CLEAN HYDROGEN MONITOR

2023

Hydrogen Europe

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Foreword

Hydrogen is happening!

The activities of the hydrogen sector shaping up in Europe and globally are starting to yield results. Projects especially in Europe are mushrooming. However, only 4 percent of them are getting to final investment decision. This shows how important it is to understand the interconnections and interdependencies of different technologies and energy sectors in order to de-risk investments into hydrogen projects.

Europe has managed to raise the main pillars of the regulatory framework that will define the progress of its hydrogen sector. Most of the rules are in place, and now it's time for action. From mobility to industry, from power to infrastructure, hydrogen will touch many parts of our economy - helping us to decarbonise our society and ensure energy security and stability at the same time.

The best overview of this complex and exciting new industry taking shape is Hydrogen Europe's annual Clean Hydrogen Monitor.

Our publication contains a comprehensive trove of information about the value chain, explanations on how the regulatory framework will influence its development, and crucial analysis of the funding and financing landscape. With developers lining up for domestic and European auctions for hydrogen, grasping the financial aspect of this revolution is paramount.

Whether it's tracking the increasing numbers of hydrogen vehicles on the road, the build up of key infrastructure, or statistics on electrolyser manufacturing capacity, the Clean Hydrogen Monitor breaks these themes down to national level, providing a clear view into which countries are leading the charge and which ones are working to improve.

Being right at the source of all hydrogen data and information, it is our pleasure to connect the many dots and to present this 2023 of the Clean Hydrogen Monitor. We hope you will find it fascinating and useful as we continue striving for a decarbonised world!

Jorgo Chatzimarkakis
Chief Executive Officer
Hydrogen Europe

Preface

Last 12 months saw hydrogen retain its place at the highest level of political agenda in the EU, with the adoption of REDIII, the establishment of the Hydrogen Bank and its prominence in the EU industrial plan just to name a few. But while it is increasingly clear that hydrogen will be a cornerstone of the European Green Deal and of the EU's objective to become the first climate neutral continent, there are still challenges ahead. 2024 is the year of Fit-for-55 package implementation at national level with national governments expected to implement not only regulatory targets and policies, but also coordinate the deployment of infrastructure to ensure their industries' access to hydrogen. At the same time, if the ambitious hydrogen targets are to be met, the European electrolyser manufacturers need to accelerate the pace of capacity expansion, while the European industry needs to progress from the current stage of project preparation and feasibility assessment to accelerate the pace of final investment decisions (FIDs) and subsequent project deployment.

To fulfil policy objectives and deploy the hydrogen sector at scale, transparent, accurate, and accessible data is key. It is not only necessary for science-based policy making but indispensable for creating the trust and confidence that is needed among stakeholders to dedicate billions of euros of public money for the support of the sector on one hand and helping the many hundreds of clean hydrogen projects in preparation to reach FID.

In this context, the Hydrogen Europe team is working throughout the year on the Clean Hydrogen Monitor. It is not a publication for bullish claims and aggressive outlooks, but rather a publication which has the single aim of providing a clear view of the hydrogen market status to-date.

As was the case in previous editions, this year's Monitor provides a comprehensive overview of the clean hydrogen landscape, encompassing current hydrogen demand and production capacity, as well as an assessment of clean hydrogen production costs and the financial gap that persists. In addition, it also dispenses guidance to navigate the complex labyrinth of EU policies and EU funding opportunities relevant to the hydrogen sector. Following the adoption of AFIR and key new regulations affecting the maritime and aviation sectors, for the first time the Monitor also provides data on the development of hydrogen in the mobility applications – with a firm commitment from the Team to keep expanding this part of the Monitor in future editions.

Finally, the Monitor also provides a glance into the future by assessing the existing clean hydrogen production pipeline, electrolyser manufacturing capacity build-up, as well as the pipeline and storage infrastructure development plans.

Publishing of the Clean Hydrogen Monitor would not have been possible without the expertise and dedication of my team as well as the valuable insights and data provided by the member companies of Hydrogen Europe. Special credit also needs to go to the Clean Hydrogen Partnership and the recently re-launched European Hydrogen Observatory for which Hydrogen Europe provides data and which serves as the authoritative source on hydrogen developments in Europe.

Stephen Jackson
Deputy CEO
Chief Technology & Market Officer
Hydrogen Europe

Executive summary

The Clean Hydrogen Monitor is published by Hydrogen Europe every year and presents quantitative and qualitative indicators that track the state of play of the emergence of the clean hydrogen market in Europe. The 2023 edition provides an updated assessment of current hydrogen production capacity and demand, addresses European policy developments, evaluates the funding and financing landscape, estimates production costs, sheds light on announced clean hydrogen production and consumption projects, and for the first time provides an assessment of hydrogen deployment in selected mobility applications.

When it comes to the current hydrogen market, the European hydrogen production capacity remained stable for the reporting year 2022 at around 11.5 Mt (**chapter 2**). Power-to-hydrogen/water electrolytic capacity rose by 23% to 228 MWel by September 2023 compared to December 2022. It now represents 0.3% of the total operational European production capacity up from 0.15% three years ago. While 23% is a high growth rate for mature industries, Europe would need a 150% annual growth rate to reach 140 GW_{el} of installed electrolysers needed to produce the 10 Mt envisaged by REPowerEU. Due to lack of official hydrogen statistics, Hydrogen Europe tracks the approximate hydrogen consumption which amounted to 8.2 Mt in 2022 compared to 8.7 Mt in 2020 (**chapter 1**). While hydrogen consumption in refining increased by 8% to compensate for sanctioned imports of Russian oil products, the total decrease was caused by production suspensions in ammonia and various chemical sectors due to high gas prices.

While the current hydrogen market is dominated by fossil fuels, European decarbonisation policies are driving the emergence of a clean hydrogen market (**chapter 6**). Two years after the publication of the Fit for 55 package, some of the key policy drivers for clean hydrogen production and consumption are finally in place. The long-awaited Renewable Energy Directive (RED) sets obligations for hydrogen consumption in transport and industry, while providing the definition of renewable fuels of non-biological origin (RFNBO). FuelEU Maritime and ReFuelEU Aviation offer a clear direction for decarbonising these sectors with a key role for hydrogen and synthetic fuels. The Alternative Fuels Infrastructure Regulation (AFIR) will ensure the rollout of hydrogen refuelling stations across Europe to accommodate the increase in zero-emission vehicles. The legislation underpinning the transport and storage of hydrogen, Hydrogen and Decarbonised Gas Package, is about to be finalised and will clarify the low-carbon hydrogen definition. While there are outstanding policy files relevant for the hydrogen sector related to standardization, certification, industrial policy, raw materials, and others, the policy framework is almost complete. That is providing the necessary clarity for the market to begin moving from announcements to final investment decisions (FIDs).

With many emerging clean technologies and industries competing against incumbents, the clean hydrogen sector also needs support to mature and scale-up to eventually compete on its own. In Europe, between EUR 1.2 and 2.6 trillion must be mobilised, amounting to EUR 50 to 100 billion in annual investments until 2050, with higher investments through the 2030s to make clean hydrogen a reality (**chapter 7**). The EU answered this challenge with a myriad of funding instruments: Clean Hydrogen Partnership for R&D investments, Innovation Fund for the deployment of first-of-a-kind industrial projects, and the Hydrogen Bank as a market making tool aiming to support renewable hydrogen producers with a fixed premium, as well as the Important Project of Common European Interest (IPCEI) programme, among others. Despite the different funding streams, substantial funding needs remain, underscoring the pivotal role of private finance. Currently, corporate finance, predominantly in the form of equity investments, is the primary financing method for the sector. However, to scale up the hydrogen economy effectively, equity must be complemented with debt through project finance. Over the past few years, banks and debt finance providers have been formulating hydrogen strategies to enhance their understanding of the sector. While banks and debt finance providers have been familiarizing themselves with the sector, non-recourse financing is still not common. To fully unlock the sector's economic and decarbonisation potential, the development and timely implementation of innovative and centralized market-making instruments will be imperative to mitigate risk and attract the whole private finance value chain.

The funding support remains one of the key levers for hydrogen production projects reaching maturity and final investment decisions. The number of power-to-hydrogen (PtH) projects planned to be operational by 2030 increased from 628 in 2022 to 813 in 2023 across all stages of development from concepts to projects under construction (**chapter 2**). The trend of increasing project announcements is a positive development, but similarly to previous years, projects continue being delayed. While 2022 Clean Hydrogen Monitor data reported 257 projects with plans to come online in 2024, this year's version reports only 196 after accounting for revised timelines. The real number that will have come online by the end of 2024 will, most likely be lower. The main reasons behind project delays included regulatory uncertainty and lack of funding. Additionally, producers also often cite lack of off takers due to the cost gap of renewable vs fossil hydrogen, component delivery issues, project development delays due to first-of-a-kind nature of projects, standardisation and certification uncertainty, and slow development on hydrogen transmission and storage. Despite the delays in the short to medium term, the clean hydrogen production project pipeline is strong and if all planned production projects for 2030 were realized, there could be 15.6 million tonnes of hydrogen a year made by electrolysis and by reforming natural gas with CCS. However, only 4.4 Mt a year of that planned capacity is currently in a more advanced development stage and only ~0.2 Mt represented by 1.7 GW_{el} of PtH capacity passed FID and is under construction. That is a positive development compared to the 380 MWel that were under construction by September 2022.

7.1 Mt/year of new clean hydrogen consumption has been announced by industrial off takers in Europe until 2030 which is an overall increase of 1.3 Mt/year compared to last year. (**chapter 1**) This demonstrates that, despite many challenges, the outlook for the use of clean hydrogen in industry is positive. The largest volumes have been announced in the ammonia and steel sectors with around 2 Mt/year of clean hydrogen demand each. 84% of the announced clean consumption is expected to be produced via electrolysis with the remaining 16% coming from reforming of natural gas with CCS/U. 41% of total announced consumption is planned to come online in 2030, which is an indication that a significant number of projects are being developed in response to the Renewable Energy Directive targets concerning the consumption of renewable hydrogen by 2030

– especially affecting ammonia producers and refineries. The steel sector is also under increasing pressure to decarbonise with the decreasing free allocation of allowances due to planned CBAM implementation. The fact that the announced clean hydrogen consumption projects in industry are less than half of the announced clean hydrogen production volumes is representative of one of the issues that producers currently face with finding willing off takers.

The hydrogen mobility market is steadily increasing as well, with original equipment manufacturers (OEMs) constantly researching ways to further develop hydrogen powertrains (both fuel cells and hydrogen internal combustion engines) (**chapter 8**). Heavy-duty sectors show the fastest uptake of hydrogen powertrains – only 2022 shows major increase in trucks (55 in 2022, compared to 14 in 2021), buses (206 in 2022, compared to 165 in 2021), while the maritime sector is still in its infancy (4 operational hydrogen-powered ships in 2022, with 28 on order by 2028). However, hydrogen mobility faces several challenges including the development of standards and deployment of refuelling infrastructure, competitive pricing at the hydrogen refuelling station level, and certain support for hydrogen vehicles until the technology scales up to become price competitive on the market.

With the emergence of the clean hydrogen market, both developers and national governments are realising that there are limits to local production and consumption of clean hydrogen and are emphasising the development of hydrogen infrastructure (**chapter 4**). From the transmission perspective, Belgium and the Netherlands are the most advanced countries because of their respective plans, adopted legislation, and having begun construction of their national hydrogen networks. On hydrogen storage which will be needed both for seasonal energy storage as well as on a smaller scale for individual consumers to optimise their production and consumption profiles, Hydrogen Europe tracks 29 hydrogen storage projects in Europe larger than 30 GWh in salt caverns, aquifers, depleted fields, and lined rock caverns. The countries with most large-scale hydrogen storage projects in development, albeit in early stages, are Germany, France, and Spain.

The clean hydrogen industry has gone a long way since the publication of the European Hydrogen Strategy in 2020. The regulatory framework has been almost completed; regulatory demand for renewable hydrogen (RFNBO) in industry and transport has been set; there are billions of euros available for clean hydrogen projects from European and national funding schemes; and countries have begun developing their national hydrogen networks. As a response, production projects are maturing with 4.4 Mt being at least in FEED stage and planning to come online by 2030. While some struggle to find off takers, the first movers focus on green ammonia, green steel, refining, methanol, and e-kerosene. It is important to focus on scaling and maturing these projects as many are first industrial deployments of that size; private finance; and continuous support to bridge the gap between production costs and off takers' willingness to pay. If successful, Europe will become a strong clean hydrogen player in a net zero world

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Hydrogen demand

Clean hydrogen consumption announcements by industrial offtakers continue to increase every year. The largest volumes have been announced in ammonia, steel, and refining which reflects the positive prospects for both the decarbonisation of existing industry and the generation of additional clean hydrogen demand.

- In 2022, Europe's total hydrogen demand reached 8.2 Mt, and industrial off-takers have outlined plans to consume 7.1 Mt/y of clean hydrogen by 2030, of which 4.3 Mt/y are dedicated to new demand from emerging applications and greenfield initiatives.

- The most advanced offtakers are currently in the ammonia and steel sectors, strategically locating projects in areas with large existing hydrogen demand such as Germany and optimal access to low-cost renewable sources and low-carbon grid infrastructure such as Spain and Sweden.

- If the currently announced pipeline of electrolytic projects in industry materialized and complied with RFNBO rules, 10 Member States would satisfy the REDIII industry target by 2030.

Current hydrogen demand in Europe

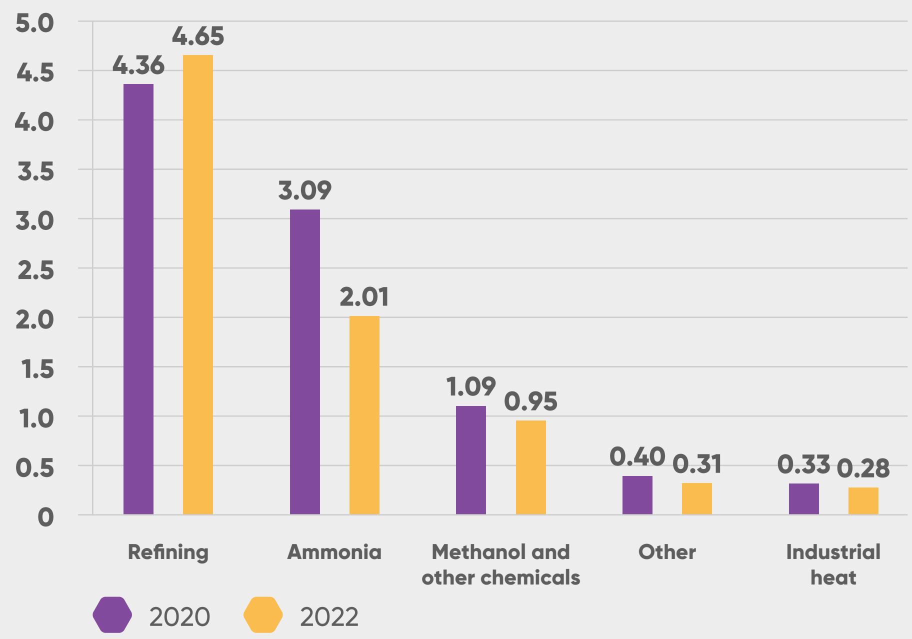
The biggest share of hydrogen demand in 2022 came from refineries, responsible for 57% of total hydrogen use (4.7 Mt), followed by the ammonia industry with 24% (2.0 Mt).

In 2022, the total demand for hydrogen in Europe was 8.2 Mt. This was 1 Mt less than our revised 2020 estimation[1]. Despite the increase in natural gas prices in 2022, the use in refineries increased, mostly due to the embargo on refined oil products from Russia, which increased the need for domestic refining, consequently increasing the demand for hydrogen in the sector by 6.8%. Furthermore, the impact of natural gas prices is not as significant in refining as in other sectors, as natural gas feedstock can be partially replaced with refinery off-gases and there is generally relatively smaller impact of hydrogen costs on the overall business. In contrast, in sectors, such as the ammonia industry, where hydrogen costs are a critical element of the total costs, the increase in natural gas prices led to the shut-down of multiple facilities, decreasing overall hydrogen use and demand by 35% compared to 2020, off-setting the increasing trend in the refining sector and translating into an overall decrease of hydrogen demand in Europe.

The refining and ammonia sectors together account for 81% of the total consumption of hydrogen in the EU, EFTA, and the UK (referred to as Europe in the rest of the chapter). Hydrogen is also used in various industries like methanol production and as a fuel for industrial heat. It is also used in small-scale applications such as automotive and semiconductor manufacturing. The transport sector only accounts for 0.04% of current demand. In contrast to the European market, the global demand for hydrogen grew in 2022 from 93 to 95 Mt. As a result, the share of Europe in global hydrogen consumption fell from 8.5% in 2021 to 8%[a].

FIGURE 1.1

Hydrogen demand by end-use in Europe in 2020 vs 2022 (Mt/year)



Source: Hydrogen Europe.

1 / The estimate of hydrogen demand for 2020 has been revised to 9.2 Mt from the Clean Hydrogen Monitor 2022 due to adjustments made in the ammonia sector utilization considering Eurostat data.

Germany (21%), the Netherlands (12%), Poland (10%) and Spain (8%) are responsible for more than half of total hydrogen consumption in Europe.

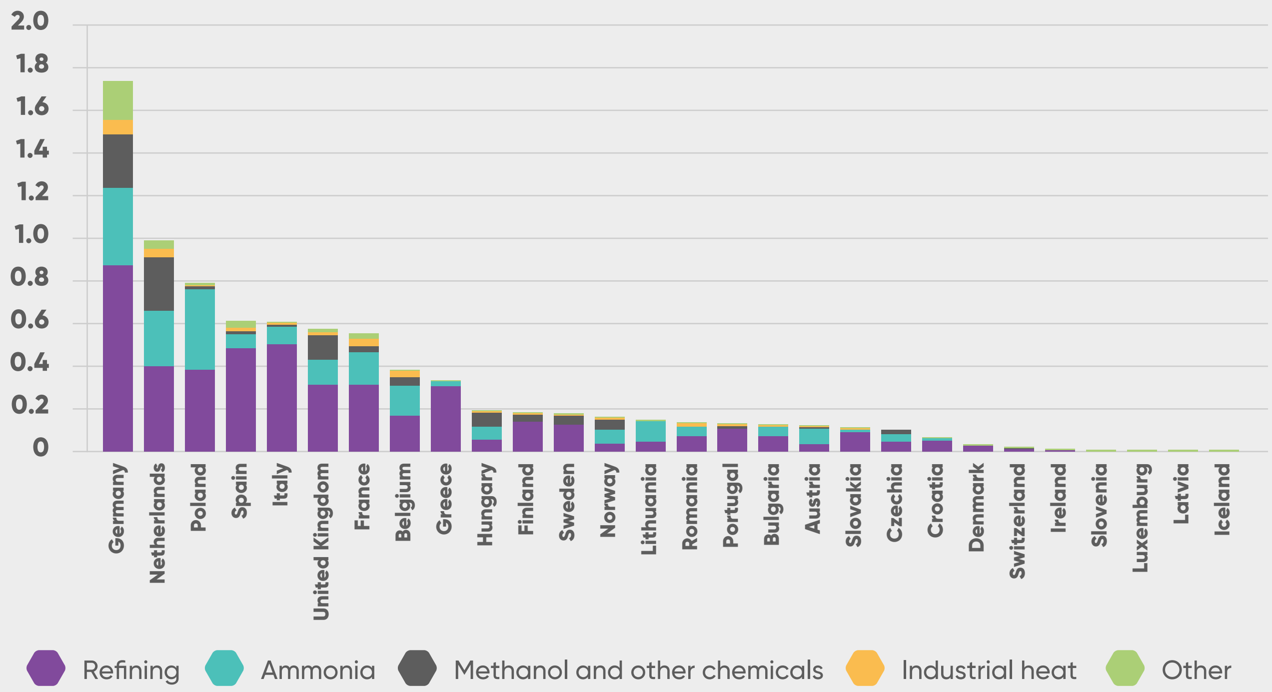
In most countries, hydrogen is mostly used for refining. However, in Norway, Lithuania and Austria, ammonia production is the main use. In some countries, such as Denmark or Greece, refining was responsible for more than 90% of domestic hydrogen consumption in 2022.

The largest ammonia producers in Europe are Germany, Poland, and the Netherlands, with Belgium and France also notable in this regard. These countries, especially Germany, Poland, and the Netherlands, are expected to face significant implications due to the EU's recent commitment to achieving a 42% consumption of renewable hydrogen in industrial applications by 2030. It's worth noting that this target does not cover the use of hydrogen in refining processes or for industrial heat production.

Ammonia production used to be the dominant hydrogen consumer in Poland. However, because of increased refinery utilisation and the temporary ammonia production shutdowns, both refining and ammonia consumed almost 0.4 Mt each. In Croatia, the shutdown of the only ammonia plant in the country has cut the overall consumption of hydrogen in half.

FIGURE 1.2

Hydrogen demand in Europe in 2022 by country and end-use (Mt/year)



Source: Hydrogen Europe.

Announced consumption of clean hydrogen in industry

Industrial offtakers in Europe have announced projects that would generate up to 7.1 Mt of annual demand for clean hydrogen by 2030.

Industrial buyers in Europe have announced plans to consume 7.1 million tonnes of clean hydrogen annually by 2030 in a total of 268 projects. If projects that have not yet announced a start date were included, the pipeline includes 7.4 Mt/year of clean hydrogen consumption and 278 projects. While some projects were cancelled in the last year, new ones were announced and increased the total planned clean hydrogen consumption in industry by 1.3 Mt/year compared to Clean Hydrogen Monitor 2022. The largest share of consumption is set to come from the ammonia and steel sectors, with around 2 Mt/year of clean hydrogen demand for each. This demonstrates that, despite many challenges, the outlook for the clean hydrogen market is still very positive.

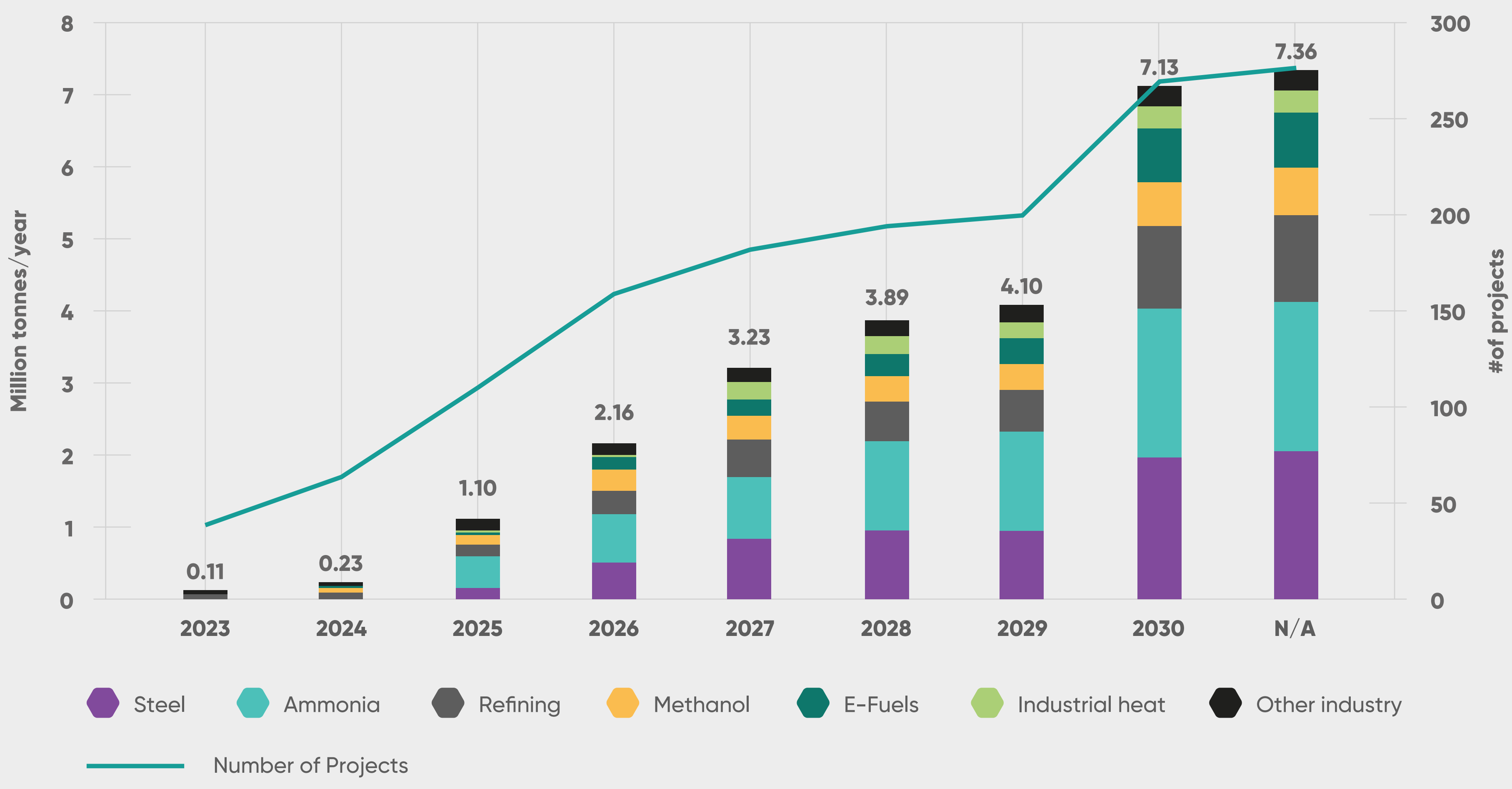
A significant majority, about 84%, of the planned clean hydrogen consumption is anticipated to be generated through electrolysis, while the remaining 16% will be sourced from natural gas reforming with carbon capture. Among the projects that have been announced, approximately 45%, equivalent to around 35% of the total hydrogen demand, have progressed to an advanced stage of development, having moved beyond the feasibility study phase.

Approximately 41% of the announced consumption is planned for a 2030 launch, aligning with Renewable Energy Directive targets. This has significant implications for ammonia producers, refineries, and the steel sector, given the impending implementation of the Carbon Border Adjustment Mechanism (CBAM).

The announced consumption of clean hydrogen amounts to 87% of the total current demand for hydrogen in Europe. However, this does not mean that a comparable percentage of fossil-based hydrogen consumption will be replaced with clean hydrogen – since close to 60% of announced hydrogen consumption is generated by greenfield projects, either for additional production of hydrogen derivatives (ammonia, methanol and other e-fuels) or new hydrogen consumption in the steel sector.

FIGURE 1.3

Cumulative announced consumption of clean hydrogen in industry by 2030 in Europe (Mt/year and # of projects)



Source: Hydrogen Europe.

Notes: Data does not represent a forecast, but announced industrial consumption project pipeline. For methodology and terminology clarifications, please consult the methodological note at the end of the chapter and the terminology section at the end of the report.

The European countries with the largest announced clean hydrogen consumption in industry are Spain, France, Germany, and Sweden.

The intensity of industrial plans to develop clean hydrogen projects in various countries is driven by a multitude of factors, including existing hydrogen demand, low GHG intensity of grid electricity or renewable energy potential. Germany and the Netherlands are the countries with the largest existing fossil hydrogen demand and are also among the leaders in terms of announced clean hydrogen consumption, mostly driven by the need to decarbonise their own industrial base.

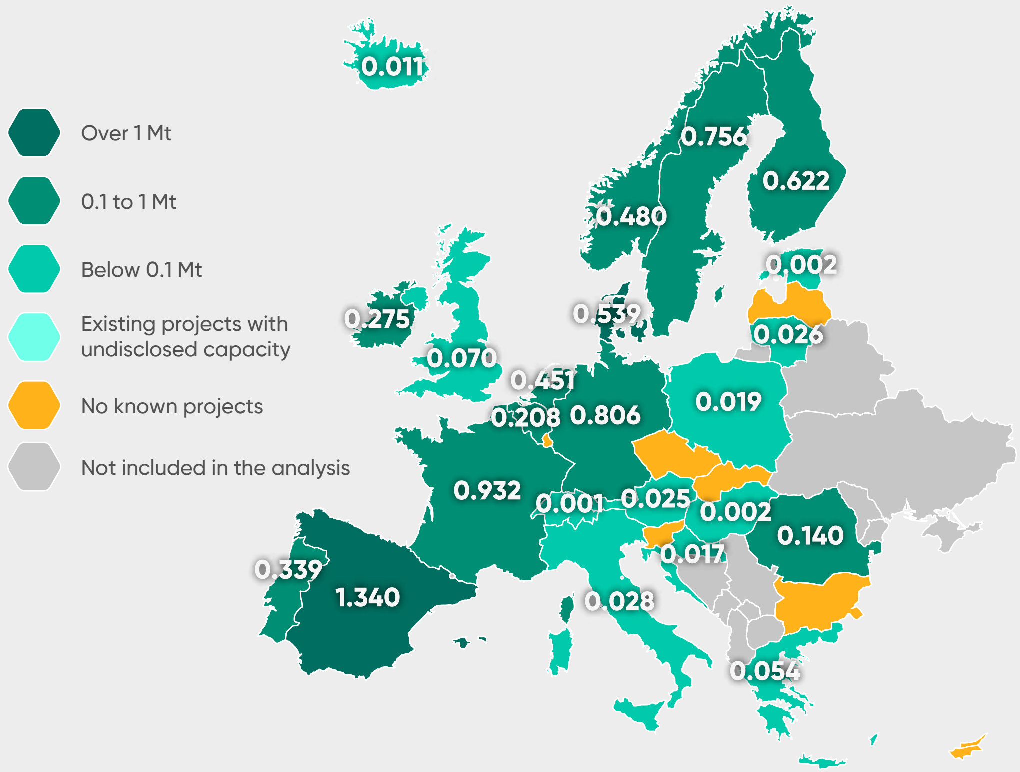
Another set of countries is those with low-carbon grid electricity (France, Finland, Sweden, Norway). Access to low-carbon grid electricity is crucial as it allows to balance variable renewables with grid electricity, without jeopardising the GHG intensity of hydrogen. This helps to minimise the need for hydrogen storage, while allowing for a steady supply of hydrogen – especially important for industrial applications.

The availability of abundant and affordable renewable energy is another crucial factor influencing the selection of clean hydrogen project locations. This has been instrumental in driving large-scale developments in Spain and Portugal.

The distribution of projects across different regions can also be attributed to the availability of subsidies, such as the SDE++ support programme in the Netherlands or other schemes in France, Germany, Denmark, and elsewhere.

FIGURE 1.4

Total announced clean hydrogen consumption in industry per country by 2030 in Europe (Mt/year)



Source: Hydrogen Europe.

Notes: Data does not represent a forecast, but announced industrial consumption project pipeline. For methodology and terminology clarifications, please consult the methodological note at the end of the chapter and the terminology section at the end of the report.

Consumption of clean hydrogen in Europe in the steel sector alone could reach 2 Mt/year if all announced projects by 2030 come online.

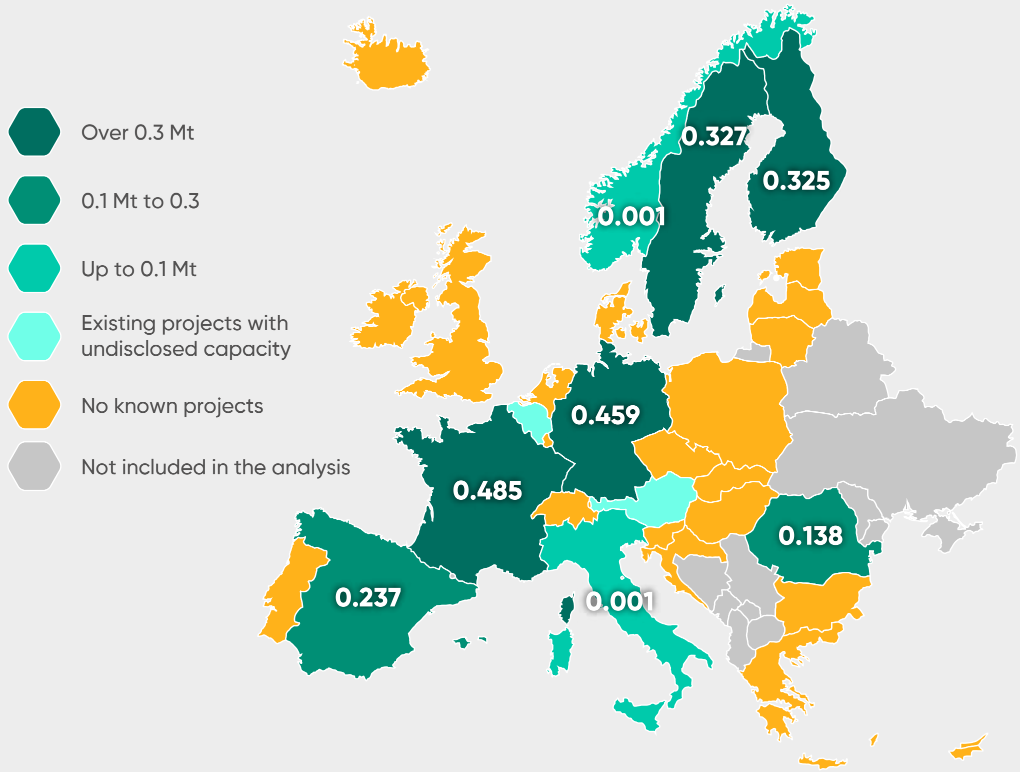
Although the current demand for hydrogen in the steel sector is negligible, clean hydrogen is one of the main promising solutions for the decarbonisation of the sector through the Hydrogen Direct Reduced Iron production route.

