhouse gas emissions help to decarbonise industry and thus indirectly support the hydrogen market ramp-up.
- From an energy system perspective, approaches can be derived with which the use of hydrogen can be hierarchised. The level at which such hierarchisation should be applied (overarching political objectives, allocation of funds, etc.) should be evaluated in greater depth (also with regard to innovation effects).

Labelling/Certification

At EU level, there are currently no specific policy instruments in this area. However, the need for action to label the footprint of energy-intensive products in order to differentiate them has already been recognised in the industry. For example, the Responsible Steel initiative has developed a voluntary system for labelling and certifying the GHG intensity of steel (cf. Responsible Steel 2021). In the building sector, there are labelling systems that use life cycle assessment approaches (e.g. DGNB certifications). However, the situation is fragmented; moreover, there are no widespread (market) standards for energy-intensive products. There is a lack of systems to (i) label the GHG intensity of energy-intensive products and (ii) translate it into specifications of downstream products. So, for example, if a vehicle manufacturer buys GHG-neutral steel: how can this be certified/documented? How can this be translated into product labelling in order to demand additional prices from end customers, etc.? Or, if a building is to be produced with low-GHG cement: how is the cement labelled, how can the labelling be transferred to the life cycle assessment of the building etc.? At this point, there is a need for action on the part of policy-makers to encourage the development of labelling systems that can be practicably used in value chains and, if necessary, to take a leading role.

3.2. Production and import of hydrogen

The EC sees in the production of renewable and low-carbon hydrogen a key priority to achieving the aims as set out in the European Green Deal and Europe's clean energy transition (European Commission 2020e). Basically, the EU intends to achieve a renewable hydrogen economy in three phases (European Commission 2020e):

- In the first phase (2020-24), the manufacturing of electrolysers for the production of renewable hydrogen, totalling 6 GW of power capacity, should be promoted. Each of the electrolysers shall reach a size of up to 100 MW, to allow a large-scale production. They should be installed close to demand centres in the EU, to reduce the investments in new infrastructures. Such a capacity would allow production of 1 million tonnes of renewable hydrogen by 2024. Furthermore, existing hydrogen plants shall be decarbonised and the take-up of hydrogen in-end use applications shall be facilitated.
- The second phase (2025-2030) refers to the ramp-up phase. In this phase, the EU aims at producing 10 million tonnes of renewable hydrogen in Europe by 2030. In order to reach such a target, 40 GW of electrolysers should be installed in the EU by 2030. To achieve this target different actions will need to be implemented and are currently discussed widely (Chatzimarkakis et al. 2021; see below). Additionally, falling prices for solar and wind energy will help to reduce the price of renewable hydrogen and thus to improve its competitiveness. This phase will also see the development of an EU-wide logistical infrastructure, establishing larger-scale storage facilities and planning a pan-European hydrogen network, possibly including the repurposing of existing gas infrastructure. Next to ramping-up the production capacities, it is likewise important to reach cost-competitiveness of renewable hydrogen.
- The third phase (2030-50) refers to the market growth phase. Renewable hydrogen will have achieved maturity while being largely used in hard-to-decarbonise sectors. In this phase, supportive schemes adopted in the previous phases should be removed. The EU hydrogen strategy does not specify the required capacity to produce renewable hydrogen in the EU, but it is expected that a quarter of the renewable electricity production in the EU might be needed.

To succeed in achieving these aims, it is necessary to clarify the framework under which such a transformation can be completed, and to provide certainty to potential investors. A clear understanding across the European Union is required on i) the hydrogen production technologies that need to be developed in Europe, and ii) what can be considered as renewable and low-carbon hydrogen (European Commission 2020e).

3.2.1. Current production patterns for fossil and renewable hydrogen and costs in the EU

In 2018 about 8.3 million tonnes (327 $\mathrm{TWh_{HHV}}$) hydrogen were required in Europe, whereas the total pure hydrogen production capacity accounts for about 9.9 million tonnes . Adding by-product hydrogen, the total capacity rises to 11.5 million tonnes . The largest producer of hydrogen is Germany, with a production capacity of 2.5 million tonnes , followed by the Netherlands (1.5 million tonnes) and Poland (1.3 million tonnes). The demand for hydrogen takes place mainly in four countries, i.e. Germany (share 22 %), the Netherlands (14 %), Poland (7 %) and Belgium (7 %) (Hydrogen Europe 2020a).

On-site hydrogen production is most common to hydrogen supply: about 7.5 million tonnes production capacity or about two thirds. The hydrogen is mainly demanded for refineries (share 45 %) and ammonia industry (34 %). The chemical industry shares about 12 %, mainly for methanol production. Emerging applications for clean energy purposes claim less than 0.1 % market share, a minuscule portion of the hydrogen market (Hydrogen Europe 2020a).

In 2018 the production of hydrogen was dominated by steam reforming of natural gas, or (less commonly) partial oxidation or autothermal reforming. The most common feedstock were fossil energy carriers, sharing about 90.6 %. The production of renewable (share less than 0.1 %) and low-carbon hydrogen (0.7 %) plays an insignificant role (Hydrogen Europe 2020a, EPRS 2021c). The rest is a mixture of different feedstock, also including renewable energies. Nevertheless, a precise assignment is not possible.

The production of renewable hydrogen commonly takes place with renewable energy via water electrolysis. Kanellopoulos and Blanco Reano (2019) estimate an electrolysis capacity of around 1 GW in the EU, which amounts to 1.6 % of total hydrogen production capacity. However, since the current electrolysers are built for industrial purposes and have to be fully dispatchable, it could be assumed that most of them are powered with the available electricity mix (Hydrogen Europe 2020a). Ramping-up renewable hydrogen capacities would need sufficient capacities to produce the required electrolysers, which are currently not available (Lambert 2020). A speedy alternative is often seen in switching from conventional carbon-intensive hydrogen production, e.g. steam-reforming of natural gas, to low-carbon hydrogen production by supplementing these sites with CCS technology. The main advantage is that a known and matured technology to produce hydrogen

Low-carbon hydrogen

The role of low-carbon hydrogen in the transformation process to a hydrogen economy is under discussion (EPRS 2021b). The principal idea of low-carbon hydrogen is to couple existing (or new) fossil-based hydrogen production sites, like steam-reforming of natural gas, with a carbon capture and storage or sequestration (CCS) facility. As an alternative carbon storage and utilisation (CCU) is also proposed. Carbon capture means separating mainly carbon dioxide from the flue gas or exhaust gas, depending on the selected technology (Markewitz and Bongartz 2015). The technology is a known technology in industry, whereas for power plants the technology is still under development (Markewitz and Bongartz 2015). The captured carbon dioxide can be stored or re-used. According to different estimation the expected provision of captured carbon would exceed the expected demand for carbon, mainly by the chemical industry (Müller et al. 2015). Therefore, a successful market penetration of low-carbon hydrogen would require sufficient and suitable storage facilities, i.e. mainly sandstones (Metz 2005; Kühn et al. 2015). Additionally appropriate transport infrastructures are needed (Bongartz et al. 2015).

The main advantage of low-carbon hydrogen is the use of a known technology to produce and to capture hydrogen. Still under investigation are the challenges to store carbon in appropriate facilities, although the technical challenges are seen to be manageable (Kühn et al. 2015). The same is understood in the case of transport (Bongartz et al. 2015). However, society's acceptance in regions with potentially suitable deposits cannot be taken for granted. Insufficient information and unclear individual or regional advantages of storage facilities "in the neighbourhood" as well as risk aversion, which could differ between rural and industrial regions, could impede the installation of storage facilities (Schumann 2015). The potential reluctance to accept storage facilities in a region could slow down a speedy installation of CCS and thus, a speedy switch to low-carbon hydrogen. The level at which such hierarchisation should be applied (overarching political objectives, allocation of funds, etc.) should be evaluated in greater depth (also with regard to innovation effects).

can be used. Carbon capture is a globally used technology (Markewitz and Bongartz 2015). The main disadvantage of CCS technology is the identification of geologically suitable and societally accepted storage sites and building up sufficient infrastructures to transport captured carbon to the deposits (Bongartz et al. 2015; Kühn et al. 2015; Schumann 2015).

The estimated costs for producing hydrogen using fossil fuels (high-carbon hydrogen) are 1.5 €/kg (38 €/MWh). This figure is the current reference for all other technologies. Under today's conditions low-carbon hydrogen costs around 2 €/kg (50 €/MWh) whereas producing renewable hydrogen under today's conditions will generate costs of around 2.5-5.5 €/kg (65–135 €/MWh) (EPRS 2021c). Thus, turning high-carbon hydrogen to low-carbon hydrogen by installing CCS technology will generate an additional cost factor of about 0.5 €/kg (12 €/MWh) or 33 %. It should be noted that in practice the costs for low-carbon hydrogen will be very location-specific, depending on the complexity of and distance to carbon storage (Lambert 2020). Consultants estimate that a 50–60€ per tonne CO2 price could make low-carbon hydrogen competitive in Europe (van Renssen 2020). Refineries may have additional potential for low-carbon hydrogen production, since the majority of CO2 emissions from refineries is caused by combustion of refinery fuel gases in process furnaces (CONCAWE 2011).

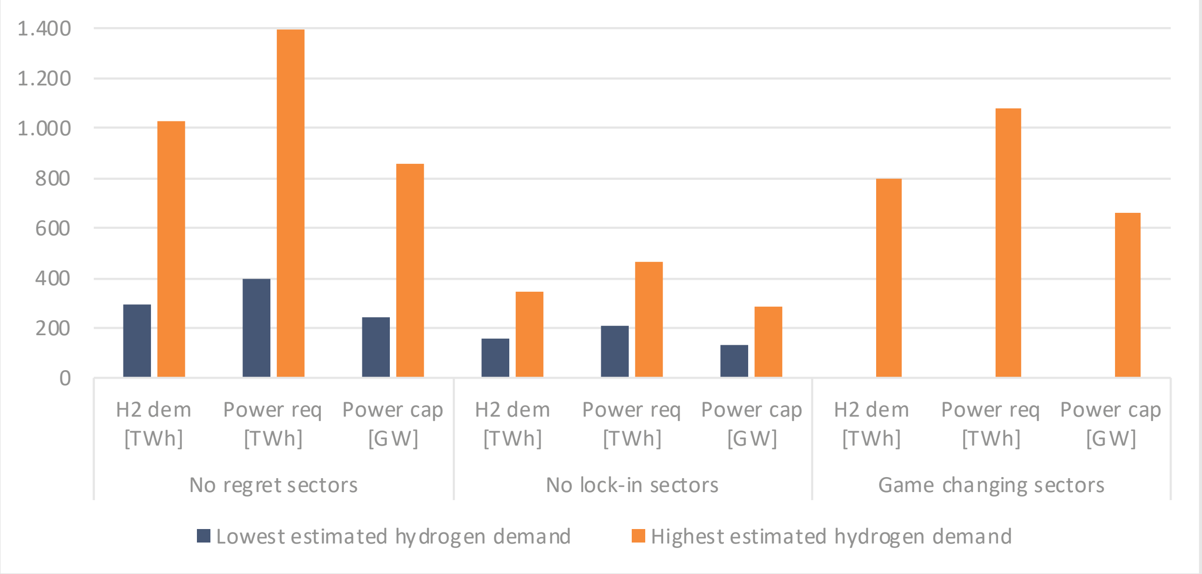
The lower end of the cost range for renewable hydrogen seems rather optimistic at present, although it may well be achievable in the longer term (Lambert 2020). Renewable hydrogen from North African solar PV is expected to cost around 2 €/kg (50 €/MWh) in 2050 (Agora Energiewende 2018). The main cost drivers for renewable hydrogen are the investment costs of electrolyser and the electricity costs. As long as the capital costs are high, to become competitive the costs for electricity have to be low (near 0 €), with a high availability rate to allow for a high share of full load hours (EPRS 2021c).

3.2.2. Projections regarding production capacities

As shown in Section 3.1.2, available studies cover a wide range of future hydrogen demand, reaching between 800 and 1,700 TWh with respect to the entire EU in 2050. Considering these different estimates, the need for renewable electricity generation only for hydrogen production will vary likewise. Assuming an average efficiency of electrolyzing of 74 % (International Energy Agency 2019) in 2050, the electricity generation requirement will vary between 1,080 TWh and 2,300 TWh. Looking at the estimated hydrogen demand of industry of about 280 TWh in 2030 (Agora Energiewende and AFRY Management Consulting 2021) and assuming an electrolyser efficiency of 69 % (International Energy Agency 2019), the additional renewable electricity requirement would amount to about 400 TWh. Since the figures give only an estimation of the entire electricity demands and capacities to satisfy the EU demand for renewable hydrogen, the figures give no indication of the share of domestically produced renewable energy. Figure 5 breaks down the electricity requirements as well as electricity capacities with respect to the hierarchy of hydrogen uses discussed in Section 3.1.2.

Following the different estimations, the no-regret sectors would demand at least 400 TWh in 2050, corresponding to an average electricity capacity of 240 GW. In case of the highest estimated hydrogen demand, the respective figures are higher by a factor of 3.6, reaching about 1,400 TWh renewable electricity and a capacity of 850 GW. According to the studies scrutinised, the demand for additional renewable electricity of the game-changing sectors ranges from 0 to 1,080 TWh and thus, the needed capacities between 0 and 660 GW, while the demand for additional renewable electricity of the no-lock-in sectors varies between about 210 and 470 TWh. Since there may be no hydrogen demand at all in the game-changing sectors, the share of the no-regret sectors could amount to up to two-thirds of the total additional renewable electricity demand and of the required generation capacities; in case of the highest estimated hydrogen demand it still amounts to almost half. Further details are provided in the Annex.

Figure 5 – Hydrogen demand, additional renewable electricity requirements and generation capacities in 2050 (split according to hierarchy from Section 3.1.2)



Notes: The estimations for power requirements assume an energy efficiency of electrolyses of 74.0 % (International Energy Agency 2019). The calculation of the power capacity assumes an electricity mix with wind onshore 47 %, wind offshore 15 % and photovoltaics 38 % (adapted from Xu et al. 2020). The assumed full-load hours are wind onshore 1,936 h/a, wind offshore 4,032 h/a, photovoltaics 903 h/a (Matthes et al. 2020).

Source: Own calculations based on Agora Energiewende and AFRY Management Consulting 2021; European Commission 2018; Matthes et al. 2020; McWilliams and Zachmann 2021; Guidehouse 2020; International Energy Agency 2019; Xu et al. 2020.

Future import of renewable and low-carbon hydrogen – estimated amounts and possible import countries

Despite the production targets of the EU, several studies conclude that the required production capacities to satisfy the expected EU demand for renewable and low-carbon hydrogen will exceed the expected production capacities (International Energy Agency 2019). That means that a notable share of demanded hydrogen has to be imported. In the 2030s, 40 GW of additional electrolysers in non-EU countries are expected to be necessary to fill the EU demand gap (European Commission 2020e). Currently, potential export regions for renewable hydrogen are seen in the Mediterranean countries of Africa and Middle East (MENA) as well as Brazil. Russia is also mentioned as a potential export country, in particular with respect to a potential export of CCS-based low-carbon hydrogen. The future position of West Australia as an export region for the EU is currently unclear (International Energy Agency 2019; Kardas 2020; van Leuuwen 2021).

In the short-term, the potential renewable hydrogen exporting regions face the same challenges as the EU, i.e. building up sufficient capacities of electrolysers and renewable electricity capacities. Additionally, reliable and appropriate transport infrastructures are needed. Furthermore, hydrogen is seen beyond the EU as an important option for the transformation of the economy, fuelling an intense competition for globally supplied renewable hydrogen and thus inciting investment into renewable hydrogen, but also enforcing the price disadvantage (Hydrogen Council and McKinsey & Company 2021; Wietschel et al. 2020; International Energy Agency 2019). Thus, in the short-term it cannot be expected that the demand for renewable hydrogen of the EU can be satisfied by imports. However, the future development of the global hydrogen market depends on a large set of competing conditions, like national policies in the main importing and exporting countries, the progress of technological development and installation of production capacities, requiring additional investigations.

With regard to the technology of imports, experts have indicated that the technological pathway is not yet clearly defined, indicating that liquid hydrogen is not the only option, and ammonia and liquid organic hydrogen are also under discussion to supply the demand for hydrogen.

3.2.3. Upcoming policies for scaling-up production

The EU has already established a broad set of supportive policy frameworks in order to foster the production of renewable and low-carbon hydrogen, although, as discussed later, some of the regulations are still contra-productive from the perspective of hydrogen production. The most important are the Renewable Energy Directive (RED) and the Emission Trading System (ETS). Additionally the Next Generation EU and the 2030 Climate Target Plan provide instruments and financial resources to accelerate the efforts of the EU towards a sustainable recovery (European Commission 2020e).

With the ETS, the EU has a market-based, technology-neutral instrument to create EU-wide incentives to develop cost-effective alternatives to fossil use in hydrogen. Almost all technologies relevant to the market and producing hydrogen which use fossil feedstock, such as steam-reforming, are covered by the ETS. However, the sectors affected will face a significant risk of carbon leakage. Consequently they receive free allocation at 100 % of benchmark levels (European Commission 2020e). In the meantime, the respective benchmark was updated (European Commission 2021e).

The goal of the Renewable Energy Directive (Directive (EU) 2018/2001 (RED II) is to establish a common framework for the promotion of energy from renewable resources by setting mandatory targets to be achieved by the Member States by 2030, regarding gross final energy consumption and fuel supplies. Although RED II does not address hydrogen directly, RED II has an important impact on the chances of success for hydrogen production. For the calculation of the mandatory targets in the transport sector, renewable hydrogen can be included, as a renewable liquid and gaseous transport fuel of non-biological origin. Importantly, these are also counted as renewable when they are used as intermediate products for the production of conventional fuels (Article 25.1 (a)). Equally important, the share of renewable electricity shall be considered to be four times its energy content when supplied to road vehicles for (Art 27.2), encouraging these types of fuels over other types of renewable fuels (e.g. biofuels and advanced biofuels) (Floristean 2019). However, it should be noted that RED II has only an indirect impact on promoting renewable hydrogen, as long as competing renewable technologies have a competitive edge.

The 2030 Climate Target Plan aims at presenting an EU-wide, economy-wide GHG emissions reduction target by 2030 compared to 1990 of at least 55 % including emissions and removals, and to preview a set of actions (European Commission 2020a). While addressing renewable hydrogen as a key priority to achieve the targets, no considerations are provided which would directly affect EU production of renewable or low-carbon hydrogen.

With the EU Recovery Plan, measures are established which could help to boost the installation of production facilities with respect to low-carbon and renewable hydrogen. The recovery plan sees two components, the Next Generation EU fund and a revised EU budget, worth a total 750 € billion and 1.100 € billion (Hydrogen Europe 2020b). Although hydrogen is not specifically addressed as a key sector for decarbonising the European economy, an impact of the recovery plan on the chances for establishing a hydrogen economy can be expected. The support programme InvestEU will focus on economically viable projects, addressing market failures and investment gaps that hamper growth, and help to reach EU policy goals. The InvestEU fund will mobilise investments through a guarantee, i.e. collateral, that will back investment projects by an implementing partner, e.g. European Investment Bank (Hydrogen Europe 2020b).

The EU Recovery Plan also sets up the Recovery and Resilience Facility. The Facility aims to 'support investments and reforms essential to a lasting recovery, to improve the economic and social resilience of Member States, and to support the green and digital transitions' (European Commission 2020c). Within that Facility, eligible hydrogen projects could receive grants and loans to overcome the impacts of the COVID-19 crisis. However, to be eligible, the facility has to be implemented in country-specific Recovery and Resilience Plans. The reinforced Just Transition Mechanism is another facility, which addresses specifically regions which would be affected by the transformation to a low carbon-economy. Low-carbon or renewable hydrogen production facilities could be eligible to receive funds.

With the launch of the European Clean Hydrogen Alliance, a forum has been established, bringing together industry, public authorities and civil society, to coordinate investments for scaling-up production and increasing demand. The hydrogen strategy has a clear focus on ensuring the appropriate priority and proper access to finance for clean hydrogen projects, mentioning the need for coherence across EU funds and EIB financing. The Alliance is expected to deliver an investment pipeline and ensure adequate policy coordination (EPRS 2021c).

The European hydrogen valleys Partnership initiative under the Commission's Smart Specialisation Platform has the objective to facilitate cooperation between European regions that want to develop production, storage, distribution and consumption of hydrogen in a geographical area (Chatzimarkakis et al. 2021). A Hydrogen Valley constitutes an integrated eco- and business system in which the production, storage, distribution and consumption of hydrogen is centralised in a geographical area (Weichenhain et al. 2021). Currently, the EU has 18 hydrogen valleys distributed in Austria (1), Denmark (1), France (3), Germany (5), Italy (1), The Netherlands (3), Romania (1), Slovakia (1) and Spain (2) (Fuel Cells and Hydrogen 2021).

Member States can collaboratively support specific innovation projects as important projects of common European interest (IPCEI), subject to the criteria defined by the European Commission. In December 2020, 22 EU Member States and Norway signed a manifesto to establish an IPCEI on hydrogen. This would be the third IPCEI, after those on microelectronics and batteries (EPRS 2021c). There is a clear potential for hydrogen IPCEIs to go beyond the practice and use all the flexibilities that the 2014 Communication offers in terms of support to transport and energy projects, coverage of 100 % of the funding gap and also in terms of operating costs eligibility (Chatzimarkakis et al. 2021).

Currently discussed, but not implemented policy instruments and regulations

As shown above, one impediment to ramping-up is the low competitiveness of low-carbon and renewable hydrogen under current conditions. In the case of low-carbon hydrogen the main increasing cost factor is the installation of CCS facilities, which will include the transport of captured CO2 to the storage sites. The competiveness of renewable hydrogen is impeded by high investment costs and the demand for low electricity costs.

From a supply side perspective different measures are currently discussed. In addition to different procurement mechanisms, direct financial support, i.e. grants, is also considered an option. One procurement option is to set a production tariff mechanism. The potential producers are guaranteed to receive a set production tariff over a fixed time period. Whether such a tariff is fixed or maybe indexed to adjust for inflation or other measures has to be clarified (Chatzimarkakis et al. 2021). The production tariff could take into account the type of hydrogen and the different starting points of Member States, in line with State aid policy. Production tariffs could guarantee bankability and an acceptable return on investment. However, a fixed production tariff would not provide price signals that reward electrolysers for the services they provide to the energy system (e.g. flexibility services, augmenting renewable production levels, reducing burden from renewable incentives).

Another option would be to provide market support schemes through competitive tenders or by auctions. In tenders and auctions the tariffs is determined through competitive tendering, but usually results in a similar contractual arrangement with the developers, as is the case for set production tariff schemes, e.g., a 25 year off-take agreement. It should be noted that the auctions have to differ between low-carbon and renewable hydrogen, if the former is also to see support. Otherwise, due to the cost advantage of low-carbon hydrogen, bids from renewable hydrogen suppliers would see no success. Also, hybrid systems, e.g., auctions for larger systems and set production tariffs for smaller systems are common.

An alternative to procurement options is direct financial support to producers of renewable and low-carbon hydrogen. The high investment and operational costs could prevent investors from investing in hydrogen production facilities. The disadvantage is increased by the expected low energy costs in potential hydrogen exporting countries. One possible arrangement could be to finance the eligible cost gap, defined as the difference between the positive and negative cash flows over the entire lifetime of the investment. This is the approach taken by the Innovation Fund. Another important example are CCfDs, which are discussed in detail in Section 3.1 and Section 5.2.2.

Together with other new emerging fuels the treatment of hydrogen within the Energy Taxation Directive (ETD) needs a revision. The ETD does not ensure the preferential tax treatment of low-carbon or renewable fuels, which could promote the competitiveness of renewable hydrogen (Jovan and Dolanc 2020), as hydrogen could also be used as a storage for electricity. The ETD states that electricity shall be taxed, when it is released for consumption. How to treat supplying electricity to hydrogen storage facilities is unclear, allowing double taxation (European Commission 2019b). In addition, a phasing out of fossil fuel subsidies, tax and levy exemptions would enforce the impact on hydrogen production (European Parliament 2021).

Policy gaps according to relevant stakeholders and scientific studies

The starting point of all considerations of most stakeholders is the large cost gap between high-carbon hydrogen production and low-carbon and renewable hydrogen, as well as the minuscule share of low-carbon and renewable hydrogen at hydrogen production. All analyses see a massive need for support by the EU and national governments.

Using the deployment of renewable energy carriers as an example, most stakeholders formulate their expectation that a comparable supply-side focussed policy could achieve the same results, e.g. a rapid decline of production costs with a considerable ramping-up of production. The support would not only ensure a required level of return on investment for private investors, but also reduces the risks of market failures. Following from this, the propensity of the investors to invest in the emerging technologies would increase considerably and thus, the volume of private capital. However, stakeholders differ in their preferences regarding the precise policy. For example, Hydrogen Europe supports direct financial grants to reduce the capital and investment costs (Chatzimarkakis et al. 2021). But also procurement options could lead the way. The massive support by the EU and the national governments should endure as long as the European hydrogen production is not competitive and the share of low-carbon hydrogen and renewable share is not noteworthy (Chatzimarkakis et al. 2021; Energy Transitions Commission 2021). The financial support for hydrogen production shall be accompanied by an appropriate carbon pricing. Such a policy would not only diminish the competitive edge of high-carbon hydrogen, but would also enforce an additional incentive on the demand side (Energy Transitions Commission 2021).

An open question is whether only renewable hydrogen production shall face massive support, or also low-carbon production, at least as long as renewable hydrogen production is not competitive. Many stakeholders assume that low-carbon hydrogen would quickly reduce the GHG footprint of hydrogen production, since the technology of carbon capture is an established technology. However, a massive installation of carbon capture technology would raise the question of how to store carbon in a safe and acceptable way for society. Therefore, some stakeholders demand that only renewable hydrogen shall experience State aid (Energy Transitions Commission 2021; Chatzimarkakis et al. 2021; EPRS 2021b).

The discussed options to enforce a substantial increase of low-carbon and renewable hydrogen production also represents the complete field in the academic discussion (Lambert 2020; Bataille 2020; Quarton and Samsatli 2021; Song et al. 2020). All the propositions leave a number of questions unanswered, particularly in the area of regulation. Implementing the policies considered above would need major changes, in particular of competitive rules and cross-border trade (Lambert 2020). A main challenge is to identify appropriate criteria on how to avoid lock-in pathways, as well as precise definitions, to identify matured hydrogen markets, which are seen as a pre-condition to reduce the required State aid (Chatzimarkakis et al. 2021; Energy Transitions Commission 2021).

3.2.4. Implications for future policy options

Ramping-up the production of renewable or low-carbon hydrogen, according to the plans of the EU, needs different policies and measures. Since the long-term aim is to establish an international competitive and sustainable hydrogen economy, and considering the high investment costs, the measures should not pre-determine an unsustainable pathway, i.e. avoid lock-in effects. Focussing only on production, two different policy approaches to promote production can be identified:

- Policies and instruments which support indirectly or directly the production of hydrogen.
- Initiatives gathering public and private actors to promote hydrogen production, like the European hydrogen valleys Partnership and the European Clean Hydrogen Alliance.

Although the focus of this section is on production, a successful ramping-up of production should not only focus on production, but be seen as a part of a value chain. The downstream perspective is mainly covered in other sections, namely

- Demand for hydrogen (see Section 3.1)
- Hydrogen infrastructure and markets (see Section 3.3)

In addition, storage capacities for captured CO2 are relevant. A pre-condition to turn high-carbon hydrogen into low-carbon hydrogen is the appropriate capture of CO2. Since the expected amount of captured CO2 will exceed the demand for utilised CO2, the excess has to be stored in appropriate sites, e.g. oil and gas reservoirs, deep saline formations, or un-minable coal beds (Metz 2005; Markewitz and Bongartz 2015).

In the upstream perspective, there is a need for sufficient availability of electrolyser capacity. The current electrolyser production capacity in Europe is well under 1 GW per year. Achieving the 2030 production goal of 40 GW requires a very rapid scale-up of electrolyser production or implies a strong reliance on imported electrolysers, most likely from China (European Commission 2020e, Lambert 2020). Moreover, there is a need for sufficient availability of low-cost renewable energies in the case of renewable hydrogen and the respective grid to transport electricity to the production site. To produce one kg hydrogen about 52 kWh electricity is necessary (International Energy Agency 2019). Using renewable electricity as a feed, production on-site of demand centres will be not possible; even nearby-site production will be the exception, as the demand centres are mostly located in densely populated areas (Hydrogen Europe 2020a), demanding reliable infrastructure to transport renewable energy to hydrogen production sites (European Parliament 2021).

One additional obstacle in hydrogen technologies is often seen in its safety. However, the fear of unsafe hydrogen addresses mainly the application of hydrogen, less in respect to producing hydrogen. Producing and handling of hydrogen at production facilities is well-known. Hydrogen is already used extensively in large-scale industrial applications despite its high flammability. Similarly, ammonia is safely produced, stored and transported globally today despite its high toxicity. Nevertheless, international standards need to be further extended for hydrogen and its derived fuels: i) to enforce minimum hydrogen leakage, which is important from both a safety and climate change perspective, and ii) to support end-use applications to facilitate the growth of hydrogen demand. Local standards and certification regimes will in addition be required if hydrogen is to be used extensively in multiple smaller-scale residential and transport applications. These regimes should provide public assurance that hydrogen can be safely deployed in all applications, which will be critical to securing high levels of social acceptance (Energy Transitions Commission 2021). In addition, quality standards and clean hydrogen standards are required, which go hand-in-hand with certification (see Section 3.3).

Key conclusions on hydrogen production and imports

- A fast ramping-up of hydrogen production in Europe would need comprehensive support by the EU and MS since renewable hydrogen is not price competitive, impeding currently any private incentives to invest.
- As a bridge technology low-carbon hydrogen seems to be promising. However, geological and infrastructural hurdles and societal concerns could hamper a quick transformation.
- The need for additional renewable electricity capacities is noteworthy, but depends on the demand for hydrogen and the competitiveness of hydrogen production in the EU.
- Probably the EU will not be able to satisfy the domestic expected demand for renewable hydrogen on its own.

3.3. Hydrogen infrastructures and markets

The EU hydrogen strategy foresees the need for a Pan-European hydrogen infrastructure in the long-term after 2030 (European Commission 2020e). In the first phase until 2024, the Strategy expects that direct transport via pipelines, or pipelines on a business-to-business level will be sufficient. In the transitional period until 2030, hydrogen networks could emerge locally and be combined to a hydrogen backbone network, enabling a more flexible connection between producers and users. The required investment in hydrogen transport, distribution and storage by 2030 is estimated to about EUR 65 billion (Fuel Cells and Hydrogen 2019).

Today, the need for transporting hydrogen in the EU is limited due to the low demand and local production. Accordingly, the European hydrogen network has a length of about 1,600 km, which is tiny compared to the pan-European gas grid of more than 3,000,000 km (EPRS 2021a), including about 250,000 km of transmission lines. The hydrogen infrastructure consists of several non-interconnected, privately run pipelines at chemical industry sites, mainly in Belgium (613 km), Germany (376 km), France (303 km) and the Netherlands (237 km). Small-scale users are served by trailers. However, the transport of hydrogen via pipeline is the cheapest option for transport distances below 1,000 km (European Commission 2020d). Given that the large-scale production of renewable and low-carbon hydrogen and its consumption are expected to be geographically distinct, a large-scale application of hydrogen will lead to a need for a substantial expansion of the European hydrogen network (Sensfuß et al. 2021). However, as described in Section 3.1, the future hydrogen demand is deeply uncertain, resulting in large uncertainties about the exact future infrastructure needs.

The current Gas Ten-Year Network Development Plan (TYNDP) does not yet consider hydrogen infrastructures but includes energy transition projects for the first time (ENTSOG 2020). It lists 44 ETR projects related to the production and use of hydrogen, with only two of them at final investment decision (FID) or advanced status. First infrastructure demonstration projects are also under development (Hydrogen Europe 2020a), in particular on repurposing of gas pipelines (MosaHyc) and on establishing a public hydrogen network open to new users and producers (GET H2 nucleus).

As described in Section 3.2, most hydrogen is currently produced on-site (two-thirds or about 7.5 million tonne production capacity) by refineries or ammonia production, mainly through steam methane reforming. Only minuscule shares are currently used for energy purposes (0.1 %). In terms of production pathways, only 0.1 % is produced as renewable hydrogen and 0.7 % as low-carbon hydrogen (classification is discussed below). A market for hydrogen per se currently therefore does not exist, particularly for hydrogen from renewable electricity. This has been reconfirmed by stakeholders. The formation and regulation of hydrogen markets - and even the need thereof - is therefore under debate among stakeholders.

A clear and harmonised definition of the product does not yet exist. As recognised as necessary by many, the EU hydrogen strategy mentions that 'a comprehensive terminology and European-wide criteria for the certification of renewable and low-carbon hydrogen' will be introduced. This is an essential prerequisite to shape the market, as it defines what will actually be traded on the market. The EU hydrogen strategy sets out different categories, summarised as follows.

- electricity based: hydrogen produced by electrolysis of water
- renewable or clean: as above, using renewable electricity
- fossil-based: fossil fuels are used as feedstock (coal or gas)
- fossil-based with carbon capture: as above, using carbon capture
- low-carbon: is the combined category of 'fossil based with carbon capture' and 'electricity-based hydrogen' with significantly reduced GHG emissions compared to conventional production

This classification can only be the starting point for detailed regulation, and the EU hydrogen strategy states that a harmonised terminology and certification criteria should be put in place for low-carbon hydrogen, also stating that this should be based on either the Renewable Energy Directive II or the existing ETS guidelines, also referencing the CertifHy project. This is discussed in more detail below.

3.3.1. Options and needs for infrastructures and regulation

European hydrogen infrastructures

One option for transporting hydrogen from producers to consumers is to blend it in the natural gas grid and separate it later if needed. However, admixtures of hydrogen can be transported in existing natural gas networks only up to 10 vol- %, which is only about 3 % with respect to the energy content. For higher concentrations, dedicated hydrogen infrastructure would be more useful than admixture to methane (European Commission 2020d). The main issue here is not the network itself, which could be adapted relatively easy, but the sensitivity of end-users. These often face strong restrictions with respect to the purity of the gas consumed, e.g. gas turbines and gas stations (Wachsmuth et al. 2019). The adaptation of all end-users to higher shares of hydrogen would be more costly and also logistically challenging. The admixture of hydrogen is thus only reasonable to ramp-up the production in an early phase, but not a viable long-term solution. The admixture of hydrogen also requires a detailed monitoring of the gas quality to avoid local excession of the threshold. Nevertheless, the option of deblending should be further explored.

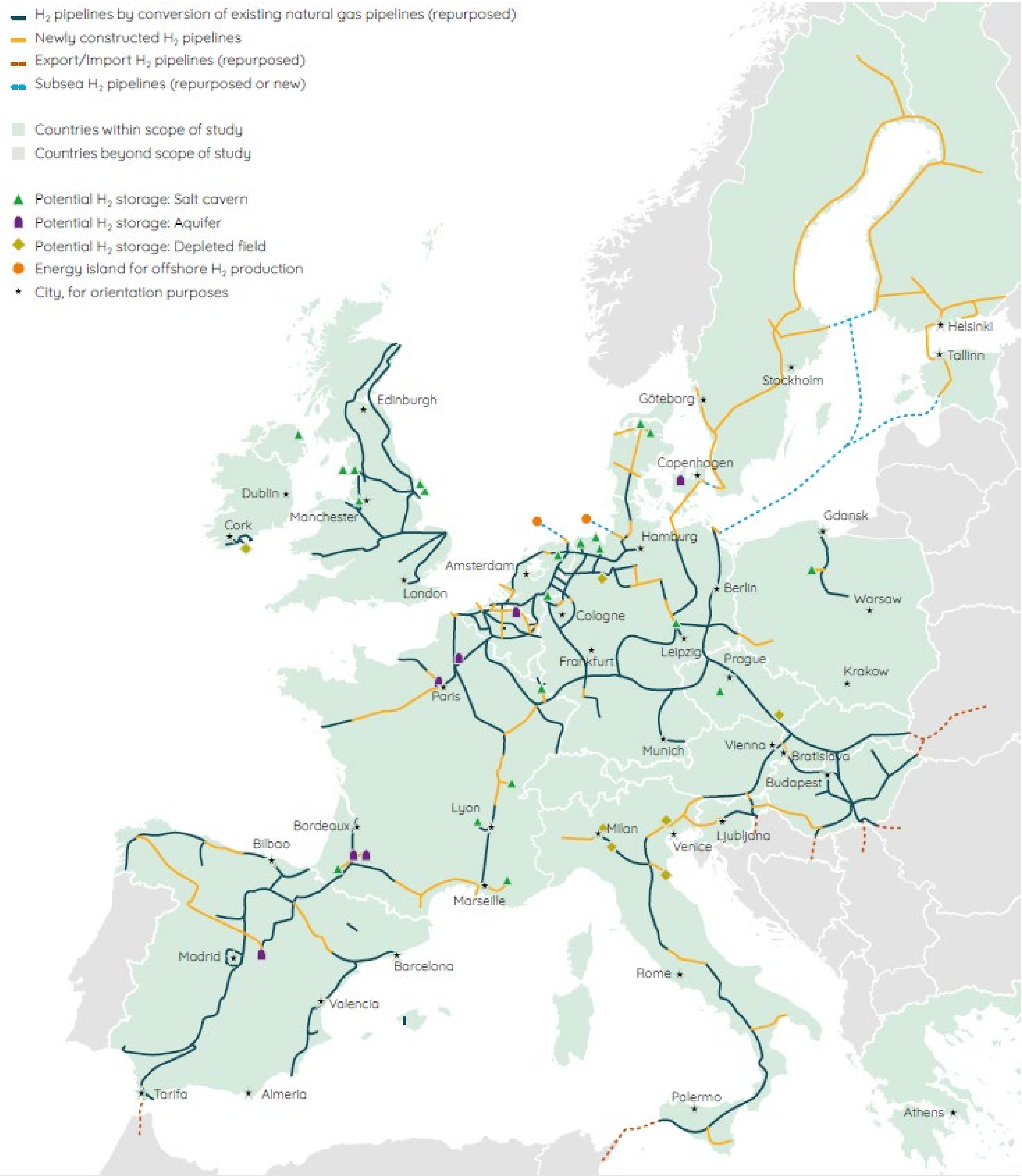
To build a hydrogen network, there are in principle the two options to build up new pipelines dedicated to hydrogen, and to repurpose parts of the existing gas grids. The required investments for repurposing can be expected to be much lower, in particular if lines are already depreciated, even though these are highly dependent on local circumstances (EPRS 2021a). The available studies also agree that the specific transport costs in repurposed gas pipelines will be lower than in newly-built hydrogen pipelines (whereever repurposing is possible), with levelised costs of transport per MWh and 600 km of 4.60 – 49.80 EUR for newly-built pipelines and of 1.26 – 3.70 EUR for retroffitted pipeline (Agora Energiewende and AFRY Management Consulting 2021).

However, repurposing only works when gas pipelines are not needed anymore. In the near future will mainly arise due to the depletion of Dutch gas fields, or when there are parallel pipelines and a decrease in the demand for natural gas makes one of the pipelines dispensable (Wang et al. 2020). While the latter case becomes more common with decarbonisation, the dynamic process is rather complex and requires detailed planning. In any case, it is clear that establishing a hydrogen backbone will require closing gaps in the repurposed network with new lines, at least to a certain extent. While the hard-to-abate industrial sectors with the largest potential for using hydrogen are mainly energy-intensive industries, only a certain share of these is directly connected to the transmission gas grids. In Germany, for instance, this applies to almost half of the industrial consumers with consumption above 100,000 MWh/a and more than half of the gas plants with capacity above 10 MW (Matthes 2021). This means that even when the focus is on energy-intensive industries, it is not sufficient to address only the transport grid; it is also necessary to consider repurposing options on the distribution grid level, which has not yet been done in a systematic manner.

Driven by major European gas TSOs, a potential design for a European Hydrogen Backbone network and its benefits was put forward by the Gas for Climate Initiative in 2020 (Wang et al. 2020). In April 2021, an update of the European Hydrogen Backbone was presented (Jens et al. 2021). While the original version described a network of 23,000 km across ten countries, the revised proposal covers 39,700 km connecting 21 European countries by 2040. About 70 % of the proposed European Hydrogen Backbone consists of repurposed gas pipelines. The 30 % newly-built pipelines mainly help to integrate countries with less developed gas grids but potentially high hydrogen supply and demand. The total required investment is estimated at 43 – 81 billion EUR, resulting in an average cost of 0.11-0.21 EUR for transporting one kilogram of hydrogen over 1,000 km. The originally proposed starting grid for 2030 covered 6,800 km of pipelines with an even higher share of repurposed pipelines (Wang et al. 2020), which has also been updated (see Figure 6 for the fully connected backbone in 2035). Deepened studies on a hydrogen backbone have been carried out by German and Dutch TSOs (Hydrogen Europe 2020a). A recent study commissioned by the German Ministry for Economic Affairs and Energy based on multi-model cost optimisation finds that a starting grid of 2,800 to 4,900 km length will be required in 2030, also mainly based on repurposing. In the longer-term until 2050, the study finds a wide range for the required hydrogen grid (2,800 to 32,600 km), mainly depending on whether or not hydrogen is also used for heating purposes.

In a recent study, Agora Energiewende and AFRY Management Consulting (2021) look at the demand for hydrogen in the mid and long term with a focus on no-regret uses of hydrogen (see Section 3.1). With respect to the infrastructure needs, the study points out that the long-term hydrogen demand across scenarios is only 20-40 % of today's gas demand, concluding that a European hydrogen network will not reach the size of the present gas grid. Moreover, the no-regret demand is even lower so that the infrastructure build-up should focus on the local clusters with highest no-regret demand until there is more clarity about future demand. The study identifies four such local clusters (in Spain, the Benelux area, Poland/Lithuania and Bulgaria/Romania). Only the Spanish and the Benelux clusters are part of the European Hydrogen Backbone, which shows that there is as yet no agreement on the required infrastructure.

Figure 6 – European Hydrogen Backbone in 2035



Source: Jens et al. (2021)

In a future large-scale trading of hydrogen between producers and end consumers, there will also be a need for sufficient large-scale hydrogen storage capacities (Agora Energiewende and AFRY Management Consulting 2021). It has been demonstrated that technically, it is possible to use depleted gas fields and salt caverns for hydrogen storage (Caglayan et al. 2020), in particular those currently used for large-scale storage of natural gas. However, no large-scale hydrogen storages are in place and their regulation with respect to economic operation as well as safety requirements are lacking. Moreover, given the uncertainty about the future volumes of hydrogen markets, the required volumes for hydrogen storage also remain largely uncertain. The levelised costs of large-scale hydrogen storage range from 6 – 104 EUR per MWh of hydrogen (EPRS 2021a)

Regulation and market rules

As noted above, there is currently no open market for hydrogen since most production takes place on-site of consumers. Depending on how the market will shape in itself and in relation to the natural gas market, it is debated how regulation should be developed over the course of time.

The EU hydrogen strategy recognises open and competitive markets as beneficial to balance differences in demand and supply between Member States. For this, the related infrastructure should be accessible to all on a non-discriminatory basis with neutral network operators, clear rules for third party access and streamlined permitting and administrative hurdles. In addition, the Strategy states that energy users should be able to make informed decisions on the energy carrier they wish to consume and whether they consume it, retaining the energy efficiency first principle and providing hydrogen to those who value it most. This speaks for clear defining criteria for hydrogen product categories as discussed below.

Current regulation in the gas market (transposed through Regulation (EC) 715/2009 and Directive 2009/73/EC) is scheduled to be revised in Q4 2021 in the so-called Hydrogen and Gas markets Decarbonisation Package. Within this package, the Directive sets out common rules for the internal market in natural gas based on the principle of free movement of goods, separating networks from production and supply, and installing independent transmission operators (unbundling). It defines the rules of authorisation, monitoring and regional cooperation for storage and transmission and distribution system operators as well as for accessing the system. The regulation further specifies rules for access. However, there is no mention of hydrogen in this regulation, which is expected in the revision Q4 of 2021. After the transition to a decarbonised and partly hydrogen-based economy, hydrogen networks will mirror the current natural gas networks, likely in smaller scale (see above). They will likely be mostly monopolistic infrastructures with high fixed costs recovered over longer time periods. Until this state is reached, the creation of local hydrogen networks in the no-regret clusters that are later integrated in a single network, is a promising option that should be explored further (European Commission 2020d).

To prepare for the transition towards a hydrogen backbone network, a secure and stable investment environment is required. This points to the need for an early regulation of the transition, either by setting out a clear roadmap of the transition or by determining today how the future market should be shaped. In this respect, private investment in new hydrogen networks can be insufficient. While gas TSOs could play an important role in establishing hydrogen networks by repurposing of existing infrastructure, decreasing revenues from natural gas transport may pose an obstacle for investment.

As a prerequisite to shaping the future market, the EU hydrogen strategy sets out a rough classification of hydrogen with renewable and low carbon hydrogen being the categories mainly under discussion for shaping future markets (see above). In parallel, there is a common colour code classification. Main categories here are often grey hydrogen - produced from fossil feedstock, mostly via steam methane reforming;[3] blue hydrogen - as grey hydrogen but with CCS; turquoise hydrogen - produced via pyrolysis of methane, which leads to carbon in solid state as by-product, and green hydrogen - produced via electrolysis of water using renewable electricity.[4]

While the colour code seems intuitive, it also does not provide the regulatory certainty to define specific product categories, as does the classification according to the EU hydrogen strategy. It states that a harmonised terminology and certification criteria should be put in place for low-carbon hydrogen, also stating that this should be based on either the revised Renewable Energy Directive (RED II) or the existing ETS guidelines. The RED II set out definitions by which renewable fuels of non-

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[3] Not to be confused with grey electricity, which is that sourced from the grid (referring to a mix of renewable and non-renewable origin) and sometimes complemented by black hydrogen as hydrogen using coal as feedstock.

[4] Pink hydrogen denotes hydrogen produced via electrolysis of water using nuclear power.

biological origin (RFNBOs) based on electricity can be counted as renewable (RFNBOs in this regard overlapping in definition with the renewable hydrogen of the hydrogen strategy). The ETS monitoring, reporting and verification guidelines could be applied as a guiding document to develop a definition of low-carbon hydrogen. As this is more general and also currently accounts for hydrogen produced from steam methane reforming, this could be used as a reference document for the definition of fossil-based hydrogen with carbon capture or other technologies, so for the more general low carbon hydrogen. The current (ETS phase 3) benchmark value for the production of hydrogen via steam methane reforming is at 8.85 tCO2/t hydrogen, while the revised benchmark for phase 4 (2021-2025) is defined at 6.84 tCO2/t hydrogen. How this will be translated into a threshold for GHG emissions for low-carbon hydrogen is currently unclear.

The hydrogen strategy also mentions the CertifHy project as a possibly reference to define life cycle GHG emissions. This project has proposed criteria for CertifHy Green hydrogen and CertifHy Low-carbon hydrogen. In order to count as low-carbon hydrogen, the CertifHy project has proposed a threshold of 60 % GHG emission savings relative to a benchmark of 91 gCO2/MJ (lower heating value, close to the fossil comparator of 94 gCO2/MJ set out in RED II for biofuels), i.e. setting a limit of 36.4 gCO2/MJ or 4,37 tCO2eq/tH2, with more specific requirements outlined in the CertifHy criteria document (CertifHy 2019a). CertifHy Green hydrogen also needs to meet this threshold, and in addition sources only renewable energy, which in turn needs to be proven by cancelling respective Guarantees of Origin for electricity gas or heat. In its second stage, CertifHy has developed the scheme and its integration with existing regulation (CertifHy 2019b). Currently, the CertifHy project is working to establish a Hydrogen Guarantee of Origin market and developing a certification scheme for RED II.

3.3.2. Overview of current and upcoming policies and plans

As the regulation of infrastructures and markets is closely related, the following paragraphs give a joint overview of respective current and upcoming policies.

- Revised TEN-E regulation and TYNDPs

At the European level, cross-border energy infrastructure planning is covered by the TEN-E regulation. When the TEN-E regulation was established in 2013, there was no need to consider hydrogen. In 2020, the Commission has published a draft of the revised TEN-E regulation (European Commission 2020f), which was publicly consulted recently. One particular objective of the revision is to cover hydrogen infrastructure and electrolysis projects, in particular enabling such initiatives to become projects of common/mutual interest (PCI/PMI). To this end, the draft regulation suggests three priority corridors for hydrogen and electrolysers, one in Western Europe, one in Eastern Europe and one in the Baltic Region, and lists potential types of projects, including hydrogen storage and pipelines, both newly-built and repurposed ones. Moreover, it defines criteria for an assessment, including the energy efficiency first principle, sustainability requirements and size thresholds. According to the draft of the revised TEN-E regulation (European Commission 2020f), the TYNDP 2022 will need to also cover the hydrogen infrastructure and storage planning. For a project to become a hydrogen PCIs/PMIs, it needs to be part of the TYNDP before. As hydrogen infrastructure projects will be part of the TYNDP 2022 for the first time, the first such projects will not enter the PCI/PMI list before 2024.

By end of 2023, the draft revision of the TEN-E Regulation also requires the European Networks of Transmission System Operators ENTSOE and ENTSOG to come up with an integrated infrastructure planning for electricity, gas and hydrogen. This is meant to make sure that there is sufficient harmonisation between the different infrastructure plants. This seems to be imperative, given that the build-up of the hydrogen infrastructure needs to be adjusted to the repurposing of gas infrastructures, and there is a trade-off between producing hydrogen close to renewable electricity sites transporting the hydrogen to end-users, and producing hydrogen at end-user sites transporting the electricity. Nevertheless, the current TYNDPs for electricity and gas grids are based on modelling of the individual infrastructures and thus cannot take into the mutual interdependencies.

- TEN-T and AFID to the extent relevant for industry

The Trans-European Transport Network (TEN-T, based on Regulation 1315/2013) sets out the regulations defining this infrastructure. The Alternative Fuels Infrastructure Directive (AFID, European Parliament 2014) sets out regulations for the infrastructure required to deploy alternative fuels. Among others, hydrogen is defined as an alternative fuel. It is concerned solely with refuelling stations for the transport sector and has limited direct influence on other sectors. It defines standards for refuelling stations and obliges Member States to set up an appropriate number of hydrogen refuelling stations, if they decide to include hydrogen refuelling in their national policy frameworks. The report of the Commission on the AFID (European Commission 2021c) summarises that registration rates of hydrogen fuelled vehicles have remained low, with higher shares in buses and trucks as an emerging field of application. There are currently (2020) 125 hydrogen stations in operation, with 600 in current plans by Member States. However, some currently do not plan any infrastructure, which would lead to low connectivity (European Commission 2021c). This has also been highlighted by the briefing to the European Parliament (EPRS 2020a), which points out that similar concerns have been raised by car manufacturers. A revision of the AFID is planned as part of the FIt-for-55 package in 2021.

- Expectations for the Hydrogen and Gas markets Decarbonisation Package

Currently, there are no commodity markets for hydrogen and thus no regulation which deals explicitly with hydrogen. Accordingly, the current gas market regulatory package (Directive 2009/73/EC and Regulation (EC) No 715/2009) already in its title carries forward the focus on natural gas as a regulated commodity. The legislation is foreseen to be revised as 'the Hydrogen and Gas markets Decarbonisation Package' (indicated for Q4 2021) to better reflect a changing and diversifying gas market (European Commission 2021a). This regulation shall in the future also accommodate for hydrogen, but also other decarbonised gases, such as biomethane and synthetic methane. It will be necessary to partly repurpose the existing natural gas infrastructure. The current regulation does not foresee distributed production and injection facilities or changing gas quality. The revision will regulate a diversification of market participant roles, such as the question whether TSOs are allowed to undertake hydrogen electrolysis, or the role of local communities of production and consumption. Consumer rights will also be more adequately addressed. The upcoming revision will also address imports and storage aspects. Also, the future integration of different energy markets requires that networks are jointly planned. The topic is described as one that cannot be efficiently addressed by individual Member States, so an approach ensures that the EU targets are tackled in a consistent manner, which avoids the costs of ex-post harmonisation (European Commission 2021a).

- Renewable Energy Directive II (RED II) and related Delegated Acts

An amendment of the RED II (Directive (EU) 2018/2001) is planned as part of the Fit-for-55 package in July 2021. Possibly more important for the definition of hydrogen classes are the Delegated Acts defining in detail the conditions under which electricity for the production of renewable fuels of non-biological origin (RFNBOs, among which hydrogen) can be counted as fully renewable, and which GHG thresholds shall apply. These Delegated Acts are scheduled for the end of 2021. RED II sets out these requirements for fuels to be defined as renewable for the transport sector, but this is one of the reference documents cited by the EU hydrogen strategy to be used a basis for a more general definition of clean hydrogen. As implied by the energy source, the RED II DA will only be able to cover renewable hydrogen in the sense of the hydrogen strategy, so low carbon hydrogen will need to be defined by referencing a different document (e.g. the ETS guidelines or through the CertifHy project, as discussed above).

RED II sets out three ways to define RFNBOs. If the installation is connected to the grid, it may claim renewable energy content to the percentage of renewable electricity, as long as the GHG emissions savings criterion of at least 70 % savings relative to the fossil fuel comparator is met. The exact value of this fossil comparator will be defined by the delegated act for GHG emissions of RFNBO expected at the end of 2021. In case the installation producing RFNBOs is connected directly to a generator of renewable electricity, it may claim 100 % renewable energy content if the installation generating the electricity comes into operation after or at the time of the installation producing the RFNBO, and proof can be delivered that the electricity used for producing the RFNBO has been sourced exclusively from this installation (RED II Art. 27.3). The third, most general case, defines criteria under which the RFNBO can be seen as 100 % renewable even if the electricity is sourced from the grid, and sets out respective criteria. Renewable electricity must be used exclusively and claimed only once (RED II Art. 27.3) with Recital 90 specifying that in addition, a temporal and a geographical correlation with the electricity producer must be assured, and that 'there should be an element of additionality, meaning that the fuel producer is adding to the renewable deployment or to the financing of renewable energy (RED II Recital 90). In sum, these requirements are stricter than those put forward under the CertifHy project. The Delegated Acts related to these criteria will bring clarity to the definition of RFNBOs under RED II and whether they can be aligned or merged with the provisions under CertifHy.