With around 55-60 kg of H2 necessary to produce 1 tonne of steel, 6 Mt/year of clean hydrogen could decarbonise the entire domestic primary production of steel in Europe. In addition to the decarbonisation of already existing plants, there are also several new greenfield DRI projects located in countries with favourable access to low-carbon electricity. An example of this are projects developed by H2 Green Steel. The company has unveiled greenfield projects in Sweden, a country with access to both local iron ore resources and grid electricity characterized by an extremely low greenhouse gas intensity. This unique advantage means the projects could secure renewable electricity without the need for additional requirements. Another project is planned on the Iberian Peninsula, with low-cost and abundant renewable energy resources.

It should be noted that at least 23% of the total announced consumption in this sector comes from projects intending to start with natural gas, before gradually transitioning into using clean hydrogen. It helps steelmakers transition into the DRI technology. However, the use of hydrogen from reformed natural gas will make them fall within the scope of RED targets for the minimum share of RFNBO consumption in industry.

FIGURE 1.5

Announced consumption of clean hydrogen in the steel sector per country by 2030 in Europe (Mt/year)



Source: Hydrogen Europe.

Notes: Data does not represent a forecast, but announced industrial consumption project pipeline. For methodology and terminology clarifications, please consult the methodological note at the end of the chapter and the terminology section at the end of the report.

The ammonia sector has announced projects with aggregated consumption of 2.1 Mt of clean hydrogen per year in Europe by 2030.

So far, Spain and Norway are in the lead as the countries with the highest amount of clean hydrogen consumption announced in the ammonia sector by 2030.

The sector is facing more pressure to use renewable hydrogen with the Renewable Energy Directive setting targets for replacing hydrogen with renewable fuels. By 2030, at least 42% should be replaced, increasing to 60% by 2035.

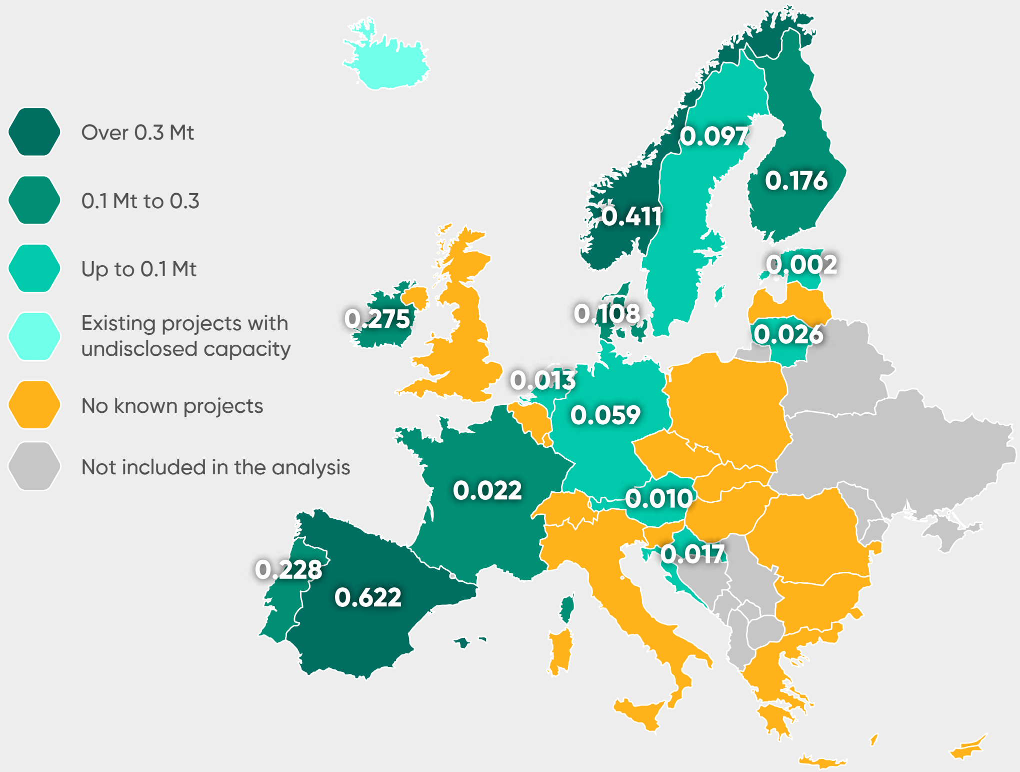
The announced consumption of clean hydrogen by the ammonia sector already matches the total demand in 2022 and 70% of the demand in 2020. While this might suggest that the sector is on track to meet its RED obligations, the reality is more complex.

Firstly, around 1/3 of all planned hydrogen projects in the sector are at a very early development stage (concept) with a high risk of cancellation or delays. Another important fact is that 3/4 of planned clean ammonia production comes from greenfield projects, aiming to use ammonia as an energy carrier or a fuel rather than a feedstock to produce fertilisers and other chemicals. Furthermore, reforming with carbon capture accounts for 12% of total clean hydrogen production in this sector, representing 81% of clean ammonia projects in France and 53% in Norway.

Finally, while the overall quantity of planned clean ammonia production is significant, in some countries it is far from the level required by RED targets. In Germany, the announced projects together amount to just 12% of current demand. In Poland, the second-largest ammonia producer in Europe, no significant plans for renewable ammonia production have been announced yet.

FIGURE 1.6

Announced consumption of clean hydrogen in the ammonia sector per country by 2030 in Europe (Mt/year)



Source: Hydrogen Europe.

Notes: Data does not represent a forecast, but announced industrial consumption project pipeline. For methodology and terminology clarifications, please consult the methodological note at the end of the chapter and the terminology section at the end of the report.

1.2 Mt/year of clean hydrogen consumption has been announced by the refining sector by 2030.

The refining sector is the largest hydrogen consumer in Europe, with 4.6 Mt demand in 2022. Hydrogen is used in refineries for hydrotreating and hydrocracking of conventional fuels.

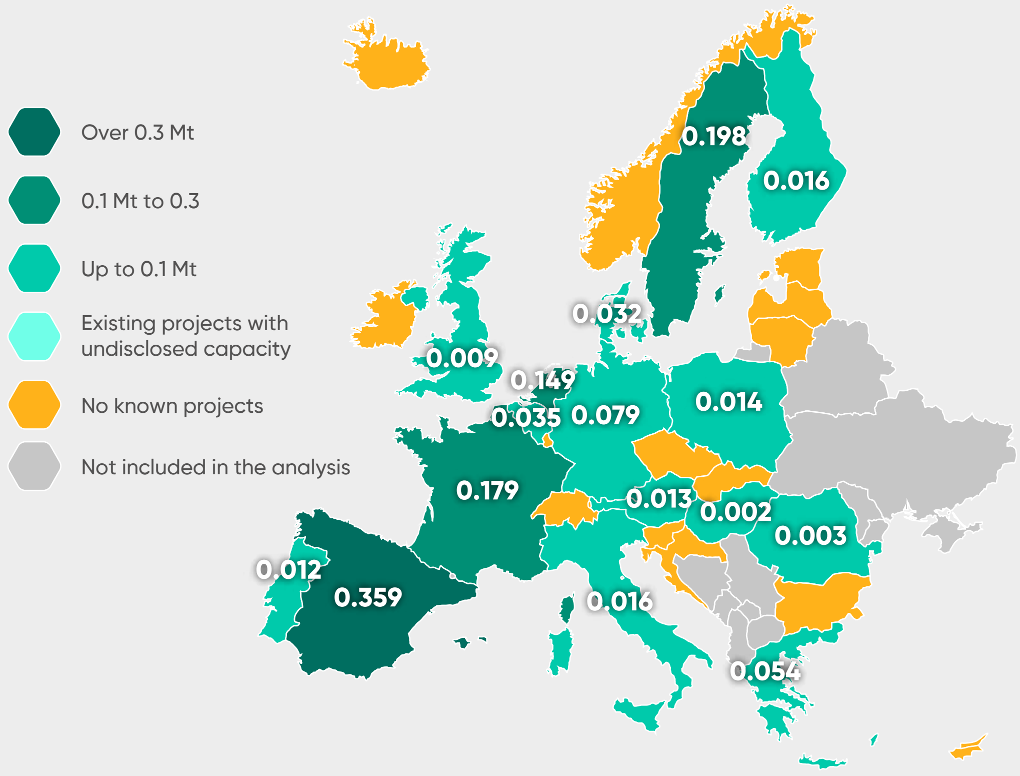
Within Europe, the refining sector leads in terms of the projected consumption of hydrogen produced through natural gas reforming with carbon capture. This includes both operational and planned projects, totalling 0.376 Mt by 2030. Announced clean consumption (renewable and reforming with carbon capture) amounts to 85% of current demand in the sector in Spain and 76% in France.

While this sector isn't included in the industry's 42% target for RFNBO consumption, the use of renewable hydrogen as an intermediary in oil refining can contribute to RFNBO targets in the transport sector. This offers an incentive for EU fuel suppliers to invest in clean hydrogen projects.

Of the total 1.2 Mt/year of planned clean hydrogen consumption in the oil refining sector, close to 0.8 Mt/year are PtH projects. Assuming all would be based on fully renewable electricity, those projects could contribute around 0.7% of the total energy used by the transport sector in the EU, already close to the 1% target. It's important to emphasize that the target needs to be achieved at the Member State level.

FIGURE 1.7

Announced consumption of clean hydrogen in the refining sector per country by 2030 in Europe (Mt/year)



Source: Hydrogen Europe.

Notes: Data does not represent a forecast, but announced industrial consumption project pipeline. For methodology and terminology clarifications, please consult the methodological note at the end of the chapter and the terminology section at the end of the report.

E-fuels are synthetic hydrogen-based fuels like e-kerosene, e-methane and e-methanol that are produced through the combination of hydrogen and CO or CO2. Ammonia can also be considered an e-fuel, produced from the combination of hydrogen and nitrogen, but it is not included in this analysis as it has already been presented in previous sections.[2]

E-fuels are especially important for the decarbonisation of heavy mobility. The shipping industry has been exploring both e-ammonia and e-methanol as the main alternative fuels. This explains why all the e-methanol production projects in our database are greenfield projects, creating a demand for hydrogen that would be 2.5 times greater than the current demand.

In the case of aviation, one of the main decarbonisation options is e-kerosene. The announced pipeline of projects dedicated to the production of SAF by 2030 has a combined annual production capacity of around 16 TWh (i.e. 3.1% of the expected aviation market size in 2030, compared to the 1.2% target in Refuel EU Aviation regulation).

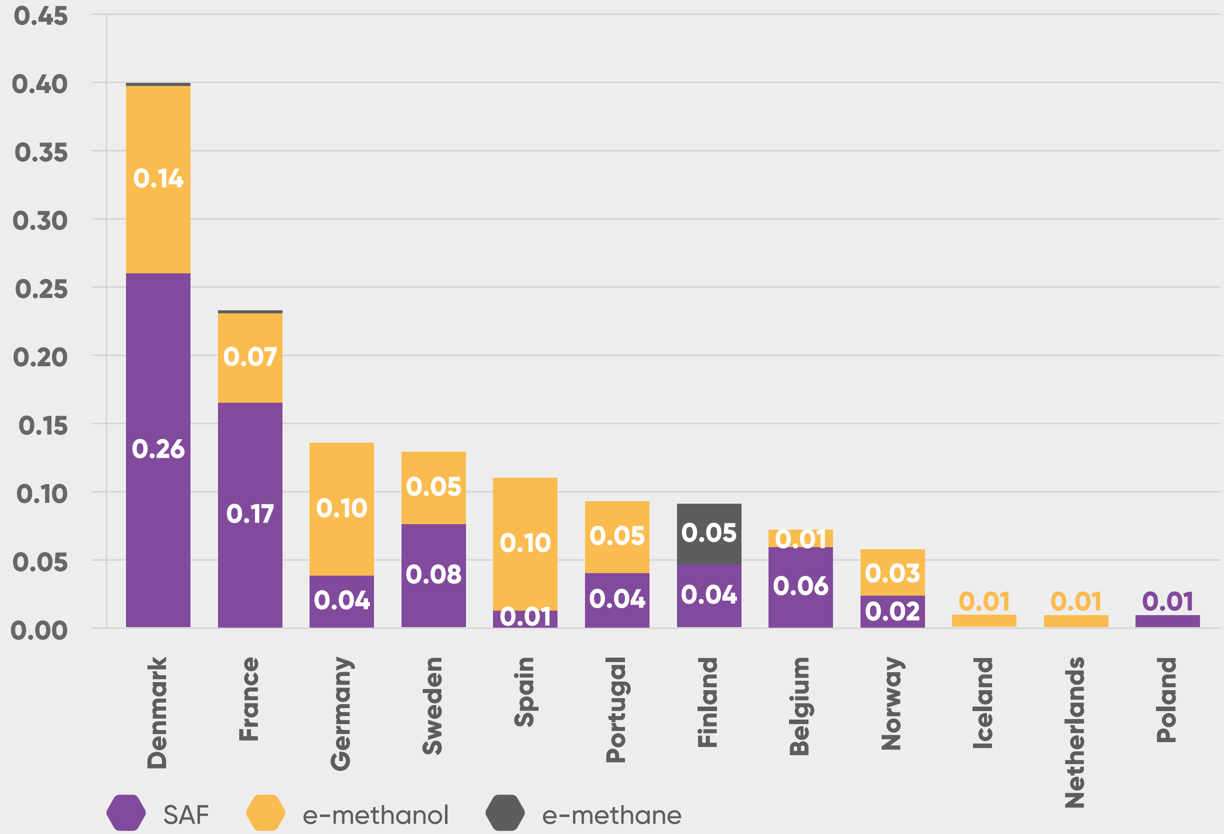
While the production of e-fuels involves the transformation of CO2 molecules, its use ultimately leads to the release of such emissions back into the atmosphere, which makes the source of such CO2 very important for sustainability reasons. The use of CO2 emissions from hard-to-abate industries will only comply with RFNBO production rules until 2041. Other sustainable sources can be through direct air capture or the production or combustion of biofuels. If all projects come online following this timeline, it will create an estimated demand of 10 Mt CO2/y to produce synthetic fuels.

2 / Although e-fuels are ultimately used in the transport sector, the consumption of hydrogen during its synthesis is still an industrial process and is therefore included in this chapter.

1.3 Mt of clean hydrogen has been announced to be used to produce e-fuels by 2030, 51% of it focusing on e-methanol production, 46% on sustainable aviation fuels and 3% on e-methane.

FIGURE 1.8

Announced consumption of clean hydrogen for the production of e-fuels per country by 2030 in Europe (Mt/year)



Source: Hydrogen Europe.

Notes: Data does not represent a forecast, but announced industrial consumption project pipeline. For methodology and terminology clarifications, please consult the methodological note at the end of the chapter and the terminology section at the end of the report.

Announced consumption against RED industry targets

According to the recently approved revision of the Renewable Energy Directive, 42% of the hydrogen consumed by industrial players excluding refineries in each Member State must be replaced with RFNBOs by 2030.

Normal demand for hydrogen in the EU's industry, excluding refineries, amounts to around 3.8 Mt/year of H2 (2020 levels, as 2022 cannot be considered business as usual). The brownfield projects planned for development at existing industrial sites would collectively account for 0.286 Mt of renewable hydrogen consumption, equivalent to approximately 7.5% of the current demand. However, including greenfield projects and assuming those projects would be using only hydrogen meeting RFNBO criteria, **the EU could be on the right track to achieve the target, with a total share of RFNBO in industrial hydrogen consumption at 55% by 2030.**

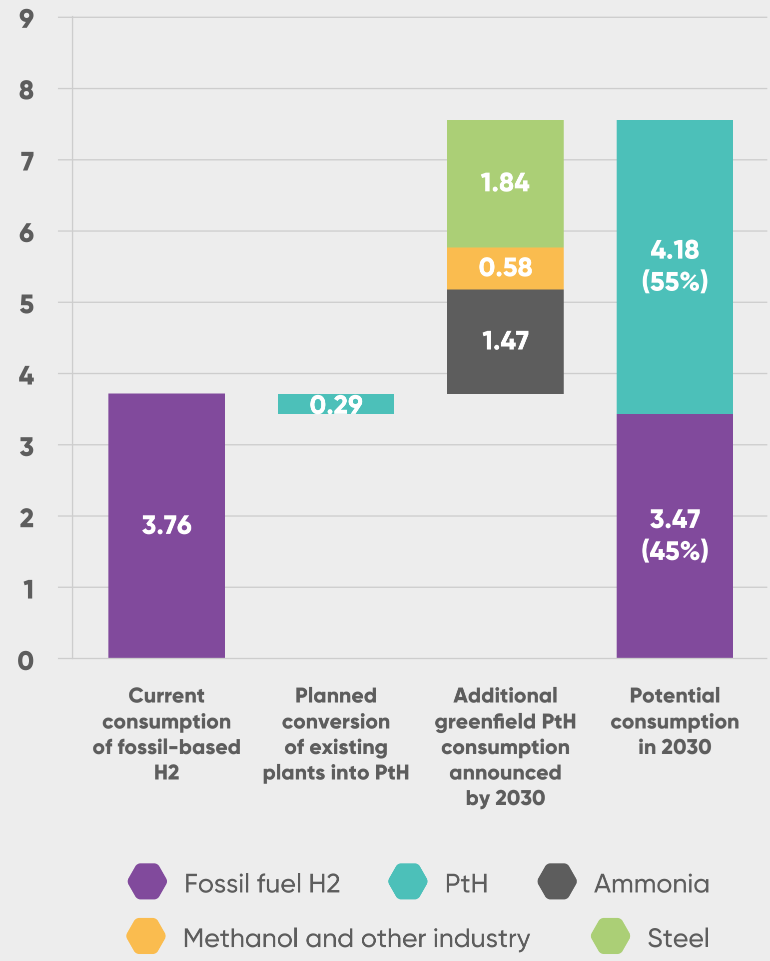
However, the target must be met on a Member State level, and not all countries are at the same stage. In the case of countries with many greenfield projects (H2-DRI projects or new ammonia plants) and low existing industrial hydrogen use, such as Spain, Portugal and Ireland, the share of RFNBO use in industry by 2030 will far exceed the minimum 42% target, and is close to 100%, opening the door for intra-EU trading of RFNBOs.

On the opposite end of the spectrum are countries such as Poland and Lithuania, which have substantial existing consumption of fossil fuel-based hydrogen and a limited pipeline of PtH projects. As a result, in those countries, the share of RFNBO in industrial consumption of hydrogen in 2030, implied by the existing pipeline of projects is grossly below the RED targets.

Furthermore, it should be also stressed once more that the analysis above is based on the assumption that all electrolysis-based projects will be using exclusively RFNBO-compliant hydrogen, which might not be the case, especially in countries with a significant share of nuclear energy in the electricity grid, such as France and Finland.

FIGURE 1.9

Current and planned consumption of hydrogen in sectors affected by the RED industry target (Mt/year)

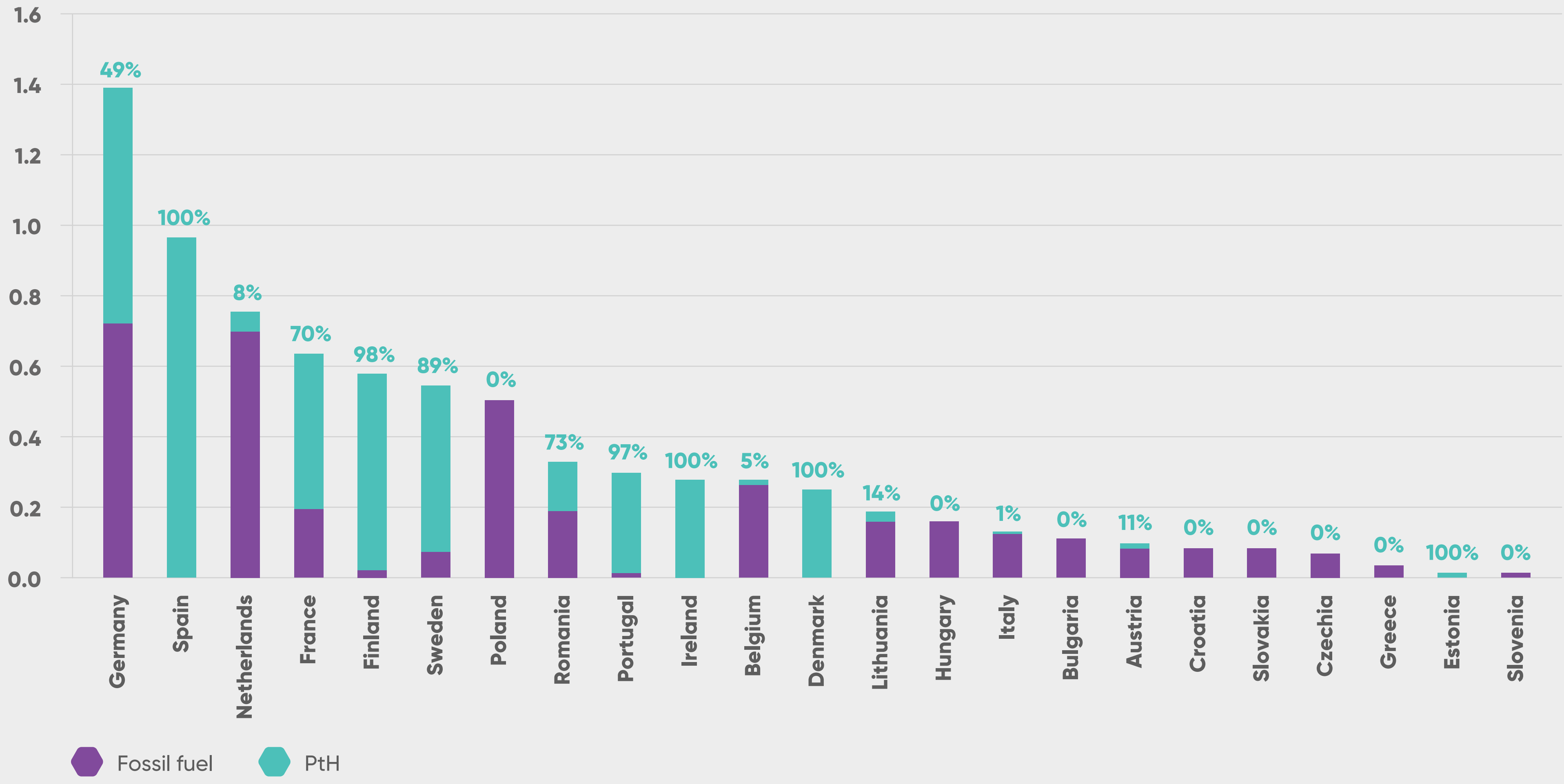


Source: Hydrogen Europe.

Notes: Data does not represent a forecast, but announced industrial consumption project pipeline. For methodology and terminology clarifications, please consult the methodological note at the end of the chapter and the terminology section at the end of the report.

FIGURE 1.10

Hydrogen consumption in EU Member States according to announced plans by 2030 (Mt/year)



Source: Hydrogen Europe.

Notes: Data does not represent a forecast, but announced industrial consumption project pipeline. For methodology and terminology clarifications, please consult the methodological note at the end of the chapter and the terminology section at the end of the report.

Methodological Note

In this chapter, announced consumption in industry refers to data collected from projects announced by industrial offtakers, including consumption of clean hydrogen as a feedstock in chemical processes (i.e., for the synthesis of other products) and as a fuel for industrial heat production. Projects envisioning direct consumption of hydrogen in mobility, residential heating and power generation or injection in the gas grid are out of scope of this analysis.

The authors have adopted an inclusive approach when compiling this list of projects to develop the most exhaustive compilation of European projects envisioning the consumption of clean hydrogen in industrial processes. The collected projects include hydrogen consumption from power-to-hydrogen (water electrolysis) and reforming natural gas with carbon capture process. This analysis excludes any other hydrogen production methods such as biomass reforming, gasification, methane splitting, pyrolysis of waste, etc.

The list of projects has been collected by Hydrogen Europe from both public and confidential sources. The data collection closed in early September. While project announcements are common for hydrogen production projects, cancellations are rarely publicized. The authors cancel projects if they find confirmation of the project's restructuring or if there are no news for 18 months.

This chapter covers the 32 countries in the EU, European Free Trade Association, and UK, but refers to Europe in the text. Results in this chapter may purposefully exclude some countries depending on the quantity and quality of the collected information.

The authors are not judging the feasibility of announced facilities but are reporting various public and private data points. As a result, outputs in this chapter include projects in all stages from concept, feasibility study, preparatory stage (FEED, detailed design, and permitting), construction, and operation. Currently operational conventional projects are included in this chapter as the purpose is to be able to estimate how much clean hydrogen could be consumed in the next decade. Advanced projects refer to operational projects, those under construction, or in a preparatory stage. If the authors of this report refer to specific projects and provide any project details, this information is either public or relevant project partners have given explicit permission.

The term "project" refers to an individual project or a project phase with a separate FID. One project can have multiple phases that gradually enlarge its consumption and are counted as separate projects in the report.

Whenever actual hydrogen consumption is not available for a given project, an estimation is made considering the hydrogen that would be required to produce the announced quantity of final product. Whenever final product amounts are not available either, or in the case of refineries and e-fuels production where direct conversion is often difficult, final consumption is estimated to equal to the final amount of hydrogen that would be produced considering announced installed capacity in the case of power-to-hydrogen and produced hydrogen in the case of reforming with carbon capture projects. If only estimate ranges have been given for capacity or start dates, the authors adopted the average of the provided values.

Endnotes

a / IEA, 2023.

02

Hydrogen production capacity

Clean hydrogen production announcements in Europe are increasing every year. However, some projects have been delayed due to lack of regulatory certainty whilst others are being delayed due to slow funding processes, challenging economics for first movers as well as issues with contracting long-term offtakers.

- Clean hydrogen production project pipeline is growing and maturing with total announced capacity 15.7 Mt/year from 813 projects by 2030, with 4.4 Mt/year in an advanced stage and 0.2 Mt/year under construction.

- The most advanced power-to-hydrogen projects are in the Nordics, Iberian peninsula, and certain Western European countries due to availability of new renewable sources, cheap low-carbon grid electricity, government ambitions/support, and willing offtakers.

- Clean hydrogen production projects' most common end-uses are ammonia, steel, refining, methanol, and e-fuels, but 49% of the announced volume by 2030 has not yet identified an end-use.

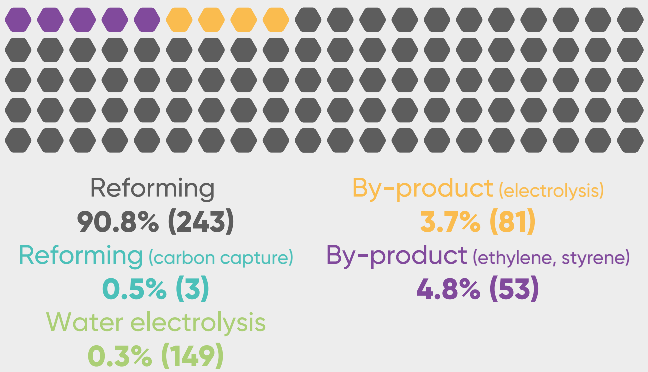
Water electrolysis capacity reached 0.3% of the total hydrogen production capacity in Europe in 2022, compared to 0.1% in 2020. Conventional production capacity accounted for 95.6%.

529 hydrogen production sites have been identified as being in operation in the EU, EFTA, and UK (referred to as Europe in this report) by the end of 2022, with a total production capacity of 11.4 Mt per year. This compares with 504 production sites and 11.5 Mt per year of capacity by the end of 2020 reported in the Clean Hydrogen Monitor 2022. The changes reflect an increase in electrolyser deployments and occasional decommissioning of conventional production capacity in refining and ammonia industries. The conventional production methods of reforming, partial oxidation, gasification, by-product production from refining operations, and by-product production from ethylene and styrene represent 95.6% of total capacity. By-product hydrogen production via electrolysis of brine accounts for 3.7%. Reforming with carbon capture contributes 0.5%. These percentages and absolute values have remained stable compared to 2020. Water electrolysis/power-to-hydrogen capacity increased to 0.3%, producing about 30,000 tonnes of hydrogen annually. Based on the estimated size of hydrogen consumption in 2022 (see **Chapter 1**), the average production capacity utilisation in 2022 was 72% compared to 76% in 2020.

Figure 2.2 shows 11 countries with the largest production capacities. The five largest, Germany, Netherlands, Poland, Italy, and France, account for 56% of the total capacity in Europe.

FIGURE 2.1

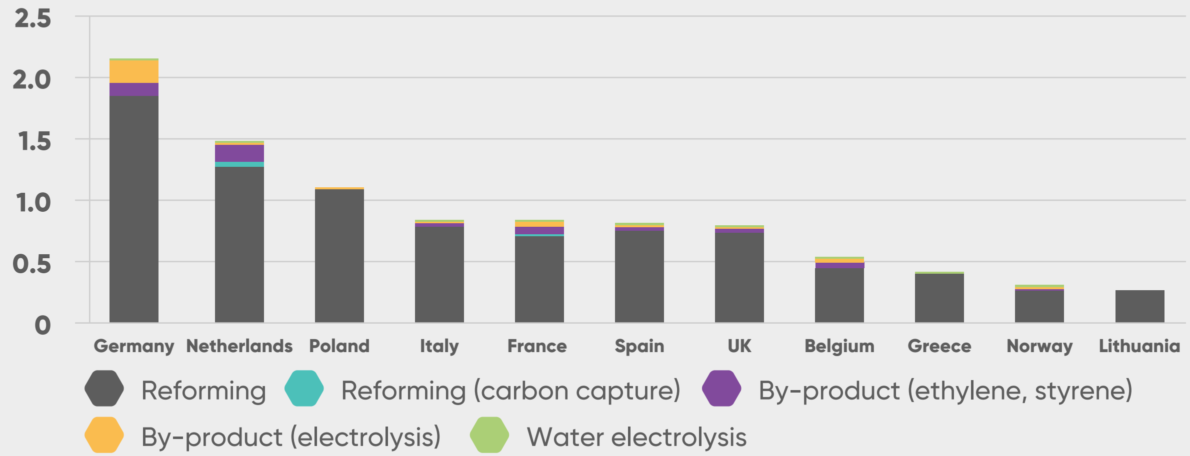
European hydrogen production capacity in 2022 by production process (% of total volume and # of installations)



Source: Hydrogen Europe.

FIGURE 2.2

11 European countries with largest hydrogen production capacity in 2022 (Mt/year)



Source: Hydrogen Europe.

Notes: Explanations of the used terminology can be found in the terminology section at the end of the report.

The increasing deployment of water electrolysis will diversify the concentration of hydrogen production capacity from industrial clusters to other areas, mostly with available RES resources.