3.3.3. Policy gaps in infrastructure and market development

The academic literature identifies important gaps in the current legislation with regard to hydrogen. According to a study by Oeko Institute for the German think-tank Stiftung Klimaneutralität (Matthes 2021), there are several gaps in the current policies on hydrogen infrastructures. First, the usual administrative procedures for commissioning of large-scale energy infrastructure projects take several years. This poses the risk that a hydrogen backbone grid cannot be realised sufficiently fast. So there is a need to accelerate the commissioning processes. Second, given that there is currently no established regulation regime for hydrogen infrastructure, there is also a need for a separate financing mechanism that targets so-called no-regret hydrogen pipelines, that is hydrogen pipelines that appear useful in any future pathway consistent with the EU climate targets. Third, the unbundling principle requires that there is no cross-financing between hydrogen and gas networks. However, the repurposing of gas pipelines entails financial impacts from one or the other infrastructure for the owner of the pipeline. Therefore, the repurposing of pipelines calls for additional provisions clarifying how to deal with such cases. According to the Gas Roadmap of the German Environment Agency (Wachsmuth et al. 2019), the current regulation allows gas grid operators to stop supplying gas to customers, when they can prove the supply is no longer economically viable. A repurposing of gas pipelines to hydrogen on the distribution grid level may then result in left-over gas users with the need for a different kind of supply. There is a need to regulate if and how such customers will need to be supplied.

Some positions state that blending in existing natural gas networks should be an option (ENTSOG 2021), while others highlight the need for purity (VIK 2021) or the advantages of local, network independent production and supply altogether (WindEurope 2021). Blending of hydrogen into the gas grids is seen an option for the early ramp-up phase, which should be considered carefully given the restrictions at the end-user applications.

A screening of positions regarding the revision of the TEN-E and the gas market package reveals no principle opposition to adjusting this regulation. The EUP mainly welcomes the proposals by the Commission on the regulation of hydrogen infrastructure, in particular the corresponding provisions in the draft revisions of TEN-E regulation and the TYNDP. In addition, it points out the need for gas infrastructure regulation to ensure that all new gas infrastructure is hydrogen-ready and that there is clear guidance on the ownership of new and repurposed pipelines. In particular, the unbundling principle should apply to avoid unnecessary costs for end-users. The role of network operators, storage facility operators and producers need to be clearly defined, which is expected with the gas market package.

The association of TSOs, ENTSOG, expects that the future hydrogen market will replicate the basic attributes of the current natural gas market, i.e. a natural monopoly in the sense that it requires networks used by many to be controlled for the purpose of transportation in a non-discriminatory manner (ENTSOG 2021). The paper stresses the similarity in markets between natural gas and hydrogen, excluding an initial period which serves to set up the market rules for hydrogen. ACER and CEER on the other hand, have published a joint white paper, which highlights the need for a gradual approach to the rollout of hydrogen networks and also regulation (ACER / CEER 2021). They warn that future demand is still uncertain so that a large-scale infrastructure rollout should be avoided, until the future use of hydrogen in an integrated energy system becomes clearer. ACER and CEER therefore suggest it is too early to intervene, but only to clarify the main principles of future regulation of hydrogen networks, to provide investment security. In particular, such a regulation should make sure that there is no double financing and avoid risks of stranded assets resulting in higher consumer prices. Meanwhile, it is deemed useful that national TSOs already identify existing gas infrastructure for potential repurposing to hydrogen.

With regards to hydrogen markets, the EU hydrogen strategy mainly references the hydrogen and gas market decarbonisation package (European Commission 2021a), emphasising the need for a liquid market open to all participants. It envisions that prices reflect production and carbon costs and external costs and benefits. While this points towards an alignment of natural gas and hydrogen markets, the details of the policy package are still open. While the final status of a liquid hydrogen market is recognised as a value by most parties, the pathway and timeline towards reaching this goal are debated. ENTSOG pushes towards a rapid adoption of natural gas markets rules, arguing that the market will mirror the natural gas market and stating that early harmonisation will avoid a costly readjustment of regulation at a later point in time. ACER/CEER on the other hand argue for a gradual approach to the market regulation as the scope and size of the market are not well-defined currently. The two approaches also lead to differences in the financing of infrastructures. While ENTSOG consequently argue to mutualise costs with natural gas network costs (expecting at least partially overlapping customers), ACER/CEER argue against this, proposing to distribute costs among a larger group. Certainty in regulation will also influence the risk perceived by investors, transposed into higher risk premiums.

Hydrogen Europe, the European hydrogen association comprising more than 260 companies and the 27 national hydrogen associations, published a position paper on hydrogen infrastructure and markets, called 'A Hydrogen Act' (Chatzimarkakis et al. 2021). Overall, they argue that regulation related to hydrogen is currently spread across various regulations, posing an obstacle for a coherent framework. Therefore, they argue that there is a need for dedicated regulations on hydrogen infrastructures and hydrogen markets. With respect to a hydrogen infrastructure, Hydrogen Europe calls for a distinct legal framework, which respects the principles of unbundling, third-party access and transparency for consumers. Moreover, they argue strongly for an early build-up of a European hydrogen backbone infrastructure based on the expected large-scale demand from the steel sector and higher cost efficiency of centralised production. Hydrogen Europe also promotes support for local hydrogen valleys in the conversion of regional gas grids to hydrogen as a test bed for connecting all kinds of end-users. With respect to hydrogen markets, Hydrogen Europe expects that continental and intercontinental markets will emerge, building on the existing natural gas market. The kick-start phase sees the need for support policies beyond CAPEX support, proposing to exempt hydrogen applications from eligibility thresholds in State aid guidelines. The ramp-up phase could be characterised by a combination of tariffs and auctions, the former possibly linked to the carbon price via carbon contracts for difference. The paper in addition proposes to set quotas, particularly for ammonia, steel and gas supply. In the market growth phase after 2035, hydrogen is seen to become competitive and support can be reduced to certification. This is proposed to be implemented through Guarantees of Origin (GOs), building on the work of the CertifHy project, with GOs ultimately traded on an emissions trading marketplace.

One recurring issue among replies to the gas market package is the need for a harmonised and transparent nomenclature relying on the CO_2 footprint. The resolution of the EU Parliament (European Parliament 2021) emphasises that a clear classification 'is of utmost importance'. The resolution stresses that this classification should serve to certify and track hydrogen in the EU, taking into account the GHG footprint throughout the value chain, including transport. It should serve to inform consumers of the type of hydrogen, setting out 'a regulatory framework for hydrogen that ensures standardisation, certification, guarantees of origin, labelling and tradability across Member States.' The report of the ITRE committee highlights a need for further clarification in this respect (Geier 2020). In line with other actors, Hydrogen Europe proposes introducing a clear definition of clean hydrogen based on the associated GHG reduction along the entire value chain (Chatzimarkakis et al. 2021). They favour an approach with increasing requirements, starting with a relatively high threshold as proposed by CertifHy (4.37 tCO2eq/tH2). Guarantees of origin are often mentioned as the prime option to certify hydrogen (CEER 2021; ENTSOG 2021; WindEurope 2021; SolarPower Europe 2021; International Association of Oil & Gas Producers 2021), while details with regards to technologies to be certified differ among stakeholders.

3.3.4. Implications for future policy options

The EU hydrogen strategy has sketched a stepwise approach to the creation of a European hydrogen network, from bilateral pipelines over local networks to a hydrogen backbone, which can be extended further. The establishment of a backbone hydrogen infrastructure connecting main demand and supply regions can be expected to be the crucial step to enable a rollout of hydrogen to the most important uses. Accordingly, the actors from the hydrogen and gas sectors push for an early and far-reaching realisation, while the regulators are more cautious. Evidence from scientific studies is not clear about the necessary timing and extent, but points out that the long-term planning processes require early action, if a hydrogen backbone is to be realised by 2030. This means that the necessary provisions need to be established very soon, while still leaving the option to navigate the rollout. The most promising option seems to be given by starting with a few regionally-focused test cases. Different approaches to regulation based on the same overarching principles could be applied for an *a priori* limited timeframe and compared afterwards. This kind of explorative regulation based on experimentation clauses has proven helpful in the regulation of smart grids, for instance in Germany.

While the recitals to the draft TEN-E revision mention the important role of repurposing gas pipelines to hydrogen transport, this is not yet fully reflected in the provisions. The provisions on the scenarios for TYNPDs could point to considering the need to identify suitable gas pipelines for repurposing. Moreover, the provision on infrastructure gaps could also address the decommissioning of redundant gas, when gas demand decreases. The cost-benefit analyses in the TYNDPs could then compare decommissioning of gas grids with their repurposing to the transport of hydrogen. Furthermore, there will be substantial delay in establishing hydrogen PCI/PMIs based on the current draft revision, in particular for hydrogen infrastructures, as the current TYNDP covers only supply and demand projects. Here, a first list of infrastructure PCIs might be established earlier by carrying out a cost-benefit analysis separate to the TYNDP. It is very important to start the planning process early enough. Therefore, national TSOs should be obliged to assess the domestic need for hydrogen infrastructures as soon as regulatory updates allow, and also to identify gas pipelines that can be repurposed in a dynamic perspective, i.e. providing a schedule for potential repurposing to hydrogen based on expected future gas demand. Moreover, all energy carriers and related networks require a joint planning to determine overall optimal pathways as soon as possible.

Given the current lack of hydrogen markets and large-scale networks and the regulatory principle of minimal intervention, there is no urgent need for their regulation. However, the expected benefits of a hydrogen backbone infrastructure call for establishing at least the general principles already in the hydrogen and gas market decarbonisation package, in order to avoid a later need for the harmonisation of regulations. Such main principles include free access to third parties and overarching principles for renumeration. The renumeration of gas grids differs in certain regards in the Member States today. So there is room for experimentation here, for instance with respect to splitting the funding between producers, consumers and the public. Once the network achieves a sufficient load factor, the specific transport costs will be small compared to the production costs of hydrogen. However, hydrogen projects will require large upfront investments with uncertain revenues. Not all gas grid users will benefit from a hydrogen network, while new actors may benefit from it. This speaks against a mutual funding of the hydrogen grid by the gas grid users. The expected need for hydrogen in decarbonisation and the benefits of a hydrogen network speak in favour of public support for the establishing a European Hydrogen Backbone. Whether to spend public money or not should be based on an individual cost-benefit analysis, as is common practice in the identification of PCIs and PMIs.

The criteria for renewable and low-carbon hydrogen are not yet defined, while this is a prerequisite for a liquid market of hydrogen. The Delegated Acts following from RED II will determine rules to ensure renewable energy content of RFNBOs, while the CertifHy project is going for less strict norms and thresholds. The definition of criteria for RFNBOs in the transport sector may be transposed also to other applications and it will then need to be assured that these are operationalised in a way similar to the proposal put forward by CertifHy. This conflict will need to be resolved to build a market of renewable hydrogen, while the definition of low-carbon hydrogen will require a different basis. In this regard, experts have raised the need for a checklist of key sustainability assessment criteria as part of a certification system, and a monitoring framework, for instance fugitive methane emissions for low-carbon hydrogen. This extends to imports of hydrogen from outside the EU, where the detailed regulations put forward here may not apply.

Key conclusions on hydrogen infrastructures and markets

- Hydrogen demand and production can be expected not to be strongly dispersed but to be clustered in certain regions in the EU.
- There will be regions with mainly only demand and mainly only production.
- The interconnection of local clusters and the integration of large-scale storage will provide strong benefits with respect to market formation and security of supply, while the best network topology remains uncertain.
- There are strong arguments to create a European Hydrogen Backbone in an iterative and adaptive manner, meaning that its exact shape should not be defined today but be based on emerging needs.
- First corridors need to be established in the coming years to avoid a delayed expansion. The first infrastructure IPCEI can already be used today to identify priority areas for first regional grids.

3.4. EU in international perspective

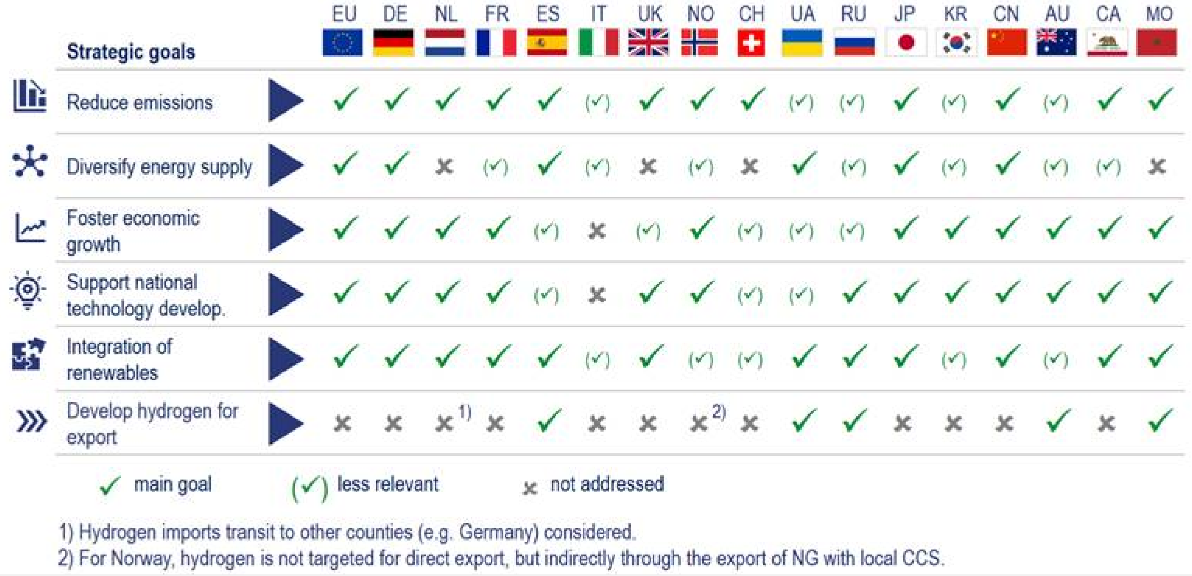
Beyond the primary sustainability and climate targets imposed on itself, the EU strives for technological and industrial leadership (European Commission (EC) 11/25/2020) including hydrogen technologies for a variety of reasons: These include technology sovereignty, maintaining and expanding value creation and employment opportunities, securing access to and strong positions in future markets, but also increasing the ability to promote climate neutral technologies in partnerships with third parties. The EU laid out its hydrogen strategy (European Commission 2020e), which is promoted by numerous policies such as dedicated research and development funding within the Horizon Europe framework programme, dedicated infrastructure planning (CEF/TEN), or strategic structural (EFRE etc.) and innovation (EU Innovation Fund) funding. Beyond that, the EU designated hydrogen technology among areas for Important Projects of Common European Interest (IPCEI) (European Commission 2019c). This mechanism aims to overcome market failures in the industrial ramp-up of novel technologies by enabling Member States to compensate initially higher costs. Once a field has been designated for an IPCEI, interested Member States (a) initiate a public call for interest and (b) form national consortia, before (c) the national auth0rities aggregate those to an EU-wide application for (d) its final examination and approval by the EU Commission (DG Comp) as basis for individual State aid approvals for industrial beneficiaries. The initial implementation (on semiconductors) faced criticism for the duration of its approval process, which was shortened from two to one year for battery IPCEIs. The initial hydrogen IPCEI process recently entered phase (c).

In this section, we introduce and discuss the status and prospects of the EU regarding key areas of hydrogen technology (as defined in sections 2.1 through 2.3 above) in comparison to international partners and competitors (International Energy Agency 2019). This identifies particular strengths and weaknesses of EU industries and applied research at present and enables an analysis of technological opportunities for EU industry to claim its share in the emerging global hydrogen technology markets, as well as technological threats such as potential gaps in future value chains or lack in key competencies. In this light, we discuss strategic technology development (European Commission (EC) 11/25/2020) and investment requirements necessary to secure the technological sovereignty of the EU within the future global hydrogen economy and the continuous success of its industries on global markets.

The general field of hydrogen technologies covers the entire chain of hydrogen generation, over its distribution and storage, to its final utilisation in various sectors including mobility, grid scale, and industrial use. Here, the EU acts in the context of international partners and competitors that may strive for similar goals or may hold traditionally strong positions in certain technological aspects in the emerging field of hydrogen technologies. A full global comparison of particular national policies for hydrogen technology development policies is beyond the scope of the present study and may produce misleading results, since strategies and policies of key actors may not be public in the first place, or hardly accessible due to language barriers. However, Figure 7 shows a comparison between published general hydrogen strategies of 16 nations, most of which explicitly include support for national technology development among their priorities.

Even if full and even access was achievable, the efficiency and efficacy of international policy mixes might be hard to predict. In contrast, we rely on transnational patent analyses as a robust measure to compare past technological trajectories and assess the present technological status of the EU within an international comparison. While patenting activity is often seen as an indicator of commercialisation of technologies, alternate motivations exist and vary widely between countries, as do hurdles to and benefits of patents. In contrast, transnational patent applications require more substantial efforts, and thus clearly indicate commercial utilisation interests in multiple markets, forming a far more valid foundation for international comparison.

Figure 7 – A comparison of national hydrogen strategies



Strategic goals	EU	DE	NL	FR	ES	IT	UK	NO	CH	UA	RU	JP	KR	CN	AU	CA	MO
Reduce emissions	✓	✓	✓	✓	✓	(✓)	✓	✓	✓	(✓)	(✓)	✓	(✓)	✓	(✓)	✓	✓
Diversify energy supply	✓	✓	✗	(✓)	✓	(✓)	✗	(✓)	✗	✓	(✓)	✓	(✓)	✓	(✓)	(✓)	✗
Foster economic growth	✓	✓	✓	✓	(✓)	✗	(✓)	✓	(✓)	(✓)	(✓)	✓	✓	✓	✓	✓	✓
Support national technology develop.	✓	✓	✓	✓	(✓)	✗	✓	✓	(✓)	(✓)	✓	✓	✓	✓	✓	✓	✓
Integration of renewables	✓	✓	✓	✓	✓	(✓)	✓	(✓)	(✓)	✓	✓	✓	(✓)	✓	(✓)	✓	✓
Develop hydrogen for export	✗	✗	✗ 1)	✗	✓	✗	✗	✗ 2)	✗	✓	✓	✗	✗	✗	✓	✗	✓

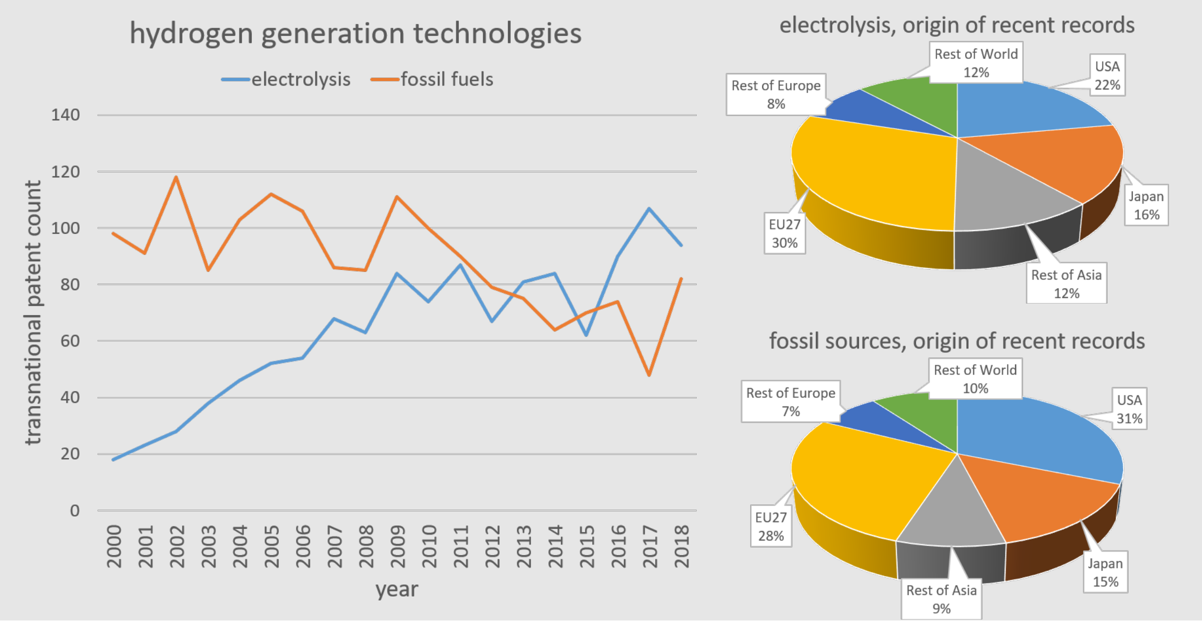
✓ main goal (✓) less relevant ✗ not addressed

1) Hydrogen imports transit to other counties (e.g. Germany) considered.
2) For Norway, hydrogen is not targeted for direct export, but indirectly through the export of NG with local CCS.

Source: World Energy Council: International Hydrogen Strategies. (2020)

Hence, transnational patent activities serve as a robust indicator of current technological strengths in a given field independent of potentially biased third-party judgements (International Energy Agency 2019, Guidehouse 2020). Temporal trends foreshadow the perceived development of its economic relevance in the future, but also may trace the effects of past policy objectives and preferences attributed to that field. With regard to sustainable hydrogen technologies, generation techniques play a specific key role, as evidenced by the data in Figure 8. An established hydrogen economy continues to exist to support traditional industrial hydrogen demands, particularly in the chemical industry (e.g. ammonia generation for artificial fertilisers or hydrocracking in refineries).

Figure 8 – Transnational patent analysis comparing traditional hydrogen generation technologies based on fossil fuels with electrolysis



Source: Fraunhofer ISI, own research.

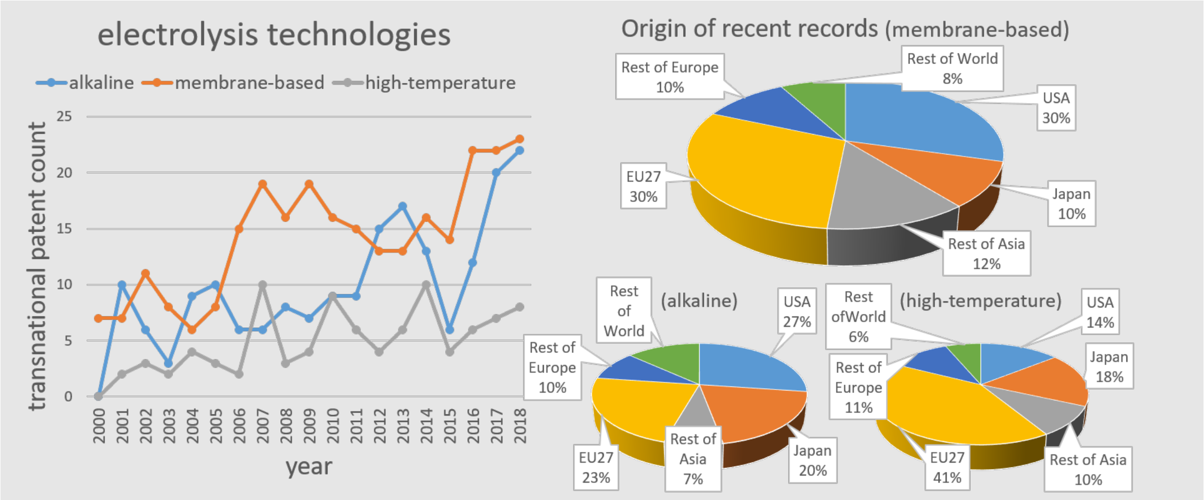
A substantial number of new transnational patents still covers the conversion of fossil resources (including coal, oil, natural gas; the latter being the dominant source) into hydrogen supply streams. In principle, electrolysis promises a pathway towards a more sustainable hydrogen economy, evading the direct utilisation of fossil fuels in the generation process and supporting its decarbonisation when driven by a renewable electricity supply. Figure 8 shows a substantial increase in electrolysis-related patenting activity over the past two decades, but still only roughly at a level with fossil-driven generation techniques (such as coal gasification or steam reforming of oil or natural gas). The remainder of substantial technology development in the latter field evidences the continuous relevance of the established hydrogen economy (limited industrial use cases, local generation, no major decarbonisation trend yet). Only a subtle decline of fossil hydrogen generation technology occurred over the past decade, which may indicate a slow shift of priorities towards renewable resources.

The latest data points likely only represent statistical noise, but a potential reversal of that trend may need to be considered as well. Rising political and societal interest in hydrogen technology as a means of decarbonisation counterintuitively may also substantially increase economic interest in fossil-based generation techniques, with at least questionable motivations and a potential for detrimental side-effects. Legitimate interest in establishing bridge technologies (such as CCS) prior to abundant availability of renewable resources may be hardly distinguishable from green-washing and strategic lobbyism driven to leverage existent technology portfolios and protect present capital investments. In the worst case, path dependencies may effectively delay the overall transformation process, or simply globally shift emissions (by import of fossil-generated hydrogen, or by preferential export of green hydrogen).

Fortunately, technology development and diffusion policy of the EU may impact the overall global development. Figure 8 shows that almost a third of all transnational patents covering electrolytical hydrogen generation in the past decade stem from actors based within the EU, turning it to the global leader of the field, followed by the USA and Japan. This strength not only creates an opportunity for technology leadership and economic growth in the field, but also a responsibility to scale its application to enable cost-effective supply on a global scale (including fair licensing policies as a decarbonisation incentive for developing economies). However, EU actors also filed a substantial number of patents for fossil-based hydrogen generation techniques (only second to the USA), which provides some leverage to enforce their responsible utilisation (in case relevant measures and policies were developed). Note that alternative hydrogen generation techniques such as direct photo-electrochemical water-splitting (driven by sunlight), or thermo-chemical water splitting cycles (potentially driven by nuclear heat) largely remain research visions with rather low expected impact for the foreseeable future (up to mid-term scale), as evidenced by only minute transnational patenting activity in these fields.

Hence, we can identify electrolysis as the key enabling technology for the transition to a sustainable hydrogen economy for the foreseeable future. Here, we can distinguish three major technological strains (as shown in Figure 9): Traditional alkaline electrolysis, membrane-enhanced techniques (i.e. proton/anion exchange membrane, PEM/AEM) as well as high-temperature electrolysis enabled by solid oxides.