Figure 2.3 visualizes production sites and their relative capacities. Most of the large-scale production is centralised in industrial areas and ports near refineries, ammonia producers, and chemical plants, which is significant for future hydrogen or derivative imports. By-product hydrogen production from ethylene and styrene production is generally located around refineries and chemical plants. Chlorine and sodium chlorate production operates also outside of the main industrial clusters. As mentioned above, current hydrogen production is largely concentrated and benefits from economies of scale. As a result, the average size of reforming plants in 2022 was 42,740 tons of hydrogen a year. Ethylene and styrene had an average production capacity of 10,372 tonnes per year, and an average by-product electrolytic plant had a capacity of 5,179 tonnes of hydrogen a year. Compared to conventional plants, the average operational water electrolysis plant has a capacity of 205 tonnes of hydrogen per year and their locations are more distributed. This trend will continue as more water electrolysis is deployed in Europe in or near locations with available renewable energy resources.

FIGURE 2.3

Map of hydrogen production sites in Europe

- Reforming
- By-product (ethylene, styrene)
- By-product (electrolysis)
- Water electrolysis

Source: Hydrogen Europe.

The total announced clean hydrogen production capacity increased to 24.8 Mt/year, but only 4.4 Mt/year is in an advanced stage with only 0.2 Mt/year under construction.

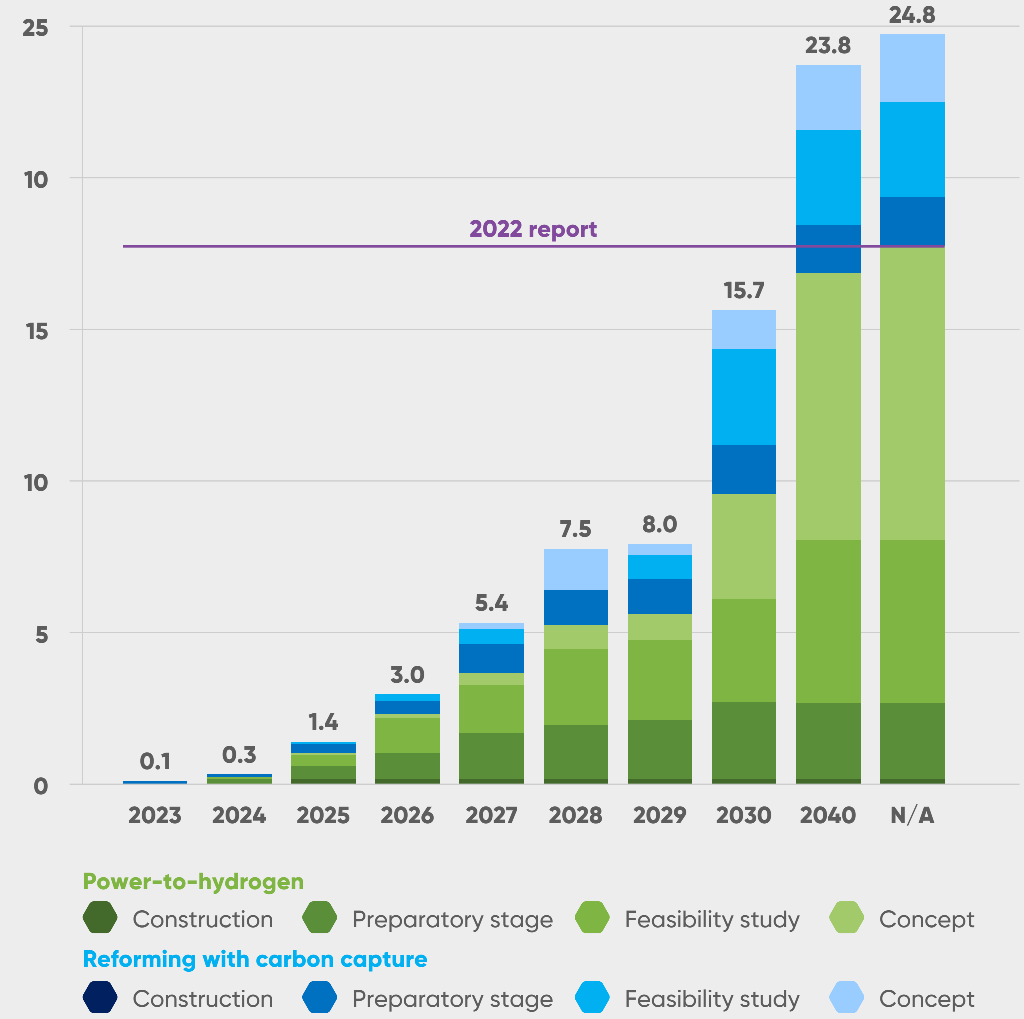
Hydrogen Europe is currently monitoring 924 clean hydrogen production projects with total production volume of almost 25 Mt/ year and announced start dates by 2040. These include 52 projects planning to reform natural gas and capture the associated emissions (reforming with carbon capture/RwCC) amounting to 7 Mt/year and 872 power-to-hydrogen projects amounting to 17.7 Mt/year. Compared to last year's report, the total clean hydrogen capacity increased by 40% from 17.7 Mt/year and projects increased by 5% from 876.

82% of those almost 25 Mt/year are currently in an early development stage (concept or feasibility study), but ~4.4 Mt is in advanced stage (preparatory or under construction). Almost 0.2 Mt/year of PtH capacity is under construction and 2.5 Mt/year is in a preparatory stage. Regarding RwCC, 1.6 Mt/ year is in a preparatory stage.

A significant surge in announced deployments can be observed in 2030 as many projects intend to come online by 2030 rather than specifying a year. Potential supply announcements are far outstripping the minimal regulatory demand for RFNBOs at approximately 1.9 Mt/year by 2030.

FIGURE 2.4

Cumulative announced clean hydrogen production capacity up to 2040 (Mt/year)



Source: Hydrogen Europe.

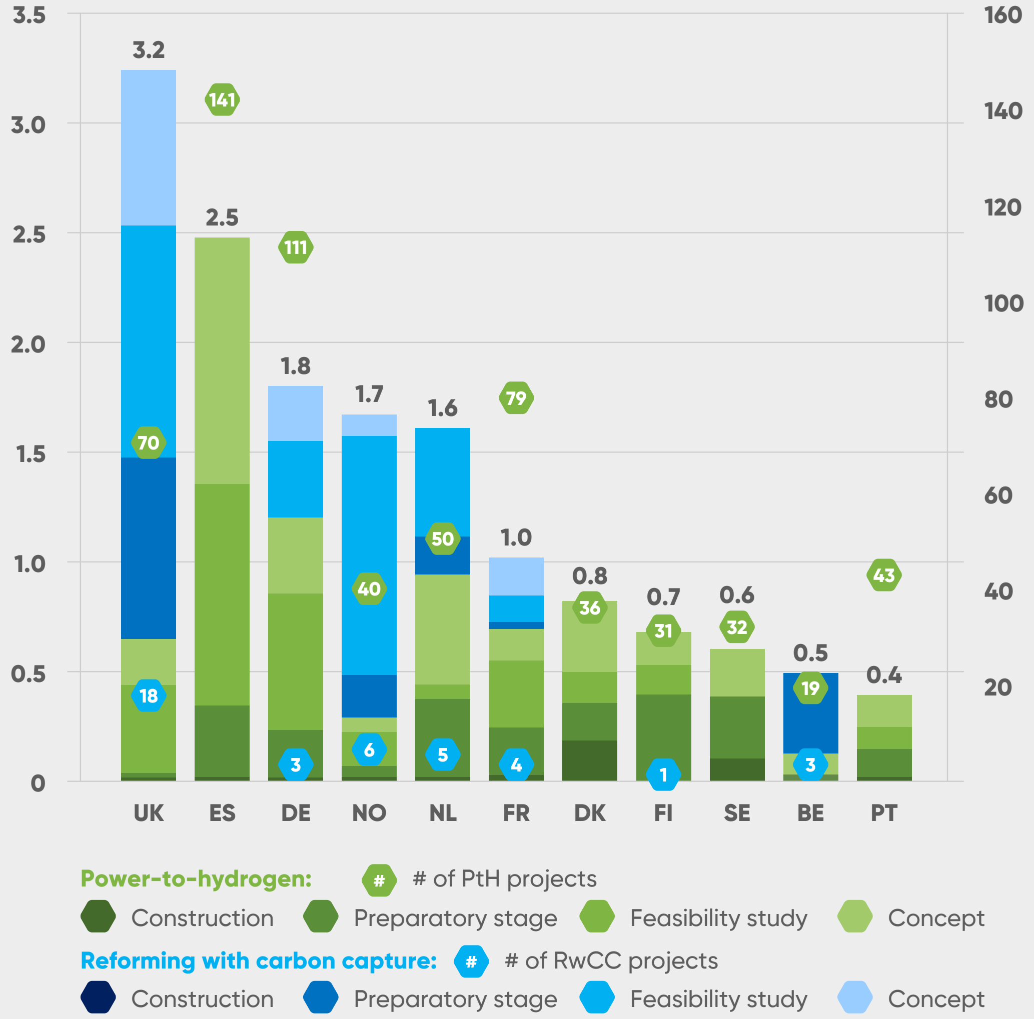
Notes: Data does not represent a forecast, but announced production project pipeline; For methodology and terminology clarifications, please consult the methodological note at the end of the chapter and the terminology section at the end of the report.

The clean hydrogen project pipeline is dominated by Nordic, Iberian, and Western European countries due to RES availability, cheap grid electricity, gas and CO2 infrastructure, government ambitions, and willing offtakers.

The clean hydrogen project pipeline varies greatly from country to country due to factors such as their energy resources, existing infrastructure, national hydrogen ambitions, and level of national support. The UK has the largest clean hydrogen project pipeline by 2030 at 3.2 Mt/y, but mostly due to its large portfolio of announced RwCC projects. These continue to mature due to UK's strong government leadership in decarbonizing its industrial clusters and availability of both natural gas and CO2 transport and storage infrastructure. Its PtH projects doubled from 35 last year to 70. Even though Spain's total announced PtH capacity decreased due to a few large projects being cancelled or postponed for post-2030, it dominates the PtH project pipeline with 2.5 Mt/year by 2030 due to its large renewable energy potential and strong government ambitions. The market is very active and there are 141 announced PtH projects in our database compared to 87 last year. Other countries like the Netherlands are developing a mix of RwCC and PtH to utilise its renewable energy potential, mostly offshore, and the existing and new hydrogen and CO2 infrastructure. The number of projects and capacity has increased in most countries except Greece and Bulgaria whose project pipelines relied on very large projects which have been cancelled.

FIGURE 2.5

11 countries with largest announced cumulative clean hydrogen production capacity by 2030 (Mt/year & # of projects)



Source: Hydrogen Europe.

Notes: Data does not represent a forecast, but announced production project pipeline; For methodology and terminology clarifications, please consult the methodological note at the end of the chapter and the terminology section at the end of the report.

Production projects are maturing with 4.4 Mt/year of clean hydrogen having passed a feasibility stage planning to be online by 2030 compared to 3.2 Mt/year last year.

By September 2023, total announced project capacity that has passed a feasibility stage amounts to 4.4 Mt/year by 2030 split among 364 projects, but only 0.2 Mt/year was under construction. More than half of those announced 4.4 Mt/year is electrolytic, but in the United Kingdom, Belgium, and Norway, the announced capacity of production projects in advanced stages is dominated by RwCC.

The clean hydrogen production that passed a feasibility study of 0.86 Mt/year in the UK could satisfy its current hydrogen consumption of 0.56 Mt/year. While Spain dominates the PtH project pipeline, the largest advanced PtH capacity is in Finland, followed by the Netherlands, Sweden, and Denmark. This can be explained by available new RES, access to low-carbon grid electricity, willingness to pay on the customer side, and government support for electrolytic hydrogen. In addition to economic conditions, the increasing maturity of projects compared to last year's Clean Hydrogen Monitor has been aided by several IPCEI rounds and subsequent awarded state aid, Innovation Fund results, regulatory clarity regarding Renewable Energy Directive Delegated Acts and industry targets, and emerging national support schemes.

FIGURE 2.6

Cumulative announced clean hydrogen production capacity of advanced projects up to 2030 (Mt/year & # of projects)

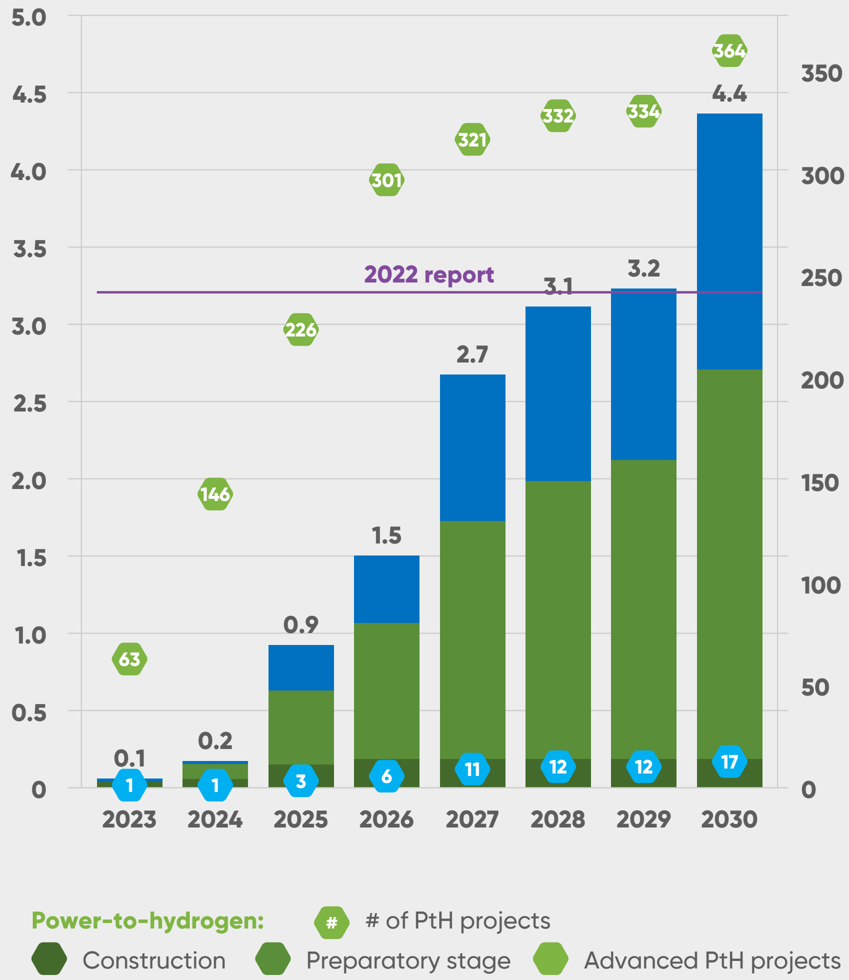
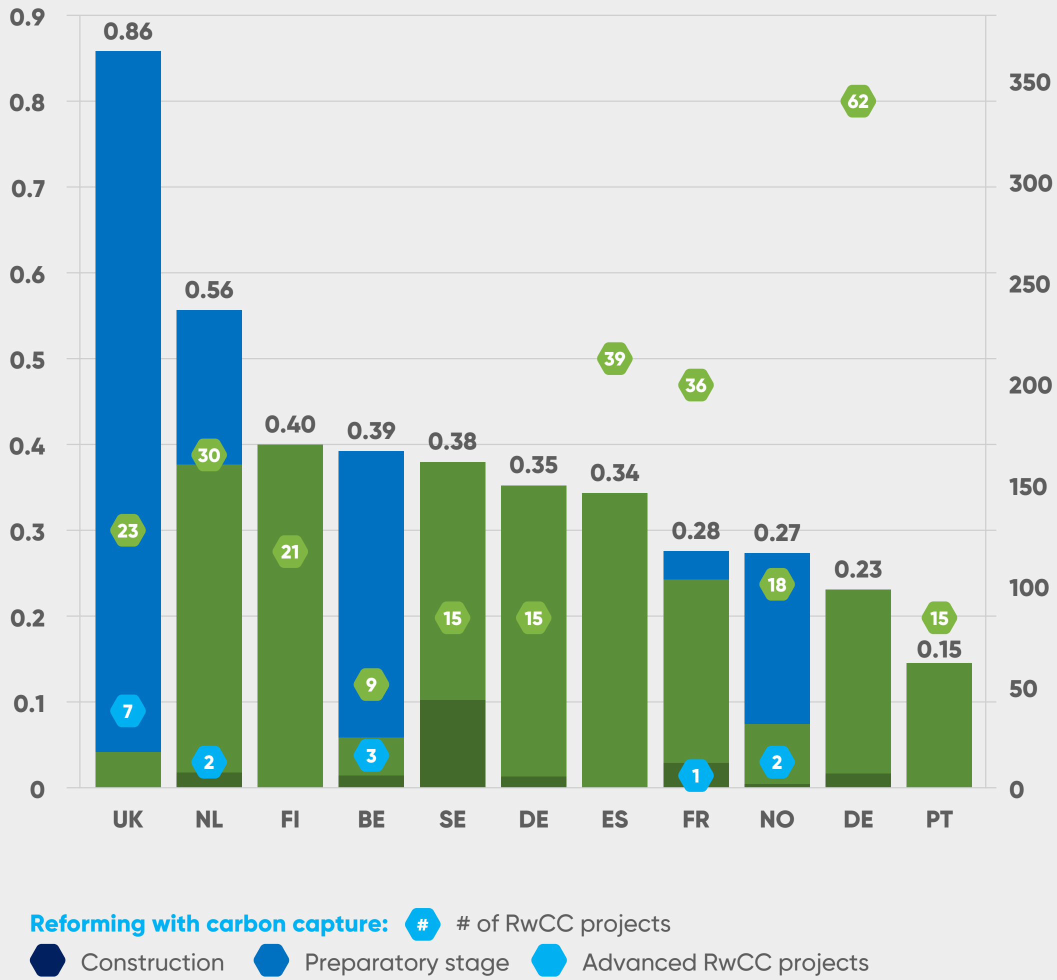


FIGURE 2.7

11 countries with largest advanced cumulative announced clean hydrogen capacity in Europe by 2030 (Mt/year & # of projects)



Source: Hydrogen Europe.

Notes: Data does not represent a forecast, but announced production project pipeline; For methodology and terminology clarifications, please consult the methodological note at the end of the chapter and the terminology section at the end of the report.

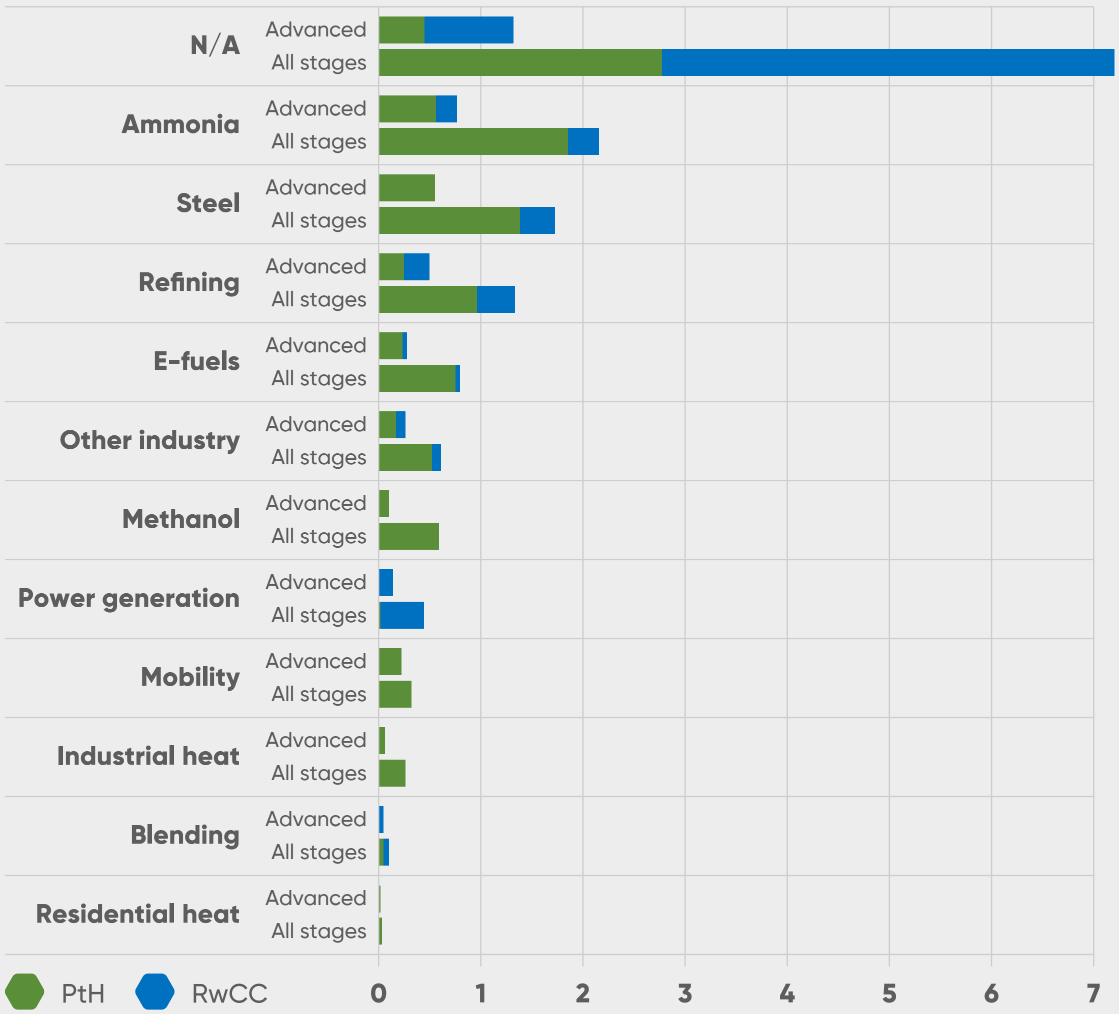
While end-users for many production projects are not known, most clean hydrogen volumes are targeting ammonia, steel, and refining industries.

Of the 15.7 million tonnes per year of clean hydrogen production projects, 7.2 Mt/year has not yet specified or disclosed how their hydrogen will be used. This is a common situation among early stage projects. The largest end-use is ammonia with 2.2 Mt/year, 1.8 Mt/year of it from PtH. If all those projects were realised, that would satisfy the Renewable Energy Directive Industry target of 42% which would require around 1.5 Mt of RFNBO hydrogen for ammonia production. From advanced projects (post-feasibility), there is a potential 1.3 Mt/year of clean hydrogen that has not identified a main offtaker, or the produced hydrogen has multiple end-users. 0.8 Mt/ year of the advanced projects has been announced to produce green, or clean ammonia and 0.6 Mt for green steel production.

The results of tracking clean hydrogen production projects in this chapter and industrial consumption projects in **Chapter 1** show a large inconsistency in terms of volumes between what the production developers (15.7 Mt/year) and industrial consumption developers (7.1 Mt/year) are planning by 2030 (**Chapter 1**). While the supply and demand project pipelines will become closer as the projects mature, this also supports the current state of the industry when the demand side needs to firm up for large volumes of clean hydrogen to materialise.

FIGURE 2.8

End-uses by announced clean hydrogen production projects planning to be online by 2030 (Mt/year)



Source: Hydrogen Europe.

Notes: Data does not represent a forecast, but announced production project pipeline; For methodology and terminology clarifications, please consult the methodological note at the end of the chapter and the terminology section at the end of the report.

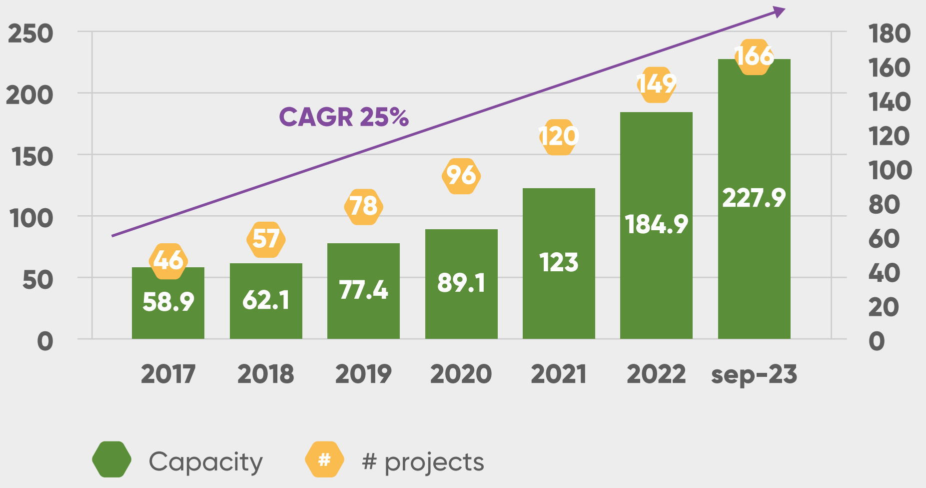
Installed water electrolysis reached 228 MW_{el} in September 2023 with CAGR of 25% from 2017. At this rate, barely 1 GW_{el} would be installed in Europe by 2030.

By September 2023, Hydrogen Europe identified 166 PtH sites in operation in Europe, amounting to 228 MW_{el}. So far, they are a marginal part of the market, constituting only 0.33% of the total 2022 installed European hydrogen production capacity of 11.5 Mt/ year. For comparison, the total operational PtH capacity identified in Europe is lower than the world's largest operational PtH facility, Sinopec's ~260 MW_{el} Xinjiang Kuqa Green Hydrogen Pilot plant in China. The average project size of operational water electrolysers in Europe is 1.37 MW_{el}, up from 0.93 MW_{el} in 2020. Recently, companies in industries like refining, ammonia production, and steel started operating industrial-scale pilot plants of 10-20 MW_{el}. There are 13 projects, larger or equal to 5 MW_{el}, constituting 52% of the total installed capacity.

Electrolysers are also being decommissioned. In the past years, it was mostly research projects while in 2022, there were several hydrogen refuelling stations with on-site electrolysers that have been decommissioned for economic reasons. Countries with highest installed capacity by September 2023 are Germany at 72 MW_{el}, Spain at 33 MW_{el}, and Sweden at 30 MW_{el}.

FIGURE 2.9

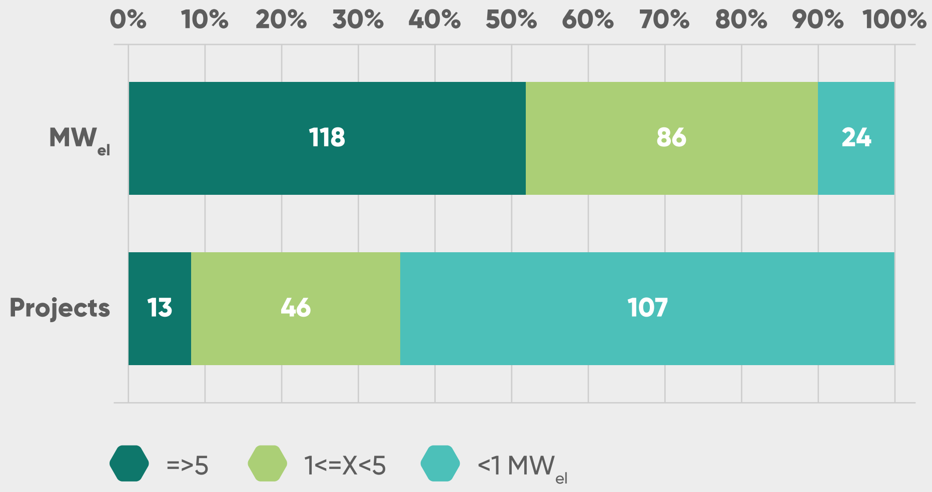
Operational PtH projects in Europe (MW_{el} & # of projects)



Source: Hydrogen Europe.

FIGURE 2.10

Operational PtH projects in Europe in Sept 23 by size (MW_{el} & # of projects)



Source: Hydrogen Europe.

Notes: For methodology and terminology clarifications, please consult the methodological note at the end of the chapter and the terminology section at the end of the report.

PtH developers experience delays in the short and medium term, but the pipeline of announced PtH projects to be online by 2030 grew by 30% compared to 2022.

The number of announced PtH projects planning to be operational by 2030 increased by 30% year on year to 813 and almost doubled compared to 2021. The trend of increasing project announcements is positive, but similarly to previous years, projects continue being delayed. The 2022 Clean Hydrogen Monitor reported 146 projects planning to start in 2023. Last year's Monitor reported 257 announced projects with plans to come online in 2024 while this year's version reports only 194 after accounting for revised timelines. Similarly on the capacity side, while 2021 and 2022 reports tracked ~6 GW_{el} to come online in 2024, this year's report tracks 2.4 GW_{el} as the rest was delayed or cancelled. The real number that will have come online by the end of 2024 will likely be significantly lower.

The main reasons behind project delays include regulatory uncertainty and funding access. Producers also often cite lack of offtakers due to the cost gap of renewable vs fossil hydrogen; components delivery issues; project development delays due to first-of-a-kind nature of projects; standardization and certification uncertainty; and slow developments on hydrogen transmission and storage. Announced PtH capacity also continues to increase. Adjusting for a single large project that has been removed from our tracking, the PtH pipeline increased by 9 GW_{el} compared to 2022. The current project pipeline, if realized, would almost reach the approximately 100 GW_{el} needed for 10 Mt/year as envisaged in RePowerEU.

+30%

Number of projects planning to be online by 2030 increased by 30% from last year

+9 GW_{el}

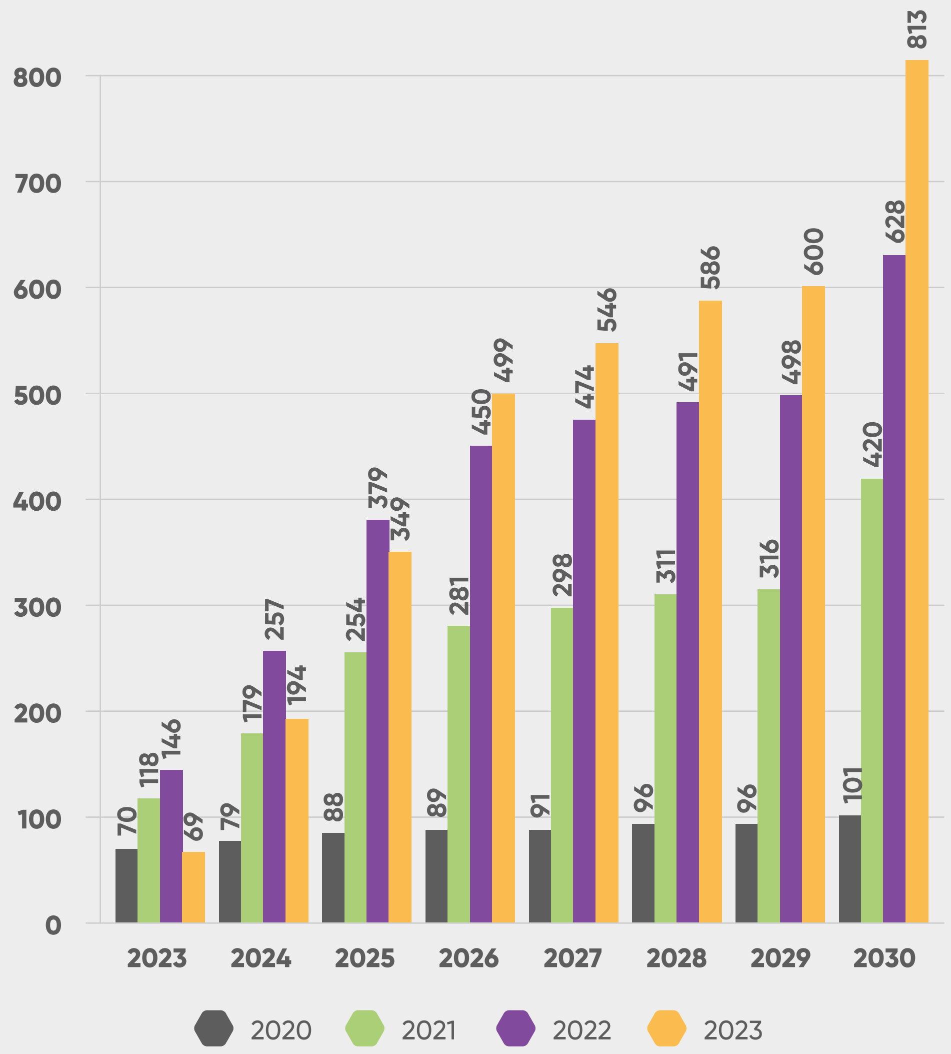
Increase in announced PtH capacity by 2030 since last year (after adjusting for cancelling a single large project)

-4 GW_{el}

Decrease in projects planning to be online by the end of 2024 due to prolonged regulatory uncertainty, lack of funding, lack of demand targets in the last years

FIGURE 2.11

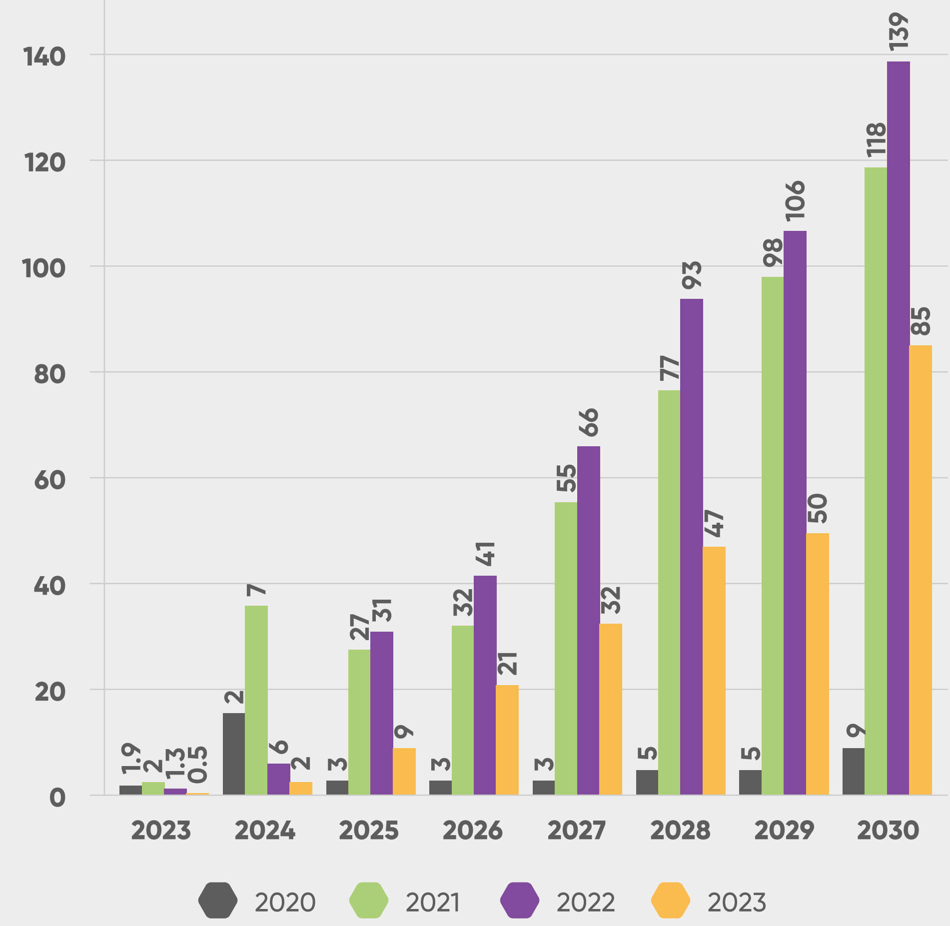
Cumulative announced # of PtH projects compared to previous years (# of projects)



Source: Hydrogen Europe.

FIGURE 2.12

Cumulative announced PtH capacity compared to previous years (GW_{el})

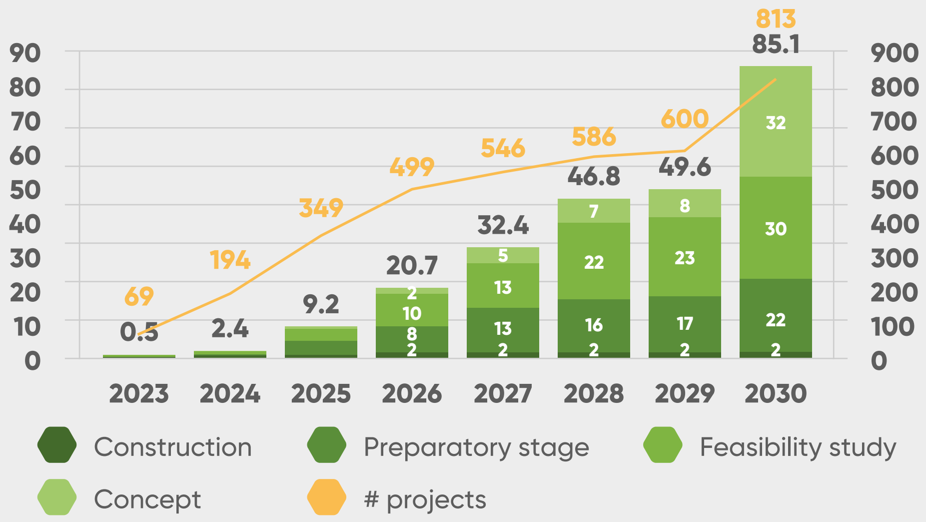


Source: Hydrogen Europe.

Notes: Data does not represent a forecast, but announced production project pipeline; For methodology and terminology clarifications, please consult the methodological note at the end of the chapter and the terminology section at the end of the report.

FIGURE 2.13

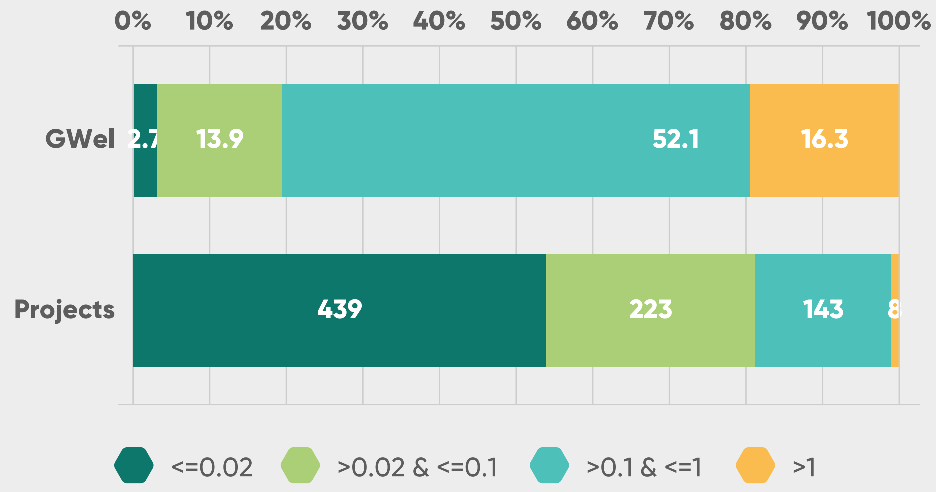
Cumulative announced PtH projects in Europe by 2030 (GW_{el} & # of projects)



Source: Hydrogen Europe.

FIGURE 2.14

Announced PtH projects in Europe up to 2030 split by size (GW_{el} & # of projects)



Source: Hydrogen Europe.

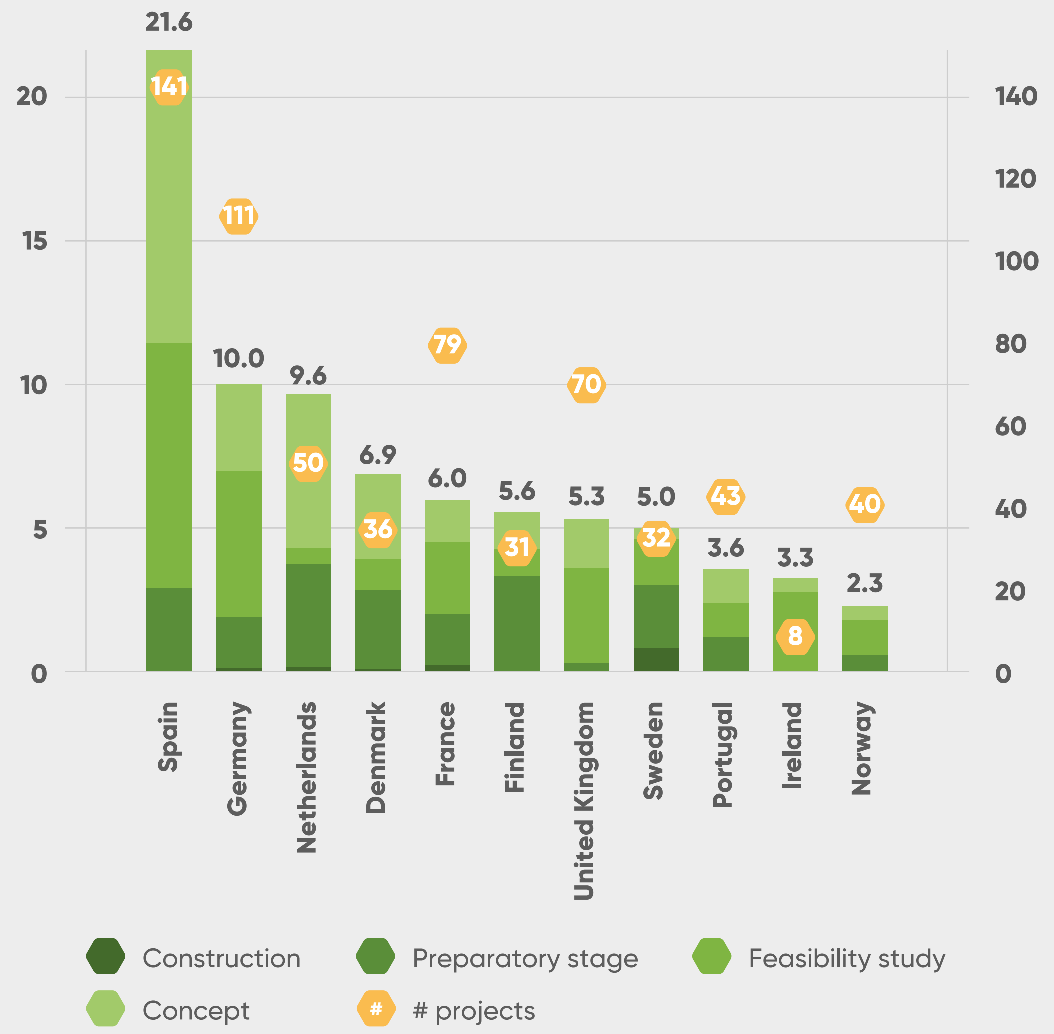
The projects are maturing as 60% of capacity planning to be online by end of 2025 is in an advanced stage. 81% of announced capacity is spread among 151 projects larger than 100 MW_{el}.

The total announced PtH capacity in Europe by 2030 is 85 GW_{el}, split among 813 projects. The announced pipeline by 2024 is 2.4 GW_{el}. Even with the 228 MW_{el} already in operation, the announced projects fall short of the European Hydrogen Strategy's goal of 6 GW_{el} by that year. The database tracks 0.45 GW_{el} of projects announced to come online by the end of 2023. 90% of that capacity is in an advanced stage with 75% under construction and 15% in a preparatory stage. Based on previous years, most of that will be delayed to 2024, but it is likely the total PtH addition for 2023 will exceed 2022's 62 MW_{el}.

In the medium term, 60% of the capacity planning to be online by the end of 2025 is in an advanced stage with 1.3 GW_{el} under construction and 4.2 GW_{el} in the preparatory stage. The capacity is less mature if the completion date is further. Currently, 73% of the announced 85 GW_{el} by 2030 is in early development (concept or feasibility study stage). Compared to 2022 results by 2030, about 63 GW_{el} has been removed from the database due to cancelation or delay to post 2030 and around 9 GW_{el} has been added. Most of the 35 GW_{el} that announced to come online in 2030 are from early-stage projects or additional project phases. The average project size among announced projects is over 105 MW_{el}. More than half of the 813 tracked projects are under 20 MW_{el}. Large projects over 100 MW_{el} amount to 81% of the announced PtH capacity.

FIGURE 2.15

11 European countries with largest announced PtH capacity (GW_{el} & # of projects)



Source: Hydrogen Europe.

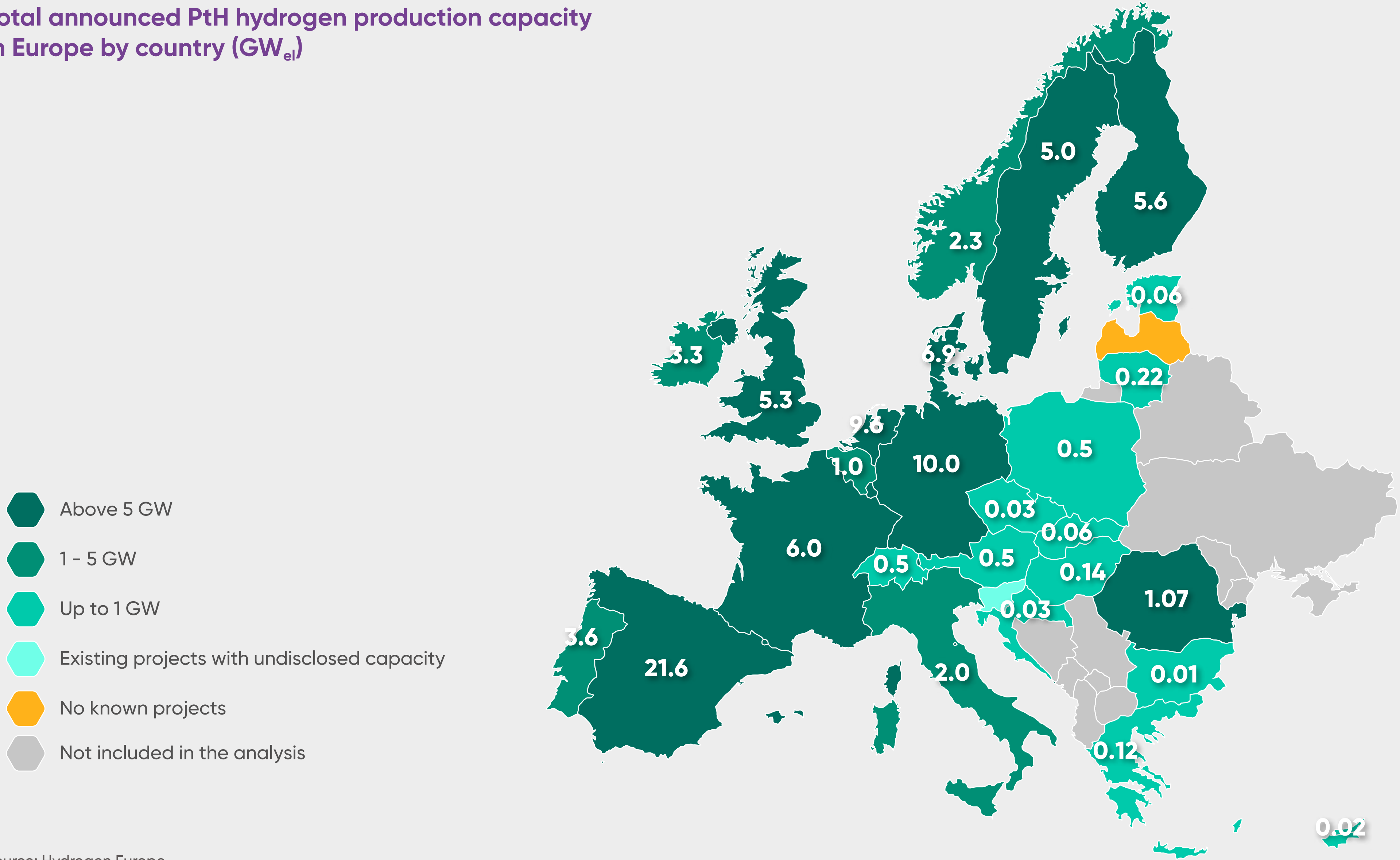
Factors in being power-to-hydrogen frontrunners are RES availability, cheap low-carbon grid electricity, government ambitions/support, and willing offtakers.

Spain with 21.6 GW_{el} retains its spot as the country with the largest announced PtH project pipeline. Germany is in second place with 10 GW_{el} and the Netherlands is in third place with 9.6 GW_{el}. Sweden's advanced-stage projects make up 61% or 3.1 GW_{el} of their project pipeline. Finland follows with 59% and 3.3 GW, and Denmark with 42% and 2.9 GW. Spain is at 14% or 3 GW_{el}, Germany is at 19% or 1.9 GW_{el}, and the Netherlands at 40% or 3.8 GW_{el}. These numbers reflect the relative attractiveness of the Scandinavian countries and their position as first movers in developing PtH projects due to affordable and low-carbon grid electricity and willingness to pay from local offtakers. Central European countries continue to lag behind due to less developed renewable energy resources, often less potential for RES, less government decarbonization impetus, and lack of clarity on the treatment of electrolytic hydrogen from nuclear until 2024-2025. Compared to last year, our database added nearly 4 GW_{el} in the UK, 3 GW_{el} in Finland, and 1.4 GW_{el} in Sweden. With multi-GW_{el} projects cancelled in Spain, Greece, and Bulgaria, these countries all saw significant decreases. Currently, the biggest and most advanced project pipelines still depend on the availability of renewable energy sources, inexpensive low-carbon electricity from the grid, government support and ambitions, and buyers who are willing to pay premium for renewable hydrogen.

Notes: The change from Spain's 74GW last year to this year's 21.6 GW reflects a cancellation of a single large project of ~60 GW in addition to other announcements and cancellations. Data does not represent a forecast, but announced production project pipeline; For clarifications regarding terminology and methodology, please consult the methodological note at the end of the chapter.

FIGURE 2.16

Total announced PtH hydrogen production capacity in Europe by country (GW_{el})



Source: Hydrogen Europe.

Notes: The change from Spain's 74GW last year to this year's 21.6 GW reflects a cancellation of a single large project of ~60 GW in addition to other announcements and cancellations. Data does not represent a forecast, but announced production project pipeline; For methodology and terminology clarifications, please consult the methodological note at the end of the chapter and the terminology section at the end of the report.

73% of the capacity in projects under construction now is alkaline while that number decreases to 48% for all announced projects by 2030.

Europe had 228 MW_{el} of operational PtH capacity by September 2023.The production database tracks 105 MW_{el} in 55 projects with PEM technology and 81 MW_{el} in 48 projects with alkaline technology. Somewhat surprisingly, most projects larger than 5 MW_{el} that came online in recent years, except for one in Sweden in 2023, have been PEM. The operational PtH capacity is small, so adding one project can greatly change the technology capacity numbers.

For projects planning to be operational by 2030, 6.8 GW_{el} has announced to use alkaline and 6.7 GW_{el} announced to use PEM. 1.2 GW_{el} of projects under construction chose to rely on alkaline technology compared to 0.4 GW_{el} for PEM.

FIGURE 2.17

Operational water electrolysers in Europe by technology

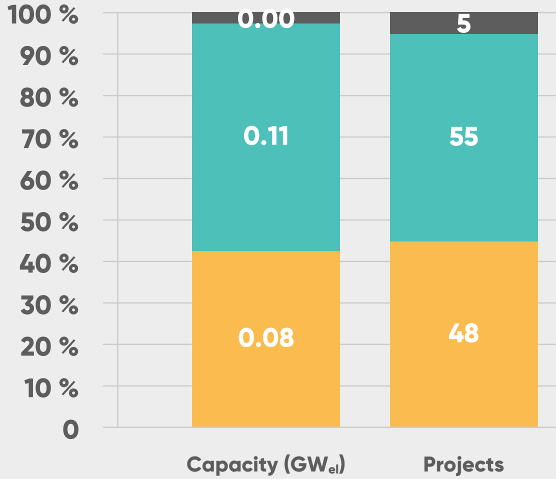


FIGURE 2.18

Water electrolysis capacity under construction in Europe by technology

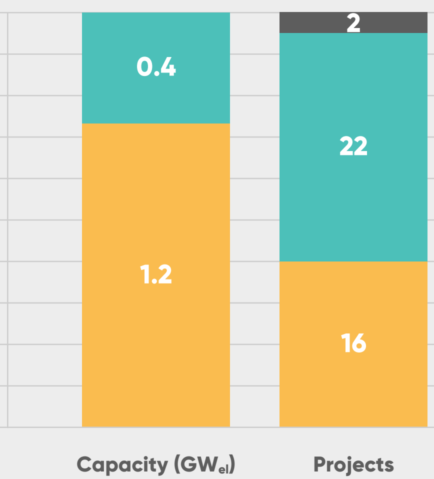
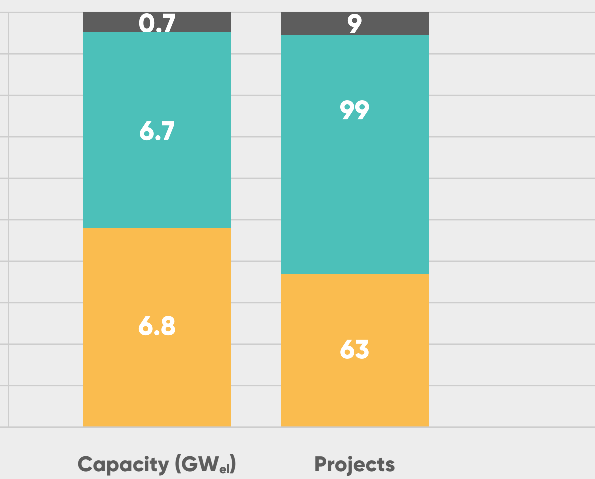


FIGURE 2.19

Announced water electrolysis capacity in Europe by technology by 2030



ALK PEM SO

Source: Hydrogen Europe.

Notes: For methodology and terminology clarifications, please consult the methodological note at the end of the chapter and the terminology section at the end of the report.

The total reforming with carbon capture project pipeline is 6.1 Mt/ year. 72% of that volume is less advanced, but flagship projects with strong backing are expected to be built in several countries.

The production database tracks 47 RwCC projects planning to come online by 2030 with a total production capacity of 6.1 Mt/year. This is compared to 32 projects and 4 Mt/year reported last year which is a 47% increase in tracked projects and a 52% increase in tracked capacity. 72% or 4.4 Mt/year is still in early development stage (concept or feasibility study). There are 23 projects with 3.8 Mt/year of capacity that are targeted to come online in 2030. Similarly to the PtH database, these can sometimes represent just aspirational start dates. There aren't any projects under construction.

The United Kingdom has the most RwCC projects with 2.6 Mt/year and 18 projects. The UK has a strong government support for the technology, commitment for decarbonizing its industrial clusters, and availability of natural gas and CO2 infrastructure. Norway has the second largest tracked capacity of 1.4 Mt/year by 2030 followed by Netherlands and Germany. Projects using this production pathway continue to mature across the continent despite the lack of regulatory clarity regarding classification of hydrogen from natural gas with carbon capture with GHG intensity less than 28.2 gCO2/MJ.

FIGURE 2.20

Cumulative announced RwCC production capacity up to 2030 (Mt/year & # of projects)

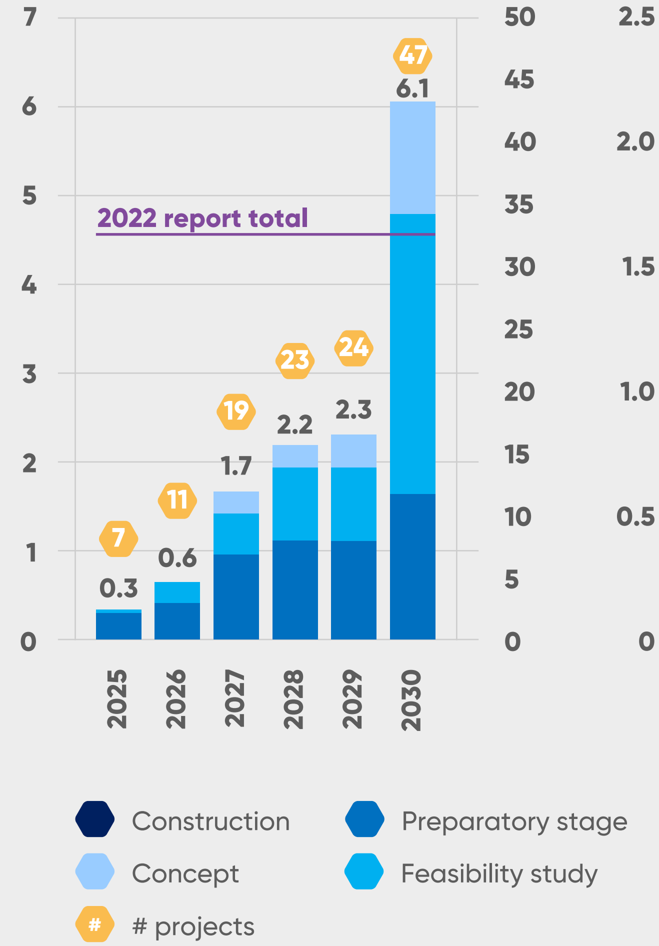
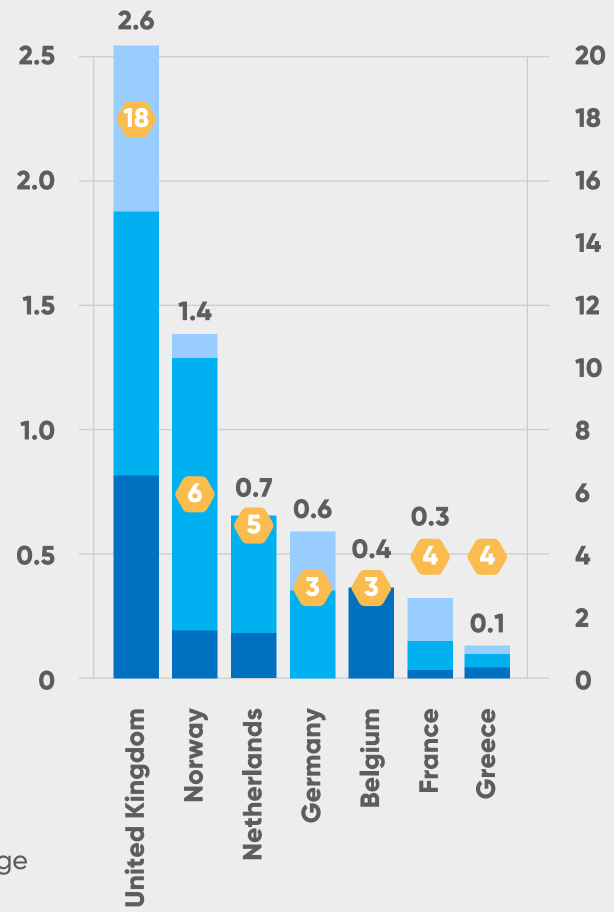


FIGURE 2.21

Selection of countries with RwCC projects in Europe by 2030 (Mt/year & # of projects)



Source: Hydrogen Europe.

Notes: The capacities for some projects are not available; Data does not represent a forecast, but announced production project pipeline; For methodology and terminology clarifications, please consult the methodological note at the end of the chapter and the terminology section at the end of the report.

Methodological Note

The outputs in this chapter provide a potential future snapshot of clean hydrogen production based on announcements by the industry and do not represent a forecast in any way.

This chapter covers the 32 countries in the EU, European Free Trade Association, and UK, but refers to Europe in the text. Results in this chapter may purposefully exclude some countries depending on the quantity and quality of the collected information.

The authors have adopted an inclusive approach when compiling this list of projects to develop the most exhaustive compilation of European power-to-hydrogen and reforming with carbon capture projects. This analysis excludes any other hydrogen production methods such as biomass reforming, gasification, methane splitting, pyrolysis of waste, etcetera. The data collection closed in early September. While project announcements are common for hydrogen production projects, cancellations are rarely publicized. The authors cancel projects if they find confirmation of the project's restructuring or if there are no news for at least 18 months.

The authors collected this information to the best of their abilities but cannot guarantee the absolute completeness or accuracy of the collected data.

The list of power-to-hydrogen and reforming of natural gas with carbon capture projects that form a basis for the analysis have been collected by Hydrogen Europe from both public and confidential sources.

If only estimate ranges have been given for capacity or start dates, the authors adopted the average of the provided values. The authors never made their conclusions about the start date, capacity, technology, or other project information.

Years refer to end of the year. By 2030 refers to "by the end of 2030".

The authors are not judging the feasibility of announced facilities but are reporting various public and private data points. As a result, outputs in this chapter include projects in all stages from concept, feasibility study, preparatory stage (FEED, detailed design, and permitting), and construction(post FID). Advanced projects refer to projects either under construction or in a preparatory stage. If the authors of this report refer to specific projects and provide any project details, this information is either public or relevant project partners have given explicit permission.

The term "project" refers to an individual project or a project phase with a separate FID. One project can have multiple phases that gradually enlarge its capacity. For the purposes of this report, each phase of a project with three phases of 10 MW, 100 MW, and 300 MW in the same location and with the same project partners is counted as a separate project.

ASSUMPTIONS

The data on collected projects tracks their production capacity in MW_{el} (PtH) and MW(RwCC) respectively. To achieve outputs in Mt of H2, the following utilization assumptions have been used:

- Reforming with carbon capture projects - 8000 hours a year at full capacity

- Power-to-hydrogen – For projects connected to the grid, a capacity factor of 68% was assumed which reflects 5957 hours a year. In real life, there will be grid connected projects that will have significantly higher and lower utilisation. For projects that are planning to be directly connected to their renewable energy sources and do not plan to rely on a grid connection, the electrolyser capacity factor is equal to solar/onshore wind/offshore wind's capacity factor for the top 10% available locations in that member state as reported by Joint Research Centre's ENSPRESSO dataset from 2019.

03

Hydrogen production costs

Hydrogen production costs for all key technologies increased in 2022. While there are countries in Europe where renewable hydrogen is cost competitive against conventional hydrogen, on average, the fossil fuel option remains the lowest cost option.

- Extremely high natural gas prices in 2022 have led to record high fossil hydrogen production costs, more than 100% above 2021 annual average, and several times higher than in the years before 2021.

- With the current level of the CO2 emission price in the ETS (around 85 EUR/t), natural gas reforming with CCS is at cost parity with conventional fossil-fuel hydrogen.

- High inflation and tightening renewable PPAs market, caused an increase of EU average estimated renewable hydrogen production costs, from 4.4 EUR/kg in 2021 to close to 7 EUR/kg in 2022. Electricity costs are expected to drop in the short to medium term (as are natural gas prices).

The fossil-fuel benchmark

Extremely high natural gas prices in 2022 have led to record high fossil hydrogen production costs, more than 100% above 2021 annual average, and several times higher than in the years before 2021.

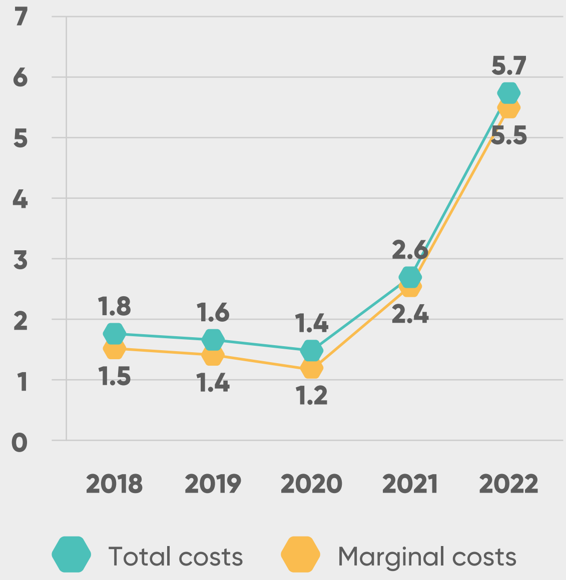
Today, the vast majority of hydrogen production in the EU (and worldwide) comes from fossil hydrogen. This means it is produced from fossil fuels, usually natural gas through steam methane reforming. Replacing fossil hydrogen presents the most immediate market opportunity for clean hydrogen, hence production costs through the SMR process provide a useful price benchmark for all other production technologies.

For 2022, we estimate that, on average, the levelized production costs of hydrogen by SMR in the EU-27 were approximately 5.7 EUR/kg. Furthermore, as SMR plants are already operational (and in many cases long amortised), marginal – not levelized - costs may, in many cases, be a better benchmark. In 2022, the estimated cost to produce fossil hydrogen in the EU-27 was around 5.5 EUR/kg, excluding CAPEX or other fixed costs.