Figure 9 – Transnational patent analysis comparing major electrolysis technologies

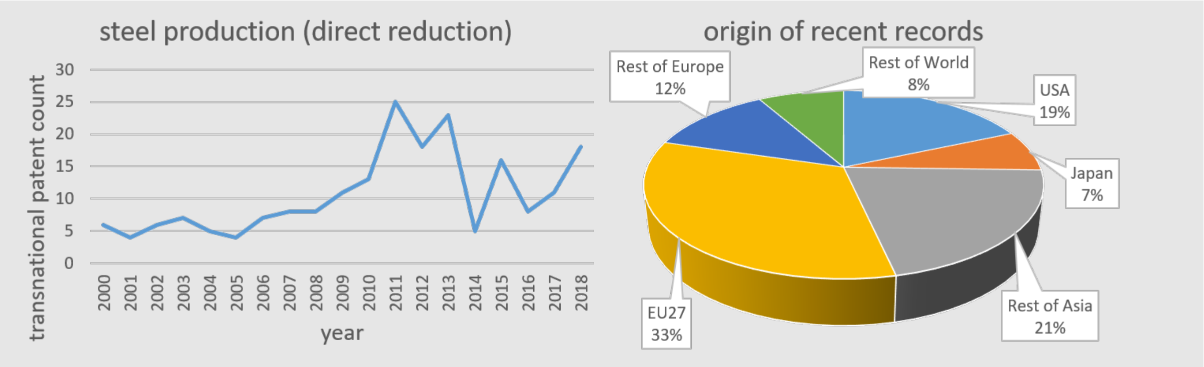


Source: Fraunhofer ISI, own research.

Figure 9 differentiates transnational patenting activity between the major fields of electrolysis technologies. It clearly shows that initial rise of interest in electrolysis in the second half of the 2000s decade can mostly be attributed to the emerging membrane-based electrolyser technologies (combining PEM and AEM). The associated patenting activity slightly dropped in the following years, but consistently marked new peak levels most recently. In contrast to the earlier phase, activities in all electrolysis technologies increased over the last years. In particular, renewed interest in enhancing the established alkaline electrolysis technology (as evidenced by transnational patents in that field) confirm the growing economic importance of renewable hydrogen generation. In a global context, EU actors particularly excel in advanced electrolysis technologies. While they filed roughly a quarter of recent transnational patents (comparable to both the USA and Japan) in the established alkaline field, they account for nearly a third among the membrane-based sector (at level with the USA). In contrast, high-temperature electrolysers based on solid oxides still only represent a small but growing niche technology, which is largely dominated by European actors.

In contrast to the above, technologies for hydrogen transport and storage may be less distinct or specific, rendering according patent analyses less precise. Please refer to the Annex, and Figure 13 in particular, for a rough overview of transnational patenting activity in this field. In general, these results indicate a rather high and slightly rising global patenting activity in the general field of hydrogen transport and storage. In a certain analogy, also hydrogen utilisation branches out substantially. However, we are able to identify a few crucial key technologies, while others rather re-emphasise the relevance of hydrogen supply (and generation technology). The latter category largely includes the chemical industry, where hydrogen utilisation has often been established for many decades (such as the Haber-Bosch process for ammonia production or the Siemens process in the silicon industry), but requires a transition to a renewable supply. Other aspects (such as hydrocracking of heavy oils) may render obsolete in the longer term or transform substantially in terms of artificial fuel generation (which is beyond the scope of the present study). In contrast, in other industrial processes, a switch of the feedstock from a fossil fuel to hydrogen may constitute the only credible decarbonisation pathway. In this regard, steel making stands out for feasibility and potential impact when replacing traditional blast furnace processes by the direct reduction of iron employing hydrogen (see above). Hence, we recognise substantial transnational patenting activity in this particular field as shown in Figure 10.

Figure 10 – Transnational patent analysis on direct reduction of iron involving hydrogen



Source: Fraunhofer ISI, own research.

Here, we recognise a substantial increase of transnational patenting activity, particularly around the beginning of the last decade. Yearly numbers fell back substantially after that peak, but the activity rose again in recent years. Notably, EU actors filed about a third of recent transnational patents in this field, followed by the USA. In contrast, Japan ranks fifth in this statistic after China and Korea (which make up the 'Rest of Asia' almost entirely here). Overall, the field of individual actors filing these patents remains less diverse, as steel making constitutes a rather consolidate branch with many large-scale industrial entities who also dominate the transnational patent records on hydrogen-based direct reduction of iron.

Beyond specific industrial use cases, fuel cells constitute the primary key enabling technology for widespread hydrogen utilisation throughout numerous sectors, including industrial and residential power supply, for grid-scale storage and subsequent re-generation of electricity, and for hydrogen-based mobility solutions, of course. Please refer to the Annex, and Figure 14 in particular for an overview of transnational patent activities in this field. In general, fuel cell technologies remain deeply entangled with the promise of a future sustainable hydrogen economy as they offer versatile re-conversion opportunities, but primarily beyond primary industrial sectors. Technologically, we recognise substantial overlap with electrolysis, as both fundamentally represent electrochemical conversion steps of inverted order.

Overall, we recognise EU actors currently holding a strong position for various key enabling technologies for the emerging sustainable hydrogen economy in international comparisons. Our findings based on transnational patent analyses is in line with current perceptions of the involved industries as confirmed by experts. The expert interviews pointed out two potential bottlenecks in maintaining this position and its commercial exploitation:

(a) The EU technological advantages in the hydrogen field are often based on smaller industrial players that only recently outgrew the small- and medium-sized enterprise (SME) category or still reside within it. Their rather small size and particular demand for capital to sustain growth and expansion may easily turn them into objects of mergers and acquisitions also by non-EU actors which, thus, may effectively gain control over their intellectual property and know-how. Experts exemplified this perceived threat for European technology sovereignty with a recent take-over in the electrolyser branch.

(b) Administrative and regulatory hurdles may slow down the development of hydrogen technology markets within the EU, which constitutes the highest importance for domestic actors. For instance, experts claimed that the current implementation of the additionality principle largely prevents private investment in wind-powered electrolysis capacity.

The present global position of the EU in terms of hydrogen technology also confirms the overall success of earlier EU research and development policies. Hence, keeping hydrogen a focus in

Horizon Europe and subsequent framework programmes appears helpful. Traditionally, EU often lags behind the commercialisation of scientific results, thus the conversion of invention into the diffusion of innovation. EU start-ups and SMEs may lack sufficient access to equity (due to the underdeveloped venture capital environment). Mitigation opportunities include the further development of an innovation chain beginning with established research funding (Horizon Europe), to novel technology implementation and diffusion mechanisms such as the Innovation Fund and the InvestEU programme. However, the elaborate creation of a prosperous domestic market for hydrogen technologies (such as electrolysers) may constitute the most effective measure for the development of a dedicated hydrogen industry in line with the EU industrial strategy (European Commission (EC) 11/25/2020).

Here, it might be of utmost importance to develop a credible long-term policy perspective balancing primary (carbon emission reduction) and secondary objectives (growth of a successful domestic hydrogen industry, becoming a net exporter of hydrogen technology). It might form a foundation to resolve shorter-term trade-offs (International Energy Agency 2019) (such as ramping-up electrolysis without immediate abundance of renewable electricity). In the long run, achieving a regime of economics of scale for key technologies such as electrolysers earlier may constitute the most effective measure to reduce local and global carbon emissions. Beyond direct and indirect support of according investments (e.g. in the frame of the IPCEI mechanism), an environment of predictable market growth (by ramp-up goals for electrolysis, quotas for hydrogen feed-in, etc.) may constitute the most effective support for the emerging EU hydrogen technology industry. Defining a balance between conflicting (short-term) objectives may constitute a primary policy challenge, in the light of massive interests (e.g. corporate investments in established technologies, public acceptance issues for renewable infrastructure projects) and relevant lobby groups (where SME and novel technologies may often be underrepresented).

Key conclusions on the international perspective

- Transnational patents reveal current strengths of the EU in key hydrogen technologies.
- In particular, electrolysers constitute a key element of the transformation to a sustainable hydrogen economy – and EU actors carry substantial IP in the field.
- East Asia and North America will likely become major global competitors for hydrogen technology leadership.
- The results confirm success and efficacy of EU and member state fundamental R&D policies.
- The EU traditionally lags behind in technology commercialisation (scaling production, growing markets).
- Present policy initiatives (such as IPCEI, Innovation Fund) already aim to resolve such shortcomings.

3.5. Actors and regions

This section presents an analysis of current and potential actors and regions involved in the hydrogen economy in Europe, focusing on the industrial sector. The section also discusses research and policy gaps in respect to socio-technical-economic aspects, and provides suggestions for future hydrogen policies. Main barriers identified are acceptance issues for production and infrastructure site selection, environmental impacts due to expanding renewable energies and required material flows (i.e. water), and socio-economic impacts due to job and just transitions and end-user costs.

3.5.1. Societal networks (actors)

We identify four main actors in the hydrogen economy, which are discussed in detail below:

- hydrogen economy enabler actor network (upstream perspective)
- value chain adaptation actor network (downstream perspective)
- (pro- and con-) stakeholder organisations and interest groups
- people and companies (in-)directly concerned and impacted by the hydrogen economy

The **hydrogen economy enabler actor network** consists of actors actively pushing the transitions towards a hydrogen economy. This relates to innovators in research and development, in science, business and industry, and political decision-makers. Enabling the technology refers to process engineering, plant construction and supply chain organisation from pilot technical feasibility to full market scale (e.g. transport, storage). In addition, policy regulators and stakeholder groups actively supporting the transition, are part of the enabler network.

In such a context, the European Commission through the hydrogen strategy set the ground for the development of a hydrogen economy in Europe. The hydrogen strategy includes the formation of the European Clean Hydrogen Alliance, which is a central enabler actor network by joining stakeholders and facilitating investments in the hydrogen value chain. In addition, most of the EU Member States have already included hydrogen in their National Energy and Climate Plans and some have created strategic plans to increase the participation of hydrogen in national energy systems (Gérard et al. 2020). At the current stage, the hydrogen economy in Europe is at a demonstration-scale level. All this stimulates the debate among actors and investors in the hydrogen value chain. For instance, Hydrogen Europe representing industry players, large companies and SMEs suggested a framework that integrates regulations of infrastructure, demand and production of hydrogen in a hydrogen infrastructure act and a hydrogen market act (Chatzimarkakis et al. 2021). At the national level, actions can also be observed in EU countries via IPCEI projects to push forward the hydrogen economy (e.g. the German government just announced 8 billion Euros of investment in 62 of IPCEI projects in Germany (Bundesministerium für Wirtschaft und Energie 2021b). Moreover, soon after the release of the European hydrogen strategy, a group of eleven gas infrastructure companies suggested a European hydrogen backbone across 10 European countries (see Section 3.5.3). Thus, it becomes clear that transport infrastructure development is an essential component of a hydrogen economy. Establishing large-scale infrastructure will most likely play a crucial role for local and national acceptance issues. However, it is striking is that there is a lack of current hydrogen economy public perception research available.

The **value chain adaptation actor network** relates to direct beneficiaries of a hydrogen economy from a downstream value chain perspective. This is the actor network of energy intensive industry as the main target group for substituting fossil fuels with green hydrogen. Actors involved in the energy-intensive industry relate to branches such as cement, aluminium, steel, glass etc. Since the EU is home to these industries, such (potential) actors can be found across the EU. Nevertheless, current beneficiaries of 'mini' hydrogen economies are concentrated in the Member States of Austria, Denmark, France, Germany, Italy, The Netherlands, Romania, Slovakia, Spain and Portugal. These countries are largely those in which the 22 (planned, being implemented or already implemented) EU hydrogen valleys are or will be located (Fuel Cells and Hydrogen 2021).

Currently, there is a lack of value recognition in the industrial value chain of hydrogen. This is mainly because the development of a (green) hydrogen market is still at an initial stage, and the final use of green hydrogen is still not valorised (e.g. steel cannot be labelled as 'green' if produced using green hydrogen see Internationale Organisation für erneuerbare Energien 2020). Nevertheless, the transition towards a European hydrogen economy offers a big industrial opportunity for climate-friendly innovation. Science, business and industry innovators in the field of process innovation, engineering, plant construction, energy system integration, and business case developers may profit both at a large company level and at the SME level. On a macro-economic level, it provides the opportunity to raise EU competitiveness within a future climate protection regime. For this, it is important that the EU and its Member States set clear visions and framework regulations to pave the way towards a hydrogen economy (see policy implications below). However, what is currently still missing is a level playing field with a regulatory framework which favours substituting fossil-based energy with green hydrogen energy. Value chain adaption requires a competitive business model based on green hydrogen.

The **(pro and con) stakeholder organisation and interest groups** consist of stakeholder organisation and interest groups centred on pro- and con positions within the public discourse and the policy-making arena. The network comprises the whole range of organised interests, including associations of employers, unions, non-governmental groups (NGOs) such as environmental groups, and consumer associations. In such a context, socio-economic aspects related to added value and job creation; sustainability of the hydrogen economy (including socio-environmental impacts); social (non-) acceptance of hydrogen-related projects; and plurality of stakeholders leading the hydrogen economy are important (see below). What can be seen is that stakeholders from business and industry (and corresponding associations), and federal state and national policy-makers are largely in favour of enabling a hydrogen economy. However, environmental and societal groups are more reserved towards a hydrogen economy, expressing the need for compliance with sustainability criteria and for limited use of hydrogen in selected areas (e.g. use in industry, non-use in transport).

With respect to adding value and employment creation, scenarios have pointed out that the hydrogen economy can generate up to 29 billion EUR annually of value-added and up to 357,630 direct and indirect jobs in the EU28[5] by 2030. Four Member States (Germany, Italy, France and Spain) are foreseen to concentrate the major share of value added and employment generated in the value chain of hydrogen (Gérard et al. 2020). Another study suggests that green hydrogen could create from 300,00 to 450,00 direct and another 650,00 to 900,000 indirect jobs by 2050, in particular in the construction and industry sectors (Navigant 2019).

Another factor refers to different shades of social acceptance covering production, storage, and transport. In respect of the use of salt caverns for hydrogen storage, it should be noted that about half the Member States have underground salt layers that could be used to store hydrogen. Some Member States are already using salt caverns for the storage of natural gas that can be partially or fully converted for hydrogen storage. While studies have highlighted the possibility to store hydrogen in salt caverns as a way to increase seasonal energy flexibility (Chatzimarkakis et al. 2021; Gérard et al. 2020), we identify that little or no attention has been given to the societal acceptance of the use of salt caverns for hydrogen storage.

The social acceptance of CCS facilities for CO2 storage in the production of blue hydrogen is another important point to be further addressed by research and policies. The EU in its hydrogen strategy has highlighted the need to invest in low-carbon hydrogen production in the short- and medium-term, as a strategy to reduce CO2 emissions of current carbon intensive hydrogen production, and to accelerate the hydrogen economy (European Commission 2020e). However, previous research has identified resistance in European society in respect to the acceptance of CCS facilities and storage. The case of CCS in Europe around the year 2010 shows that in several countries (e.g. Germany, The Netherlands) local resistance and non-acceptance among environmental groups (besides lack of coordination and long-term strategies scaring off investors) led to the failure of an EU CCS ramp-up (Oltra et al. 2012; Scheer et al. 2017). The analogy shows that such societal

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[5] The study refers to the EU28, including the UK Gérard et al. 2020.

resistance can impose burdens and challenges to the current plans of the EU to invest in blue hydrogen or store hydrogen in salt caverns.

For the supply of green hydrogen, the EU intends to increase wind and solar energy projects in Europe (in the north and south, respectively) for the production of green hydrogen cross country-borders, as well as to increase the import of green hydrogen from non-European countries. In both cases (local production and import), the hydrogen should be transported and distributed mainly by trucks and pipelines across European countries. In relation to additional wind and solar energy projects, it is important to address how willing European society is to accept such new projects for the production of hydrogen, considering the existing societal resistance to local projects for renewable electricity production (e.g. NIMBY phenomena). The same is valid for ways of transport and distribution of hydrogen cross-countries in Europe, in particular in the case of new pipelines. To conclude, acceptance issues may play a fundamental role in establishing renewable energies, hydrogen production sites, and hydrogen transport infrastructure, and little attention has been given to societal acceptance issues in the design of a hydrogen economy.

With respect to the plurality of stakeholders supporting the hydrogen economy, it is worth noting that the Clean Hydrogen Alliance (one of the main proponents of the hydrogen economy in Europe) is mostly composed of oil and gas companies (PfEU 2020). In such a context, our study identifies that increased engagement of civil society, NGOs and local authorities in the Clean Hydrogen Alliance or other hydrogen initiatives and associations will stimulate legitimacy and acceptance. In addition, a transition towards a hydrogen economy should be understood as a socio-technical transition in which society will play an essential role in determining the means and ways of such a transition. Therefore, stakeholder consultation and enhanced participation with the public is necessary.

One additional socio-related issue can arise in respect of the environmental sustainability of a hydrogen economy, in particular in relation to water use for the production of hydrogen, not only in Europe but also in regions with a scarcity of water supply (e.g. MENA countries). One should note that for the production of one tonne of hydrogen, nine tonnes of pure water, or about 20 tonnes of impure water, are needed on average (Slav 2021). In this sense, in regions with a shortage of water supply, society can react against the production of green hydrogen because such hydrogen production can result in an additional source of water stress. The hydrogen economy needs a set of sustainability criteria and requirements which take critical issues into account.

Finally, we have **people and companies (in-)directly concerned and impacted by the hydrogen economy** referring to people who live nearby technology and infrastructure installations, or consumers and companies suffering higher product prices due to the hydrogen transition. Also those people suffering potential side-effects from a hydrogen economy (e.g. job losses in hydrogen transition and water competition in regions with a scarcity of water supply) can be included in this group of actors. In such a context, policies addressing just transitions (detail below in policy implications) are of high importance to avoid or minimise undesired side-effects of a hydrogen economy, in particular over disadvantaged populations and social groups (e.g. people already suffering water stress in MENA countries).

3.5.2. Regions

A twofold differentiation of regions within a hydrogen economy is reasonable. These are:

1. Hydrogen feasibility and demonstration regions in the EU
2. (Potential) hydrogen full-scale supply regions in and outside the EU, including EU-strategic partnerships abroad countries (e.g. MENA region Africa, Australia)

Regions demonstrating the technological feasibility of a hydrogen economy on pilot and demonstration scale for decarbonisation of industry using hydrogen refers to high technology regions mainly within the EU, which are suitable for proving technology feasibilities (integration of renewable energies, electrolysis, CO2 capture, hydrogen storage and use, etc.).

Currently, such demonstration regions can be found in the EU in those countries that already have hydrogen valleys (i.e. Austria, Denmark, France, Germany, Italy, the Netherlands, Romania, Slovakia and Spain). Hydrogen valleys are pioneers of the hydrogen economy and will be decisive for demonstrating the roles that hydrogen can play in decarbonising the European economy, in particular industry (Weichenhain et al. 2021). In the medium term, hydrogen valleys are expected to be interconnected via a European backbone using gas pipelines adapted for the transport of hydrogen. Most of the current pipelines used for the transport of gas are already suitable for the transport of hydrogen blended with natural gas (Chatzimarkakis et al. 2021). Existing pipeline infrastructure adapted for the use of hydrogen is a crucial enabler for connecting a Europe-wide hydrogen economy which most likely will not suffer non-acceptance issues.

Security of supply for green hydrogen will be most important for industry customers when substituting fossils with hydrogen energy. Among the main barriers for the implementation and running of hydrogen valleys, are: (a) securing public and private funding for the realisation of local and regional projects; (b) securing commitments from clean hydrogen buyers, in particular for long-term agreements; (c) permission issues at the local and regional level for the implementation of hydrogen-related projects and infrastructure; and (d) technological readiness and feasibility (Weichenhain et al. 2021).

Hydrogen full-scale supply regions, in contrast, will be located in and outside Europe with suitable conditions for efficient green hydrogen production at large scale volume (e.g. sufficient renewable energy and water resources). One may expect that some of the demonstration regions in the EU will become full-scale supply regions in the long run. Additional concerns refer to regional Hydrogen Valley clustering as a strategic approach for production, storage, distribution and consumption of hydrogen feasibility demonstration in Europe. In this domain, additional research could explore which roles hydrogen valleys play in just transition, and what this means for countries and regions without hydrogen valleys, in the aim for a just and low-carbon economy that should 'leave no-one behind'.

Hydrogen valleys can be found not only in the EU but around the world, and are expected to grow and mature over the 2020s. Currently, non-EU hydrogen valleys can be found in Australia, United Kingdom, Japan, China, USA, Chile, Thailand and Oman (Weichenhain et al. 2021). It will be essential for the EU to establish strategic hydrogen alliances worldwide and to find the right balance between EU and abroad Hydrogen Valley siting. Full scale hydrogen supply from non-EU countries may mark the long-term hydrogen strategy. Due to cost and resource efficiency, the EU aims at strategic partnerships with other countries in order to establish a global import infrastructure for scaled-up hydrogen supply. From a technical efficiency point of view, these countries need to have at their disposal sufficient space, sun, wind and water resources. Regions foreseen as strategic partner countries are, for instance, the MENA region in Africa and Australia.

A major challenge thus refers to establishing a sustainable large-scale hydrogen economy in EU Member State countries, and in particular in non-EU countries. Increasing competition of water and renewable energy use may occur, especially in regions where there is already scarcity of drinking water supplies. Thus, a key success factor will be a sustainability criteria and certification regime for green hydrogen, which still needs to be established, with environmental and societal groups participating in its development. The development of a sustainability certification regime needs to build on current efforts (e.g. Certificate of origin according to RED II, EECS and CEN/CENELEC 16325; the CertifHy-Project developing a H2 certification scheme for RED II). Besides focusing on green hydrogen, there is also a need to consider the sustainability of blue hydrogen in order to prevent undesirable developments. A recent study elaborated on sustainability issues of hydrogen, which are listed in Table 3.

Table 3 – Sustainability aspects in the certification of imported hydrogen

Colour of the hydrogen	Sustainability Aspects	Examples of issues to be addressed
Green hydrogen	Electricity	• Renewable electricity from additional, new plants • No negative externalities in the local power system • No impediment to local energy transition by depriving local residents of existing RE sites • Additional electricity generation for local population
	Water	• Minimisation of water requirements for H2 production • No increase in water prices • No aggravation of scarcity • Additional water supply for local population
	Area	• No ecological and cultural protected areas • No areas subject to international law
	Economic effects	• Enable value creation in the exporting country • Consideration of local companies & workforce • Capacity building on site
	Human Rights & SDGs	• Compliance with corporate due diligence requirements • Independent project-specific risk assessment regarding SDGs
Blue hydrogen	Methane emissions	• Seamless recording incl. the natural gas supply chain
	Final disposal	• Recording of CO2 emissions, safety

Note: aspects that are considered to be less critical for imports from European countries but are relevant for imports from non-European countries are highlighted in light gray.

Source: (Matthes 2021) (own translation)

Besides structural change issues via hydrogen valleys and pipelines, as well as sustainability criteria and certification, this study identifies additional factors that can contribute to developing the hydrogen economy in the EU Member States, in particular in those Member States in which hydrogen does not yet play any important role. These are:

A. national strategic plans to increase the participation of hydrogen in national energy systems;
B. just transition – jobs creation/reformation and industry reformation (intensive industries candidates for substituting fossil fuels with green hydrogen and/or bio-economy and phase-out of coal energy);
C. potential for increasing renewable energies solar and wind; and
D. value recognition in the industrial value chain of hydrogen.

Also concerning these factors the Member States differ significantly. For instance, currently only Austria, France, Germany, the Netherlands, Norway, Portugal and Spain have elaborated national hydrogen strategies (Chatzimarkakis et al. 2021). Thus, looking to the different conditions mentioned above that can promote the hydrogen economy in the Member States, the most promising countries are currently Austria, Denmark, France, Germany, Italy, the Netherlands, Romania, Slovakia and Spain. These are the countries that already present advances in the conditions discussed above (e.g. via the existence of national strategic plans for hydrogen or the existence of hydrogen valleys). The further development of the hydrogen value chain in the above-mentioned Member States, as well as in additional Member States that currently do not play a significant role in the hydrogen economy in Europe, will be key to reduce the dependence on imported hydrogen in the medium- and long-term.

3.5.3. Implications for the design of future hydrogen policies

Regarding **implications for the inclusion of stakeholders and just transition**, a possible concentration of value added and job creation in a few EU countries (e.g. Germany, Italy, France and Spain) point to the importance of policies addressing just transitions within the hydrogen economy. In this sense, EU policies should give more attention to those EU countries that currently are not 'big' players in the hydrogen transition, considering the solidarity spirit of the EU and an inclusive energy transition. Policies to promote just transitions would be relevant not only for EU countries but also from non-EU countries, considering that the EU expects to import a considerable part of the hydrogen that should be consumed in Europe.

Also, policies that promote the (re)qualification of industrial workers are of importance to minimise job losses in the new hydrogen economy in Europe. In addition, policies addressing inclusivity in the hydrogen strategy across Europe are relevant, and in particular with respect to diverse stakeholders in the hydrogen economy. This could increase stakeholder plurality and avoid the dominance of oil companies' related interests (which in general have low trust levels among the public) in hydrogen initiatives.

In respect to **societal acceptance**, this study notes that European and non-European societies may react in opposition to the implementation of infrastructure projects (in)directly connected to the hydrogen economy (e.g. storage of hydrogen in salt caverns, CCS(U) technologies, new pipelines and additional renewable energy projects in (non-)European countries for the production of hydrogen). Also societal resistance to the use of water in the hydrogen economy is possible. Thus, policies addressing the sustainability of the full hydrogen value chain are highly relevant to increase societal support for hydrogen-related projects, and avoid or at least minimise burdens and side effects of the European hydrogen economy on society (Europe and abroad).

Regarding **hydrogen valleys and (long-term) hydrogen supply regions**, additional (risk mitigation) policies are important to help overcome the barriers identified above (Section 3.5.2), such as for securing public and private funding for the realisation of local and regional projects and securing commitments from clean hydrogen buyers. Also policies at the European and national levels on setting and/or strengthening the regulatory framework for further development of hydrogen demonstration and full-scale supply regions are important. In such a context, particular attention should be given to provide a clear procedural vision for investors and authorities, guaranteeing a level playing field at the local and regional levels, since permission issues are still a bottleneck for the implementation of local and regional projects (Weichenhain et al. 2021).

Key conclusions on actors and regions

- Little or no attention has been given to the societal acceptance of the full value chain of hydrogen.
- The establishment of new large-scale infrastructure can be influenced by local and national acceptance issues.
- A transition towards a hydrogen economy should be understood as a socio-technical transition in which society will play an essential role in determining the means and ways of such a transition.
- Policies addressing just transitions are of high importance to avoid or minimize undesired side-effects of a hydrogen economy.
- Hydrogen Valleys located in the EU have the potential to become hydrogen full-scale supply regions.

In relation to **non-EU hydrogen imported to the EU**, additional policies are important to create a system seeking to guarantee the origin of green hydrogen consumed in industrial processes, in particular for hydrogen produced abroad (e.g. via certificates). On the one hand, such policies may add value to end-use applications of hydrogen as well as enhance local sustainability of hydrogen production, in particular in non-EU countries. On the other hand, such policies may lead to economic burdens for green hydrogen producers and users. In this sense, policies should be rigid enough to promote the sustainable production and consumption of green hydrogen and flexible enough to avoid additional burdens to green hydrogen producers and users.

4. Conclusions

The main **objective** of this study was to take stock of the current situation with respect to the realisation of the EU hydrogen strategy and to identify policy options addressing gaps in the current hydrogen policy landscape. In Section 3, we provided an evaluation of the scientific literature and position papers along the whole hydrogen value chain, while also covering cross-cutting aspects such as the role of actors and regions. Here, we provide a summary of the main findings and the derived implications for future policy options.

Low-carbon and renewable hydrogen can be expected to remain relatively scarce and costly[6] resources during the next decade, which raises the question of prioritising its use. For passenger cars and heating buildings, electrification is more efficient from an overall energy system perspective. Widespread use in these areas is therefore questionable. In heavy-duty transport, it is still open whether hydrogen and its derivatives or direct electrification will prevail, or whether both systems will exist in parallel. So there is large uncertainty about the future demand for hydrogen in the transport sector. With respect to the **role of hydrogen use in industry**, there is a broad consensus that hydrogen is a technically feasible and promising decarbonisation option. From a technical viewpoint, ammonia production and refineries are potential first adopters due to their current use of fossil hydrogen. However, the need to reduce fossil fuel consumption implies that transformation plans are required for use in refineries, which outline how hydrogen will be used there in the future (e.g. to produce renewable methanol). For the steel industry, the use of hydrogen is also considered very important due to the limited alternatives, whereby the operation of direct reduction plants with natural gas already enables large emission reductions, while a steady switch to renewable hydrogen in these plants is possible. The use of hydrogen for heat generation is likely to be limited, as more efficient electrification options exist in many areas.

A **major barrier to the market introduction of renewable hydrogen** in industry is higher costs compared to fossil fuels. This is particularly relevant for energy-intensive industry, because the share of energy costs in gross value added is higher there than in the rest of the manufacturing sector. If the additional costs on the way to a GHG-neutral economy cannot be passed on or compensated, then this represents a serious barrier to transformation, because the industries concerned are in international competition. This has already been addressed by the recently launched EU Innovation Fund. Moreover, policy-makers have become aware that higher operating costs are a major barrier to widespread market introduction of many low-carbon technologies in the energy-intensive industries. A pilot programme for carbon contracts for differences (CCfDs), which is envisaged to fund the difference between the cost price of the technologies and the market value of the product the technologies deliver, is seen as a promising option by both policy-makers and industry actors. While the concrete design remains open, the provisions of the Innovation Fund can serve as a blueprint.

Current European hydrogen consumption (11.5 million tonnes including by-products) is mainly produced on-site via steam methane reforming with only very minor shares (0.7 %) to be considered low-carbon hydrogen. Nevertheless, the EU hydrogen strategy plans to **ramp-up renewable hydrogen production** via electrolysis to 6 GW capacity in 2024, producing 1 million tonnes, achieving the production of 10 million tonnes of hydrogen by 2030, with an installed capacity of 40 GW electrolysers. This massive scale-up of hydrogen and electrolyser capacity needs to be flanked with adequate support policies in research and innovation, but also with policies to foster investment. However, the exact amount of investment requirements are not yet clear due to the

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[6] Low-carbon hydrogen can be expected to stay more costly than natural gas in the coming decade, even in view of the strong increase of EU ETS and natural gas prices in 2021. However, these developments substantially reduce the cost gap of renewable hydrogen to conventional and natural-gas-based low-carbon hydrogen.

large uncertainty about the extent of its future use. Despite the EU's production targets, the production capacities required to satisfy the expected EU demand for renewable and low-carbon hydrogen will exceed the expected production capacities. That means that a notable share of renewable and low-carbon hydrogen demand will have to be imported.

The **role of low-carbon hydrogen based on CCS** as a bridging fuel is a highly debatable issue. A switch from high-carbon hydrogen to a low-carbon alternative is technically feasible, since the technology of carbon capture is known and established in many production processes. The pretended advantage of a quite speedy switch could evaporate due to technical, economic and (in particular) societal impediments in respect to storing the excess supply of CO2, which cannot be utilised due to low demand for such carbon. Furthermore, excessive installation of CCS facilities could generate lock-in pathways, which should be avoided.

Establishing a backbone hydrogen infrastructure can be expected to be an important step to move from individual pilot projects to a rollout of hydrogen. While important areas for hydrogen production and use can already be anticipated, the amounts required are still uncertain and the infrastructure required is hard to predict. Building up the infrastructure too early may result in sunk costs, to be carried by end-users. However, long-term planning processes require early action, if a hydrogen backbone is to be achieved by 2030. This means that the necessary provisions need to be established very soon, while still leaving the option to navigate the rollout. Therefore, national TSOs should be obliged to assess the domestic need for hydrogen infrastructures as soon as regulatory updates allow, and also to identify gas pipelines that can repurposed in a dynamic perspective, i.e. providing a schedule for potential repurposing to hydrogen, based on expected future gas demand. Moreover, all energy carriers and related networks require joint planning to determine overall optimal pathways as soon as possible.

Given the current **lack of hydrogen markets** and large-scale networks and the regulatory principle of minimal intervention, there is no urgent need for their regulation. However, the expected benefits of a hydrogen backbone infrastructure call for establishing at least the general principles in the forthcoming hydrogen and gas market decarbonisation package, in order to avoid a later need for the harmonisation of regulations. Such main principles include free access to third parties and overarching principles for remuneration. The remuneration of gas grids differs in certain regards in the Member States today. So there is room for experimentation here, for instance with respect to splitting the funding between producers, consumers and the public. Therefore, the most promising option seems to be by starting with a few regionally-focused test cases. Different approaches to regulation based on the same overarching principles could be applied, for an *a priori* limited timeframe, and compared afterwards. An important prerequisite for shaping the market is a clear classification and certification scheme, possibly based on Guarantees of Origin as proposed by CertifHy, but also considering the options to classify RFNBOs as put forward in RED II.

If the EU wants to form a hydrogen industry that is globally competitive, it will need to make sure to maintain and foster research, development and innovation as well as commercialisation across all key technologies. In **international comparison**, EU actors currently hold a strong position throughout key enabling technologies for the emerging sustainable hydrogen economy, as evidenced by transnational patent analyses and confirmed by experts. Here, electrolyser technology is recognised as being of utmost importance for (a) the immediate decarbonisation of the pre-existing hydrogen economy (mostly serving key industrial processes based on on-site conversion of fossil fuels); (b) the decarbonisation of major industrial processes (such as steel making) by replacing their traditional feedstock; and (c) the potential general diffusion of hydrogen technology as a sustainable energy supply option throughout various sectors. Once electrolyser production reaches an economy of scale regime, continuous improvements of cost and efficiency, and thus competitiveness, may occur, but the initial market ramp-up critically depends on regulatory priorities and the availability of renewable electricity. The EU may leverage its currently favourable technological position to lead the commercialisation of sustainable hydrogen technologies, but other regions may compete in this regard. Here, experts recognise threats in the draining of relevant intellectual property and in the consistency and priorities of EU regulation, while policy-makers face a complex balance of short- and long-term decarbonisation goals, industrial and technological leadership, and complex stakeholder interests. The important project of common interest (IPCEIs) on hydrogen currently being established are a first step to deal with this in a strategic way.

With respect to **hydrogen actors**, a strong movement engaging mainly policy-makers and regulators, industries, SMEs and scientists can be observed as bringing the new hydrogen economy forward in the EU, in particular in the European Clean Hydrogen Alliance. In this sense, it can be stated that, in general, the EU follows a strategic approach to stimulate and implement a hydrogen economy in Europe. The approach builds on a momentum combining industry and competition policy with transformational change towards sustainability. Establishing a low-carbon hydrogen economy could pave the way for providing defossilised energy for industrial use. Nonetheless, this study has identified weak civil society participation in the design and construction of the new hydrogen economy. Studies investigating societal aspects, including acceptance, of the hydrogen value chain have been concentrated on mobility (end-user), while societal aspects related to production, storage, transport and use of hydrogen in industry have received less attention from academics and stakeholders. What is still needed is an integrative impact assessment covering multi-criterial dimensions of economic, ecological and social impacts of hydrogen valleys. In that sense, it is of high importance that stakeholders currently leading the new hydrogen economy take the development of such an economy as a socio-technical development, in which society will play a key role in the adoption and use of hydrogen technologies.

With respect to **hydrogen regions**, these can be found in and outside Europe. The approach of hydrogen valleys involving different actors can contribute substantially to fostering low-carbon hydrogen in the medium term and renewable hydrogen in the long term as important energy carriers for the achievement of the ambition of climate neutrality by 2050. Most of the current regional initiatives are demonstration projects, forming 'mini' hydrogen economies demonstrating technical feasibility. Currently, there are 36 hydrogen valleys around the world (planned, being implemented or already implemented), 22 of them in the EU and 2 in the United Kingdom. In Europe, hydrogen valleys are expected to be interconnected in the medium term via a European backbone that will take advantage of the current gas pipeline infrastructure. Such demonstration regions can become hydrogen full-scale supply regions in the medium and long term. In this sense, the EU has a promising ecosystem that can lead to a global leadership position in the entire value chain of hydrogen in the long term, including a functioning market. However, a regulatory framework is needed in the short term that provides a level playing field for a renewable hydrogen economy.

In **summary**, recent activities such as the European Clean Hydrogen Alliance, the launch of the EU Innovation Fund, the formation of hydrogen valleys and the hydrogen IPCEIs seem to provide promising first steps to fostering a European hydrogen economy. Nevertheless, important policy gaps remain to ensuring the sustainable realisation of the EU hydrogen strategy's targets, in particular with respect to certainty for investors, cost-competitiveness with fossil technologies, regulation of hydrogen infrastructures, certification of renewable and low-carbon hydrogen as well as civil society participation. Some of these are at least partially addressed by the revised regulations proposed with the Fit for 55 package, where the details remain to be negotiated though. Others will likely be addressed with the hydrogen and gas market decarbonisation package scheduled for the end of 2021. The opportunity provided by the negotiations of these two policy packages should be used to ensure that the EU is well on track to realise the benefits of a hydrogen for decarbonising industry while limiting undesired side-effects.

5. Policy options and their assessment

In this section, we outline and compare a selected set of options in key policy action fields under the EU hydrogen strategy, which were developed based on the conclusions from the literature research and expert interviews presented in Section 4, in particular the policy gaps identified. While the policy options presented can be helpful with getting started on filling the main policy gaps, it is clear that the realisation of the EU hydrogen strategy will require a much more comprehensive framework. Before turning to the policy options, we provide an overview of the identified policy gaps. More details about the policy options and their comparison can be found in the annex.

5.1. Overview of identified policy gaps

The realisation of the EU hydrogen strategy will require large investments, in particular in the longer term but to a certain extent also up to 2030. However, hydrogen is and will stay an energy carrier with high costs. Therefore, it should be used predominantly in applications without more cost-effective routes for decarbonisation (such as direct electrification). Clear guidelines for preferred hydrogen use cases including a hierarchy of priority uses are lacking, which results in high uncertainty for investors.

For a rollout of hydrogen production and use in line with the EU hydrogen strategy, there is a need for additional support schemes, as currently support schemes are mainly tailored to individual demonstration projects. Support schemes for boosting demand and fostering production also need to consider where to prioritise the use of hydrogen.

Currently, there is no European-wide hydrogen market and no large-scale hydrogen network. Accordingly, a European regulation of hydrogen infrastructures does not exist. This leads to high uncertainty for both market participants and operators of a hydrogen infrastructure. It is therefore of utmost importance to clarify at least the general rules of future market and infrastructure regulation.

The trading of hydrogen both within the EU and beyond requires an exact specification of the traded products, in particular renewable and low-carbon hydrogen. Certification schemes are under development, but the specific criteria to be applied have not yet been agreed.

Finally, acceptance issues and the involvement of civil society have not been addressed to a sufficient extent. Moreover, the role of hydrogen in just transitions 'leaving no-one behind' is yet to be defined. Thus, future policies need to support the participation of additional stakeholder groups across all European regions and also foster a sustainable approach to international hydrogen partnerships.

5.2. Policy options

5.2.1. Options to foster investments

The considerations of the investment requirements in hydrogen-use technologies, hydrogen and renewable electricity production, as well as hydrogen infrastructures, have shown that there is a need for large investments in particular in the longer term, but to a certain extent also up to 2030. An important measure to stabilise investors' expectations about future investment conditions is seen by many, but not all, stakeholders in the implementation of a dedicated target system (European Commission 2021b). The most common starting point for a target system is the demand for renewable and/or low-carbon hydrogen at the EU and/or the Member State scale, expecting trickle-down effects on the production, transport and imports of such hydrogen, on building-up necessary renewable energy plants and storage facilities as well as electrolyser manufacturing capacities. The trickle-down impacts are influenced by the precise design of the target system, e.g. how imports of renewable and/or low-carbon hydrogen is treated. Legal and trade-related implications are beyond the scope of this study.

It is debatable whether target systems for a specific technology are useful to most effectively and efficiently establish a climate-friendly hydrogen economy. The main concerns address the lack of knowledge in respect to economy-wide impacts and on the R&D activities of potentially more appropriate alternative technologies, since the dynamics of markets, economic and societal frames, as well as the improvement of technical knowledge, are neglected. Streamlining target systems by taking into account the techno-economic impediments to reducing GHG emissions can help to overcome some of the above-mentioned concerns. For example, the target systems should focus on the 'no-regret' sectors, i.e. ammonia, olefins, refineries and steel, as well as aviation and shipping. Since these sectors could contribute to half of the expected hydrogen demand in 2030 and 2050, supporting these could speed up the establishment of competitive hydrogen production (see Sections 3.1 and 3.2).

Target systems could be either indicative or compulsory. The success of a target system depends on the grade of commitment and the respective sanctions. The grade of harmonisation of the targets and commitments could be also crucial for success. Three different options will be discussed in the following:

A. *Compulsory targets for the EU*: In a joint consultation, the European Commission, European Council and European Parliament define a compulsory target system for the EU with no binding agreements for each Member State. The EU Commission is responsible for achieving the targets. However, if the targets set by the Member States are insufficient to achieve the targets for the EU, the Commission can initiate additional hydrogen projects based on the renewable energy financing mechanism (European Commission 2020b).
B. *Compulsory targets for each Member State*: In a joint consultation, the European Commission, European Council and European Parliament define binding targets for each Member State in compliance with sanctions. The Member States are responsible for achieving the targets. Necessary measures to achieve the national targets have to be in accordance with the rules set out by the EU.
C. *Indicative targets at EU level*: At EU level, the EU hydrogen strategy is updated, but the decision whether a compulsory target system shall be implemented is left to each Member State. In case a Member State executes a target system accompanied by respective measures, it has to follow the general rules of EU, such as the single market rules.

Assessing the different options, a rather diverse picture emerges, with no clear 'best option'. Option B '*Compulsory targets for each Member State*' could generate the highest benefit for the EU hydrogen strategy and should show the highest effectiveness, but the lowest feasibility and the lowest chance to deal with possible risks. If the Member States, in compliance with the European Commission, European Parliament and the European Council, could find a common ground for the targets, sanction mechanisms and a frame for possible national policies, the implementation of the systems agreed on should be rather smooth, although possible delays at national level are also possible. However, Option B may result in intensive bargaining before the implementation of the national target systems, affecting the feasibility of (ambitious) targets. The same will be true in case of necessary adjustments to the implemented system, due to changing political, economic, technical or societal conditions globally or in the EU.

The main strength of Option A '*Compulsory targets for the EU*' is the achievement of high benefits for the EU hydrogen strategy, comparable to those of Option B. Ex-ante, however, a precise comparison between both options with respect to benefits is hard to achieve, since the setting of the precise targets could differ between both options. Compared to Option B, this option should perform better with respect to feasibility and dealing with risks, since Option A provides Member States and the European Commission with higher flexibility. The main disadvantage is the resulting burden for the EU budget. Also, the effectiveness of Option A could be lower compared to Option B. This results mainly from the non-binding national targets, possibly requiring additional bargaining between the European Commission and Member States in respect of appropriate gap-filling measures, even if the political, economic, technical and societal conditions would not change but the national policies will not allow for the EU targets to be achieved. The effectiveness of Option A could be increased, if the European Commission could initiate the financing mechanism independently from available voluntary national contributions. With the European Commission being responsible for achieving the target system, it could be expected that other EU objectives, like a just transformation, will obtain higher relevance compared to Options B and C.

From the EU perspective, Option C '*No activities at EU level*' seems to be the least desirable option. Although the feasibility and dealing with risks are the highest of all considered options, in respect of benefits, effectiveness, ecological sustainability, and coherence with other EU objectives, Option C has the lowest grade. The main reason for this is the low expectation that the Member States will themselves set ambitious targets in all Member States or for the entire EU without consultation between the European Commission, European Parliament and European Council. Option C could encourage a 'beggar-thy-neighbour' policy in the Member States.

5.2.2. Measures for boosting demand and scaling up production

The stocktaking of supporting measures for boosting demand and fostering production showed that there is a particular need to compensate for the high OPEX, both in the production of renewable hydrogen and its use.

Carbon contracts for difference (CCfDs) are identified as a key option to overcome the funding gap to large scale application in the area of low-GHG production technologies for energy-intensive products, thus also for the use of renewable hydrogen in industry. Currently, the Netherlands has developed a CCfD-like system (SDE++) and Germany has presented overarching principles for a CCfD pilot programme (CCfD-Pilot). The Innovation Fund also contains CCfD-like elements. However, the main difference is that the Innovation Fund focuses on the demonstration aspects, as it targets highly innovative technologies and large-scale flagship projects. The other two approaches also support innovative projects, but are more focused on market diffusion of these technologies.

A comparison of the funding conditions of the existing approaches and programmes shows that the award and subsidy mechanism of all three approaches are similar. In terms of eligibility, there are clear differences between the Innovation Fund, SDE++ and CCfD-Pilot. The German CCfD pilot targets industrial sectors with process emissions and sets thresholds for GHG emission reductions for eligible projects (>50 % at start, >90 % long-term), while under the Dutch SDE++, projects are eligible if certain eligible technologies are used; sector affiliation is not relevant here. The difference in the area of CCS is worth highlighting; while this is explicitly also permitted for permanent underground storage in SDE++, this option is explicitly excluded in the German CCfD-Pilot. The Innovation Fund funds projects from energy-intensive industries, as well as in other sectors. Carbon capture and storage is an explicit funding pillar.

The differences found raise the question of whether there is a need for harmonisation at European Union level. We discuss this in respect of the following three basic principles.

A. *Full regulation at EU level:* CCfD programmes are being developed at EU level that exceed the scope of the existing Innovation Fund, both in terms of funding scope and existing funding budget.

B. *EU directive to be elaborated at Member State level or EU regulation with direct applicability:* A directive will provide Member States with a framework for the design of CCfDs. If the directive is correctly transposed into national law, a State aid assessment is no longer necessary. Alternatively, a regulation could be drafted that determines how CCfDs should be specifically designed if the Member States do so.

C. *Full control of CCfD programmes at Member State level:* No harmonisation efforts are made on the part of the EU.

The benefits of Option A lie particularly in the fact that access to CCfDs can be improved for companies in the EU across all Member States. In addition, positions on technologies can be harmonised across the EU, which can be of great advantage for cross-border projects. In principle, there are no direct risks, but in terms of feasibility, the question is whether sufficient capital can be made available for a European CCfD programme. A benefit over the existing Innovation Fund would be to go beyond innovation funding and support the market diffusion of technologies, which may well require a large budget.

The benefit of Option B is that the harmonisation goals in the EU can be achieved with comparatively low (only administrative) costs. However, the pitfalls here lie in the details. If a directive allows too many degrees of freedom, the harmonisation goals will not be achieved. In this case, the directive would not be effective and change little compared to the current situation. If the directive allows too few degrees of freedom, it may not be implementable because it does not take the different characteristics of the Member States into account. A common directive, however, has the advantage that State aid notification of individual CCfD programmes would likely not be necessary due to the nature of the directive.

Doing nothing (Option C) has the benefit of not incurring any costs and not limiting Member States' ability to design CCfD programmes to fit into their respective energy and climate policy architecture. A risk, however, is that certain Member States lack capital and know-how to set up their own CCfD programmes, and companies in these countries may fall behind other Member States in terms of transformation.

In summary, Option A offers the greatest benefits but also involves high costs, which hampers feasibility. Option C does not incur costs but does not change current policy design and therefore does not deliver benefits compared to the current situation. Option B offers policy design options at comparatively low cost, but here, whether benefits can be achieved compared to the current situation, depends on the details.

5.2.3. How to design a supportive framework (market rules and infrastructure)

The synthesis of the scientific literature, stakeholder position papers and expert interviews in Section 3.3 has revealed that a stepwise approach for building hydrogen networks is crucial for fostering the European hydrogen economy and that the corresponding legislation needs to ensure a quick expansion while being flexible with respect to the exact infrastructure needs. Certain key principles have proven useful in developing the internal energy markets at the EU level. In particular, the natural monopolies associated with the ownership of energy infrastructures have led to the requirement of non-discriminatory access for all interested parties, which goes hand-in-hand with both the vertical and the horizontal unbundling of the network system operators. However, different splits of costs between users, suppliers and the public are possible. In particular, it is clear that the high up-front investments in hydrogen networks can be prohibitive for an expansion of the infrastructure, as long as supplies and users of hydrogen are limited.

A key conclusion on the regulation of hydrogen infrastructure is that, while currently there is no immediate need for an overarching regulation as there are almost no cross-border networks in the EU yet, clarification is needed as to what the overarching principles will be and which concrete setups seem favourable. To provide clarity on when the legislation for hydrogen networks will be established or start to apply, the definition and monitoring of key indicators and thresholds may be useful. Such indicators could include the length of cross-border hydrogen networks, the volumes of cross-border hydrogen transport and trade, as well as the number of actors, i.e. potential market participants. We elaborate below on several options to address these issues within the hydrogen and gas market decarbonisation package to be drafted by the Commission before the end of 2021. In principle, the EU has three overarching options to deal with the present lack of a regulatory framework for hydrogen infrastructures:

A. *Full regulation at EU level:* The hydrogen and gas market decarbonisation package is expected to establish an EU-wide regulatory framework comparable to the existing gas infrastructure legislation, with EU-wide fixed rules on unbundling, third-party access, roles of system operators, network codes and remuneration of costs.
B. *EU directive to be elaborated at Member States level:* The hydrogen and gas market decarbonisation package is expected to establish EU-wide principles, in particular on unbundling and third-party access, and to announce thresholds for key indicators triggering further regulatory steps, but to leave room for experimentation at Member State level during a certain pre-defined period, in particular with respect to roles of system operators, network codes and remuneration of costs. This has similarities with the concept of regulatory innovation zones, which have been useful for testing the regulation of peer-to-peer electricity trading in Germany.
C. *Maintain control at Member States level until further notice:* The EU could announce thresholds for key indicators triggering regulatory steps at the EU level but leaving to the Member States to decide if and how to establish a regulation for hydrogen networks during a certain pre-defined period.

All options may include a stepwise approach, for instance requiring third-party access only after a certain period. Option A, with the most comprehensive EU-wide legislation, shows advantages with respect to fostering an integration of regional networks into a hydrogen backbone and environmental sustainability. In turn, Option A would lead to the highest administrative efforts. Moreover, it could also turn out to be not politically feasible in the near future and ineffective in finding the best regulatory setup due to a lack of experience with the regulation of hydrogen networks and markets. The more flexible approach of Option B could lead to higher political feasibility and effectiveness in finding the best regulatory arrangement. However, this comes with moderate disadvantages due to less certainty about later integration and environmental stringency as well as for investors. Finally, Option C leads to the lowest administrative effort and the highest flexibility for the Member States, but comes with high risks for subsequent integration of regional networks in a European backbone and the resulting uncertainty for investors and about its effectiveness.

5.2.4. Options for promoting research and innovation in hydrogen technologies

Hydrogen technologies exemplify EU strengths in fundamental and applied research (as established in Section 3.4). However, Europe has often lagged behind other global regions in the conversion of scientific insight into economic success in the past. Currently, the EU aims at overcoming this gap through novel innovation support mechanisms (such as the Innovation Fund), by emphasising innovation in Horizon Europe (in particular with the European Innovation Council programmes), and by establishing the IPCEI mechanism (enabling Member States to support first industrial use of critical technologies). In general, EU policy needs to balance enhancing the industrial-scale commercialisation of present strengths in fundamental and applied research, while maintaining and extending the latter in the future. Here, we discuss specific policy options to enhance the EU position in hydrogen technology implementation, i.e. maintaining a strong position in related fundamental and applied research while specifically promoting increases in their commercial implementation.

A. *Establish a dedicated R&D frame:* Beyond promoting key hydrogen technologies in the frame of Horizon Europe, the EU could create a designated research and innovation framework for critical hydrogen technology (such as electrolysers), to combine leading research groups in the field in a single, long-term funding programme that enables effective division and coordination of research tasks, systematic exchange on present results and future directions, as well as combined innovation support initiatives through industrial spin-off projects and by establishing unified support activities. Coherence of the measure and some degree of effective self-governance may be a key factor for its success. Careful analysis of success of and issues with earlier FET Flagships may provide some guidance for the implementation.
B. *Enhance support for hydrogen research and innovations across existing programmes:* So far, the first calls under the EU Innovation Fund have attracted a particularly high number of applications from hydrogen projects, while the desired broad split across sectors may limit the success rate. Including the option of dedicated calls on key technologies in the Innovation Fund Regulation could offer the opportunity to address the commercialisation of hydrogen technologies more explicitly. Similarly, dedicated calls on hydrogen could be launched under the EIC. As both explicitly allow for blending with other national and EU funds, this could trigger substantial additional innovation activities with respect to hydrogen.
C. *Enable Member State action:* State aid regulation strictly limits innovation support for technologies close to the market, but the IPCEI mechanism intends to mitigate market failures that hamper the diffusion of critical technologies. Hydrogen has been assigned to this category, and an initial hydrogen IPCEI is well into its preparation. Interested Member States already held public calls and prioritised individual projects, which are currently combined into a single, EU-wide IPCEI application for approval by European Commission Directorate-General for Competition (DG COMP). On this basis, Member States will obtain individual permission to support their beneficiaries on the costs of first industrial deployment of hydrogen technologies (including pilot production, but prior to mass application), to close the current hydrogen cost gap compared to already established technologies. The systematic continuation of this policy would enable further hydrogen IPCEI initiatives and streamline their implementation process.

Option A would establish a comprehensive research and innovation entity for critical hydrogen technology for long-term, mission-oriented research and industrialisation support in the field (in analogy to the FET Flagship programme). It would require additional funding and changes to current policies (that favour rather loose coordination through independent coordination and support actions), but promises substantial benefits in ensuring the best utilisation of funds and resources and promoting exchange across borders, disciplines and between relevant industries and researchers. In contrast, Option B would focus hydrogen topics in existing programmes, which would strictly limit organisational and budgetary burdens, except binding funds that would therefore not benefit other goals within these programmes. Option C constitutes a powerful measure to enhance the first industrial use of hydrogen technologies, and an initial hydrogen IPCEI is already in preparation. The mechanism does not require major budgets at Union level at all (as funding is exclusively provided by participating Member States that directly fund their national beneficiaries). This advantage may induce some downsides, as little coordination and oversight may occur at Union level. Strategic funding gaps may not be detected, while redundant capabilities for other aspects may be built in several Member States. The programme may also increase economic imbalances within the Union over time (as Member States with already strong industries might provide most support).