This represents more than a 100% increase vs average costs in 2021 and is 3-4x the historical level of fossil hydrogen production costs of 1.2-1.5 EUR/kg. Such unprecedented fossil hydrogen production costs are a direct consequence of high natural gas prices, which persisted in 2022, following the Russian invasion of Ukraine and the subsequent embargo on Russian natural gas.

FIGURE 3.1

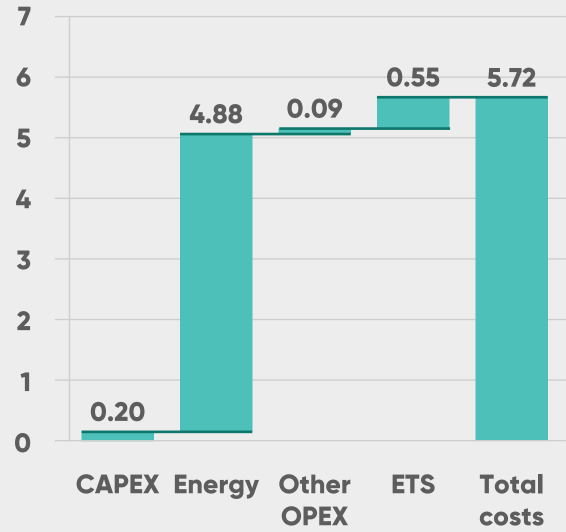
Levelized costs of hydrogen production via SMR in 2018-2022, EU-27 average (EUR/kg)



Source: Hydrogen Europe.

FIGURE 3.2

Breakdown of the EU-27 average levelized costs of hydrogen production via SMR in 2022 (EUR/kg)



Source: Hydrogen Europe.

Reforming of natural gas with CCS

With the current level of the CO2 emission price in the ETS (around 85 EUR/t), natural gas reforming with CCS is at cost parity with fossil hydrogen.

Even though using CCS technology allows for an almost complete avoidance of direct CO2 emissions, the cost-competitiveness of the CCS technology for hydrogen production is heavily influenced by the cost of CO2 transportation and storage.

If those costs can be kept under 50 EUR/tCO2, with the current level of the CO2 emission price in the ETS (around 85 EUR/t), natural gas reforming with CCS is at cost parity with fossil hydrogen.

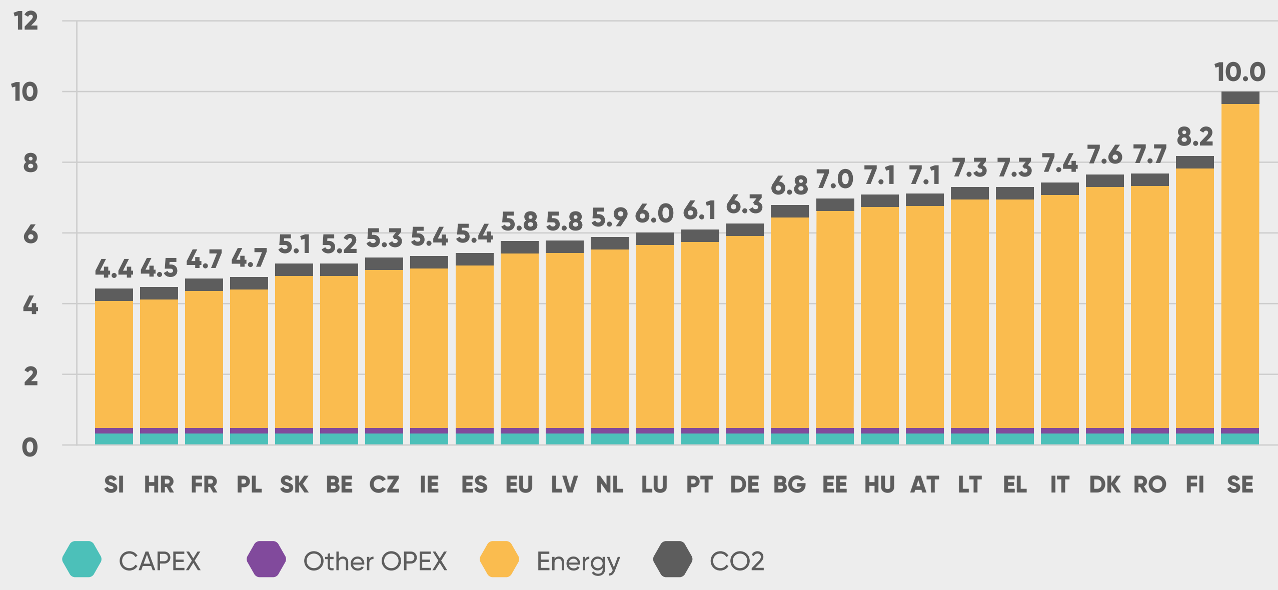
Relatively high-cost differences between various EU countries (from close to 10 EUR/kg in Sweden to 4-5 EUR/kg in France or Poland) are a result of natural gas cost differences – including gas grid costs and taxation.

The costs of natural gas reforming with CCS have been estimated assuming a new installation using the auto-thermal reforming (ATR) technology. Adding CCS to current SMR units could be less costly, but the carbon capture setup may limit the CO2 capture rate, affecting low-carbon qualification.

It should however be noted that natural gas prices have fallen back to a level of around 50 EUR/MWh throughout 2023, reducing hydrogen production costs to around 3.5 EUR/kg (EU-27 average).

FIGURE 3.3

Levelized costs of hydrogen production via natural gas reforming with CCS in 2022 by country (in EUR/kg)



Source: Hydrogen Europe.

Notes: CO2 costs include net costs/revenues from participating in the ETS system as well as costs of CO2 transportation and storage.

Grid connected electrolysis

High electricity prices in Europe in 2022 have led to more than doubling of grid connected hydrogen production costs, estimated at 3.9-16.4 EUR/kg.

In 2022, it is estimated that the cost of producing hydrogen with grid electricity in the EU (including Norway) will be between 3.9 and 16.4 EUR per kilogram. This is compared to the cost of 3.0 to 9.7 EUR per kilogram in 2021. The average for all countries was 9.9 EUR/kg in 2022 vs 5.3 EUR/kg in 2021.

This represents a significant growth as compared to the previous year, with costs having increased by more than 100% in several countries. Like fossil hydrogen, this cost increase is connected to the rise in natural gas prices. Natural gas-fired power plants are closing the merit order on most EU electricity markets. This, in turn, sets the wholesale electricity prices in those markets.

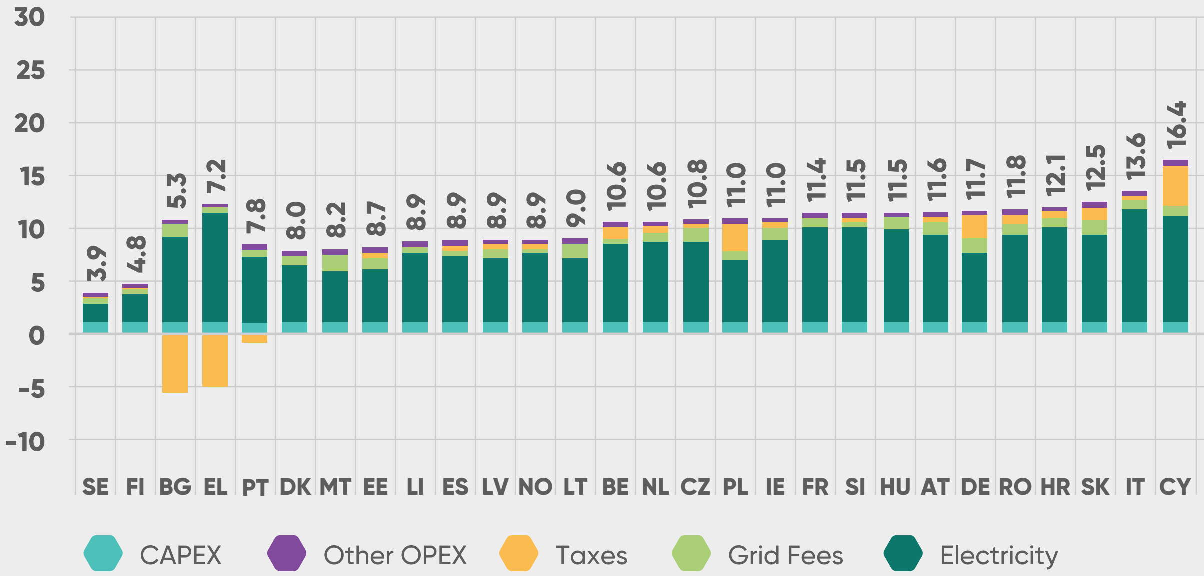
Out of all the main EU markets, Italy had the highest grid electricity hydrogen production costs, estimated to be around 13.6 EUR/kg, which is more than 230% higher than the estimate in 2021.

In contrast, we can observe Sweden and Finland, where the share of natural gas in the power generation sector is negligible (high share of renewable and nuclear energy), making them resilient to natural gas price increases.

To help the industry cope with high electricity prices, countries like Bulgaria, Greece, and Portugal have implemented various tax schemes, which have successfully limited the increase in grid electrolysis hydrogen production costs.

FIGURE 3.4

Grid-connected electrolysis hydrogen production costs in the EU (+NO) in 2022 (EUR/kg)

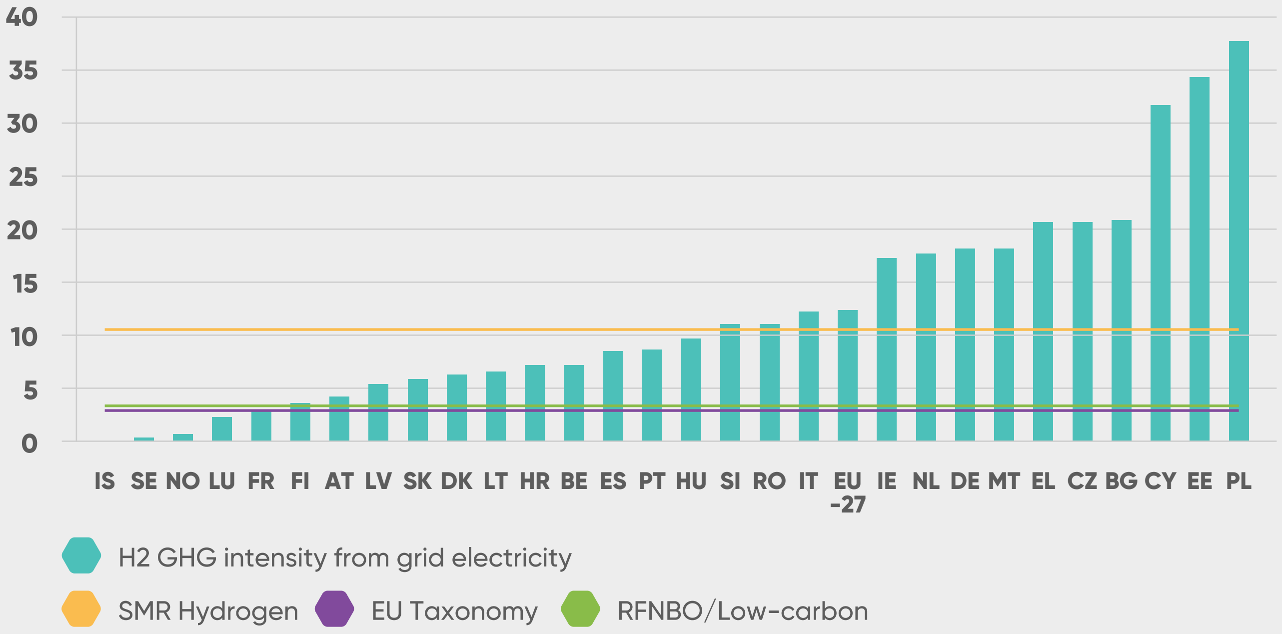


Source: Hydrogen Europe.

Water electrolysis using average EU-27 grid-mix electricity carbon intensity would lead to GHG emissions of 12.5 kgCO2e for each kg of hydrogen, which is almost 20% higher than emissions from steam methane reforming.

FIGURE 3.5

Carbon intensity of hydrogen produced from grid electricity, compared to selected benchmarks (tCO2/tH2)



Source: Hydrogen Europe. Notes: SMR Hydrogen: 10.5 kg CO2 / kg H2 (including indirect emissions), EU Taxonomy threshold for sustainable hydrogen manufacturing: 3 kg CO2 / kg H2, RED II threshold for RFNBO: 3.384 kg CO2 / kg H2 (28.2 gCO2/MJ_{LHV}).

After many years of declining GHG intensity of electricity production in Europe, 2021 saw an increase of average GHG intensity from 228 to 238 gCO2/kWh[1]. As a result, the production of hydrogen using the EU-27 average electricity mix would have resulted in emissions of 12.5 kgCO2/kgH2, which is well above the GHG emissions for steam methane reforming (the dominant fossil-fuel based production method), and clearly underlines the importance of using low carbon electricity for clean hydrogen production.

The carbon footprint of hydrogen made from water electrolysis and from grid power varies a lot in Europe. In Iceland, for example, the electricity grid is nearly 100% decarbonised, so hydrogen made from the grid has the same low carbon footprint as renewable hydrogen.

In other countries, including Norway, Sweden and France, the carbon intensity of grid electricity is sufficiently low that the produced hydrogen carbon footprint would meet all hydrogen emission benchmarks set by the EU, including the EU taxonomy on sustainable finance, and the RED II GHG limit for RFNBOs – which has been established as a minimum requirement for achieving at least a 70% reduction in greenhouse gas emissions compared to fossil fuels, equivalent to 3.384 kgCO2/kgH2.

On the other end of the spectrum are countries like Poland, which still heavily rely on coal for power generation, where using grid electricity would lead to more than three times as much GHG emissions as natural gas reforming.

1 / As estimated by the European Environment Agency (EEA).

Water electrolysis using average EU-27 grid-mix electricity carbon intensity would lead to GHG emissions of 12.5 kgCO2e for each kg of hydrogen, which is almost 20% higher than emissions from steam methane reforming.

The GHG DA[2] states that when RFNBO/RCF are produced with other non-renewable fuels, all outputs should have the same emission intensity per this requirement is mentioned in Part A, point 1 of the GHG DA Annex.

This rule limits the possibility of mixing of electricity from the with fully renewable electricity, as it can push the GHG intensity of renewable hydrogen above the required threshold. In countries with high carbon intensity of grid electricity, even a small amount of non-renewable electricity can disqualify the renewable portion of output as RFNBO.

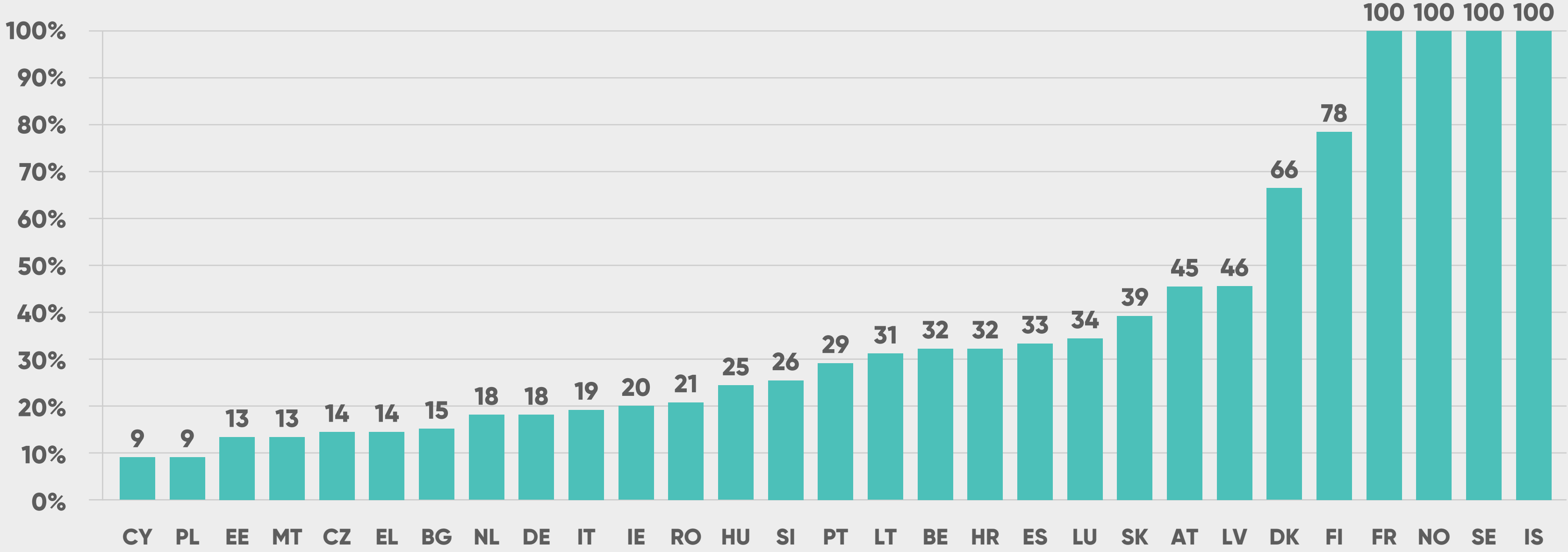
The impact of this rule varies depending on the carbon intensity of grid electricity of a country (or bidding zone). In countries with a low enough grid carbon intensity, the rule would allow operating the electrolyser at maximum capacity, without the risk of ever exceeding the 70% GHG reduction threshold (currently only Iceland, Sweden, Norway, and France would qualify for this).

In countries like Poland with a high grid carbon intensity, almost no grid electricity could be used. Even a small addition of <10% at any point would lead to the hydrogen output in that period failing to meet the RFNBO GHG emission threshold – including the share based on fully renewable electricity.

The graph below illustrates the maximum acceptable contribution of grid-mix electricity to produce RFNBO in various European countries.

FIGURE 3.6

Maximum acceptable contribution of grid mix electricity in for the production of RFNBO (%)



Source: Hydrogen Europe.

2 / Delegated Act to the Renewable Energy Directive concerning the methodology for assessing GHG emissions savings from renewable liquid and gaseous transport fuels of non-biological origin and recycled carbon fuels.

Electrolysis with fully renewable electricity

Hydrogen production via electrolysis with a direct connection to a renewable energy source avoids some electricity costs like network costs and taxes. However, the electrolyser capacity factor is limited by the capacity factor of the renewable source it is connected to. In Central and Northern Europe, solar PV may have a very low-capacity factor of around 1,000 full-load equivalent hours per year. As a result, while globally solar PV is becoming the cheapest renewable energy generation technology, in most EU countries onshore wind is still the lowest-cost technology.

Considering the average solar irradiation and wind conditions in Europe, our estimation suggests that the production costs of renewable hydrogen vary from 5.2 EUR/kg (based on solar PV in Portugal) to 9.6 EUR/kg (solar PV in Luxembourg), with an average of around 7 EUR/kg.

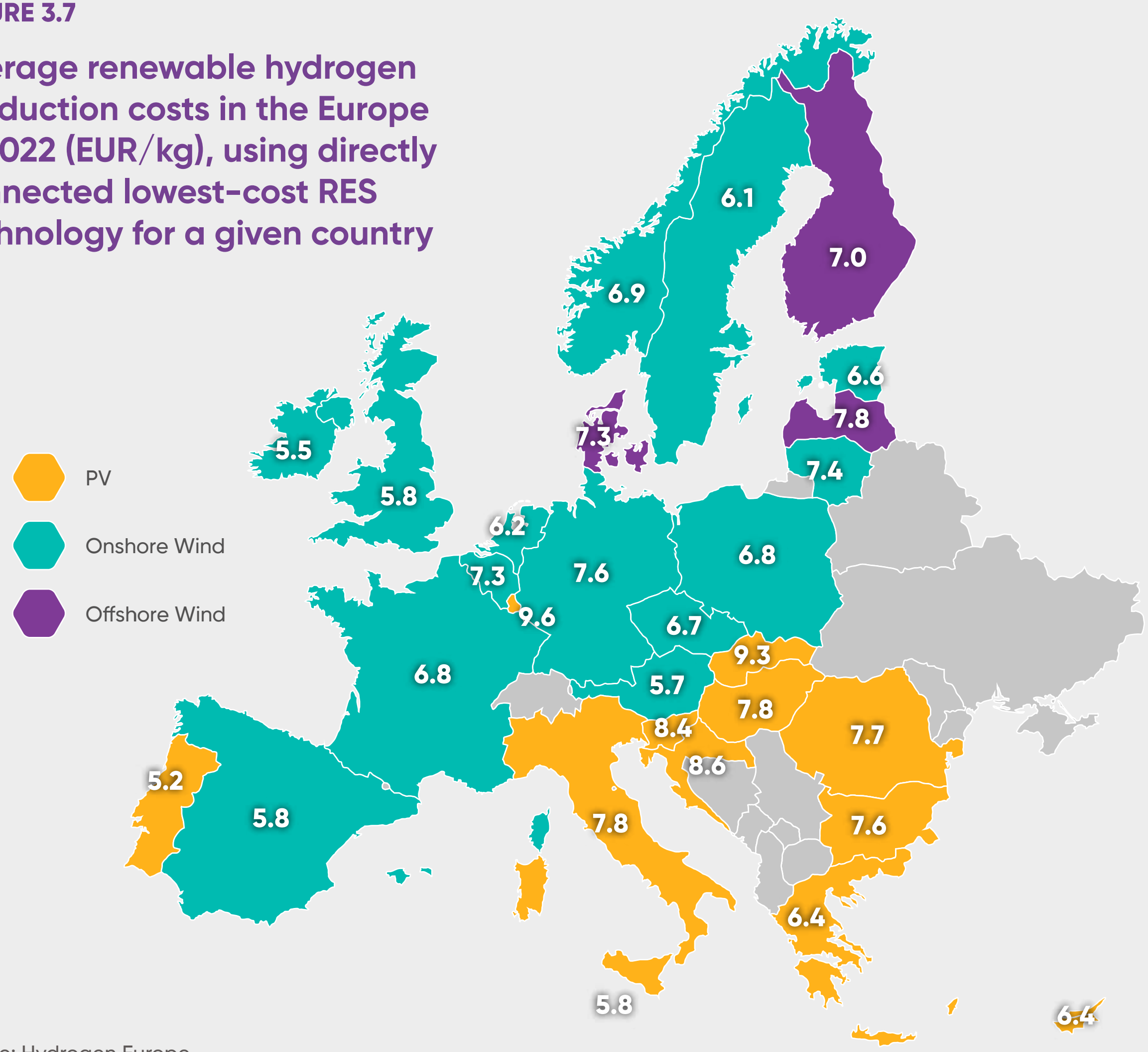
This represents a significant (60%) increase compared to last year's estimates, of 3.3-6.5 EUR/kg with an average of 4.4 EUR/kg.

One of the main reasons for the increase is inflation, causing an increase in required capital investments for both the electrolyser system as well as for new renewable energy sources. The surge in inflation has additionally resulted in higher interest rates, necessitating an upward adjustment in our projected return on investment associated with the Weighted Average Cost of Capital (WACC).

High inflation and a tightening renewable PPAs market, caused an increase of estimated renewable hydrogen production costs, from 4.4 EUR/kg in 2021 to close to 7 EUR/kg in 2022.

FIGURE 3.7

Average renewable hydrogen production costs in the Europe in 2022 (EUR/kg), using directly connected lowest-cost RES technology for a given country



Source: Hydrogen Europe.

Renewable hydrogen production costs in the EU can be as low as 3.1 EUR/kg (onshore wind in Norway, the UK, and Ireland), making it already cost-competitive with conventional hydrogen production costs observed in 2022.

The costs of making renewable hydrogen, presented on the previous page, were calculated using the average wind and solar conditions in each EU Member State[3]. Especially for large countries like Germany, Spain, or France, this can be misleading since there are areas with significantly better than average wind or solar conditions, where the production of renewable hydrogen with direct connection to the RES source would also be considerably less expensive than on average.

Therefore, it is essential, to look also at the best available conditions for new renewable energy development in Europe. The results of such an analysis are presented on the two graphs on the next page. The lower end of the cost range has been estimated, assuming the best irradiation or wind conditions available in each country[4], while the upper cost range is based on the average soler/wind conditions (corresponding to the results shown on the previous page).

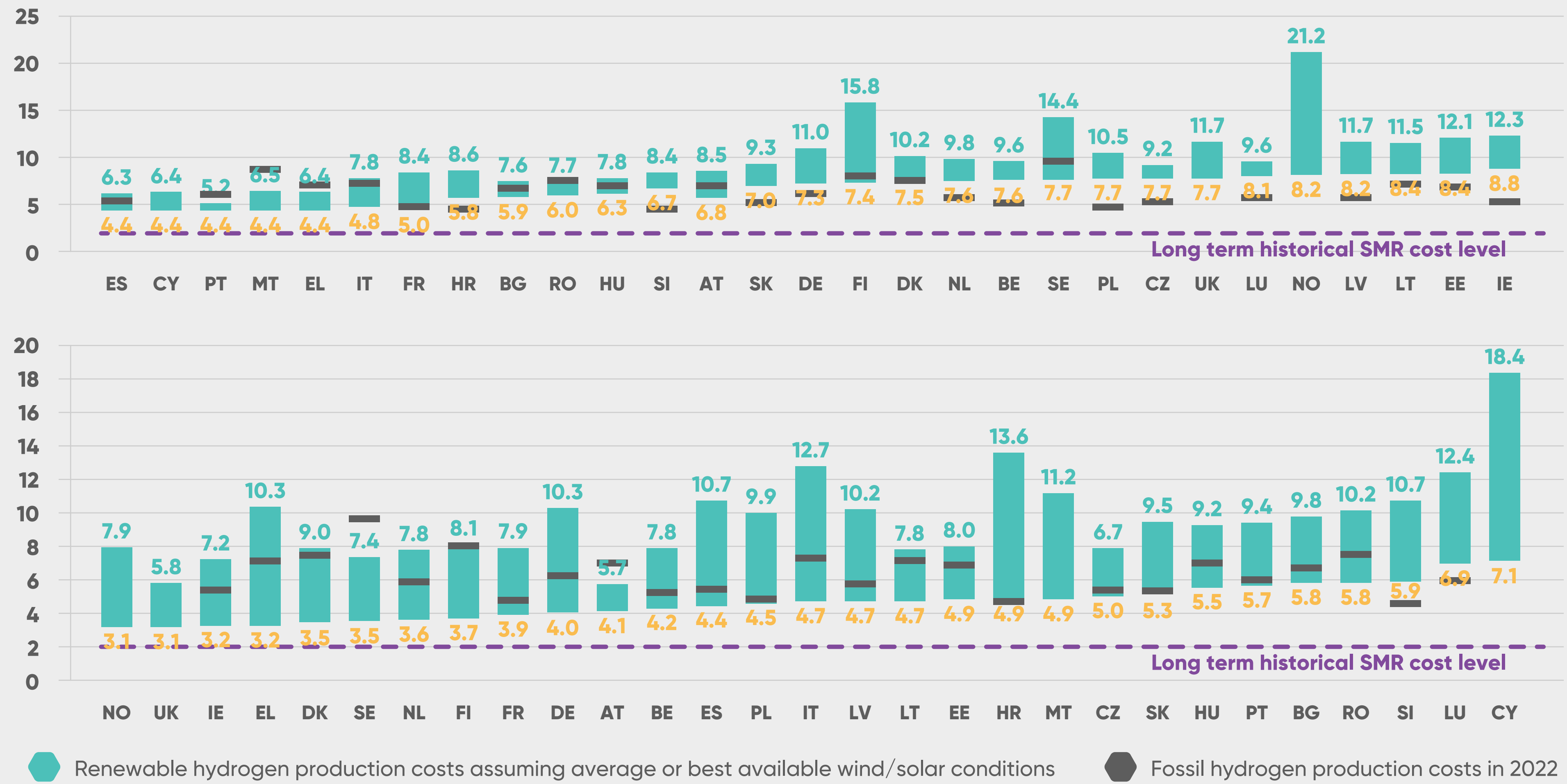
This analysis reveals that within the EU, the production costs of renewable hydrogen could potentially reach as low as 4.4 EUR/kg using solar PV (in Spain, Portugal, Greece, Cyprus, and Malta) and 3.1 EUR/kg with onshore wind (in Norway, the UK, and Ireland).

The difference between the lowest cost technology available in various EU Member States can reach up to 3.8 EUR/kg – which underlines the potential business case for the development of the European hydrogen pipeline network, with costs of hydrogen transportation by pipelines as low as 0.11 – 0.21 EUR/kg per 1,000 km[a].

3 / It also does not include other potentially cheap renewable energy sources like hydropower in Austria, Slovenia, or Scandinavia.
4 / For solar PV, the best available conditions were estimated as a maximum capacity factor for a NUTS-2 region in a country based on the ir_global_tracking with a 0.85 performance dataset. In contrast, the best conditions for wind were assumed based on the maximum wind capacity factor available for any NUTS-2 region. Both values were adopted based on the JRC ENSPRESSO database.

FIGURE 3.8

Levelized costs of renewable hydrogen production in the EU countries (with UK and Norway) in 2022, using solar PV or wind power (in EUR/kg)



Source: Hydrogen Europe.

The Renewable Energy auctions organised by EU Member States in the last 12 months indicate that further reduction of renewable hydrogen production costs is feasible, even in a tightening renewable energy PPA market.

The renewable hydrogen production costs presented in this chapter are estimations not values reported by projects (see the methodological note for detailed assumptions). The main assumptions underlying the estimates are CAPEX values for large-scale electrolysis systems and levelized costs of renewable electricity. The electricity costs are estimated for each country based on the latest IRENA renewable energy cost data for Europe. As electricity costs are by far the most important factor in the final renewable hydrogen production costs, it is key to confront these values with market prices for renewable electricity.

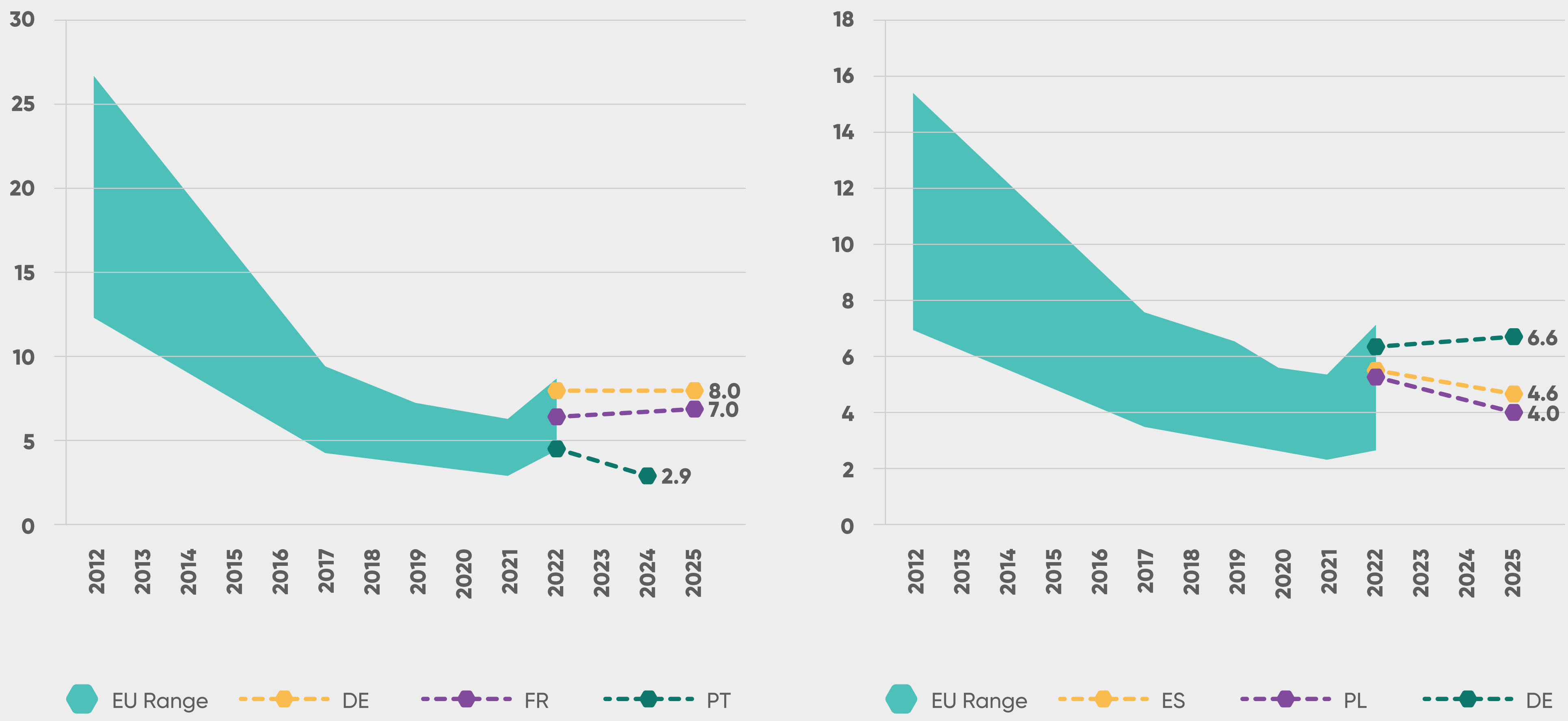
The two graphs on the next page illustrate renewable hydrogen production costs, estimated based on renewable electricity prices from winning bids in the most recent renewable energy auctions organised in selected EU countries.

This data seems to suggest that, following the increase of renewable hydrogen production costs in 2022, in the coming years we should expect the downward trend to continue, though at a much slower pace than in previous years.

However, it should be noted that the results of recent RES auctions are influenced by a tightening of renewable energy supply resulting in cost increases. For example, between 2022 and 2023 the winning bid prices for solar PV and onshore wind in Germany increased by 20 and 17 EUR/MWh respectively. This is however not as much a result of any fundamental increases in investment costs but of higher costs of capital and, at least partially, is connected to the high wholesale electricity prices reducing the willingness of renewable energy project developers to enter long term PPAs at LCOE level. Both of those issues are connected to the disruptions in the energy markets following the Russian invasion of Ukraine. They would need to be resolved before any significant renewable hydrogen production cost reductions could be expected.

FIGURE 3.9

Renewable hydrogen production costs (in EUR/kg) over the 2012-2022 period and expected developments in selected countries based on 2022/2023 RES auctions results



Source: Hydrogen Europe.

Hydrogen production costs for all key technologies increased in 2022. While there are countries in Europe where renewable hydrogen gets cost competitive against fossil hydrogen, on average, the fossil fuel option remains the lowest cost option.

In 2022, for the first time since the inception of the Clean Hydrogen Monitor, hydrogen production costs rose across all production methods.

Regarding hydrogen produced from natural gas reforming (with and without CCS), the production cost increase was a direct consequence of the natural gas supply shortages and price spikes following the Russian invasion of Ukraine.

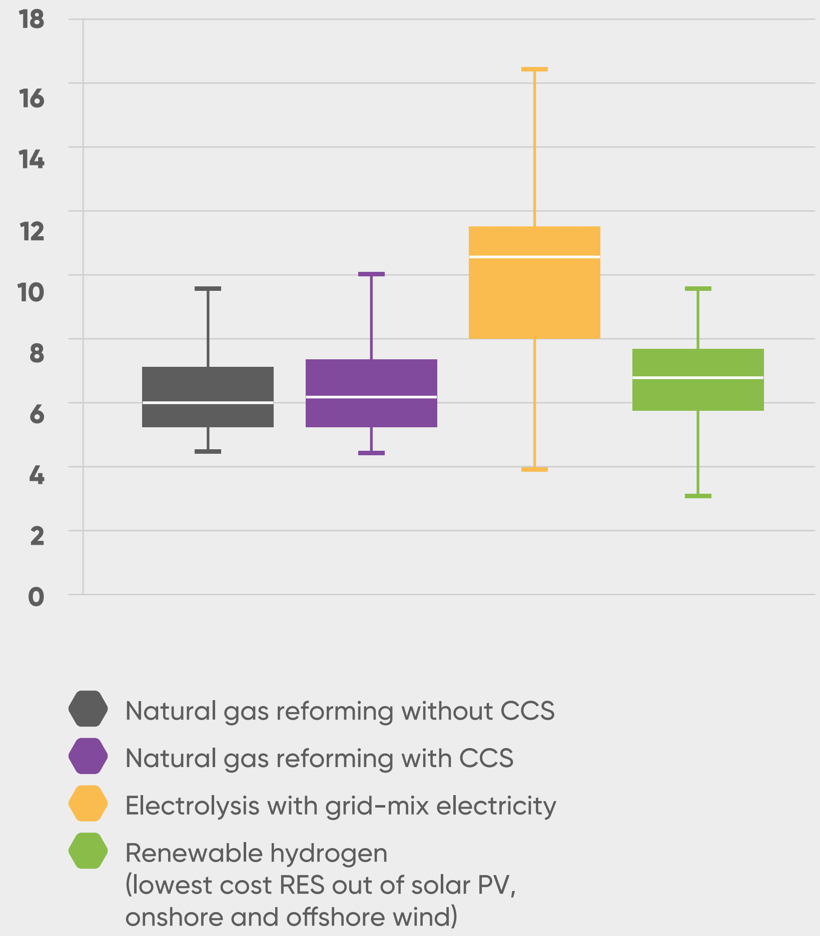
Natural gas-fired power plants are closing the merit order on most EU electricity markets and are setting the wholesale electricity market price. Thus, high natural gas prices have led to hydrogen production costs from grid electricity more then doubling more than doubling in 2022 compared to 2021.

Unusually high wholesale electricity prices in 2022 also had an indirect influence on renewable hydrogen production costs. High inflation due to high energy prices has led to an increase in interest rates. High prices on the electricity wholesale markets have limited the willingness of renewable energy developers to enter long-term PPAs at LCOE price levels. As a result, even though the cost of developing renewable energy hasn't changed much, the cost of producing renewable hydrogen has still gone up - from from 4.4 EUR/kg in 2021 to close to 7 EUR/kg in 2022 (EU average).

While there are countries in Europe where renewable hydrogen is cost-competitive against fossil hydrogen, on average, the fossil fuel option remains the lowest cost option – especially since the high natural gas prices observed in 2022, have since fallen significantly.

FIGURE 3.10

Levelized costs of hydrogen production in Europe in 2022 (EUR/kg)



Source: Hydrogen Europe.

Methodological Note

The chapter contains an analysis of hydrogen production costs in Europe for the year 2022. The production costs presented in the chapter are not reported statistical costs gathered from real projects, but estimates based on annually updated cost assumptions. The production costs were estimated for several technologies and scenarios:

- Steam methane reforming with CCS,
- Water electrolysis grid-mix electricity,
- Water electrolysis using exclusively full renewable electricity.

In all cases, the general approach to estimating the levelized cost of hydrogen (LCOH) is based on a standard discounted cash flow model and the following formula:

$$\frac{I_0 + \sum_{t=1}^{n} \frac{I_t + E_t + M_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{H_t}{(1+r)^t}}$$

Where: Where, I_0 - Investment expenditure in year 0; I_t - Investment expenditure in year t (stack replacement costs); E_t - Electricity consumed in year t, including generation costs (wholesale price or RES LCOE + capacity factor), grid costs and taxes when applicable; M_t - Other operational expenditures in year t; H_t – Hydrogen production in year t; r - Discount rate; n - Lifetime of the system in years.

The electrolysis system cost assumptions were based mainly on the latest information for current state-of-the-art alkaline electrolysis.

The various sources used for calculating the LCOH, include among others:

- European Network of Transmission System Operators for wholesale electricity costs in various EU Member States
- ENSPRESO model from the Joint Research Centre for solar PV, onshore and offshore wind capacity factors in EU Member States
- IRENA's Renewable Power Generation Costs in 2022 - for CAPEX and O&M costs for solar PV, onshore and offshore wind in Europe
- Clean Hydrogen JU Strategic Research and Innovation Agenda for electrolyser efficiency, stack durability, stack degradation and O&M costs
- IEA Global Hydrogen Review 2022 and Bloomberg New Energy Finance hydrogen LCOH analysis for 2H 2022 for electrolysis CAPEX estimates
- Eurostat statistical data for 2022 covering electricity and natural gas costs (costs of energy as well as taxes and grid fees) for non-household consumers

The discount rate (WACC) has been assumed at 6% (real).

For grid-connected electrolysis, the capacity factor of the electrolyser was assumed to be 4,000 hours, with the running hour set to fall in time with the lowest wholesale electricity prices (based on data from the ENTSO-e's transparency portal). Network costs, taxes and fees were included in this scenario (based on Eurostat data on electricity prices for non-household consumers in the consumption range from 20,000 MWh to 69 999 MWh per year).

The capacity factors for RES have been adopted based on the JRC ENTSPRESSO database. For electrolysis, the assumption is that even for directly connected off grid electrolysis the electrolyser would be scaled down vs RES power allowing for a higher capacity factor. Based on an analysis looking for a possible electrolyser power scaling down which would allow to maximise the capacity factor while reducing the amount of lost power generation, the following electrolyser capacity factor adjustments were made:

- For PV the capacity factor of electrolysis is assumed to be 25% higher than RES
- For onshore wind the capacity factor of the electrolyser is 11% higher than RES
- For offshore wind the capacity factor of the electrolyser is the same as RES

ELECTROLYSIS SYSTEM COST

Notes: Assuming a 10 MW AE electrolysis system

	UNIT	VALUE
CAPEX	EUR/kW	1250
CAPEX: Economic lifetime	years	30
OPEX: Stack durability	h	80,000
OPEX: Stack replacement costs	% CAPEX	35%
OPEX: Energy consumption	kWh/kg	52.4
OPEX: Stack degradation	per 1000 hrs	0.0012
OPEX: Other OPEX	% CAPEX	2%

Endnotes

a / Guidehouse, 2022.


ID1

04

Hydrogen infrastructure

Infrastructure development is critical to connect hydrogen production and demand regions within and towards Europe. With clear European targets, national stakeholders have started moving with their transmission and large-scale storage development plans.

- The main drivers of infrastructure projects at the national level are transmission system operators, which are presenting their plans to establish national hydrogen backbones.

- Netherlands and Belgium continue to be the most advanced countries, having national plans, legislation in place, as well as having started construction of the first hydrogen pipelines.

- There are 29 large-scale hydrogen storage projects at early stages of development, with further projects expected in the upcoming Sixth list of Project of Common Interest.

Hydrogen transmission and storage infrastructure have been increasing in importance at the national level, as indicated in TYNDPs and governmental plans across Europe.

Hydrogen transport has been an increasingly important topic for national stakeholders. Most notably this is reflected in the latest versions of the yearly Ten-Year Network Development Plans (TYNDP) that TSOs have submitted to regulatory authorities under Article 22 of the 2009 Gas Directive, where hydrogen infrastructure is featured. Moreover, some Member States like the Netherlands and Belgium have started to put forward their national legal regimes for hydrogen pipelines. The chapter examines transport infrastructure in eight EU member-states, focusing on last year's developments in hydrogen transmission infrastructure. These developments concern planning, legislative frameworks, and the construction of the national backbone.

AUSTRIA

The Coordinated Network Development Plan 2022 by Austrian Gas Grid Management,[a] tackles the development of hydrogen infrastructure in line with the goals of the national hydrogen strategy. The plan is for hydrogen to be initially transported through direct pipelines from production to consumption centres. A national infrastructure network will be built over time.

The TYNDP outlines five hydrogen projects from infrastructure operators. If completed successfully, these projects will enable the capacities for hydrogen transport at interconnection points indicated in **Figure 4.1**. These projects are:

- **H2-Readiness:** The project is preparing a roadmap for a dedicated hydrogen network through repurposing the existing gas network. Hydrogen and methane networks will be established in parallel, to ensure optimal usage of infrastructure, as biomethane is expected to play a significant role in decarbonisation. For the project, a survey of the Austrian industry was carried out. The results indicated that between 2023-2040 usage of natural gas is expected to drop by 55%, while major hydrogen demand increases are expected in 2025 (2.3 TWh), 2030 (21 TWh) and 2050 (58 TWh).

- **H2EU+ Store:** The project aims at the production of renewable hydrogen in Ukraine, its transport via the Baumgarter gas hub and storage in Austria for distribution in Central Europe.

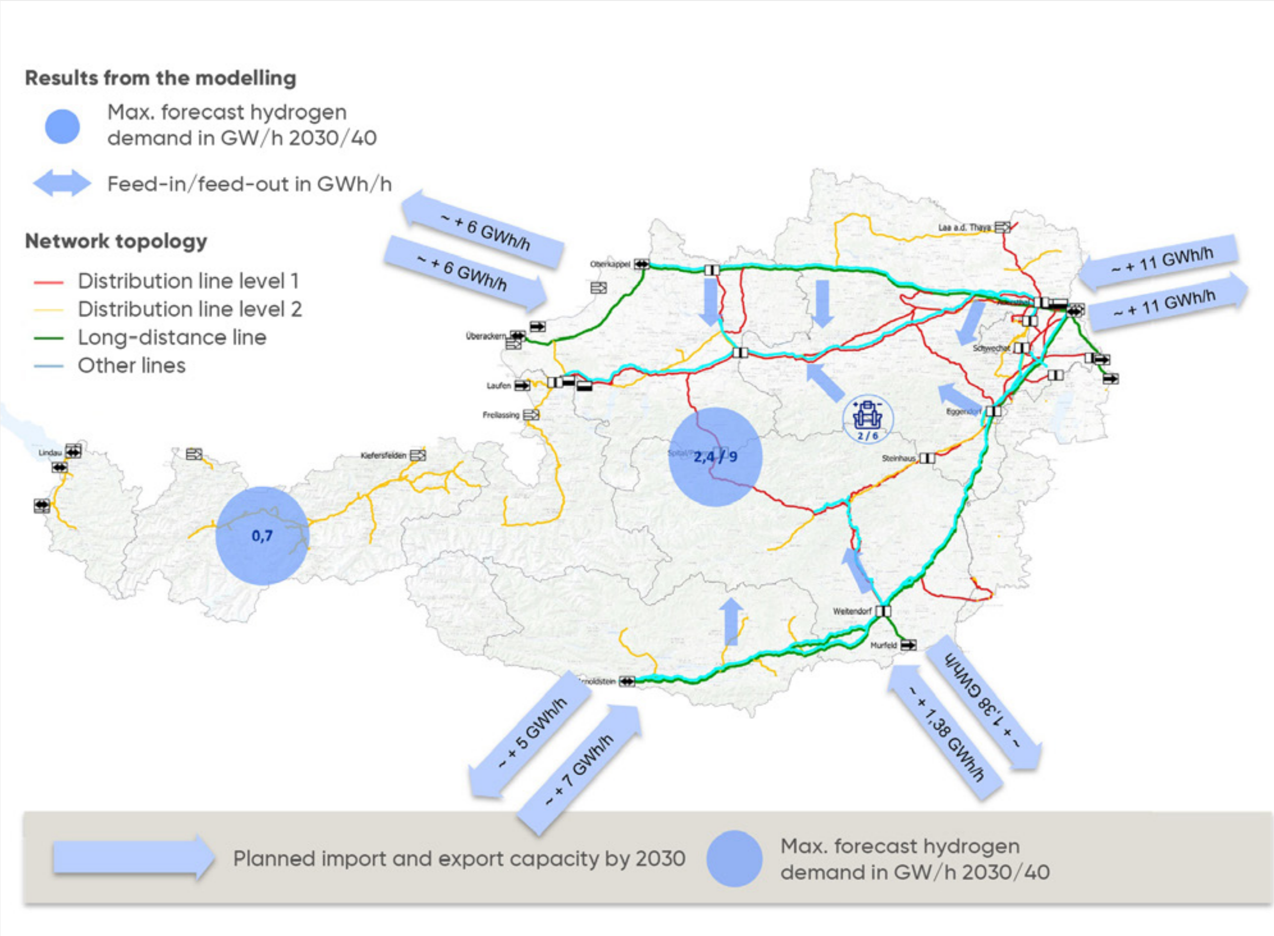
- **WAG Loop:** The project aims at closing the remaining 100 km of pipeline that runs parallel to the WAG pipeline. Upon its completion, the pipeline will offer full flexibility for methane and pure hydrogen transport to Austria and Germany from Eastern Europe.

- **SOL H2 Project:** Coordinated with the Slovenian and Croatian TSOs, the project opens the possibility of importing hydrogen from the LNG Terminal in Krk, Croatia.

- **TAG – South-North Corridor:** Within the "H2 Readiness of the TAG Pipeline System" project, a cost-efficient conversion of existing infrastructure is proposed to enable hydrogen imports from 2030. In the project's first phase, one of the three pipelines will be repurposed. This will enable the flow of hydrogen between the Austro-Italian and Austro-Slovakian borders.

FIGURE 4.1

Indicative hydrogen capacities, based on proposed projects



*If there is no second value then there is no change between 2030 and 2040.

Source: AGGM AG.

BELGIUM

The Belgian TSO Fluxys plans to progressively reconfigure parts of the natural gas network to develop systems to transport methane, hydrogen, carbon dioxide and possibly, other molecules.[b] In line with the Belgian national hydrogen strategy, an open-access hydrogen backbone should be established between Zeebrugge, Ghent, and Antwerp, linking industrial zones and neighbouring countries.

Fluxys has proposed a system that links clusters based on an entry and exit points system, combined with a virtual exchange. For infrastructure development to take place, long-term subscriptions to the network will be required, with cost-reflective tariffs. To this end, Fluxys is launching an Open Season with three steps:

1. **non-binding expressions of interest;**
2. **bilateral iterations;**
3. **binding commitment.**

In July 2023, Belgium adopted the Law on the Transmission of Hydrogen by Pipelines which will provide the legal framework until the transposition of the Hydrogen and Decarbonised Gas Market package.[c] The Law establishes an ownership unbundling regime for the hydrogen network operator (HNO), regulated third-party access to the network (rTPA), and the procedure for setting quality standards in consultation with neighbouring HNOs and industry. While existing networks can be operated by their owners, the law also establishes a procedure to appoint the HNO as an “independent operator” of existing networks.

Lastly, the dual-purpose pipeline connection between Zeebrugge and Brussels is already under construction and should become operational by the end of 2023. The connection is currently a gas pipeline and will later be converted to a pure hydrogen pipeline.[d]

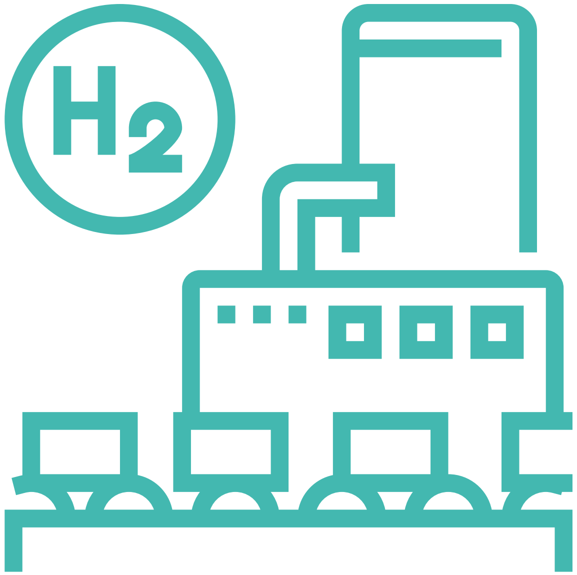
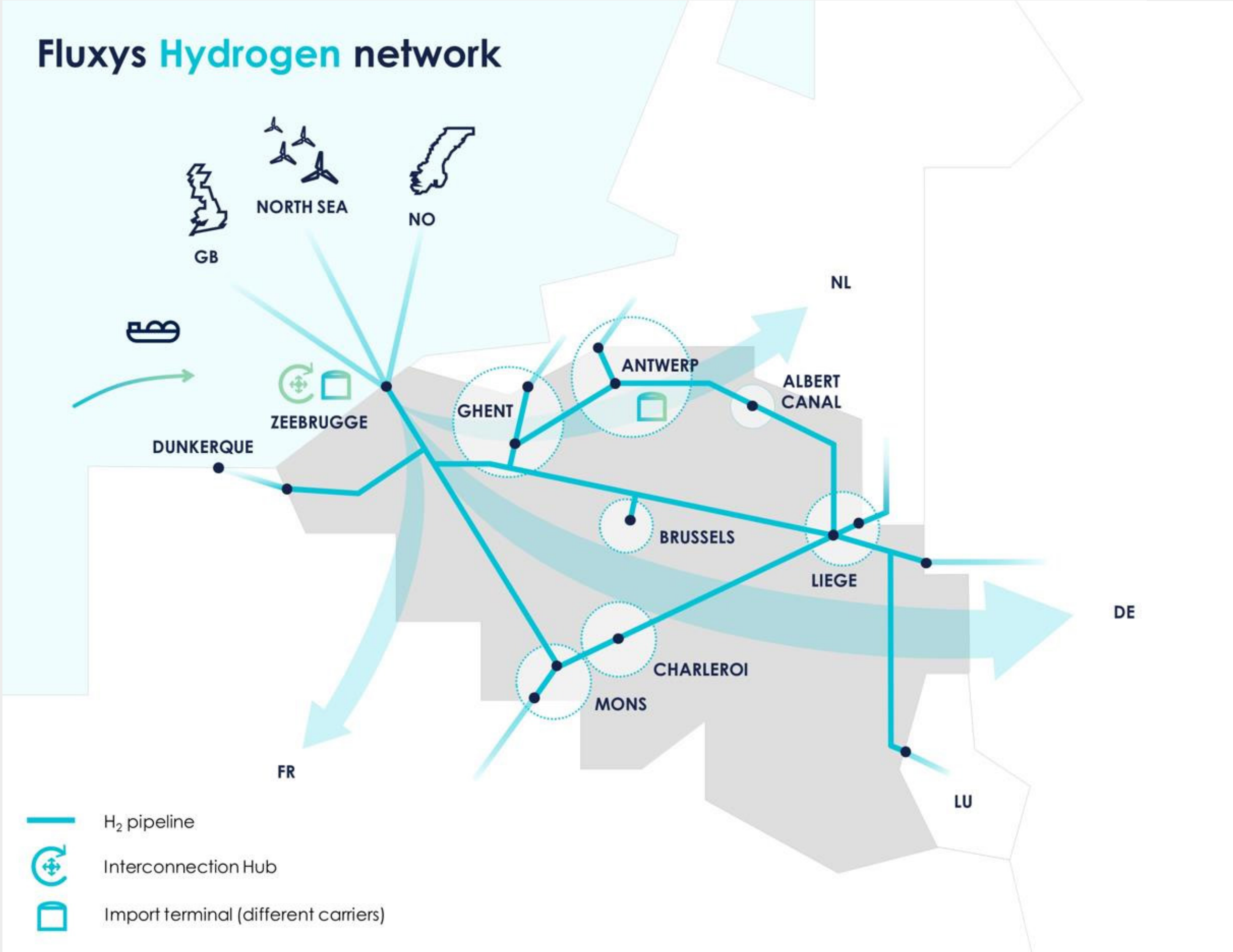


FIGURE 4.2

Fluxys planned hydrogen network



Source: Fluxys.

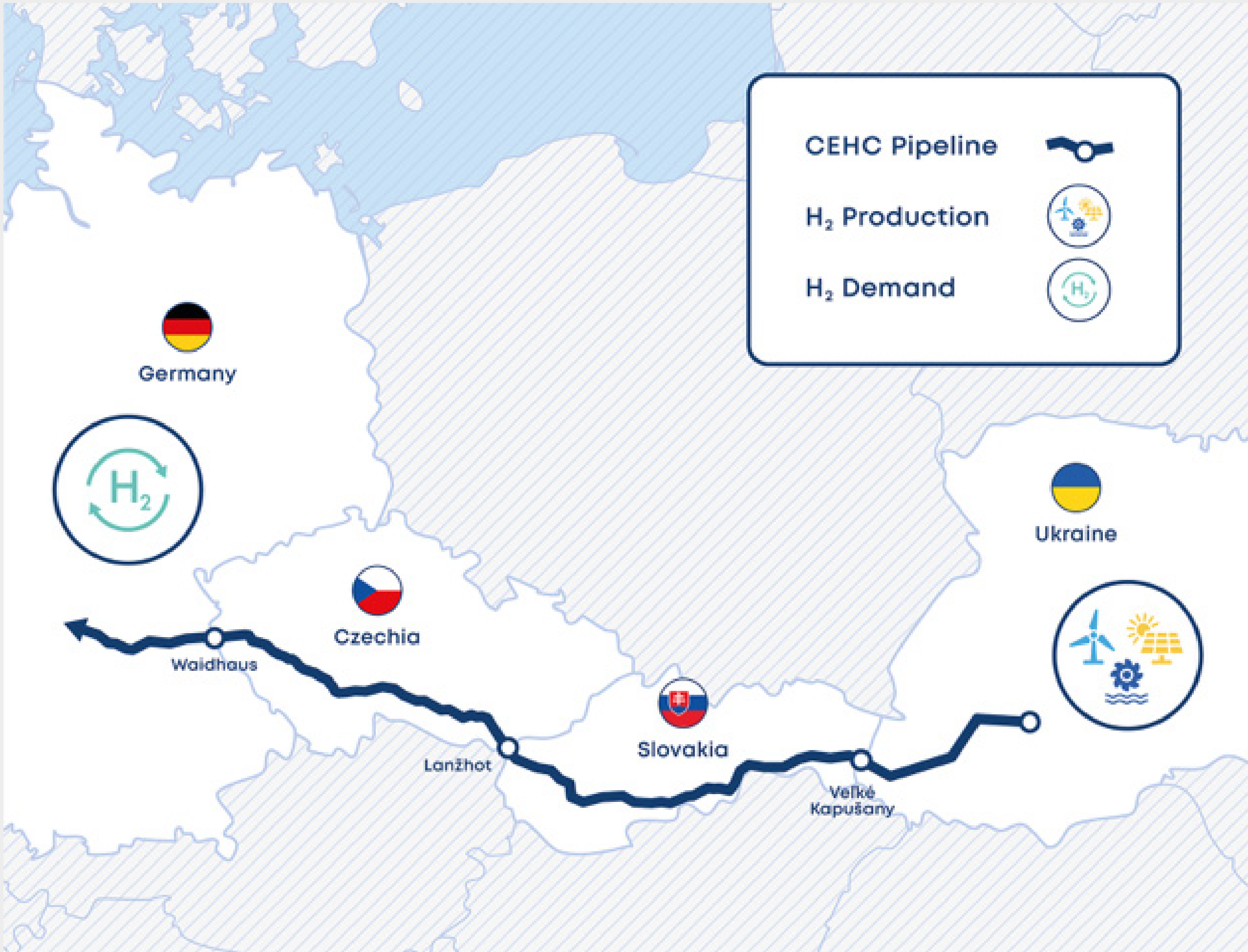
CZECH REPUBLIC

For the Czech Republic, in the 2023-2032 TYNDP of the TSO NET4GAS,[e] hydrogen is briefly addressed in line with the country's national hydrogen strategy. In the medium term, hydrogen transport is to take place both in blended form with natural gas and as pure hydrogen in separate pipelines. The first milestone is to ensure the possibility of accepting 5% of hydrogen by volume at cross-border interconnection points by 2025. In the long-term, the focus is on repurposing natural gas infrastructure for hydrogen transport, based on technical readiness, under the H2 Readiness programme.

The Central European Hydrogen Corridor is the most important project that the TSO is currently involved in.[f] The project is launched together with OGE, eustream and Gas TSO of Ukraine. It explores the feasibility of a hydrogen pipeline corridor from Ukraine to Germany via Slovakia and Czechia, linking production and consumers along the way. The planned length of the corridor is 1225 km with an expected capacity to transport 144 GWh/d by 2030.

FIGURE 4.3

Central European Hydrogen Corridor



Source: CEHC.

DENMARK

On the 22nd of May 2023, the Government of Denmark agreed on the principles which will guide the establishment of hydrogen infrastructure in the country. Energinet (TSO) and Evida (DSO), which own and operate the current natural gas infrastructure, will also operate the future hydrogen infrastructure. As a result, hydrogen infrastructure will be publicly owned. However, the principles leave the possibility of having direct privately owned pipelines where these two companies see no value in owning and operating such pipelines. This will be further developed in a future legal act. Responsibilities will be assigned to the two companies based on their existing competencies:

- Energinet will connect cross-border hydrogen pipeline infrastructure, offshore pipeline hydrogen infrastructure and cross-border hydrogen pipelines to storage facilities;

- Evida will connect domestic hydrogen producers and consumers to the interconnected hydrogen system;

Infrastructure development will take place on market-based principles and the companies's long-term development plans. This means that specific investments will have to be made by Energinet or Evida, but approved by the Ministry of Climate, Energy and Utilities. The key criteria for the projects' approval will be the specific demand from future system users that indicates a long-term need for infrastructure and willingness to pay. The criteria regarding the future framework conditions for financing are to be published at a later stage by the government.

GERMANY

Germany is one of the most ambitious member states regarding hydrogen infrastructure development. In May 2023, the German government put forward a draft legal framework for the development of the national Hydrogen Core Network (Wassertoff-Kernnetz) under the new section 28(r) of the Energy Industry Act (EnWG). As of writing of this report in September 2023, the law has not been adopted.

According to the draft law, TSOs will have to submit a joint plan for a core network three weeks after the law enters into force indicating which assets will be part of the network, expected OPEX & CAPEX and the extent to which these are the most efficient solutions in the long-term. Conversion of natural gas pipelines would be prioritised. Operators must also demonstrate that the rest of the grid can meet expected natural gas demand. If the TSOs do not submit a joint application, the Bundesnetzagentur will designate a core network within four months after the deadline. In this case, only companies which agree to be included in the plan may be obliged to carry out their projects. The projects must be operational by the end of 2032. Once approved, the network will be granted overriding public interest.[g]

By September 2023, TSOs have started modelling the Hydrogen Core Network (**Figure 4.4**) while also providing stakeholders with the opportunity to comment on the work. The current total length of 11,200 km will be evaluated and optimised in the subsequent steps. A total of 309 hydrogen projects were considered.[h]

The following step is to create an "optimised core network" to be submitted to the Bundeznetzagentur. The submitted projects will be evaluated to see if they meet the legal and technical requirements for integration into the hydrogen core network. Additionally, the infrastructure will be checked to ensure it meets transport requirements.

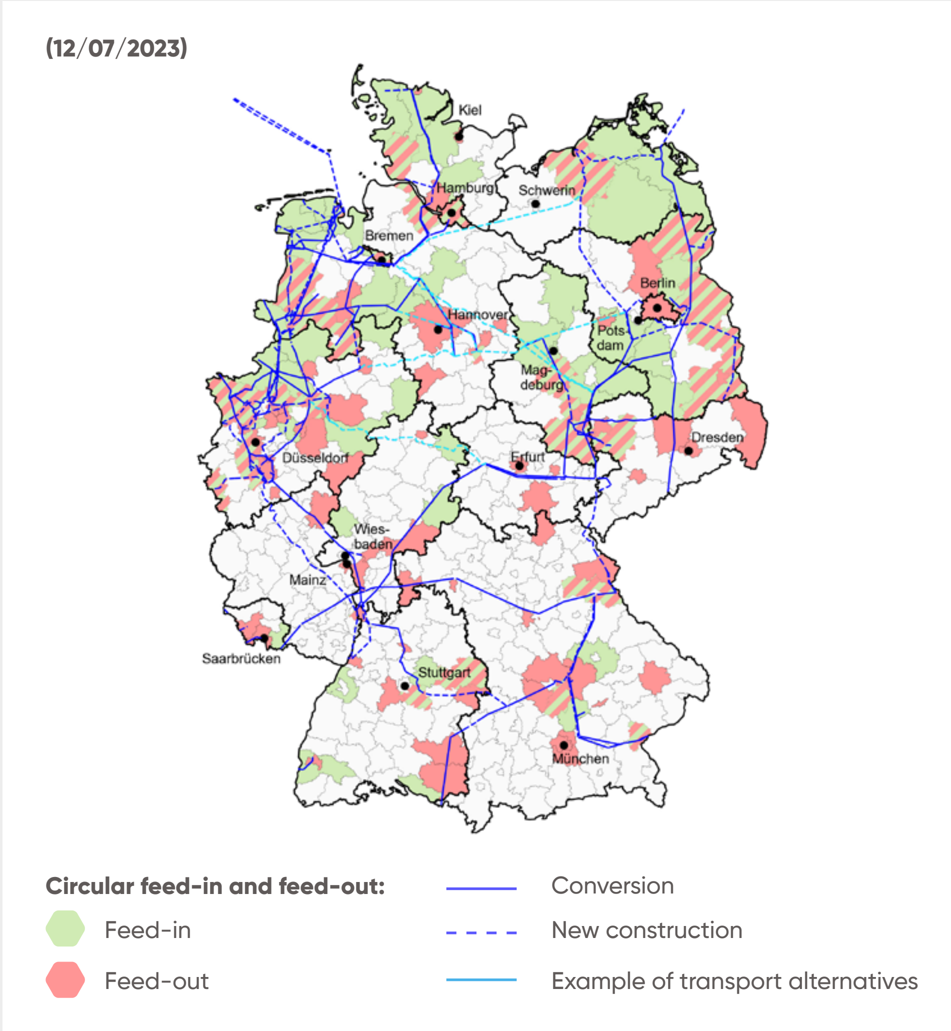
Two elements to be noted are the specific conditions of the German natural gas transmission system. Firstly, at the transmission level there are often multiple pipelines which run in parallel (**Figure 4.4**). This enables the conversion of one of the pipelines to hydrogen, while the other(s) can still meet natural gas demand, thereby facilitating the transition to hydrogen while guaranteeing security of supply of natural gas in the medium term. Secondly, distribution system operators (DSOs) so far have not been significantly involved in the abovementioned process, despite German operators owning high-pressure pipelines with plenty of end-users in hard-to-abate industrial sectors.