5.2.5. Measures for fostering international cooperation

Important conclusions from the consideration of hydrogen production and cooperation with international regions were that the import of renewable hydrogen will be crucial for the EU, and that sustainable cooperation with full-scale supply regions will be needed. To achieve a credible transition towards an extended use of hydrogen, imported hydrogen should be subject to the same classification and criteria as hydrogen produced within the EU. However, as has been outlined above (see Section 3.3), as yet there is no standardised nomenclature at the EU level. The common classification systems, as provided in the EU hydrogen strategy, RED II, the CertifHy project and the common colour code, are discussed above.

These regulatory stepping stones can all serve as a basis to define a clear nomenclature for hydrogen. The EU aims to estabish its leadership and set technical standards and regulations on hydrogen. The most common criteria applied in the regulations above are minimum threshold for GHG emission reduction compared to a fossil comparator, and the additionality of renewable electricity use. CertifHy works with electricity guarantees of origin to prove a renewable share. However, stricter approaches are under discussion. These include the requirement to enter into an exclusive PPA with renewable electricity providers. Alternatively or in addition, the correlation in time of the production of hydrogen with the generation of renewable electricity in the same geographic or grid area are discussed to prove the renewable nature of the hydrogen produced. In its third phase, the CertifHy project will also work to incorporate some of these requirements, if they become part of the regulation of RFNBOs to be developed by the end of 2021. The proposal related to the revised German Renewable Energy Sources Act takes a different approach and defines a maximum number of full load hours (5 000 hours per year) to classify hydrogen from electrolysis as renewable. A similar approach with much smaller full load hours (reaching 2 330 hours in 2026) is taken by the Dutch support programme SDE++ (see Section 5.2.2), where this threshold is used to limit the amount of funding support available to a project.

Expanding on the technical definitions, a hydrogen certification scheme could include criteria to define sustainable hydrogen production in a broader sense. These could include aspects such as propositions for the use of water or other compliance requirements with environmental standards, the use of land areas, economic effects or human rights and the compliance with the SDG's. Respective aspects are discussed above and are summarised in Table 3.

If imports of hydrogen are subject to the same requirements as hydrogen produced inside the EU, the question of monitoring and verification arises. To facilitate this process, it would be advisable to establish an international third party standard. The EU could establish this international hydrogen certification body and thereby assure that the international certification is compliant or compatible with its own regulation. As this is not part of the proposed regulation at EU level itself, options in this regard are not further discussed below.

We further investigate the following options to establish a hydrogen nomenclature within the EU. The annex provides a detailed assessment of these options.

A. *Fully harmonised regulation at EU level*: This option is much discussed by different stakeholders to define renewable and fossil-based hydrogen. A fully harmonised hydrogen classification scheme with clear criteria could be established by an EU regulation. It could cover different sectors and harmonise the approaches under RED II, ETS and CertifHy. Following the terminology used in the EU hydrogen strategy, a limited number of different types of hydrogen could be established. A trading and certification system could be implemented which builds on the

CertifHy project but incorporates the harmonised regulations set out above, and would in this sense be more strict than the current CertifHy GOs. Imports of hydrogen would be classified according to this scheme.

B. *Fully harmonised EU regulation with sustainability criteria*: A fully harmonised regulation could be established at EU level, incorporating the aspects under Option A. In addition, a coherent set of sustainability criteria could be established for the definition of sustainable hydrogen. This could include propositions on the supply of water and on land use, as well as criteria on human rights and SDGs.

C. *No further action at EU level*: No further action could be taken at EU level, meaning the provisions of RED II would define criteria for transport sector fuels and CertifHy would remain a non-binding project. Likely, more independent labels would appear as there is a general need to achieve clarity on the consumer side. Producers would define criteria for self-regulation. As there is no unified nomenclature at EU level, some Member States may fill the gap and set up a separate regulation. These classifications would exist in parallel to each other and to a remnant EU regulation. Imported hydrogen would be classified either according to a different, possibly international standard, or one of the existing sectoral EU regulations.

Options A and B both establish a clearly defined certification at the EU level, but the limited scope of the certified actions under Option A is a plus in many regards. Option A would be easier and thus faster to implement, thereby also making it more effective than Option B. Option A would also be more likely replicated by other countries, which should be considered a benefit. Option B also implements the requirements of the EU hydrogen strategy, but may take longer to establish, and an additional sustainable hydrogen class is not necessarily beneficial to the overall classification. By design, Option B outweighs Option A in terms of sustainability, which can be particularly important for regulating imported hydrogen. Both Options A and B contribute to the success of EU objectives in achieving a relevant position in the hydrogen value chain. Option B also addresses sustainability objectives. The status quo defined by Option C is not effective in providing sufficient clarity for market participants and would not make possible for the EU to establish its leadership in hydrogen regulation. The societal impacts of the options are hard to estimate by way of this study, while Option B likely has least side-effects with regards to social issues.

5.3. Outlook in relation to upcoming policy packages

The policy actions presented in the preceding section are interrelated with several ongoing policy processes at the EU level. While a deeper analysis of these policy processes would go beyond the scope of this study, we briefly mention these here to clarify when and where the different options may be tabled and/or reflected upon.

With its **Fit for 55 package**, the European Commission has provided draft revisions of the Renewable Energy Directive (RED) and the ETS Regulation. The target system discussed under Policy Action 1 is strongly related to the draft revision of the RED, which the Commission has provided as part of the Fit for 55 package. In particular, the draft revision suggests establishing a target of 50 % renewable hydrogen for the industry sector. Related to Policy Action 5, it is suggested to extend the current RED provisions on RFNBOs in the transport sector to other sectors as well. The role of CCfDs discussed under Policy Action 2 is mentioned in the draft of the ETS revision but not further addressed as yet. However, the Commission has suggested increasing the amount of emission certificates dedicated to the Innovation Fund and to establish the option to feed it to CCfDs, thereby strengthening the option to fund hydrogen production and use. Moreover, the ongoing **revision of the European State aid rules** is highly relevant for the design of CCfDs, as well as for further strengthening the IPCEIs relevant for Policy Action 4.

While a few aspects of the regulation of hydrogen infrastructures and markets, as discussed under Policy Action 3, are already addressed in the ongoing **TEN-E revision** process, this topic is at the heart of the **hydrogen and gas market decarbonisation package**, scheduled for the end of 2021. Based on the inception impact assessment and public remarks by the Commission, it can be expected to cover the most important policy gaps raised in this study to a certain extent. Nevertheless, it is likely that there will be high contestation between the different stakeholder groups during the negotiations, in particular on the interlinkage between gas and hydrogen regulation. Furthermore, the certification of renewable and low-carbon hydrogen, as discussed under Policy Action 5, can also be expected to be addressed in this context.

The opportunity provided by the negotiations on these policy packages should be used to ensure that the EU is well on track to realising the benefits of hydrogen for decarbonising industry while limiting undesired side-effects. When dealing with the concrete design of the policies, more detailed analyses (going beyond the scope of the study) will be needed, including on reasonable levels of sectoral hydrogen use and production targets, suitable eligibility and award criteria, as well as investment volumes for CCfDs, the concrete design of infrastructure regulations and research and innovation programmes, and the detailed criteria for certification of hydrogen.

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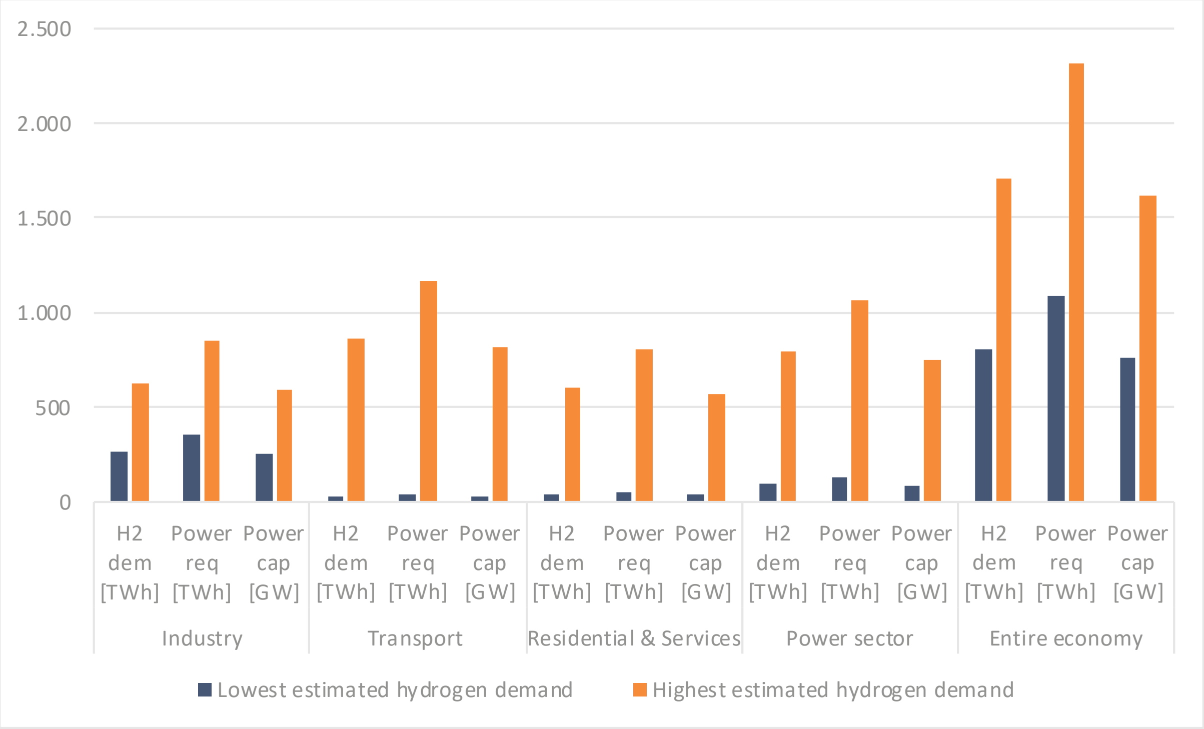
7. Annexes

Details about the need for additional renewable electricity

In this section, further details about need for additional renewable electricity for renewable hydrogen production are provided. Focussing only on industry, the evaluated studies estimate a demand for hydrogen between 265 TWh and 630 TWh in 2050, which would imply a required electricity generation 358 TWh (lower hydrogen demand) and 851 TWh (higher hydrogen demand), respectively. The required electricity capacities would vary between 251 GW and 597 GW (see Figure 11).

In more detail, the discrepancies between the lowest and highest estimated hydrogen demand is driven by the transport sector. Considering only the highest estimated hydrogen demand, space heating is the most important sector, contributing about 27.6 %. But space heating belongs in the hierarchy of uses to the lowest class (see Figure 5).

Figure 11 – Hydrogen demand, electricity requirements and electricity capacities in 2050



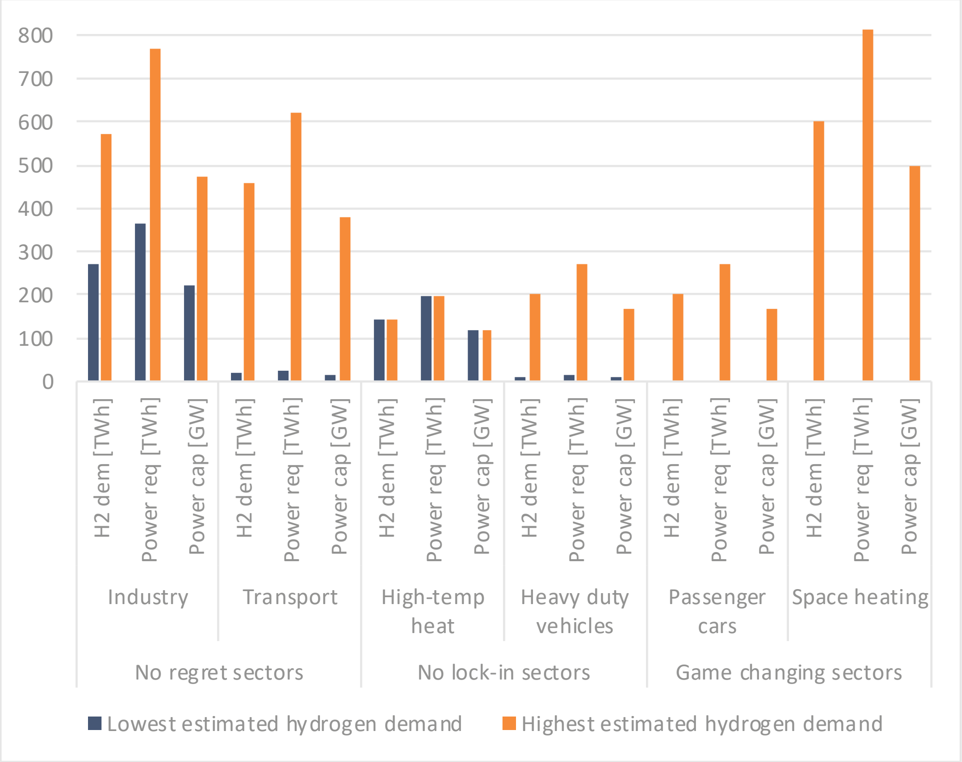
Notes: The estimations for power requirements assume an energy efficiency of electrolyses of 74.0 % (International Energy Agency 2019). The calculation of the power capacity assumes an electricity mix as follows: wind onshore 47 %, wind offshore 15 % and photovoltaics of 38 % (adapted from Xu et al. 2020). The assumed full-load hours are as follows: wind onshore 1,936 h/a, wind offshore 4,032 h/a, photovoltaics 903 h/a (Matthes et al. 2020).

Source: Own calculations based on Agora Energiewende and AFRY Management Consulting 2021; European Commission 2018; Matthes et al. 2020; McWilliams and Zachmann 2021; Guidehouse 2020; International Energy Agency 2019; Xu et al. 2020.

The estimations in respect to required electricity as well as capacities depends crucially on the expected electrolyser's efficiency, electricity mix as well as on the assumed full-load hours in the respective year (Matthes et al. 2020; Helgeson and Peter 2020). A 10 % higher efficiency or 10 % higher full-load hours will reduce the required electricity and the required capacity by 9.1 %. A combined improvement would decline the required capacity by even 21 %.

Depending how produced hydrogen is transported to the demander, additional energy requirements could emerge. The need to compress hydrogen could result in an additional electricity requirement of between 0.12 TWh (if the the gas is compressed to 250 bar) and 0.17 TWh (if the gas is compressed to 800 bar) per TWh of hydrogen produced. Liquefaction, cooling down hydrogen to -253°C, would require 0,3 TWh per TWh of hydrogen produced, with a potential improvement to 0,22 TWh electricity per TWh of hydrogen produced (Matthes et al. 2020).

Figure 12 – Sectoral hydrogen demand, electricity requirements and electricity capacities in 2050 (categorised)



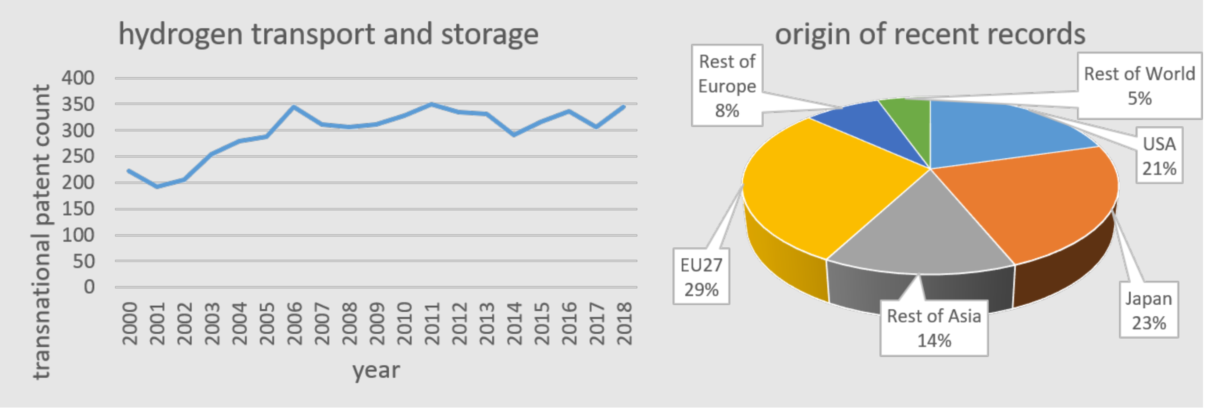
Notes: The estimations for power requirements assume an energy efficiency of electrolyses of 74.0 % (International Energy Agency 2019). The calculation of the power capacity assumes an electricity mix as follows: wind onshore 47 %, wind offshore 15 % and photovoltaics of 38 % (adapted from Xu et al. 2020). The assumed full-load hours are as follows: wind onshore 1,936 h/a, wind offshore 4,032 h/a, photovoltaics 903 h/a (Matthes et al. 2020).

Source: Own calculations based on Agora Energiewende and AFRY Management Consulting 2021; European Commission 2018; Matthes et al. 2020; McWilliams and Zachmann 2021; Guidehouse 2020; International Energy Agency 2019; Xu et al. 2020.

Further details from the patent analyses

Technologies for hydrogen transport and storage may be less distinct or specific, rendering according patent analyses less precise. Figure 13 shows an attempt to provide a rough overview, despite the lack of distinct patent classification, the diversity of particular applications (from vehicular fuel tanks over large-scale gas cavern storage to tubes and pipelines of various scales), and limited specificity of use and context. The underlying research strategy relies on prominent placement of the term hydrogen (beyond relevant key words and class restrictions) to partially screen results relevance (with limited specificity). Better results might be attainable for very specific use cases, but are beyond the scope of the present study.

Figure 13 – Transnational patent analysis on hydrogen transport and storage.

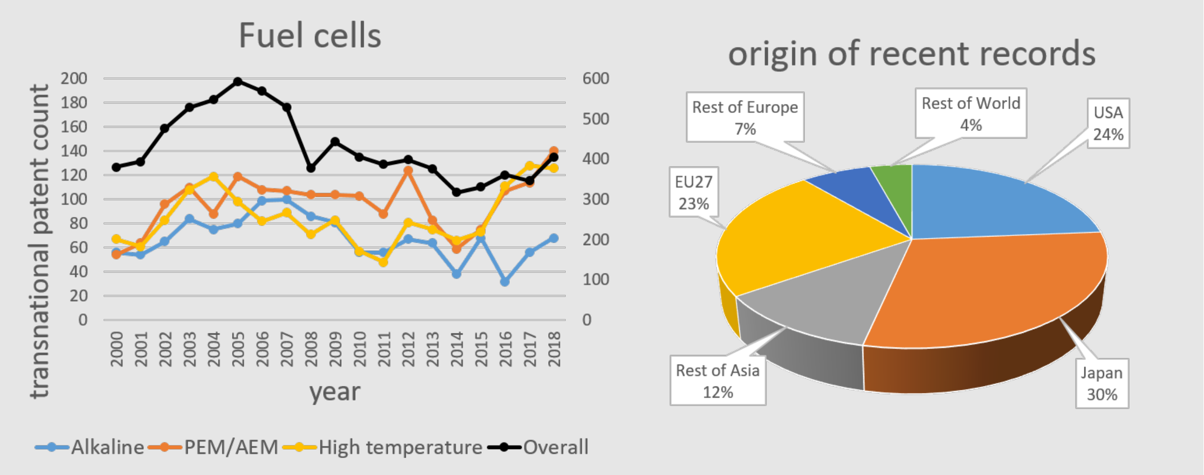


Source: Fraunhofer ISI, own research.

In general, Figure 13 indicates a rather high and slightly rising global patenting activity in the general field of hydrogen transport and storage. The regional distribution shows a substantial share of EU actors as a leading origin among the USA and Japan. Other Asian actors mainly include China and Korea, both contributing substantial numbers.

Beyond specific industrial use cases, fuel cells constitute the primary key enabling technology for widespread hydrogen utilisation throughout numerous sectors including industrial and residential power supply, for grid-scale storage and subsequent re-generation of electricity, and for hydrogen based mobility solutions. Figure 13 presents transnational patent activities in this field.

Figure 14 – Transnational patent analysis on fuel cell technologies.



Source: Fraunhofer ISI, own research.

In particular, the trajectory of the aggregated data for general fuel cell technologies (Figure 14, black line; scaled to right axis, with a factor three) still shows the impact of an earlier hype of hydrogen technologies that began in the last millennium and peaked around the year 2005 ending in 2008 (with the financial crisis). However, a substantial base level of global activity (~300 per year, roughly half of the hype level) was sustained throughout the entire period, and the field started to gain further momentum in the recent years. The vast majority of transnational fuel cell patents stem from a top-3 group of origins led by Japan closely followed by the USA and the EU, while the remainder (roughly only a fifth) is fairly distributed around the globe. In analogy to electrolysers (see above), several distinct technological strains of fuel cells can be distinguished and traced separately (Figure 14, coloured lines, scaled to left axis).

Further details on the evaluated policy options

In this annex, we provide a more detailed analysis of the policy options presented in Section 5.2. In particular, an evaluation of each of the policy options is given, including a semi-quantitative assessment of the evaluation criteria on a scale from ++ (very positive) over 0 (neutral) to -- (very negative). We emphasise that this assessment is meant to highlight advantages and disadvantages but not yield a ranking of the policy options. For a better understanding of the implications, the explanation of the assessments need to be considered.

Policy action 1: Options to foster investments via target systems

Considering the demands to establish a hydrogen economy and taking into account the existing constraints in the EU and worldwide, the question arises how to set the conditions to foster investments in renewable and low-carbon hydrogen to achieve the goals set out in the hydrogen strategy of the EU Commission (European Commission 2020e). Many, but not all, stakeholders support the idea of implementing a dedicated target system (European Commission 2021b). The most common starting point for a target system is the demand for renewable and/or low-carbon hydrogen on the scale of the EU or/and the Member States, expecting trickle-down effects on the production, transport and imports of such hydrogen, on building up of necessary renewable energy plants and storage facilities as well as of electrolyser manufacturing capacities. The following discussed target systems would exclude imports from being recognised in the fulfilment of the targets through a Member State or the entire EU. However, it is beyond the scope of this study to discuss the legal and trade-related consequences of such a design.

Target systems could be either indicative or compulsory. Indicative target systems define legally non-binding targets, i.e. the compliance with the targets cannot be enforced. The effect of indicative targets results from the political commitment to achieve them. Compulsory targets can be legally enforced, i.e. setting binding targets is associated with mechanisms to penalise if targets are not achieved. The most important advantage of binding targets in compliance with sanctions is the high probability of achieving the goals of a hydrogen economy with comparable low GHG emissions. Binding targets could stabilise the expectation of investors in respect to the development of markets producing and using hydrogen, fostering their incentive to invest in technologies with still high propensity to fail. For example, hydrogen-using technologies which could substitute current available technologies in industry or other applications are still under development with low experience in mass production. There is still a lack of experience to run large-scale electrolysers. Besides, high-carbon hydrogen production still shows a noteworthy competitive edge against renewable and low-carbon hydrogen. Long-term targets give also a frame for governments for respective policies and necessary changes of measures. Furthermore, targets are good benchmarks to indicate the success of the intended policy. Although the focus of this Policy Action is on the appropriateness of target systems, under current conditions achieving effective targets without disruptive effects on the economic development require supportive actions by the EU and/or governments of the Member States, as discussed and shown in this report (see Section 3 and the following policy actions).

Implementing a specific instrument, like targets, raises the question whether other options might lead to better results, i.e. to a quicker establishment of a climate-friendly hydrogen economy. The main concerns address the reaction of affected economic agents as well as lack of knowledge in respect to economy-wide impacts. From an economic point of view, target systems for specific technologies or specific hydrogen uses could lead to inefficient solutions if they impede the research and the implementation of alternative technologies, which could show a better performance to achieve carbon neutrality. This means target systems force the implementation of specific technologies which are seen today as the best option, neglecting the dynamics of markets, economic and societal frames as well as the improvement of technical knowledge. This could be particularly true in those sectors where the GHG abatement costs of hydrogen could be quite high (see Section 3.1). The lack of comprehensive knowledge regarding the mentioned dynamics also hamper the identification of unintended impacts.

The implementation of target systems that take into account the techno-economic impediments to reduce GHG emissions could help to overcome some of the above mentioned concerns. Following the hierarchy of hydrogen uses (see Section 3.1.), this would affect primarily the 'no-regret' sectors. These are those activities that can be fully decarbonised by hydrogen, and electrification will not lead to a full decarbonisation. The affected sectors are ammonia, olefins, refineries and steel, as well as aviation and shipping. A side-effect of such a focused target system could be the establishment of competitive hydrogen production, diminishing the need for future supportive actions. According to different scenarios (see Sections 3.1 and 3.2) the no-regret sectors could contribute to half of the expected entire hydrogen demand in 2050 and likely even more in the period up to 2030 (see Section 3.1).

The impact of target systems on establishing a competitive hydrogen economy depends crucially on the medium- and long-term competitiveness of imported hydrogen and the global demand for renewable and low-carbon hydrogen. The crucial factor is the development of renewable energy prices for hydrogen producers (see Section 3.2). The success of a target system also depends on the grade of commitment and the respective sanctions. The grade of harmonisation of the targets and commitments could be also crucial for success. Three different options will be discussed in the following.

A. *Compulsory targets for the EU*: In a joint consultation the European Commission, European Council and European Parliament could define a compulsory target system for the EU with no binding agreements for each Member States. The EU Commission is responsible to achieve the targets. However, if the targets set by the Member States are insufficient to achieve the targets for the EU, the Commission can initiate financing mechanisms comparable to the renewable energy financing mechanism (European Commission 2020b) to succeed these.
B. *Compulsory targets for each Member State*: In a joint consultation the European Commission, European Council and European Parliament could define binding targets for each Member State in compliance with sanctions. The Member States would be responsible to achieve the targets. Necessary measures to achieve the national targets have to be in accordance with the rules set out by the EU.
C. *Indicative targets at EU level*: At EU level, the EU hydrogen strategy could be updated, but the decision whether a compulsory target system is implemented would be left to each Member States. In case a Member State executes a target system accompanied by respective measures, it would have to follow the general rules of EU, like the single market rules.

In the following, the three options are discussed in more detail, using the above mentioned criteria (for an overview, see Table 6 below):

- *Costs (at EU level)*: The costs at EU level consist of costs regarding implementation, controlling, and monitoring of the target systems. Bargaining costs at the EU level or Member State level are not considered, as they are not clearly identifiable. Option A will imply the establishment of an administration for implementing, controlling and monitoring the targets and their fulfilment. Delegating the tasks to the Member States would reduce the costs, but also the controllability (Option A score --). Option B would see no implementation costs at EU level and reduced control costs, since these activities are mainly situated at the Member State level. In total, the EU costs should be lower in Option B than in Option A (Option B score: 0). The lowest costs at EU level could be expected in Option C, since all activities are carried out at Member State level, beside the control costs, whether the principles of the EU are met, when national level measures are implemented (Option score +).