As part of its broader strategy to establish hydrogen interconnections with neighbouring nations, Germany is collaborating with Norway to assess the technical and economic feasibility of a large-scale pipeline for importing hydrogen from Norway and another for transporting CO2 from Germany to Norway. This project involves Gassco, DENA, and various other industrial partners.[i]

FIGURE 4.4

Natural gas transmission infrastructure in Germany

Planning status of Hydrogen Core Network



Source: Left side: ENTSO-G, The European Natural Gas 2021. Right side: FNB Gas.

ITALY

The Italian hydrogen network plans are part of the TSO's, SNAM's, "Schede di intervento".[j] The plan is to establish a network able to transport hydrogen from the south of Italy and north of Africa to major consumption areas in the country and Europe. Priority is given to repurposing most of the existing natural gas infrastructure to enable coverage for the projected demand until 2040, while also allowing imports from North Africa and exports to North European Countries.

Table 4.1 shows the main elements of the project, namely the three pipelines' axes with their diameter (DN), length in kilometres, start and ending locations, as well as the projected CAPEX.

TABLE 4.1

Characteristics of SNAM's future hydrogen network

Name	DN	Length (km)	Start	End	CAPEX (mln EUR)
South-North Ridge	1,200/1,050	1,520	Mazara del Vallo (TP)	Minerbio (BO)	1,192
East Ridge	850/1,050	337	Minerbio (BO)	Zimella (VR)	598
West Ridge	750/1,200	410	Poggio Renatico (FE)	Passo Gries (VB)	493
Branches (6)	400/600	530			796
Compressors (Messina & Gallese)					120

Source: Snam.

FIGURE 4.5

Snam hydrogen network

Source: Snam.

NETHERLANDS

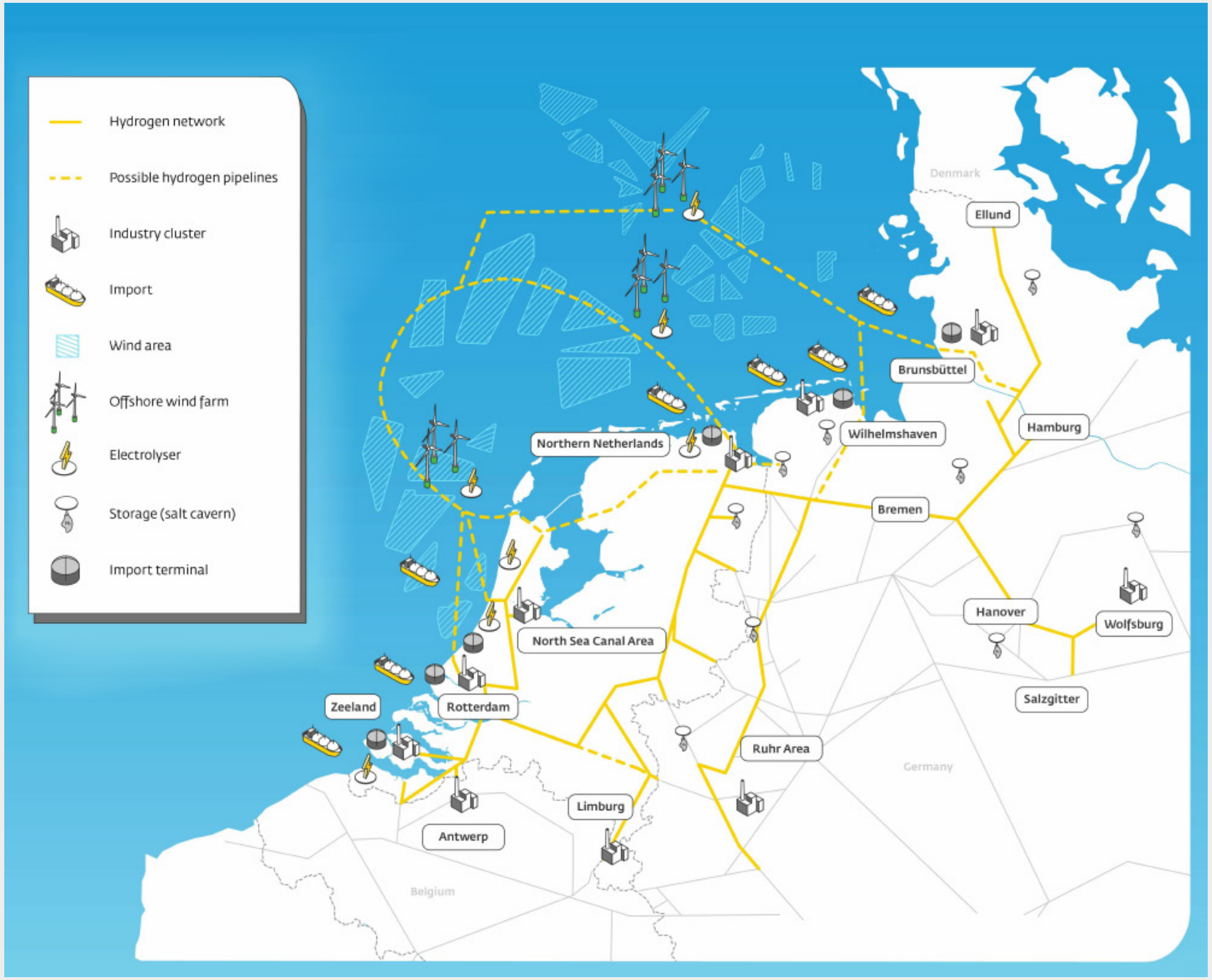
The Netherlands has been at the forefront of hydrogen transmission deployment, with three main developments taking place in the last year. Firstly, the Minister of Climate and Energy has altered the plans for Phase 1 in December 2022, due to the new gas flows caused by the war in Ukraine. Previously, gas moved in an East-West direction. Now it moves West-East because of an increased use of LNG. Therefore, the pipeline route from Wieringermeer to the Northern Netherlands will need to be repurposed at a later stage and an alternative route is currently in development. However, the connections to Germany and Belgium, which are part of Phase 1, will proceed as originally planned.[k]

The second development regarding the Dutch network relates to the purity of hydrogen. After a series of industry consultations, the decision was made to raise the purity requirements in the network to 99.5% instead of the initially proposed 98%. This adjustment will reduce purification expenses for users, as the majority of producers intend to inject at a higher purity level, which aligns with the high purity requirements of most customers.

Thirdly, in June of 2023, the Dutch TSO Gasunie took an FID on the first part of the national hydrogen network. Construction of the first 30 km between Rotterdam from the Tweede Maasvlakte to Pernis started end of October. The provisional timeline for the pipeline is to be operational in 2025.[l]

FIGURE 4.6

National hydrogen network Netherlands



Source: Gasunie.

SPAIN

The main driver behind the infrastructure development for hydrogen in Spain is the renewable hydrogen production capacity, which will need to be delivered to large industrial consumers, as well as to interconnection points for export towards Europe. To realise this, in 2022, the Spanish TSO Enagas created the subsidiary Enagás Infraestructuras de Hidrógeno, to separate its natural gas operations from the future hydrogen ones in preparation to become a Hydrogen Network Operator.[m]

As part of its strategic planning, two vision maps were published for the development of the hydrogen network, one for 2030 and another for 2040.[n] The 2030 vision prioritises export connections and guaranteed local demand, with the export connections being closely related to the H2Med corridor.

For 2040, the network will expand with further interconnections with the north of Africa and France, as well as with connections to the storage facilities in Cantabria, Basque Country, and Yela.

The development of the infrastructure is in line with the draft NECP, which raises the national target of electrolysis capacity to 11GW by 2030, thereby positioning Spain as an important exporter of renewable hydrogen towards the rest of Europe.[o]

As to the project development schedule, until 2025 the TSO will focus on gathering the necessary support under the PCI list and applications for CEF-E funding. Construction is projected to commence by the end of 2025, with operations slated for 2030.

Table 4.2 provides an overview of the main components of the national hydrogen infrastructure, together with the publicly announced characteristics.

Lastly, through the Royal Decree from the 29th of March 2022, the Spanish government also established a provisional legal regime for the operation of renewable gas pipelines, until the adoption of the Hydrogen and Decarbonised Gas Market Package.[p]

FIGURE 4.7

Spanish Hydrogen Backbone 2030 & 2040

Source: Enagas.

TABLE 4.2

Characteristics of Spanish hydrogen backbone

Name	Start	End	Length (km)	DN	Operating pressure (bar)	CAPEX (mln EUR)
H2Med-BarMar			455	700	210	2,135 (split by operators)
H2Med-CelZa			258	700	100	350 (157 for Spanish side)
Axis 1 (Cornisa Cantabrica, Valle del Ebro, Eje Levante)	Gijon	Cartagena	1,500			1,650
Axis 2 (Via de la Plata, Puertollano connection)	Gijon	Puertollano	1,250			1,850

Source: Enagas.

Belgium and Netherlands are the most advanced countries in relation to hydrogen transmission development, closely followed by Germany and Spain.

The following table summarises these eight countries' efforts in their deployment of hydrogen infrastructure. It's vital to emphasize that this presents a momentary overview and offers a simplified evaluation of each country's distinctive initiatives. Despite the limitations, two trends are to be highlighted. Firstly, Belgium and the Netherlands are the most advanced member states in terms of infrastructure development. This is in line with their intention to become frontrunners regarding trading and imports in the future European hydrogen market. Secondly, it is important to note that the scope of activities in Germany cannot be accurately summarised in this table. It has the most ambitious political plans for the national hydrogen network and is engaged in the most encompassing legislative review of energy infrastructure, covering pipelines, LNG terminals, and electrolyser system locations, among others.

TABLE 4.3

Summary table of hydrogen infrastructure development across a selection of Member States

	Adoption of National Infrastructure Plan	Adoption of National Legislation	Start of National Backbone Construction
Austria	Achieved	Work has not started	Work has not started
Belgium	Achieved	Achieved	Achieved
Czech Republic	Achieved	Work has not started	Work has not started
Denmark	Work has not started	Work in progress	Work has not started
Germany	Work in progress	Work in progress	Work has not started
Italy	Achieved	Work has not started	Work has not started
Netherlands	Achieved	Achieved	Achieved
Spain	Achieved	Achieved	Work has not started

Achieved · Work in progress · Work has not started

There are currently at least 29 announced large-scale hydrogen storage projects.

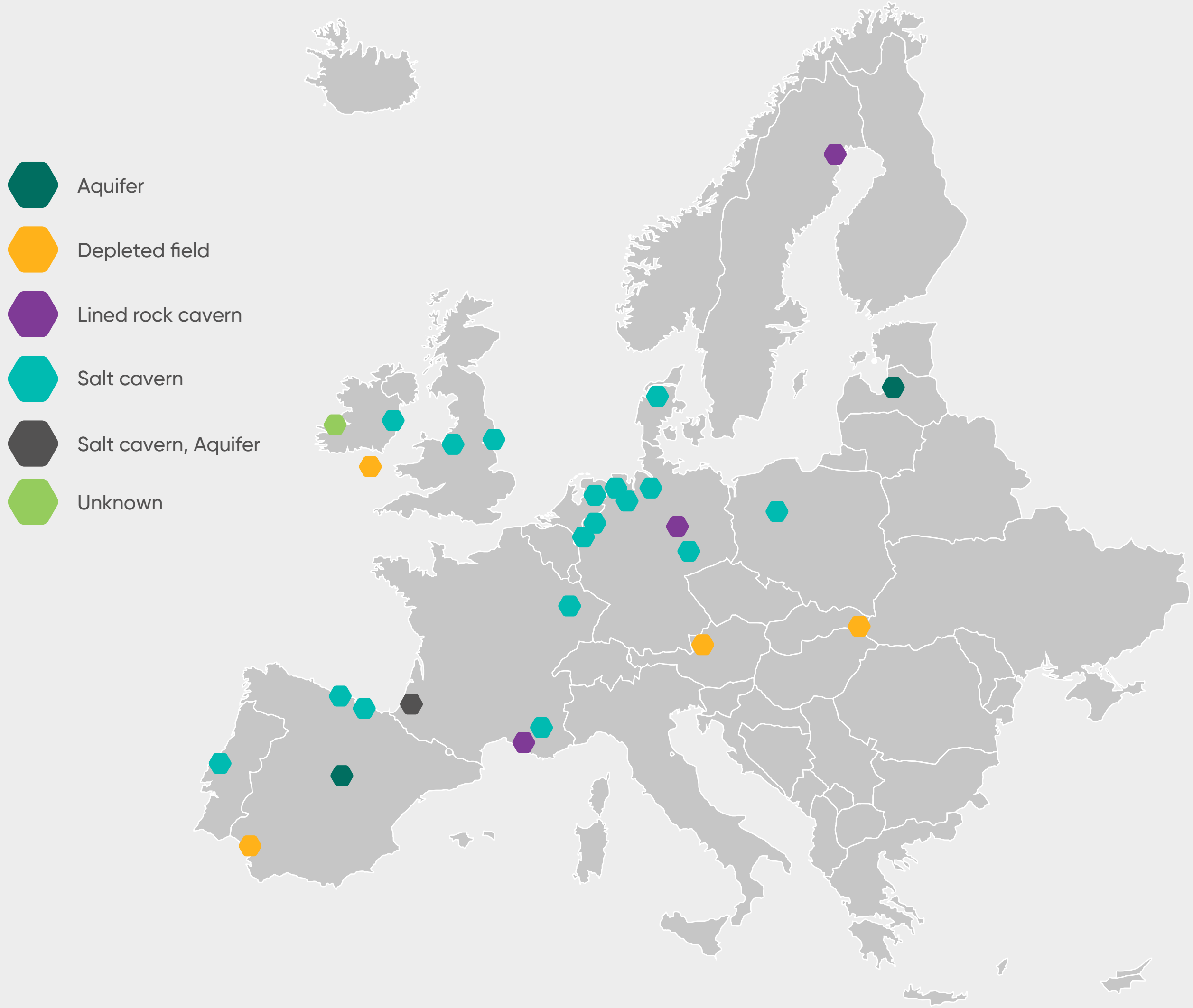
With the increased need to guarantee a large-scale supply of hydrogen for industrial and energy consumers, the development of hydrogen storage projects has also progressed. Currently, there are more than 50 hydrogen storage projects in Europe, with different levels of development, scale and technologies used. The purpose of this section is to provide a brief overview of the large-scale projects (> 30 GWh) as these will potentially be able to provide security of supply to large-scale consumers, which will need hydrogen continuously.

Currently, 29 large-scale (> 30 GWh storage capacity) have been identified across Europe, most of which (22) focus on storing pure hydrogen. Four projects focus on blending hydrogen with natural gas, while for three there is limited information, due to the early stages of development.

Due to their hydrogen storage properties, salt caverns are the preferred type of storage with 19 projects planning to use either new or repurposed salt caverns. Four projects are exploring the possibility of storing hydrogen in depleted fields. Aquifers are considered for three projects and lined rock caverns for three.

FIGURE 4.8

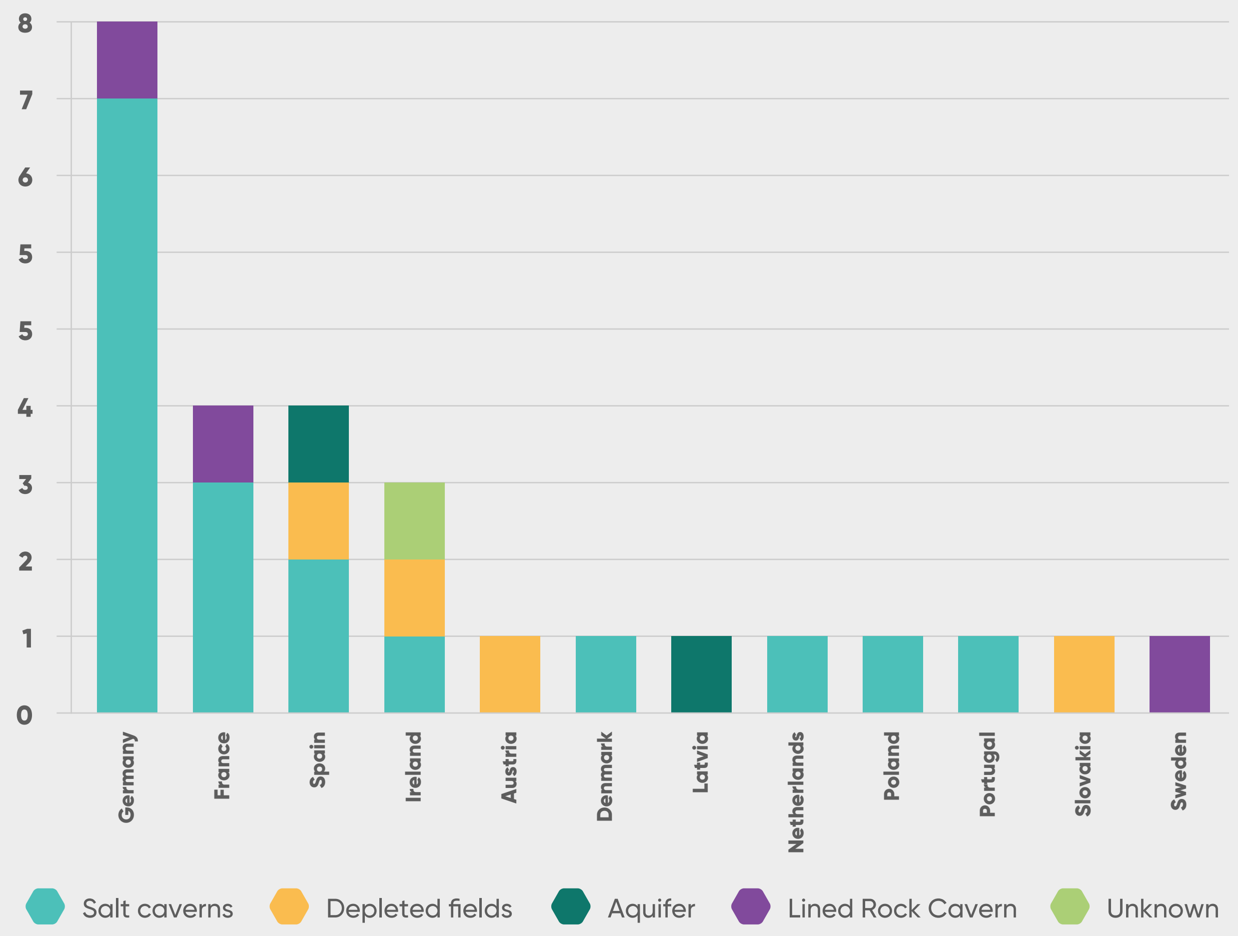
Map of selected large-scale hydrogen storage projects in Europe



Source: Hydrogen Europe.

FIGURE 4.9

Selection of large scale hydrogen storage in Europe by country and type



Source: Hydrogen Infrastructure Map.

Methodological Note

For transport infrastructure, the chapter looks at a selection of eight EU member-states and the developments that have taken place in them regarding hydrogen transmission infrastructure in the last year. These developments concern planning, legislative frameworks and construction of the national backbone. For planning, the adoption of national backbone plans, either by public authorities or by the national transmission system operator (TSO), was tracked. For legislation, the purpose was to identify what legislative regimes have been adopted, while the Hydrogen and Decarbonised Gas Market Package is being transposed into national law. These can be legislative regimes related to hydrogen network planning, as is the case for Germany, or legislative frameworks that govern infrastructure ownership, as is the case in Belgium. Lastly, for construction, the focus was on tracking the execution of the national backbone plans by focusing on the construction of pipelines that will be part of the latter.

As to storage, the presented projects in this chapter represent a first look in the development of hydrogen storage infrastructure. The purpose is to highlight announced large-scale storage projects across Europe. The threshold set was of projects with storage capacity above 30 GWh of hydrogen which are expected to satisfy large-scale demand from the industry or energy sectors.

All the data presented in the chapter is from primary sources, such as documents or announcements from public authorities or from project developers involved in the presented projects.

Endnotes

a / Austrian Gas Grid Management AG, 2022.

b / Fluxys, 2023.

c / FPS Economy, 2023.

d / Fluxys, 2023).

e / NET4GAS, 2022.

f / Central European Hydrogen Corridor, 2023.

g / Bundesministerium fur Wirtschaft und Klimaschutz, 2023.

h / FNB Gas, 2023.

i / Government of Norway, 2023.

j / SNAM, 2018).

k / R.A.A. Jetten, 2022.

l / Gasunie, 2023.

m / Enagas, 2023.

n / Arturo Gonzalo, 2023.

o / Ministerio para la Transición Ecológica y el Reto Demográfico, 2023.

p / Jefatura del Estado, 2023.

05

Electrolyser manufacturing capacity

The European electrolyser industry is ready to scale up to meet European and global demand for the technology, but economic support and non-price criteria could further accelerate those plans and allow it to remain competitive with non-European manufacturers in the long term.

- European electrolyser manufacturing capacity could increase from the current 3.9 GW_{el}/year to 27.8 GW_{el}/year by 2030 based on announced expansions.
- Europe is a region with the second largest electrolyser manufacturing capacity in the world after China and could retain this position based on current announcements.
- 58% of the operational manufacturing capacity is alkaline but 60% of the announced capacity is for PEM technology.

Operational electrolyser manufacturing capacity in Europe in September 2023 was more than 3.9 GW_{el}/year, having increased by 0.6 GW_{el}/year from August 2022.

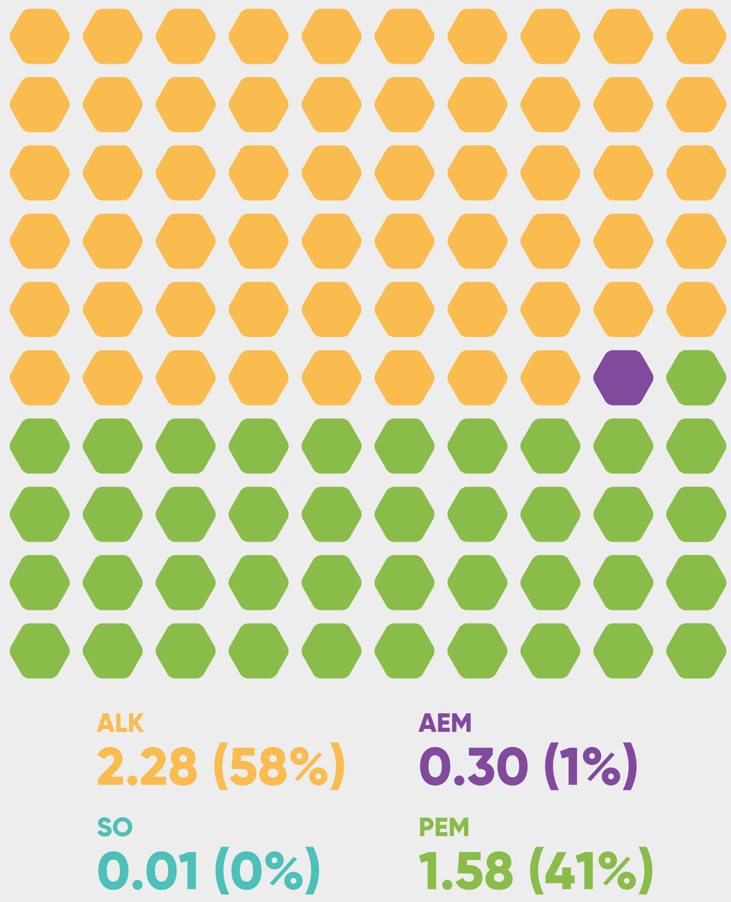
The production of water electrolysers in Europe is on the rise. As of October 2023, the annual production capacity stands at 3.9 GW_{el}/year, indicating a 0.6 GW_{el}/year increase compared to one year ago (18% y/y growth rate).

The existing manufacturing capacity is, however, arguably still insufficient compared to the EU's targets for the ramping up of renewable hydrogen production by 2030. With their current capacity, the European electrolyser manufacturers could deliver up to 23.4 GW_{el} of electrolysers by 2030,[1] assuming production at full capacity for the next seven years. To meet the ambitious REPowerEU objective of producing 10 million tons of hydrogen annually, roughly 100 to 120 GW_{el} of electrolysers would be required. Therefore, further growth in production capacity is essential if Europe wants to be self-sufficient in electrolyser manufacturing. Based on the present rate of electrolyser production and assuming no imports, to reach 100 GW_{el} of deployed electrolysis capacity, the required annual manufacturing capacity growth rate would have to be at least 40%. This underscores the need to further support the European electrolyser manufacturing capacity expansion to contribute to European decarbonisation while retaining European technology leadership manufacturing.

Regarding technology, alkaline electrolysis (ALK) represents an estimated 58% of all electrolyser manufacturing capacity in the EU. PEM (Proton Exchange Membrane) technology, constitutes 41% of the total manufacturing capacity. AEM (Anion Exchange Membrane) technology and SO (Solid Oxide) are comparatively less mature despite a single European AEM manufacturer having started shipping small modular stacks to customers. As a result, manufacturing capacities of these two technologies lag behind ALK and PEM.[a]

FIGURE 5.1

Operational electrolyser manufacturing capacity in Europe (GW_{el}/year) by technology, October 2023



Source: Hydrogen Europe.

1 / Considering a full capacity production at 3.9 GW_{el} per annum of electrolysers starting in 2024 until 2029.

Electrolyser manufacturers have announced significant capacity expansions to 27.8 GW_{el}/year by the end of 2030.

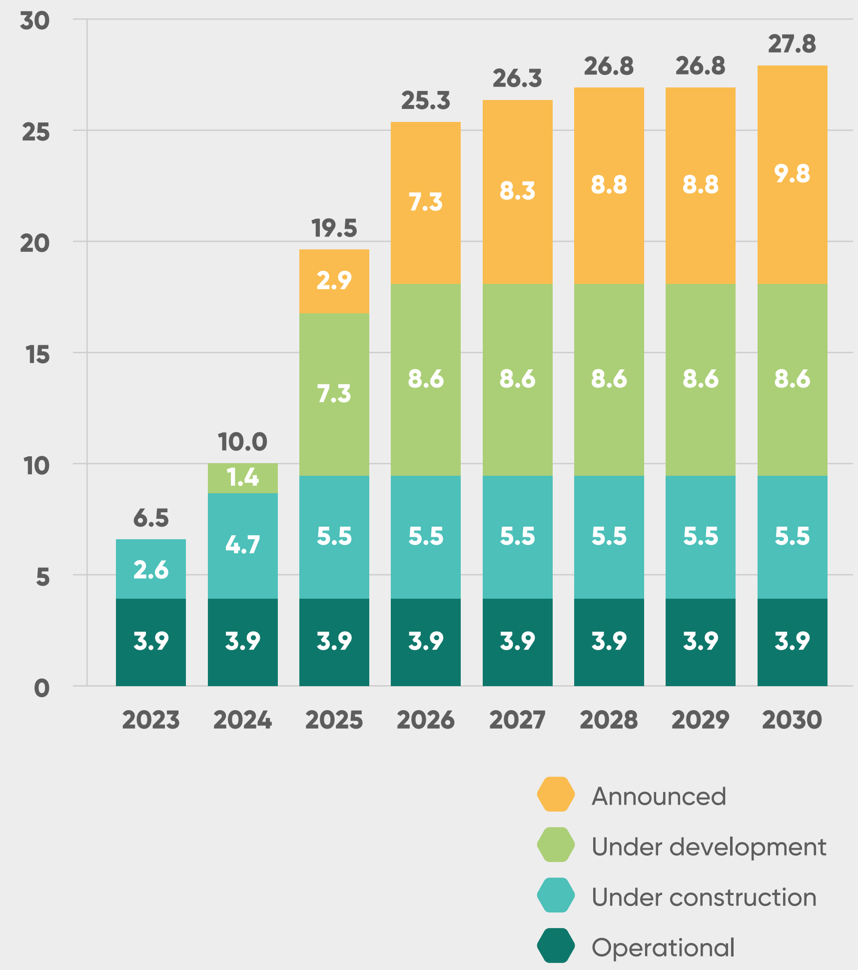
European electrolyser manufacturers announced capacity expansions reaching 27.8 GW_{el} by 2030.[2] There is a significant increase in 2025 when almost 10 GW_{el}/year of manufacturing capacity has been announced to come online. The growth will be accompanied by expansion of manufacturing capacity across Europe. By 2030, electrolyser manufacturing facilities have been announced in 12 European countries, compared to 10 today.

If all of the planned manufacturing facilities come into operation and operate at a 100% capacity utilisation, the potential total electrolyser output would amount to 169 GW_{el} by the end of 2030, with a potential to produce around 16-17 Mt of hydrogen per annum[3]– i.e., sufficient to support the realisation of REPowerEU targets. However, due to the new electrolysis deployment investment lead time of around 3-4 years, while the total planned manufacturing capacity is relatively high, further acceleration of those plans is needed. For this reason, during the European electrolyser summit,[b] the declared target for electrolysis capacity buildup was already set at 25 GW_{el}/year in 2025. With only 19.5 GW_{el}/year expected, there is still room for further action to support European electrolyser manufacturing. Furthermore, around 2/3 of all manufacturing capacity projects are still in a Pre-FID stage with a significant risk of cancellation, delay or relocation.

2 / In the 2022 Clean Hydrogen Monitor, the capacity expansion plans were estimated at 53 GW_{el} by 2030, the main reason for the fall is, however, not cancellation of plans but a change in methodology. While the 2022 data included all announcements made, for the 2023 edition the announcements with clear funding scheme, deployment date and technology were considered.
3 / Assuming 5000 hours per year full load equivalent with 50 kWh/kgH2 efficiency.

FIGURE 5.2

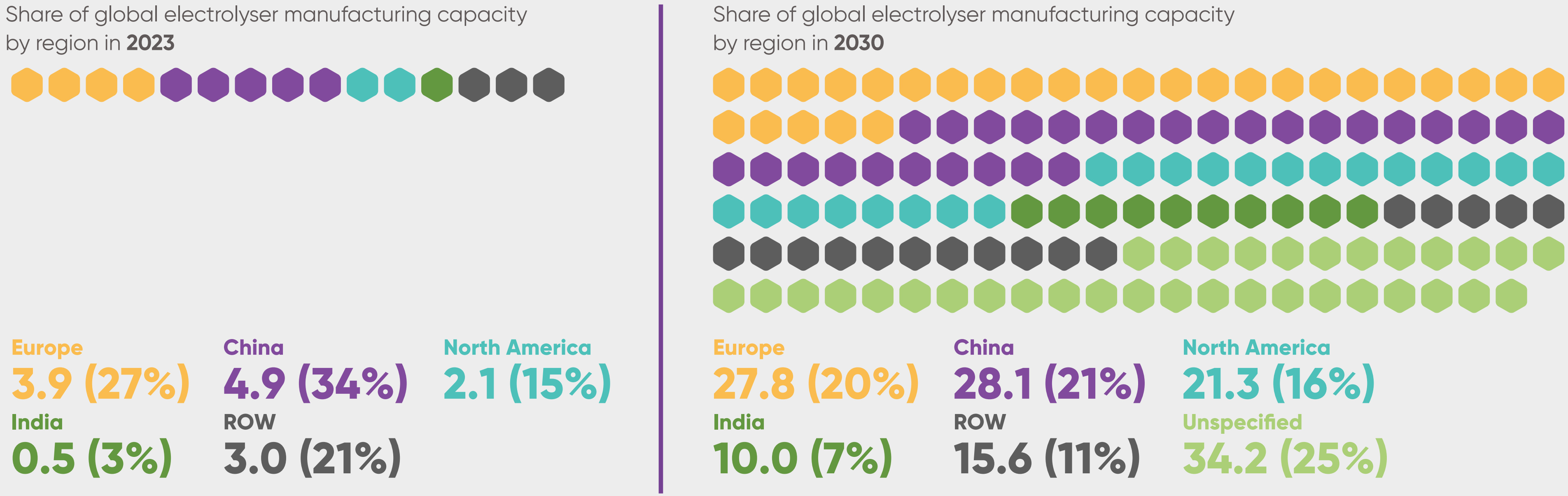
Development of electrolyser manufacturing capacity in Europe for the period 2023-2030 (GW_{el}/year)



Source: Hydrogen Europe.