- *Benefits*: Assuming that the targets in Option A shall be same as in Option B, aggregated over the entire EU, and assuming that in both regimes the targets can be achieved, the benefits generated by Option A and B shall be same (score ++). The lowest benefits can be expected for Option C. Option C allows the highest flexibility for each Member State regarding the goal and scope of any hydrogen policy, which includes the option to implement no targets. Whereas this flexibility could be advantageous from a national perspective, it allows also beggar-thy-neighbour policies. Thus, the impact on establishing an EU hydrogen economy would be rather negative (Option C score -).
- *Feasibility*: Both Option A and Option B would need a joint consultation of the European Commission, European Council and European Parliament over the targets and policies to achieve the targets. Whereas Option B includes the coordination of the Member States in respect to the national binding targets on EU level, Option A gives both the EU Commission and the Member States a higher flexibility in respect to defining targets as well as to set the potentially required gap-filling mechanisms, assuming Option A has a higher feasibility than Option B: Option A scores + and Option B scores 0. Option C leaves the relevant decisions to the Member States, indicating the highest feasibility of all Options (Option C score ++).
- *Effectiveness*: National binding and coordinated targets (Option B) should show the highest effectiveness, since each Member State could implement and control the system according to their own conditions. After implementing the target system in principle no additional bargaining is necessary (Option B score ++). The effectiveness of Option A depends crucially on the scale of required gap-filling measures, using the current renewable energy financing mechanism as a reference, and thus, the bargaining time in respect to these measures after installing a target system at EU level. Assuming that gap-filling measures will be necessary, Option A will show a lower effectiveness than Option B (Option A score +). The effectiveness of Option A could be increased, if the European Commission could initiate the financing mechanism independently from available voluntary national contributions. Since Option C allows for diverging targets with the option of establishing no target system, from an EU-perspective the effectiveness of that Option should be lowest (Option C score --).
- *Ecological sustainability:* If permissible emission levels are defined by the target system and if the emissions level in Option A equals that of Option B, the impacts of both options on ecological sustainability are comparable. If no permissible emission levels are defined, just the use of renewable and low-carbon technologies, then the ecological sustainability depends on the mix of used technologies for the production and imports. However, an ex-ante comparison between Option A and Option B is not possible. Renewable hydrogen will have the lowest GHG footprint, compared to all other hydrogen technologies. This will be also true for most other environmental impacts. The low GHG impacts of low-carbon hydrogen stem mainly from the use of CCS technology, which will add some additional environmental impacts, compared to renewable hydrogen, due to investments in storage facilities and transport. Nevertheless, Option A and Option B will generate a positive impact on ecological sustainability (Option A and Option B score +). Presumably Option C will show the lowest ecological sustainability, since the option allows for diverging targets, which should be below the agreed one in Options A and B.
- *Risks:* The most important risks of target systems are: 1) mis-estimating the appropriate targets and affected sectors, if the targets shall differ between sectors; 2) mis-estimating the need to support use and production of renewable and low-carbon hydrogen to achieve the targets; 3) underestimating the challenges to regulate the supporting schemes due to its impacts on the rules regulating the single market. Although the

knowledge about best options to close the competitive gap between renewable and low-carbon hydrogen as well as high-carbon hydrogen is wide-spread, the conditions for achieving competitive hydrogen use and production in the EU are dynamic, depending also on factors which are beyond the influence of the EU, like the global supply of and demand for hydrogen or the legislation outside of the EU. To achieve a maximum impact, the chosen regulation has to be flexible to react to changes on the markets, but rather inflexible to enable quite secure investment conditions over a longer period. Since Option A and Option B see the need for extensive consultations between the European Commission, Council and the Parliament in respect to find a common ground on targets, affected sectors, and supportive schemes, the options to react to changes of the markets and technologies are comparable. Since in Option A no national binding targets have to be agreed on, the chances to deal with risks accordingly are a bit better (Option A score + and Option B score 0). As the institutional conditions to deal with risks are less demanding at Member State than EU level, Option C should provide the lowest risks (score ++).

- *Coherence with other EU objectives*: The implementation of a compulsory target system for the EU with no binding agreements for Member States (Option A) would promote the EU objective of sustainable development based on balanced economic growth and market economy. In addition, the EU spirit of solidarity paying attention to balanced development among Member States in Option A would have the potential to promote just transition across Europe and improve opportunities for Member States to participate in the new hydrogen economy, in particular for those Member States in which hydrogen does not play any important role yet (score +). Option B would stimulate an uneven development of the hydrogen economy across Europe. That means Option B has the potential to benefit Member States that are already pioneers of 'mini' hydrogen economies. Such a potential outcome goes against the EU spirit of solidarity among Member States, and social cohesion. In addition, Option B can be seen as a burden for those Member States in which the development of a hydrogen value chain is still in an insignificant or incipient stage. In order to avoid such a burden, targets for the Member States should not be generic but rather case-by-case oriented, considering the current stage of Member States in the hydrogen value chain (score -). However, both options, that is A and B, struggle with the paradigm of technology openness since they directly (Option A) and indirectly (Option B) favour the hydrogen pathway which seems reasonable from today's perspective but leaves little room for prospective competitive approaches. Option C inherits the risk of selfish pursuit of the Member States goals, leading potentially to a 'beggar-thy-neighbour' policy (score --).
- *Other impacts*: Build-up of a target system has a very limited direct impact on safety, ethics or other social issues (score 0 for option A, B and C).

Table 4 – Evaluation of the different policy options addressing target systems

Options	Costs	Benefits	Feasi-bilitiy	Effective-ness	Ecological sustai-nability	Risks	Coherence with EU objectives	Other impacts
Option A	--	++	+	+	+	+	+	0
Option B	0	++	0	++	+	0	-	0
Option C	+	-	++	--	-	++	--	0

The criteria are assessed based on a scale from ++ (very positive) over 0 (neutral) to – (very negative).

Assessing the different options, a rather diverse picture of the options discussed emerges, with no clear 'best option'. Option B '*Compulsory targets for each Member State*' should generate the highest benefit for the EU and should show the highest effectiveness, but the lowest feasibility and the lowest chance to deal with possible risks. If the Member States in compliance with the European Commission, European Parliament and the Council could find a common ground for the targets, sanction mechanisms and the frame for possible national policies, the implementation of the systems agreed on should be comparable to Option A (see below) rather smooth, although possible delays at national level are also possible. However, characteristic of Option B will be intensive bargaining before the implementation of the national target systems, affecting the feasibility of (ambitious) targets. The same will be true in case of necessary adjustments to the implemented system due to changing political, economic, technical or societal conditions, globally or in the EU.

The main strength of Option A '*Compulsory targets for the EU*' is the achievement of high benefit, which could be comparable to Option B. However, ex ante a precise comparison between both options in respect to the benefit, since the setting of the precise targets could differ between both options. Compared to Option B, this option should show a higher grade regarding feasibility and dealing with risks, since Option A allows Member States and the European Commission a higher flexibility. The main disadvantage could be seen in the highest costs for the EU budget. Also the effectiveness of Option A should be lower compared to Option B. This stems mainly from the non-binding national targets, requiring possibly additional bargaining between the European Commission and Member States in respect to appropriate gap-filling measures, even if the political, economic, technical and societal conditions would not change but the national policies will not allow for achieving the EU targets. From the EU perspective, Option C '*No activities at EU level*' seems to be the least desirable option. Although the feasibility and dealing with risks are the highest of all considered options, in respect to benefits, effectiveness and ecology sustainability Option C has the lowest grade. The main reason for this is the low expectation that the Member States will reach ambitious targets in all Member States or for the entire EU without consultations between the European Commission, European Parliament and European Council. Option C could incite a 'beggar-thy-neighbour policy' in the Member States.

Policy action 2: Carbon contracts for difference

The stocktaking of supporting measures for boosting demand and fostering production showed that there is a particular need to compensate for the high OPEX, both in the production of renewable hydrogen and its use. Carbon contracts for difference (CCfDs) are identified as a key option to overcome the funding gap to large scale application in the area of low-GHG production technologies for energy-intensive products.

Carbon contracts for difference (CCfD) in a nutshell

In general, contracts for difference come from the financial world. They are used to hedge against volatile prices, e.g. for shares or commodities. The seller and buyer agree on a strike price for a product at a certain point in time. If the strike price is below the current market price at that time, the buyer must pay the difference between the strike price and the market price to the seller. If the market price is above the strike price, the seller must pay the difference to the buyer. CCfD use this approach to promote climate-friendly investments, where the product is in principle avoided CO2 emissions. For this purpose, CO2 abatement costs (in €/tonne CO2) are calculated for a given project. As long as the CO2 price is lower than the abatement costs, the company receives a subsidy covering the difference between the abatement costs and the CO2 price. The background is that some investments are only worthwhile if the CO2 price is high in the future. But the future CO2 price is uncertain. The CCfD reduces this uncertainty and can thus trigger investments in new production processes in energy-intensive industry, for example (Bundesministerium für Wirtschaft und Energie 2021a).

The Netherlands has already developed a CCfD-like scheme (SDE++), while Germany has presented overarching principles of a CCfD pilot scheme (CCfD-pilot), to be launched in 2022. At the EU level, the EU Innovation Fund (IF) conceptually also follows the approach of a CCfD. Overarching principles of these programmes are presented in Table 5 to Table 7 below.

Table 5 – Overarching principles of the EU Innovation Fund

Category	Innovation Fund (EU, started in 2020)
Eligibility	The EU Innovation Fund (IF) is a programme which provides funding to specific projects. It is financed by the auctioning of 450 million EU ETS allowances. The IF can provide support to large scale (no upper limit) and small scale (below €7.5 million EUR CAPEX) projects with innovations in energy intensive industry, renewable energy, energy storage and CCS. The costs are calculated with respect to a reference product (in some cases the applicant can use a different method) as relevant costs, which presents a novel approach in project funding. The relevant costs are calculated as the difference of the levelised costs of product to a reference market price. The IF funds a maximum of 60 % of the relevant costs.
Awarding	The projects compete in five categories: GHG avoidance, degree of innovation, project maturity, scalability and cost efficiency. In a two-stage selection process (calls for small scale projects uses single stage calls, the same is planned for the second large-scale call), projects compete against each other within and across sectors. By asking for less than the full 60 % of relevant costs, projects are able to influence their score in the cost efficiency criterion. If a project fails to meet the lower thresholds in project maturity, it may become eligible for project development assistance.
Subsidy mechanism and funding period	The projects receive funding in the form of grants according to their application, which takes into account the first ten years of operation. Up to 40 % of the grant can be paid in advance of the project start. The remaining grant is paid subject to GHG avoidance. If less than 75 % of the emissions are saved compared to the application, the grant amount is shortened.
Budget	Depends on the ETS allowance price. At the start, €10 billion were expected over 10 years. The first large-scale call provides funding of €1 billion.

Source: https://ec.europa.eu/info/funding-tenders/opportunities/portal/screen/programmes/innovfund

Table 6 – Overarching principles of the Dutch SDE++ scheme

Category	SDE++ (Netherlands, started in 2020)
Eligibility	The SDE++ is an operating subsidy to promote climate-friendly investments. There are five categories of technologies eligible for SDE++ support: renewable electricity (e.g. solar PV), renewable heat (e.g. geothermal), renewable gas (e.g. biomass fermentation and combustion), low CO2 heat (e.g. heat pumps) and low CO2 production, which includes CCS and hydrogen production with electrolysis (Netherlands Enterprise Agency 2020). According to Dentons (2020), technologies are only eligible if they are sufficiently marketable, have sufficient CO2 reduction potential, can be introduced on a sufficient scale and have an unprofitable share compared to a known reference technology that can be compensated by an operating subsidy. In addition, certain technological criteria must be met.
Awarding	At the start of the programme, only projects with a subsidy intensity (€/tCO2) below a limit will be admitted, whereby this is technology-specific and will be gradually increased. Applicants will also be given the opportunity to submit their projects for a subsidy intensity below the set limits. The ranking of projects is then based on subsidy intensity. In this way, applicants are encouraged to submit their projects for a lower amount in order to increase the chance of receiving funding. The maximum subsidy intensity is €300/tCO2 (Deloitte. 2020).
Subsidy mechanism and funding period	If a project is selected, the recipient is subsidised for the CO2 avoidance costs. This is done over a period of 12 or 15 years (depending on the selected technology). The subsidy intensity from which the subsidy is then derived is balanced annually. This also includes the revenue generated by the project for the grant recipient, including avoided ETS costs. If the ETS price increases, the subsidy intensity decreases (if it is an ETS-relevant area) (Netherlands Enterprise Agency 2020).
Budget	In 2020: €5 billion.

Sources: own compilation of the information in the sources provided within the table.

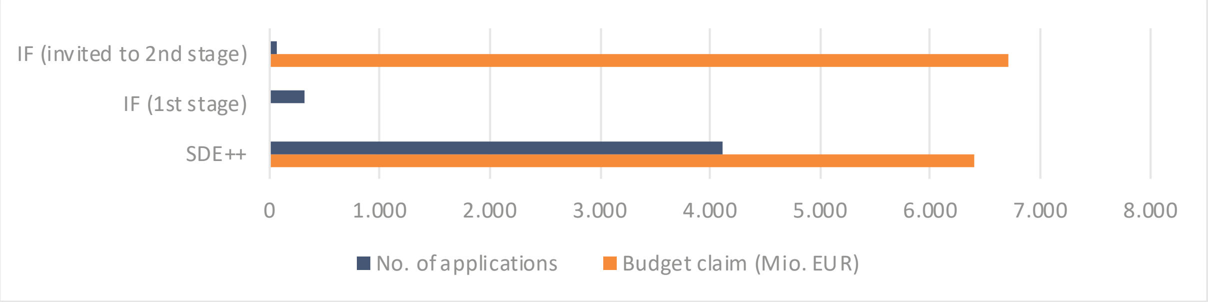
Table 7 – Overarching principles of the German CCfD pilot scheme

Category	CCfD pilot (Germany, not yet started)
Eligibility	In the first phase of the pilot programme, only companies in the steel, cement, lime and ammonia industry with process-related emissions are eligible to apply. The subject of the application are project proposals that are to be realised through the implementation of fundamentally innovative, but technologically mature processes on an industrial scale that lead to a substantial (>50 %) reduction of non-energy-related and energy-related emissions at an industrial site and, from a technical perspective, lead to the achievement of GHG neutrality in 2050 (reduction >90 %). This also includes bridging technologies, such as the partial use of natural gas and green hydrogen in ammonia plants, whereby the share of green hydrogen must increase significantly over the term of the contract. Projects that only lead to improvements in energy efficiency or resource efficiency, are excluded. The use of red, blue or turquoise hydrogen, as well as technologies for the capture of carbon with the aim of underground storage will not be supported (German Ministry of the Environment, Nature Conservation and Nuclear Safety 2021).
Awarding	A multi-stage award with competitive elements in the sense of a tender is planned. The award is to be made according to the lowest strike-price (funding cost efficiency) and further award criteria (GHG reduction, degree of innovation, degree of maturity, scalability, transfer effects). A ranking is planned, on the basis of which the projects will be funded until the budget is exhausted (German Ministry of the Environment, Nature Conservation and Nuclear Safety 2021).
Subsidy mechanism and funding period	If a project is selected, the recipient receives a subsidy covering the CO2 abatement costs. Currently, a contract term of 10 years is envisaged. If the CO2 abatement costs become negative during the contract period (e.g. due to a sufficiently effective CO2 price), i.e. if the project proves to be economic compared to the marketable reference, a subsidy is not provided and a payment obligation arises on the part of the funding recipient.
Budget	Currently €550 million (Deutscher Bundestag 2021).

Sources: own compilation of information from the sources provided within the table.

Following the first large-scale call for the IF, 311 projects were asking for a total funding of €21.7 billion. Some 70 projects requesting €6.7 billion were selected for the second stage, of which 66 have handed in an application. For SDE++, about 4 000 projects with a requested funding volume of about €6.4 billion were submitted. This shows that there are significantly more applications for SDE++ compared to the Innovation Fund and thus a significantly lower budget request per project, which reflects the different character of the programmes, see Figure 15.

Figure 15 – Number of applications and budget claimed in IF and SDE++



Source: Own representation based on European Commission (2021e) and (CMember States 2021).

In terms of eligibility, there are clear differences between the Innovation Fund, SDE++ and CCfD-Pilot. The German CCfD-pilot targets (in the first phase) industrial sectors with process emissions (steel, cement, lime and ammonia industry). Only projects that i) lead to a significant reduction in GHG emissions (>50 % at start) and ii) are technically suitable to achieve GHG neutrality by 2050 (reduction >90 %) are eligible to apply. The Dutch SDE++, in contrast, is broader in scope and targets technologies rather than specific sectors. In principle, projects can be applied for if the underlying technologies are eligible. The difference in the area of CCS is worth highlighting; while this is explicitly also permitted for permanent underground storage in SDE++, this option is explicitly excluded in CCfD-Pilot. The IF funds projects from energy intensive industries, but also in other sectors. CCS is an explicit funding pillar.

In terms of awarding, the design is more comparable. Both SDE++ and CCfD-Pilot rely on subsidy intensity or strike-price to rank the submitted applications and thus competitively award the available funding volume. This is in part also true for the Innovation Fund, which partly awards on cost efficiency.

The designs are also comparable with regard to the subsidy mechanism. In both SDE++ and CCfD, the actual subsidy volume is to be determined annually, and in both, the ETS price for CO2 allowances is taken into account. In both programmes, the subsidy recipient can be obliged to make a payment if the revenues or savings exceed the CO2 abatement costs. The funding of the Innovation Fund is not linked directly with the ETS price, but it is shortened if a certain amount of GHG emission savings are not achieved.

In terms of funding period, the designs are somewhat different. With SDE++, contract periods of up to 15 years are possible, whereas with CCfD-Pilot only contracts of up to 10 years are currently being considered. The Innovation Fund provides funding for the first 10 years of operation.

The differences found between the existing and planned CCfD-type programmes raise the question of whether there is a need for harmonisation at the level of the European Union. We discuss this for the following three basic options:

A. *Full regulation at EU level:* CCfD programmes are being developed at EU level that exceed the scope of the existing Innovation Fund both in terms of funding scope and existing funding budget.
B. *EU directive to be elaborated at Member State level or EU regulation with direct applicability:* A directive would provide Member States with a framework for the design of CCfDs. If the directive is correctly transposed into national law, a state aid assessment is no longer necessary. Alternatively, a regulation could be drafted that determines how CCfDs should be specifically designed if the Member States do so.
C. Full control of CCfD programmes at Member State level: The EU would make no harmonisation efforts.

Next, we assess these three options on the basis of the evaluation criteria:

- *Costs*: Option A has high direct costs for the EU compared to the other two options, as it requires significant financial resources to organise such a programme (score -). Option B has only administrative costs (score o) and Option C has no direct costs (score +).
- *Benefits:* Option A increases accessibility for CCfDs in the European Union, as companies from all European states can participate, regardless of what Member States do. In terms of elgibility, positions on technologies are harmonised (e.g. is CCS eligible or not, hence, a decarbonisation option that the EU is supporting or not). This may be advantageous for investors, as e.g. cross-border projects can be organised more effectively (score ++). Option B reduces the effort for Member States to implement CCfDs. In addition, certain aspects that appear important (e.g. technological focus) can be regulated. Both regulation and directive could be written in such a way that Member States have the possibilities to design CCfDs to fit into the architecture of their national energy and climate policies. (score +). The argument in favour of Option C is that there may be a reason why CCfD-type programmes are designed differently in various Member States, e.g. because the architecture of energy and climate policy instruments differs. Nevertheless, under Option C, there is a possibility that some Member States lack the capacity to develop CCfDs (score 0).

- *Feasibility:* The feasibility of Option A may be affected by the lack of funding needed to develop larger CCfD-type programmes. The feasibility of Option B might only be affected by formal obstacles. For Option C, there is no argument against doing nothing. However, all three options are in principle feasible, provided that the will of the stakeholders is there, which is why 0 is uniformly scored.
- *Effectiveness:* In terms of (market-) harmonisation, Option A offers the highest effectiveness, as for example an effective funding framework for cross-border projects can be established (score +). Option B may fail to achieve harmonisation objectives if the regulation/directive is drafted in a way that allows many degrees of freedom. If it is too narrow, it may lack acceptance in the Member States. Thus, a directive can also turn out to be a 'toothless tiger'. Therefore, the effectiveness of Option B is considered balanced (score 0). In terms of harmonisation, Option C has no effectiveness (score -).

Ecological sustainability: Limited direct impacts on ecological sustainability for all options (score 0).

- *Risks:* For Option A no immediate risks are seen if the capital is available (score +). The risk of Option B is that the harmonisation objectives are not achieved (score -). The risk of Option C is that certain Member States (with little capacity) are disadvantaged (score -).
- *Coherence with other EU objectives:* Considering the impact to other EU objectives it reveals that Option A may lead to equal and fair access for all Member States on CCfDs funds. In addition, it may stimulate cross-Member State activities based on EU-wide collaborative action. Collaborative action across Member States includes favouring technology innovation since CCfD focus primarily on financing technology substitution and innovation (score: ++). Option B can be assessed in equal terms, though to a lesser extent. It also helps favour competitive technology leadership but may lead to unequal access for Member States on CCfDs funds. In addition, Member State funds will differ by volume which leads to unequal access options (score: +). Option C, in contrast, can be judged a neutral impact due to the fact of no CCfD action (score 0).
- *Other impacts:* For the field of other impacts, we do not see relevant consequences of the Options A, B and C.

The assessment of the policy options under the second policy action field is summarised in Table 8. The benefits of Option A lie in particular in the fact that access to CCfDs can be improved for companies in the EU from all Member States. In addition, positions on technologies can be harmonised across the EU, which can be of great advantage for cross-border projects. In principle, there are no direct risks, but in terms of feasibility, the question is whether sufficient capital can be made available for a European CCfD programme. A benefit over the existing Innovation Fund would be to go beyond innovation funding and support the market introduction of technologies, which may well require large sums. The benefit of Option B is that the harmonisation goals in the EU can be achieved with comparatively low (only administrative) costs. However, the pitfalls here lie in the details. If a directive allows too many degrees of freedom, the harmonisation goals will not be achieved. In this case, the directive would not be effective and change little compared to the current situation. If the directive allows too few degrees of freedom, it may not be implementable because it does not take into account the different characteristics of the Member States. A common directive, however, has the advantage that a State aid notification of individual CCfD programmes would likely not be necessary due to the nature of the directive. Doing nothing (Option C) has the benefit of not incurring costs and not limiting Member States' ability to design CCfD programmes to fit into their respective energy and climate policy architecture. A risk, however, is that certain Member States lack capital and know-how to set up their own CCfD programmes, and companies in these countries may fall behind other Member States in terms of transformation.

Table 8 – Evaluation of the different policy options addressing the design of carbon contracts for difference

Options	Costs	Benefits	Feasi-bilitiy	Effective-ness	Sustai-nability	Risks	Coherence with EU objectives	Other impacts
Option A	-	++	0	+	0	-	++	0
Option B	0	+	0	0	0	-	+	0
Option C	+	0	0	-	0	-	0	0

The criteria are assessed based on a scale from ++ (very positive) over 0 (neutral) to – (very negative).

Policy action 3: How to design hydrogen infrastructure and market legislation

The synthesis of the scientific literature, stakeholder position papers and expert interviews in Section 3.3 has revealed that a stepwise approach for building up hydrogen networks is crucial for fostering the European hydrogen economy and that the corresponding legislation needs to ensure a swift expansion while being flexible with respect to the exact infrastructure needs. The transport of hydrogen bears similarities with the transport of natural gas to a certain extent. Even more, hydrogen networks may be established partially by the repurposing of existing gas pipelines. Therefore, it seems reasonable to develop a future legislation for hydrogen infrastructures in view of the existing gas legislation, in particular the Gas Infrastructure Regulation No 715/2009 and the Gas Market Directive 2009/73/EC.

Certain key principles have proven useful in developing the internal energy markets on the EU level. In particular, the natural monopolies associated with the ownership of energy infrastructures have led to the requirement of non-discriminatory access by all interested parties, which goes hand-in-hand with both the vertical and the horizontal unbundling of the network system operators. It is noteworthy that these principles did not apply when a major part of the infrastructure was built up, but were established later to foster competitive and transparent energy markets. Therefore, exceptions from these principles for a limited period of time could be considered an option.

According to the costs-by-cause principle, the infrastructure costs are to be borne by the causative agents, which are the users and/or suppliers of the traded good. Given the horizontal unbundling of energy infrastructures, this speaks against the option to have gas network users cross-finance hydrogen networks. Moreover, cross-financing of national transport networks via pipelines for transit purposes only is to be avoided. Still, different splits of costs between users, suppliers and the public are possible. In particular, it is clear that the high upfront investments in hydrogen networks can be prohibitive for an expansion of the infrastructure, as long as supplies and users of hydrogen are limited. Since the expansion of hydrogen is meant to the serve the societal objective of reaching climate policy targets and is, hence, of a certain European interest, it is justifiable to consider the use of public funding for hydrogen networks, in order to foster the build-up of hydrogen networks to the extent needed for security of supply of no-regret users.

A key conclusion on the regulation of hydrogen infrastructure is that while currently there is no immediate need for an overarching regulation, as there are almost no cross-border networks in the EU yet, clarification is needed on what the overarching principles would be and which concrete setups seem favourable. To provide clarity when the legislation for hydrogen networks will be established or starting to apply, the definition and monitoring of key indicators and thresholds can be useful. Such indicators can include the length of cross-border hydrogen networks, the volumes of cross-border hydrogen transport and traded, as well as the number of actors, i.e. potential market participants. In the following, we elaborate on several options how to address these issues within the hydrogen and gas market decarbonisation package to be drafted by the Commission by the end of 2021. In principle, the EU has three overarching options how to deal with the present lack of a regulatory framework for hydrogen infrastructures:

A. *Full regulation at EU level:* The hydrogen and gas market decarbonisation package would establish an EU-wide regulatory framework comparable to the existing gas infrastructure legislation with EU-wide fixed rules on unbundling, third-party access, roles of system operators, network codes and remuneration of costs.
B. *EU directive to be elaborated at Member State level:* The proposed hydrogen and gas market decarbonisation package would establish EU-wide principles, in particular on unbundling and third-party access. It could also announce thresholds for key indicators triggering further regulatory steps, but leave room for experimentation at Member State level during a certain pre-defined period, in particular with respect to roles of system operators, network codes and remuneration of costs. This has similarities with the concept of regulatory innovation zones, which have been useful for testing the regulation of peer-to-peer electricity trading in Germany.
C. *Keep control at Member State level until further notice:* The EU could announce thresholds for key indicators triggering regulatory steps at the EU level but could leave it to the Member States to decide if and how to establish a regulation for hydrogen networks during a certain pre-defined period.

All options may include a stepwise approach, for instance requiring third-party access only after a certain period. In the following, we address the evaluation criteria for the three policy options described above one-by-one and discuss the pros and cons of the different options, resulting in a relative scoring for each of the criteria. Afterwards, we summarise the most important differences.

- Costs: The direct public spending at EU level implied by a legislation for hydrogen networks and markets are limited for all options. However, any legislation will lead to certain administrative efforts related to the monitoring of indicators and compliance with the established rules. This effort will of course be the higher the more stringent the rules. Hence, the expected efforts are highest for Option A, (score -) still relevant for Option B (score 0) but rather modest for Option C (score +).
- *Benefits:* The benefits of a legislation of hydrogen networks and markets can be quite diverse and strongly differ between the considered options. Option A provides the most stringent regulation, in particular enabling an easy integration of local networks into a European backbone. The high certainty about the rules from the beginning may lead to quicker investments and thus a quicker rollout of the required infrastructure (score +). Option B allows to test the pros and cons of different setups while still ensuring harmonisation for certain key elements (score +). Option C allows to take into account the regional circumstances in the most comprehensive way. In particular, fast infrastructure roll out can be pushed easily by Member States where needed (score +).
- *Feasibility*: With respect to the political feasibility, the various options have quite different prospects. Establishing a rather comprehensive overarching regulation as in Option A would require an agreement on the preferred setup between the Commission, the Parliament and the Member States. Given the lack of experience with regulating hydrogen networks, it is likely to be difficult to reach such a far-reaching agreement (score -). However, the main overarching principles for fostering a single market, namely non-discriminatory third-party access and unbundling, are mainly accepted by all the Member States in the context of other energy infrastructures. So there will be likely no general objections to establishing these early on. This suggests that Option B of regulatory innovation zones with overarching principles has higher chances of being implemented successfully, while certain actors may still oppose it due to preferences for a different option (score +). The full national control of Option C is likely to face no strong

opposition by Member States, but still pro-active Member States and EU bodies may show reluctance towards this Option (score 0).

- *Effectiveness:* A legislation of hydrogen networks is deemed effective, when it leads to an expansion of the networks in line with the uptake of supply and demand in a plannable manner. Option A is the most effective with respect to establishing desired principles and enabling a later integration of regional networks with high certainty. However, it could turn out to be prohibitive for a quick infrastructure rollout, depending on the stringency of the concrete design principles (score 0). Option B should be as effective as Option A with respect to the overarching regulatory principles and thus a later harmonisation, but it can be expected to grant more flexibility in taking into account local circumstances, thereby enabling a network expansion tailored better to the local needs (score +). The freedom of Option C would lead to the most flexible network expansion, but would also leave highest uncertainty about the development of hydrogen networks in line with demand and supply as well as its later integration (score -).
- *Ecological sustainability:* The legislation of hydrogen networks and markets has limited direct impacts on ecological sustainability, mainly independent of the chosen option. Nevertheless, a stringent regulation as in Option A could allow to establish stricter safety regulations for hydrogen networks and additional sustainability criteria for building new hydrogen pipelines (score + for Option A, 0 for Options B and C).
- *Risks:* Two important risks of the legislation on hydrogen networks and markets can be identified: 1) too prohibitive conditions blocking the build-up of the required infrastructures; 2) an uncontrolled expansion resulting in a mismatch with actual needs, or hurdles for later integration of regional networks. Given the limited experience with hydrogen networks, Option A may fail to identify the most efficient solutions and the resulting infrastructure rollout and might not match supply and demand (score -). The uncertainty about the future harmonisation of regional regulations could lead to limited investments and a delayed expansion for Option B (score -). In turn, Option C may result in higher system costs due to an even stronger need for later harmonisation. The later integration could even face high hurdles due to incompatibilities. Moreover, there would be little control at the EU level, and the high uncertainty about future requirements could also lead to delayed investments (score --).
- *Coherence with other EU objectives:* Option A may lead to a well-balanced European infrastructure and fully integrated single market, since it favours cross-European planning from the very beginning (score +). In contrast, Option B and Option C might lead to a patchwork of singular country planning and implementation, which might lead to difficulties in integration to a common EU market (score -).
- *Other impacts:* The build-up of a hydrogen infrastructure will have a limited direct impact on safety, ethics or other social issues such as acceptance if such an infrastructure will be based on refurbishing gas pipelines with an established high level of technology safety standards. The build-up of new hydrogen infrastructure including new pipelines and CCS(U) facilities may be influenced by local and national acceptance issues, the extent of which is not possible to assess in this report (i.e. should be analysed case-by-case) (score 0 for options A, B and C). Nevertheless, strict safety regulations for hydrogen will need to be applied to both repurposed gas infrastructure and new hydrogen infrastructure in any case.

The assessment of the policy options under the third policy action field is summarised in Table 9. Option A with the most comprehensive EU-wide legislation shows advantages with respect to fostering an integration of regional networks into a hydrogen backbone and environmental sustainability. In turn, Option A would lead to the highest administrative efforts. Moreover, it could also turn out to be not politically feasible in the near future and ineffective in finding the best regulatory setup due to a lack of experience with the regulation of hydrogen networks and markets. The existing risks in Option A can delay the EU objective of a just and sustainable energy transition. The more flexible approach of Option B should lead to higher political feasibility and effectiveness in finding the best regulatory setups. Also, it can accelerate quick infrastructure for the energy transition. However, this comes with moderate disadvantages due to less certainty about later integration and environmental stringency as well as for investors. Finally, Option C leads to the lowest administrative efforts and the highest flexibility for the Member States, but comes with high risks for a later integration of regional networks in a European backbone and the resulting uncertainty for investors and about its effectiveness. This will also impose burdens for the EU objective of just and sustainable transition.

Table 9 – Evaluation of the different policy options addressing the design of hydrogen infrastructure and market legislation

Options	Costs	Benefits	Feasi-bility	Effective-ness	Sustai-nability	Risks	Coherence with EU objectives	Other impacts
Option A	-	+	-	0	+	-	+	0
Option B	0	+	+	+	0	-	-	0
Option C	+	+	0	-	0	--	-	0

The criteria are assessed based on a scale from ++ (very positive) over 0 (neutral) to – (very negative).

Policy action 4: Options to promote research and innovation in key hydrogen technologies

Thorough transnational patent analyses confirm the general strength of the EU in fundamental research to include key hydrogen technologies and application development for industrial utilisation. However, the EU often lags behind other global regions in the conversion of scientific insight into economic success. General reasons for and potential measures of overcoming this gap are part of EU discourse and already influence current EU policy:

- Novel general innovation support mechanisms such as the EU Innovation Fund have been established.
- Horizon Europe (the current phase among the traditional EU research framework programmes) strongly emphasises applied research and its industrial utilisation, in particular with the European Innovation Council (EIC) programmes.
- The IPCEI mechanism enables strong Member State support of first industrial use of novel technologies where market failures in the advancement of desirable technologies has been detected and officially recognised.

In general, EU policy goals need to balance enhancing the industrial-scale commercialisation of present strengths in fundamental and applied research, while maintaining and extending the latter in the future. Here, the overall focus of Horizon Europe on practical innovation may also produce undesirable side-effects by effectively restricting the expenditures in foundational research efforts or promoting sub-critical and ineffective ('fig-leaf' type) innovation components in many projects. coordination and support actions (CSA) across entire calls or lines of funding may mitigate such issues, but close interaction with practical research measures appears critical for their success. In the past, the FET Flagship mechanism intended to create a novel measure for dedicated mission-oriented research with longer-term commitment. Initially, their implementation allowed for comprehensive, well-integrated project consortia with a substantial degree of self-organisation. However, policy recently shifted towards rather loosely combining several topical research projects with an independently organised CSA, where the most recent initiative (Battery 2030+) essentially dropped the Flagship label. Despite organisational challenges in some of the earlier Flagships, others successfully demonstrated the systematic transformation of fundamental research excellence into industrial innovation initiatives strongly supported by a coherent integrated project structure.

Here, we discuss specific policy options to enhance the EU position in hydrogen technology implementation, i.e. maintaining a strong position in related fundamental and applied research while specifically promoting the ramp-up of their commercial implementation.

A. *Establish a dedicated R&D frame:* Beyond promoting key hydrogen technologies in the frame of Horizon Europe, the EU could create designated research and innovation frameworks for critical hydrogen technology (such as electrolysers) to combine leading research groups in the field in a single, long-term funding programmes that could enable effective division and coordination of research tasks, systematic exchange on present results and future directions as well as combined innovation support initiatives by industrial spin-off projects and establishing unified support activities. Coherence of the measure and some degree of effective self-governance may be a key factor for its success. Careful analysis of success of and issues with earlier FET Flagships may provide some guidance for implementation.

B. *Enhance support for hydrogen research and innovations across existing programmes:* So far, the first calls of the EU Innovation Fund has attracted a particularly high number of applications by hydrogen projects, while the desired broad split across sectors may limit the success rate. Including the option of dedicated calls on key technologies in the Innovation Fund Regulation could offer the opportunity to address the commercialisation of hydrogen technologies more explicitly. Similarly, dedicated calls on hydrogen could be launched under the EIC. As both allow explicitly for blending with other national and EU funds, this could trigger substantial additional innovation activities with respect to hydrogen.

C. *Enable Member State action:* State aid regulation strictly limits innovation support of technologies close to the market, but the IPCEI mechanism intends to mitigate market failures hampering the diffusion of critical technologies. Hydrogen has been assigned to this category, and an initial hydrogen IPCEI is well into its preparation. Interested Member States already held public calls and prioritised individual projects which are currently combined into a single, EU-wide IPCEI application for its approval by DG COMP. On this basis, Member States will obtain individual permissions to support their beneficiaries on costs of first industrial deployment of hydrogen technologies (including pilot production, but prior to mass application) in order to close the present cost gap of hydrogen compared to readily established technologies. The systematic continuation of this policy would enable further hydrogen IPCEI initiatives in the future and further streamline their implementation process.

In the following, the three options are discussed in more detail, using the above mentioned criteria:

- Costs: The direct public spending impact at EU level of all options above remains on a rather limited scale. In particular, only Option A would require some additional budget for a new dedicated (Flagship-type) programme on key hydrogen technologies. (score-). In contrast, Option B would not require additional funds, but mainly to dedicate certain portions of existing funds under Horizon Europe and the Innovation Fund to hydrogen. Since hydrogen technologies are already covered by these funds, the impact would be limited. Moreover, the call procedures are well-established so that additional administrative costs would be marginal (score 0). Finally, Option C would not require any additional budget at Union level at all, as all funding in the IPCEI programmes is exclusively provided by participating Member States. (score +)

- Benefits: All policy options promise substantial benefits for EU technology development in the hydrogen sector. In particular, Option A enables the EU to expand fundamental strengths in hydrogen technology, while creating a coordinated research framework to support its industrialisation (score ++). Option B directly dedicates existing EU budget towards hydrogen innovation support, which enables some centralised planning an oversight towards Union level goals. (score +) In contrast, Option C certainly represents a dedicated measure for Member States to strengthen their hydrogen related industries, which effectively does not exceed the status quo (as the hydrogen IPCEI already is in its implementation phase). (score +)
- Feasibility: All the above options appear fairly feasible, but require different levels of effort. In particular, Option A would benefit from a shift in research funding policy towards coherent project structures and reliance on (perhaps guided) scientific self-organisation. (score 0) Option B would require changes to existing regulations and additional coordination activities by the Commission. Since the costs would be covered by existing funding sources, no general opposition is to be expected. (score +) Regarding Option C, the first hydrogen IPCEI is well on its way, hence only requires little further action. (score ++)
- Effectiveness: The effectiveness of the above policy options mainly depends on the achievable level of coordination, which will likely determine the alignment of partial measures, and thus the efficiency with which the spending is utilised. For instance, Option A may create an EU-wide, long-term scientific innovation support framework in the field of hydrogen technologies with comparably low investment. (score ++) The effectiveness of Option B in terms of strengthening the EU's global position would depend on the particular operationalisation by the Commission. Since the Commission has its own interest in supporting the EU hydrogen strategy, this is no strong caveat. However, the lack of explicit coordination might limit the effectiveness. (score +) In contrast, Option C encourages Member States to primarily support their own national industries, which may lead to suboptimal overall funding allocation at EU scale (building redundant capacities in certain areas, while other might experience funding gaps). (score -)
- Ecological sustainability: In general, all options contribute to sustainable goals, but on a secondary level, we can judge potential misallocation of funds to create undesirable impacts. Option A could complement research activities towards EU sustainability and climate goals, while its coordination function may strengthen the efficient use of funding and resources. (score ++) Also, the Innovation Fund already considers GHG emission avoidance and life-cycle impacts in the evaluation. Option B allows to establish sustainability criteria even more focused to hydrogen-related issues in the dedicated calls and apply these in the evaluation. (score +) In contrast, Option C certainly aims at technologies relevant for sustainability, but competition between Member States may provoke inefficiencies in resource and funding allocation (at Union level). (score -)
- Risks: The risks of the options described above mainly depend on the scale of adverse side-effects and the ability to control those. Option A would revitalise a programme with mixed track records including success stories and disappointments. Failure to differentiate between and learn from past experiences may induce a minor risk of repeating mistakes. (score +) Option B would directly allocate EU innovation support funds specifically to hydrogen topics. Hence, scarcity of funds for other topics might increase (without overall budget increase). (score +) Option C creates substantial long-term risks including suboptimal funding allocation across the EU and effectively strengthening economic imbalances within the Union (as Member States with already strong industries might support those most). (score --)

- *Coherence with other EU objectives:* Option A will provide equal access to (cross) Member State research consortia aiming at hydrogen innovations to be established across Europe by means of a clear visible and standalone R&D framework. On the other side, a small number or even just one large flagship project is not able to cover all Member States or regions (score +). Option B may lead to R&E results on a very broad scope due to the fact of several programmes with a potentially high number of single projects covering a diverse set of topics (score +). Option C with a Member State approach will stimulate single Member State activities resulting in multi-speed activities with a frontrunner positioning of highly competitive R&D actors. Considering the objective of a just transition, this may lead to negative impacts (score -).
- *Other impacts:* Options A, B and C to promote research and innovation in key hydrogen technologies do not have considerable direct impact on other issues such as ethical, social issues (score 0). However, socio-technical energy transformations may be addressed specifically in research findings, in particular within Options A and B, and thereby help dealing with such issues.

The assessment of the policy options under the third policy action field is summarised in Table 9. Option A would establish a comprehensive research and innovation entity for critical hydrogen technology for long-term, mission-oriented research and industrialisation support in the field (in analogy to the FET Flagship programme). It would require substantial additional funding and changes in current policies (that favour rather lose coordination through independent coordination and support actions), but promises substantial benefits in ensuring best utilisation of funds and resources and promoting exchange across borders, disciplines and between relevant industries and researchers. In contrast, Option B would rather focus hydrogen topics in existing programmes, which would strictly limit organisational and budgetary burdens, except binding funds that, hence, will not benefit other goals within these programmes. Option C constitutes a powerful measure to enhance first industrial use of hydrogen technologies, and an initial hydrogen IPCEI is already in preparation. The mechanism does not require major budgets at Union level at all (as funding is exclusively provided by participating Member States that directly fund their national beneficiaries). This advantage may induce some downsides though as little coordination and oversight may occur at Union level. Hence, strategic funding gaps may not be detected, while redundant capabilities for other aspects may be built in several Member States. The programme may also increase economic imbalances within the Union over time (as Member States with already strong industries might provide most support.

Table 10 – Evaluation of the different policy options addressing research and innovation support

Options	Costs	Benefits	Feasi-bilitiy	Effective-ness	Sustai-nability	Risks	Coherence with EU objectives	Other impacts
Option A:	-	++	0	++	++	+	+	0
Option B:	0	+	+	+	+	+	+	0
Option C:	+	+	++	-	-	--	-	0

The criteria are assessed based on a scale from ++ (very positive) over 0 (neutral) to – (very negative).

Policy action 5: Nomenclature and certification of renewable and low-carbon hydrogen

Important conclusions from the consideration of hydrogen production and cooperation with international regions were that the import of renewable hydrogen will be crucial for the EU and that a sustainable cooperation with full-scale supply regions will be needed. In order to achieve a credible transition towards an extended use of hydrogen, imported hydrogen should be subject to the same classification and criteria as hydrogen produced within the EU. However, as has been outlined above (see section 3.3), there does not yet exist a standardised nomenclature at the EU level itself. The common classification systems have been discussed above:

- The EU hydrogen strategy broadly defines renewable and low carbon hydrogen and sets out the goal to establish an EU wide regulation based on ETS benchmark, RED II or CertifHy
- RED II sets out criteria for RFNBO in the transport sector, a delegated act is expected at the end of 2021
- CertifHy defines guarantees-of-origin for green hydrogen in an independent industry project also mentioned as a basis for EU regulation by the hydrogen strategy
- A colour code to label different production pathways is commonly used but provides little regulatory clarity.

These regulatory stepping stones can all serve as a basis to define a clear nomenclature for hydrogen. The EU aims to set its leadership technical standards and regulations on hydrogen. The most common criteria applied in the regulations above are minimum threshold for GHG emission reduction compared to a fossil comparator and the additionality of renewable electricity use. CertifHy works with electricity guarantees of origin to prove a renewable share. However, stricter approaches are under discussion. These include the requirement to enter into an exclusive PPA with renewable electricity provider. Alternatively, or in addition, the correlation in time of the production of hydrogen with the generation of renewable electricity in the same geographic or grid area are discussed to prove the renewable nature of the hydrogen produced. In its third phase, the CertifHy project will also work to incorporate some of these requirements if they become part of the regulation of RFNBOs to be developed by the end of this year.[7] In a broader sense, the proposal related to the revised German Renewable Energy Sources Act[8] takes a different approach and defines a maximum number of full load hours (5 000h per year) to classify electrolysis as renewable. A similar approach with much smaller full load hours (reaching 2 330h in 2026) is taken by the Dutch support programme SDE++ (see Policy Action 2), where this threshold is used to limit the amount of funding support available to a project.[9]

Currently, comparable regulation is mainly focused on technical criteria such as the composition of certain materials or shapes (DIN, ISO), or on voluntary third party initiatives (e.g. FSC) but also includes some conceptually similar standards such as for environmental management (ISO 14001) or life-cycle assessment (ISO 14044). These are voluntary standards, meaning they do not need to be fulfilled. A sector that could also serve as a blueprint to establishing international certification schemes regarding production processes is the EU organic farming certification, which has established an EU standard that is also applied to imported goods. Monitoring is either performed by national institutions or independent bodies.[10] While food may be imported and sold in other standards, all products to be sold in the EU need to fulfil the requirements of the CE marking, which assures that safety and other relevant EU regulations are met. However, this again refers only to properties of the final product, not to properties of the production process, which does not make it a full blueprint for certifying hydrogen.

Expanding on the technical definitions, a hydrogen certification scheme could include criteria to define sustainable hydrogen production in a broader sense. These could include aspects such as

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[7] See https://www.certifhy.eu/images/media/files/201214_Press_release_CertifHy_3_Launch_EN_Final.pdf

[8] See https://www.bmwi.de/Redaktion/DE/Downloads/V/verordnung-zur-umsetzung-des-eeg-2021-und-zur-aenderung-weiterer-energierechtlicher-vorschriften.html

[9] See https://english.rvo.nl/sites/default/files/2020/11/Brochure%20SDE%20plus%20plus%202020.pdf

[10] See https://ec.europa.eu/info/food-farming-fisheries/farming/organic-farming/trade_en

propositions for the use of water, or other compliance requirements with environmental standards, the use of land areas, economic effects or human rights and the compliance with SDGs. Respective aspects have been discussed above and are summarised in Table 3.

International imports could be required to comply with the standards defined by the EU. If this approach is followed, the question of monitoring and verification arises. In order to facilitate this process, it would be advisable to establish an international third party standard. The EU could establish this international hydrogen certification body and thereby assure that the international certification is compliant or compatible to its own regulation. As this is not part of the regulation at EU level itself, options in this regard are not further discussed below.

In addition to the definitions on the production of hydrogen, a hydrogen standard could also include administrative aspects. The import regulation could define that hydrogen may only be imported form a certain country if the production complies with a national plan towards full decarbonisation of the energy system. Different levels of strictness could be established in this regard. In a very strict sense, only countries which are fully decarbonised or whose CO2 footprint of electricity production undercuts a certain threshold[11] could be certified to become hydrogen producers. In a more general case, a country could be required to have an ambitious pathway towards full decarbonisation of energy supply established in a legislative framework. In addition, it would need to be assured that the country is on track to achieving it. The electricity used for production of hydrogen could then be required to be additional to this pathway, i.e. required to not count towards achieving the target while the purely domestic pathway is continuously followed. This would avoid the effect of importing hydrogen classified as green from a country that continues to supply domestic demand with energy supplied from fossil fuels. These administrative requirements are difficult to implement by an EU regulation. They could turn into high barriers to a third country producer, not only because the requirement may be difficult to meet, but also because compliance could be difficult to prove by a private actor. The requirements for hydrogen production within the EU would likely be the same with or without these administrative aspects, which is the reason why they are not discussed in one of the options below.

We further investigate the following options to establish a hydrogen nomenclature within the EU.

A. *Fully harmonised regulation at EU level*: This option is much discussed by different stakeholders to define renewable and fossil based hydrogen. A fully harmonised hydrogen classification scheme with clear criteria could be established by an EU regulation. It could cover different sectors and harmonises the approaches of RED II, ETS and CertifHy. Following the terminology of the EU hydrogen strategy, a limited number of different types of hydrogen could be established. A trading and certification system could be implemented which builds on the CertifHy project but could incorporate the harmonised regulations set out above and is in this sense stricter than the current CertifHy GOs. Imports of hydrogen could be classified according to this scheme.
B. *Fully harmonised EU regulation with sustainability criteria*: A fully harmonised regulation could be established at EU level which incorporates the aspects under Option A. In addition, a coherent set of sustainability criteria could be established for the definition of sustainable hydrogen. This would include propositions on the supply with water and on land use, but also criteria on human rights and SDGs.
C. *No further action at EU level:* The RED II provisions would define criteria for transport sector fuels and CertifHy would remain a nonbinding project. Likely, more independent labels would appear as there is a general need to achieve clarity on

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[11] This is in line with the requirement under RED II for RFNBOs in the transport sector, which need to achieve at least 70 % savings compared with a fossil comparator.

the consumer side. Producers would define criteria for self-regulation. As there is no unified nomenclature at EU level, some Member States may fill the gap and set up a separate regulation. These classifications would exist in parallel to each other and to a remnant EU regulation. Imported hydrogen would be classified either according to a different, possibly international standard or one of the existing sectoral EU regulations.

Next, we assess these three options on the basis of the evaluation criteria:

- *Costs:* Option A entails establishing an EU regulation and setting up an institution to give out and regulate the trade with certificates similar to CertifHy (score -). Option B adds to these requirements but does not fundamentally differ in terms of costs, while the required effort in monitoring is increased (-). Option C does not entail additional costs to those foreseen for regulation now (score +). In absolute terms, costs are small for all options.
- *Benefits:* None of the options bring direct monetary benefits to the EU. Option A has a slightly higher chance of being replicated in other countries, putting the EU in a position to lead the rules of an emerging hydrogen economy (score +). Additional sustainability criteria may be beneficial to the environment but also increase the inertia in regulation, making it less attractive to replicate. The time lag could then also lead to indirect monetary burdens (score 0). Option C entails no benefits to the EU (score -).
- *Feasibility:* In light of the discussions around the certification scheme and the willingness by many to adopt such a regulation, Option A seems feasible (score +). Option B includes more criteria, some of which are not trivial to monitor and therefore seems slightly less feasible (score 0). Option C would likely receive opposition from the various progressive actors, making it improbable (score -).
- *Effectiveness:* Option A is effective in establishing a hydrogen certification scheme that incorporates the requirements of the EU hydrogen strategy (score ++). Option B goes beyond the requirements set out in the strategy. An additional class of hydrogen may reduce the clarity of the overall classification, making it less effective. But overall, Option B is still very effective in implementing a certification (score +). Option C would lead to a clutter of different certification schemes, which is not effective in providing the clarity required (score --).
- *Sustainability:* The sustainability of the options can be clearly ranked. Option A sets clear standards at the EU level particularly for the energy content of hydrogen but does not include sustainability criteria explicitly (score +). Option B expands the requirements of Option A particularly to include sustainability aspects (score ++). Option C does not address sustainability and the different certification schemes evolving weakens the overall sustainability (score -)
- *Risks:* Option A bears the risk that a substantial amount of imported hydrogen leads to problems of sustainability in other countries, where water scarcity or labour rights may become a side-effect of hydrogen production (score -). Option B explicitly addresses this problem but comes with the small risk that the certification scheme takes longer to implement (score 0). Option C entails the risk of many parallel labels, which dilute the objective of a certification as such. It also does not provide the clarity to put the EU in a leadership position regarding technical requirements of production (score --).
- *Coherence with EU objectives:* Both Options A and B would promote the EU and Member States to assume a relevant and international position in the entire value chain of hydrogen, in particular regarding technical standards and regulation. Although sustainability criteria are not specifically addressed in Option A, this option would promote the EU objective of sustainable development based on balanced economic growth and market economy (score +). Option B adds to the sustainable objectives of

the EU, including SDGs and the role that the EU plays in addressing SDGs at the international level. On the other hand, Option B is likely to impose additional barriers for a market economy (score +). For Option C, we do not see any contribution to the EU objectives (score -).

- *Other impacts:* Since Options A and C do not address broader sustainability criteria, these options can have indirect impacts on ethics and other social issues such as water stress and violation of human rights in third country producers of renewable hydrogen. Nevertheless, the extent of such impacts is difficult to forecast in this report (score 0). The sustainability criteria added in Option B will help avoid side-effects of hydrogen production on ethics or other social issues (score +).

A summary of the evaluation across all criteria and options is provided in Table 11. Options A and B both establish a clearly defined certification at the EU level, but the limited scope of the certified actions under Option A is a plus in many regards. Option A would be easier and thus faster to implement, thereby also making it more effective than Option B. Option A would also be more likely replicated by other countries, which should be considered a benefit. Option B also implements the requirements of the EU hydrogen strategy, but may take longer to establish, and an additional sustainable hydrogen class is not necessarily beneficial to the overall classification. By design, Option B outweighs Option A in terms of sustainability, which can be important particularly for regulating imported hydrogen. Both Options A and B contribute to achieving EU objectives in achieving a relevant position in the value chain of hydrogen, Option B also addressing objectives of sustainability. The status quo defined by Option C is not effective in providing sufficient clarity for market participants and provides no headway for a leadership of the EU with regards to hydrogen regulation. Societal impacts of the options are hard to estimate by way of this study, while Option B likely has least side-effects with regards to social issues.

Table 11 – Evaluation of the different policy options addressing the certification of hydrogen production

Options	Costs	Benefits	Feasibilitiy	Effectiveness	Sustainability	Risks	Coherence with EU objectives	Other impacts
Option A:	-	+	+	++	+	-	+	0
Option B:	-	0	0	+	++	0	+	+
Option C:	+	-	-	--	-	--	-	0

The criteria are assessed based on a scale from ++ (very positive) over 0 (neutral) to – (very negative).

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Given the vast potential for renewable electricity generation, the production of renewable hydrogen is a promising option for the hard-to-decarbonise energy-intensive industry sectors. A growing hydrogen sector will also result in job creation and economic growth while fostering innovation and reducing pollution. The European Commission published its Hydrogen Strategy in 2020 with the aim of boosting hydrogen use in the EU while promoting the uptake of renewable hydrogen production. Recent activities, such as the launch of the European Clean Hydrogen Alliance and the EU Innovation Fund, the formation of Hydrogen Valleys and the promotion of Important Projects of Common European Interest (IPCEIs), provide promising first steps to foster a European hydrogen economy. Nevertheless, important policy gaps still need to be addressed.

This study takes stock of the current situation with respect to the realisation of the EU Hydrogen Strategy and identifies policy options to address gaps in the current landscape.

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