FIGURE 5.3

Comparison of global electrolyser manufacturing in 2023 and 2030 (GW_{el}/year)



Source: International Energy Agency and Hydrogen Europe.

Europe could retain its position as a major electrolyser manufacturing supplier in 2030.

Europe is currently one of the leaders in electrolyser manufacturing worldwide, with 27% of the global capacity, with China leading production with 34% of the global market. The global capacity currently stands at 14.4 GW_{el}/year, but every region is poised to increase their capacity significantly in the next years. If all capacity expansion plans are realized as announced in 2030, Europe's global capacity share would drop to 20%, catching up with China, whose share would represent 21% while retaining its position as the manufacturing leader. India could also become a more prominent actor in this market, capturing 7% of the market compared to 3% today.[c] 34.2 GW_{el}/year have been announced for 2030 but haven't chosen (or disclosed) a location for the investment.

Notes: Europe numbers from Hydrogen Europe; rest is from IEA.

60% of the announced electrolyser manufacturing capacity in Europe by 2030 is PEM, 32% is ALK, while AEM and SO are only starting to announce their expansion plans.

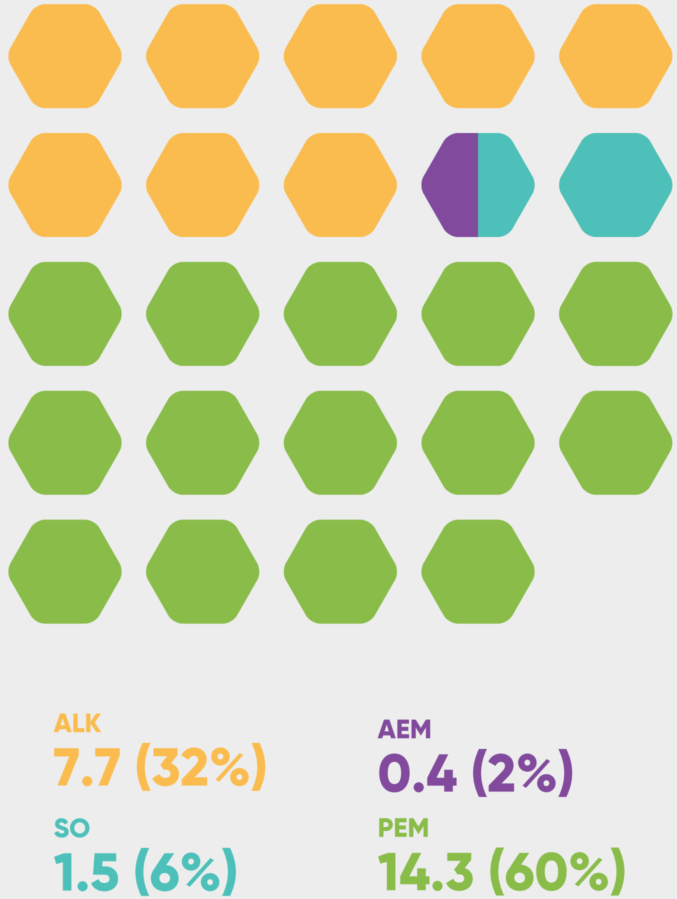
In 2030, technology-wise, we can expect to witness a higher diversification of electrolyser technologies. If all planned investments in manufacturing capacity go ahead, PEM technology would take the lead with 60% of the manufacturing capacity of plants to come online, while the previously dominant ALK accounts for 32% of the announced new projects.

Additionally, AEM and SO technologies will also see an increased market share, respectively, with 2% and 6% of the announced new capacity. These two technologies are reaching industrial maturity and have advantages (as well as disadvantages) compared to PEM and ALK technologies. AEM electrolysers are less reliant on critical raw materials, while SO electrolysers are more efficient, for example.

Each of these electrolyser technologies comes with its own set of advantages and disadvantages. Alkaline electrolysers have a long track record, are durable and do not need critical raw materials such as Platinum Group Metals (PGMs). PEM electrolysers have high flexibility to load changes, high power density, allowing for a compact design and high out pressure. SO electrolysers have the highest energy conversion efficiency of up to 84%[d], and use cheap ceramics for their operation; on the other hand, they require high temperatures (above 600°C), making them particularly suitable for industrial applications with access to waste heat sources. AEM electrolysers combine high load flexibility, a compact design and low reliance on critical raw materials but suffer from their emerging technology status and low materials lifetime.[e,f] Therefore, it's crucial to consider the unique characteristics of each technology and ensure they are readily available to cater to the specific needs of customers.

FIGURE 5.4

Announced electrolyser manufacturing capacity by technology in Europe by 2030 (GW_{el}/year)



Source: Hydrogen Europe.

Methodological Note

The data presented in this chapter includes water electrolysis manufacturing capacity in European factories, as planned by electrolyser manufacturers. Hydrogen Europe did not make any projections about potential capacity increases. The data is collected from public announcements, complemented by Hydrogen Europe's confidential information.

Whenever timelines are unclear but credible to be operational by 2030, it is assumed that facilities will become operational by 2030. This potentially underestimates manufacturing capacity shortly before 2030 and overestimates capacity in 2030. The data is reported assuming 100% utilisation capacity. The reported total announced capacity includes plans in all stages of development, e.g., initial ambitions set out in business plans and facilities under construction. Although plans at the initial stages of development depend on several market conditions, e.g., future demand, and can significantly change or even be cancelled, they compose a reliable indicator of potential ramp-up speed and capacity.

Endnotes

a / Hamish Andrew Miller, 2020.

b / European Clean Hydrogen Alliance, 2023.

c / International Energy Agency, 2023.

d / Sunfire, 2022.

e / Oldenburg, 2022.

f / Bernuy-Lopez, 2023.

06

Hydrogen policies, strategies, and standards

Two years after the European Commission published its Fit for 55 package, the main policy drivers for hydrogen production and consumption have been adopted. The legislation underpinning the transport and storage of hydrogen is about to be finalised alongside legislation on industrial-scale manufacturing and enhanced access to CRMs.

- The Renewable Energy Directive sets the obligations for hydrogen consumption in transport and industry by 2030, creating a regulatory demand of at least ~1.9 Mt of RFNBO hydrogen and additional potential demand up to 4.3 Mt. It also provides a definition of RFNBOs that can count towards these obligations.

- 20 countries in Europe and 43 globally have adopted national hydrogen strategy/policy documents.

- Hydrogen certification and standards are unclear, complex, or under development posing challenges for production and consumption project developers.

EU Regulatory Framework

The EU's flagship Fit for 55 package embarked on bringing structural changes to Europe's industry, transport, and energy sectors, with hydrogen as one of the key drivers of decarbonisation of these sectors. REPowerEU pushed the ambitions further to speed up phasing out of fossil fuels and reducing dependence on imports from Russia. Now, two years after the European Commission published its Fit for 55 package, key policy drivers for hydrogen production and consumption have been adopted. The legislation underpinning the transport and storage of hydrogen is about to be finalised.

The long-awaited Renewable Energy Directive (RED) sets obligations for hydrogen consumption in transport and industry. It defines renewable fuels of non-biological origin (RFNBO) that can count toward these obligations. FuelEU Maritime and ReFuelEU Aviation provide clear direction for decarbonising these sectors where hydrogen and synthetic fuels have a key role. The Alternative Fuels Infrastructure Regulation (AFIR), in addition, will ensure the rollout of hydrogen refuelling stations across Europe to accommodate the increase in zero-emission vehicles, which are to become mandatory for new sales as from 2035 (for light duty vehicles). All these technology-focus legislative pieces are complemented by the underlying Emission Trading System (ETS) and Carbon Border Adjustment Mechanism (CBAM), which provide the two main pillars for economy-wide decarbonisation. CBAM covers hydrogen and other vital products, including iron, steel, fertilisers, cement, aluminium, and electricity. The introduction of CBAM as of 2026 will lead to the phasing out of free allowances under the ETS by 2034.

Since last year's Clean Hydrogen Monitor, we have also seen the EU's response to the US Inflation Reduction Act (IRA). The Green Deal Industrial Plan, with its Net-Zero Industry Act, Critical Raw Materials Act, and the Strategic Technologies for Europe Platform (STEP), aims to support domestic manufacturing of clean technologies, inducing electrolysers and fuel cells by providing a stable and predictable regulatory framework, speeding up permitting processes and easing access to finance. Furthermore, the Hydrogen Bank will launch its first auction for domestic hydrogen production in November 2023. It will complement other EU and national funding programs supporting hydrogen projects, many of which are described in detail in **Chapter 7**.

FIGURE 6.1

European policy framework for hydrogen

H2 Production & Transport

H2 end-use

Gas Package
(Q4 2023)
Gases definitions and infrastructure

Net-Zero Industry Act
(2024)
Response to the US Inflation Reduction Act

Critical Raw Materials Act
(Q4 2023)
EU legislative framework on CRMs

Standards and Certification
Need for acceptance and harmonization of methodologies and rules

RED3
(agreed)
42.5 % renewables target RFNBOs

Binding targets by 2030
Transport: RES-T:
14.5% GHG reduction or 29% RES
5.5% adv. biofuels & RFNBOS
(of which 1% RFNBO)

Industry:
42% of H2 to be RFNBO

Can be reduced by MS by 20% if:
On track for RES 2030 target
Fossil fuel-based H2 consumption is > 23% in 2030

ReFuel EU Aviation
(agreed)
Quotas for SAF & specific quota for RFNBO

Fuels EU Maritime
(agreed)
GHG saving targets & specific quota for RFNBO

AFIR
(agreed)
Targets for the deployment of hydrogen refueling stations

ETS & CBAM
(adopted)
Scheme for GHG emission allowance trading within the EU

RFNBO H2 Definition
H2 derived from RES sources, meets additionality criteria & GHG emission reduction threshold of 70% compared to fossil fuels comparator (94 g CO2eq/MJ) (agreed)

Low-Carbon H2 Definition
H2 derived from non-RES sources & meets GHG emission reduction threshold of 70% compared to fossil fuels comparator or other criteria (Q4 2023)

Source: Hydrogen Europe.

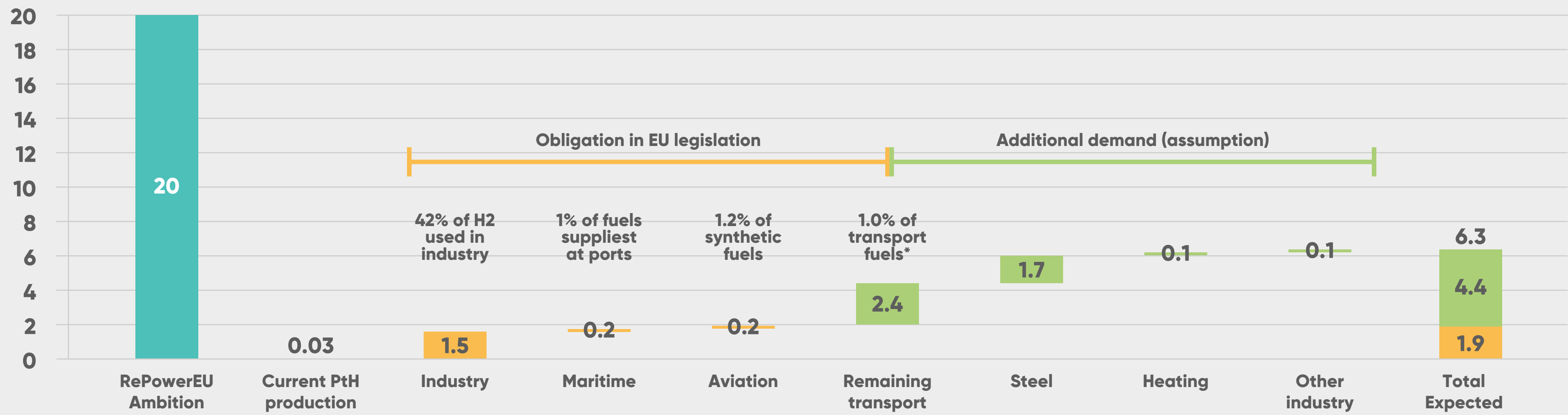
That said, the legislative work does not stop here. The adopted legislation doesn't match the EU's ambitions of REPowerEU nor the goals set with the 2020 Hydrogen Strategy (**Figure 6.2**).

In particular, the ambition within the transport sectors has been significantly diluted with low binding obligations for fuel suppliers. The challenges for scaling up the technology and adapting the processes in the industrial sector remain high. Incorporating electrolytic hydrogen within industrial processes, quickly deploying the hydrogen backbone, and meeting the highly demanding requirements of additionality and temporal correlation within a relatively short time frame will require strong industry collaboration and firm governmental support to increase investments and help de-risk technology innovation and large commercialisation.

While the industry is assessing the impact of the adopted legislation, it is keeping an eye on the upcoming European elections. Planned for June 2024, these elections will lead to an instalment of a new European Parliament and the European Commission, which will outline their vision for the future of the European Green Deal with 2040 climate targets in mind. In parallel, it is now up to the Member States to start implementing the targets and rules defined in the European legislation while ensuring this process does not result in additional challenges to creating a truly European hydrogen market.

FIGURE 6.2

REPowerEU 2030 ambitions compared with legislative obligations and targets



*-1% RFNBO in transport fuels with a x2 multiplier, i.e. effectively 0.5% share.

Source: Hydrogen Europe.

Renewable Energy Directive

Renewable Energy Directive sets the target for hydrogen use in industry and transport and will be one of the key drivers of hydrogen demand. It also provides definition of renewable fuels of non-biological origin (RFNBOs), which will count towards these targets.

FIGURE 6.3

RED III targets

42% of H2 used by industry must be RFNBO by 2030

60% by 2035

An aggregate quota of **5.5%** of energy in the transport sector must be met from advanced biofuels or RFNBOs by 2030

A sub-quota reserved for RFNBOs of **1%** energy in the transport sector

RFNBO counts double towards the fuel supplier obligations

RFNBO used in aviation and shipping are **multiplied by 1.5**

Source: Hydrogen Europe.

Initially introduced in 2010, the Renewable Energy Directive has been the driving force behind developing renewable energy in the EU. As the EU has increased its climate ambitions for 2030 to become the first carbon-neutral continent by 2050, the Directive underwent revision as part of the Fit for 55 package in 2021 and later under the REPowerEU Plan in 2022, until it was finally adopted in Fall 2023. The Directive sets the binding target for the share of renewables at 42.5% by 2030. Concerning the hydrogen sector, it also sets clear targets for the use of renewable fuels of non-biological origin (RFNBOs), including in industry and transport.

Under the Renewable Energy Directive, the industrial sector will have to increase its use of renewable energy by 1.6% annually. Furthermore, 42% of the hydrogen used in industry should come from renewable fuels of non-biological origin by 2030, increasing to 60% by 2035. However, the level of ambition of the new industry target could be diluted over the general construction of the target as well as from ammonia-specific measures. The Directive allows Member States to reduce their industry renewable hydrogen target by 20% if they can comply with several criteria, including being on track to meet the 2030 renewables target and/or prove that the share of hydrogen, or its derivatives, produced from fossil fuels (which is consumed in that Member State) is not more than 23% in 2030 and not more than 20 % in 2035. In this case, their industry target is lowered to 33.5%. Moreover, how the target has been formulated means that the more ammonia and methanol are imported (and thus less hydrogen demand domestically), the lower the target becomes (even if the imported products are fossil-based). Efforts to meet the target are based on the hydrogen demand of a particular Member State. Therefore, if the ammonia is produced abroad, there is no hydrogen consumption and thus no need to make it "green". In addition, the final text of the Directive is based on a proposal by the Swedish Council Presidency to "acknowledge" the difficulties in asking hard-to-abate ammonia facilities to move into renewable-based ammonia, mainly if they have already engaged in plans to retrofit their installation with CCS technology. These acknowledgements have been reflected in two recitals 62 and 63 in the final text. However, those were accompanied by a Commission Declaration stating the EU executive would *"on a case-by-case basis decide not to take into account these existing plants"* for meeting 2030 green hydrogen targets, as long as these plants are already making efforts to move to reduce emissions in the fossil-based ammonia plants.

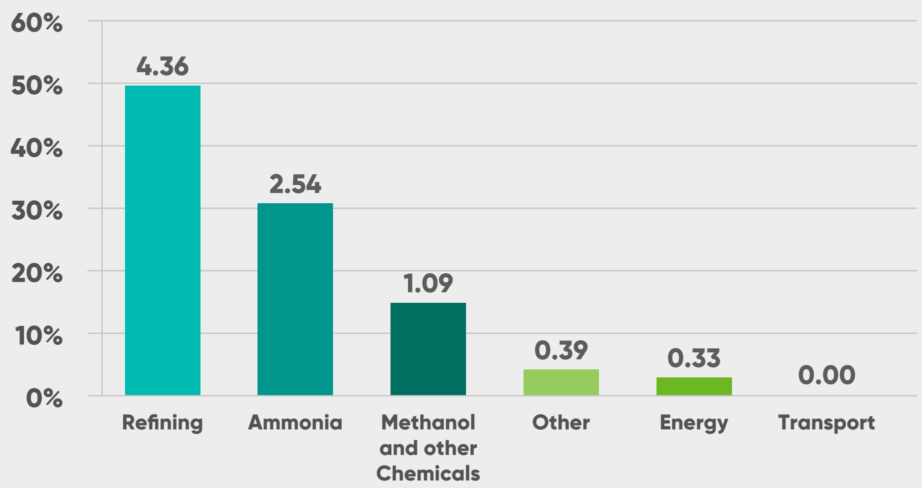
Member States still have a lot of room to design the targets more coherently, perhaps even addressing the issues outlined above. In the meantime, the targets allow for a rough estimation of potential demand resulting from their implementation. In other words, the binding industry RFNBO target could lead to approximately 1Mton of renewable hydrogen demand for producing renewable ammonia, representing 2/3 of the overall industry target. Furthermore, we expect a significant demand for renewable hydrogen in the steel sector, which could lead to up to 1.7 Mtons of additional industrial demand by 2030.

Member States have two options for the transport sector to set targets to increase the share of renewable energy. They can opt for a binding target of 14.5% greenhouse gas emissions intensity reduction in the sector by 2030 by using renewable energy fuels, or a binding share of at least 29% of renewables within the final consumption of fuels by 2030. Demand for hydrogen is to be increased further via a binding combined sub-target of 5.5% for advanced biofuels and RFNBOs by 2030. Furthermore, this sub-target is strengthened by an additional sub-sub-target of 1% of RFNBOs in the share of energy supplied to the transport sector in 2030. It should be noted that the Directive also sets specific multipliers for the contribution of RFNBOs to the targets in the transport sector: the share of biofuels and biogas produced from the feedstock listed in Annex IX and RFNBOs shall be considered as twice their energy content (art 27.2.c). Also, the share of RFNBOs supplied in the aviation and maritime transport modes shall be considered 1.5 times their energy content (art 27.2.e). Consequently, RFNBOs in these two transport modes can be counted as three times their real contribution (the text does not explicitly prevent the combination of the two multipliers resulting in 1.5x2= multiplier of 3). In concrete terms, it would mean that if all produced RFNBOs were to be used in the maritime and aviation sectors only, the actual fuel supplied would correspond to 0.3% instead of the planned 1% sub-target. Moreover, the refineries can also use RFNBOs to decarbonise conventional fuel production to reach the overall RED mobility target (29% RES share or 14.5 GHG reduction). Hence, calculating the actual volume resulting from the 1% target is uncertain.

While its targets might be far from the REPowerEU ambitions, the Renewable Energy Directive provides the market with a stable and predictable legal framework with clear obligations for the offtakers. As such, it will have a major positive impact on the deployment of clean hydrogen technologies, particularly on the production of renewable hydrogen as well as its use in end sectors. That said, the next 18 months during which the Member States will be transposing the Renewable Energy Directive into their national law will be critical to ensuring that the Directive's ambitions will not be hindered by adding complexity at the national level or fragmenting the European market. Furthermore, additional implementing legislation will be required to supplement the newly adopted revision of the Renewable Energy Directive. The Delegated Act on additionality, described below, will have to be adapted to establish the methodology for when the electricity used to produce RFNBOs is considered fully renewable beyond the narrow application to the transport sector. The European Commission will also be working on recognising voluntary schemes for renewable hydrogen certification, which will provide detailed rules regarding the treatment and categorisation of imported RFNBOs.

FIGURE 6.4

Demand by end use



Source: Hydrogen Europe.

Delegated Acts

A key part of the Renewable Energy Directive is the two Delegated Acts detailing specific regulatory framework governing the production of RFNBOs, which entered into force in July 2023. The first defines the conditions under which electricity used to produce hydrogen, hydrogen-based fuels or other energy carriers can be considered fully renewable. The second provides a methodology for calculating life-cycle greenhouse gas emissions for RFNBOs and recycled carbon fuels (RCF).

When assessing whether the electricity used in hydrogen production is renewable, key criteria applied are those of additionality and temporal and geographical correlation. The additionality criteria mean that the renewable electricity used for producing RFNBOs must come from assets that would not exist without RFNBO production. In practice, the renewable energy installation must be commissioned not earlier than 36 months before the electrolyser. Furthermore, the installation cannot benefit from any public financial support. That said, the act provides a transitional phase for additionality in which RFNBO installations that become operational before the end of 2027 will only be subject to additional requirements from 1 January 2038 onwards, while the RFNBO installations operational after 2027 will have to comply with additionality from the start.

As to GHG emissions, the maximum GHG emission intensity threshold is defined at 70% of the fossil fuel comparator, which is 94 gCO2eq/MJ. In other words, RFNBOs produced must have a GHG intensity of no more than 28.2 gCO2eq/MJ, delivered to the final consumer. Therefore, to be considered as RFNBO, four ways of sourcing renewable electricity are recognised under this framework:

1

The default option is to use electricity from the grid. In this case, the country's average share of electricity from renewable sources, as measured in the two years before the year in question, is used to determine the share of renewable energy. In most Member States, this will not deliver RFNBO production, as they cannot achieve the 70% GHG emissions reduction. This is either because the GHG intensity of the power grid is too large or because the RFNBO output would be too small.

2

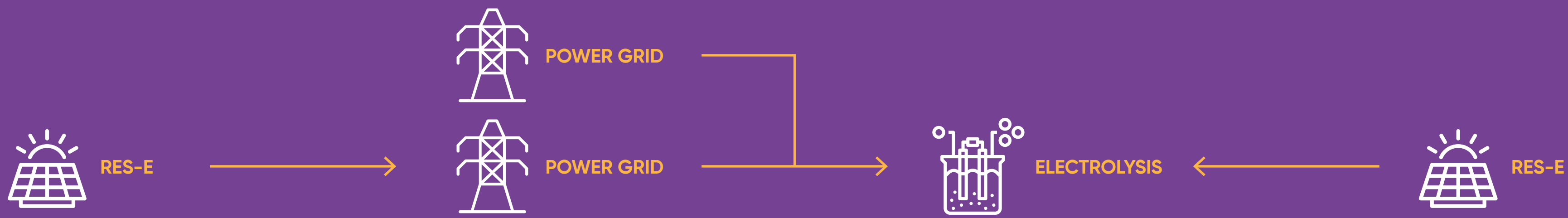
The second option is to source fully renewable electricity directly between the RFNBO facility and a renewable generation installation. However, two preconditions must be fulfilled to count the electricity as fully renewable, additionality being one of them. Furthermore, the installation producing electricity must not be connected to the grid, or if it is connected to the grid, it must have a smart meter to measure all electricity flows to show that no electricity from the grid has been taken to produce RFNBOs.

3

The third case under which electricity can be counted as fully renewable is when electricity is taken directly from the grid, if it is produced exclusively from renewable sources and the renewable nature is demonstrated and claimed only once. In other words, this case covers situations where electricity for RFNBO production is sourced via a Power Purchase Agreement (PPA). However, three conditions must be met for electricity to be counted as fully renewable. These include additionality, temporal correlation meaning that production matches temporally the electricity production unit with which it has a PPA; and geographical correlation, where the electrolyser and renewable power plant are in the same bidding zone or in an interconnected bidding zone, where the prices are higher compared to the bidding zone where the electrolyser is located.

4

The option includes a mix of fully renewable electricity (via direct connection or PPA) and electricity taken from the grid used to produce RFNBOs. This is advantageous as it can enable the electrolyser's utilisation and adjust the hydrogen production profile to the needs of the offtake.



Alongside the rules for calculating the GHG footprint of electricity, the DA also specifies the exact rules for GHG allocation for cases where hydrogen is produced in processes yielding multiple products, allowing for separate GHG accounting for processes in which renewable hydrogen is co-processed with conventional (fossil) feedstocks, and states serval conditions for the use of captured CO2 in e-fuels production.

While far from perfect, the two RED delegated acts provide a much-needed framework, clearing ground for future investments in RFNBO (and RCF) production.

Hydrogen and decarbonised gas market package

Hydrogen and decarbonised package, once adopted, will contribute to the development of hydrogen market and roll-out on infrastructure. It will also set the definition for low-carbon hydrogen.

In December 2021, the European Commission published the Hydrogen and decarbonised gas market package, consisting of proposed revisions of the Gas Directive and Gas Regulation to accommodate the penetration of renewable and low-carbon gases, which will progressively replace fossil gas in the EU. While the package is being negotiated and the precise contents of the package are not final, the proposals do recognise the importance of hydrogen as a key vector for the decarbonisation of the natural gas sector. In the short and medium term, the role of low-carbon hydrogen as an enabler of decarbonisation is foreseen, intending to support the uptake of renewable fuels such as renewable hydrogen.

The key provisions of the Package are organised around three topics – networks, market, and consumers.

Networks

The proposals lay down common rules for hydrogen transport, supply, and storage. Furthermore, the organisation and functioning of the sector, including market design and main regulatory principles such as unbundling and third-party access, are also addressed. On the latter, the European Commission's proposal goes slightly further than existing rules for natural gas with full ownership unbundled regimes recommended for all Hydrogen Network Operators as of 2030. The Gas Directive foresees two periods for the development of hydrogen networks, before 2030 all vertical unbundling models would be allowed (Full Ownership Unbundling (OU), Independent Transmission Operator (ITO) and Independent System Operator (ISO)). A year after the Directive's entry into force, Hydrogen Network Operators are to be unbundled according to these existing models. After 2030, however, Hydrogen Network Operators are to be unbundled or organised, following the independent system operator model. Regarding third-party access, in general, it is to be ensured both onshore and offshore for hydrogen networks. However, to allow for flexibility, Member States may allow negotiated third-party access until 2030. After 2030, the regime ought to move to regulated third-party access.

Furthermore, the Gas Regulation envisages the establishment of an independent body for hydrogen networks - the European Network for Network Operators of Hydrogen (ENNOH) whose tasks would include writing the relevant network codes, non-binding ten-year network development plans for hydrogen infrastructure, cooperation with ENTSO-E and -G, developing recommendations for technical cooperation and others.

Markets

The proposed Gas Regulation includes definitions for "low-carbon fuels", "low-carbon hydrogen" and "low-carbon gasses". Concerning low-carbon hydrogen, a 70% GHG emission reduction threshold is set, with the European Commission defining the exact methodology used to count the threshold in a delegated act expected by the end of 2024 (or earlier, depending on the result of the trilogues still in progress). While the Commission proposal steers away from delving into what precisely should be in the delegated act, the European Parliament proposed to introduce some preliminary criteria: the GHG emission savings from the use of low-carbon fuels shall be at least 70% relative to a fossil fuel comparator with a threshold of 94 gCO2eq/MJ and based on their life-cycle emissions. To ensure comparable GHG emission savings across sectors, the Commission may differentiate between fossil fuel comparators to distinguish between end-use sectors. For the Parliament, the methodology shall define clear, credible, science-based and realistic minimum carbon capture rates and upstream methane emissions performance standards

FIGURE 6.5

Low-carbon H2 definition

Council of the European Union

H2 derived from non-RES sources & meets GHG emission reduction threshold of 70% **compared to fossil fuels comparator (94 g CO2eq/MJ)**

European Parliament

H2 derived from non-RES sources & meets GHG emission reduction threshold of 70% & additional criteria **(i.e. distinguish between fossil fuel comparators for different end-use sectors)**

Source: Council of the European Union, European Parliament.

and take into account best available performance standards as well as industry initiatives. Also, the methodology shall ensure that credit for avoided emissions is not given for carbon dioxide the capture of has not already received an emission credit under other provisions of the law. The Commission has entrusted the preparation of the delegated act to the Joint Research Centre.

When it comes to low-carbon hydrogen, there are no targets for industry offtake, nor a direct funding mechanism. The only incentives are a proposed discounts for renewable and low-carbon gases in the form of entry-exit tariffs. The Gas Regulation also proposes a limit of 5% by volume of hydrogen blending into natural gas at interconnection points. This means that while at different points of the system the blending percentage can be higher, at interconnection points, TSOs can refuse gas with a higher blending ratio, but cannot do so if the ratio is lower than 5%. This is to avoid that blending becomes a market restriction and to safeguard end-users in different markets, where hydrogen uptake is slower.

On the question of cross-subsidization, the Regulation emphasizes the incompatibility of cross-subsidies with the principle of cost-reflective tariffs. Nevertheless, in exceptional cases, the benefits of the former are acknowledged in terms of societal benefits and predictable tariffs for early network users. The final decision lies with the Member States.

Consumers

The package includes several provisions relating to consumer protection, which already exist in the electricity sector. These include faster switching of providers, access to comparison tools for households, billing information and facilitation of smart meters for natural gas and hydrogen.

Once it is adopted in 2024, the Hydrogen and decarbonised gas package will provide much-needed legal predictability that is critical for driving investments into hydrogen infrastructure.

Alternative Fuels Infrastructure Regulation

FIGURE 6.6

Alternative Fuels Infrastructure Regulation

HYDROGEN REFUELLING STATIONS

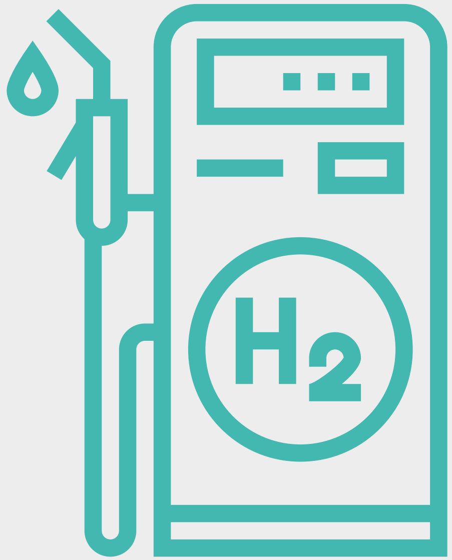
At least 1 H2 refueling station at every **200 km** on main roads by 2030.

One 700bar refueling point at every HRS.

One HRS in every urban node.

Mandatory cumulative daily capacity of 1t of H2.

Ad hoc payment systems at HRS and price transparency.



Source: Hydrogen Europe.

The Alternative Fuels Infrastructure Regulation (AFIR) establishes a common framework for deploying alternative fuels infrastructure across the EU's transport corridors. By mandating the deployment of hydrogen refuelling stations (HRS) in Member States, the Regulation aims to address the limited penetration of hydrogen-powered vehicles in the EU market. In other words, it ensures refuelling certainty and, as such, lays the foundation for the scale-up of hydrogen-powered mobility.

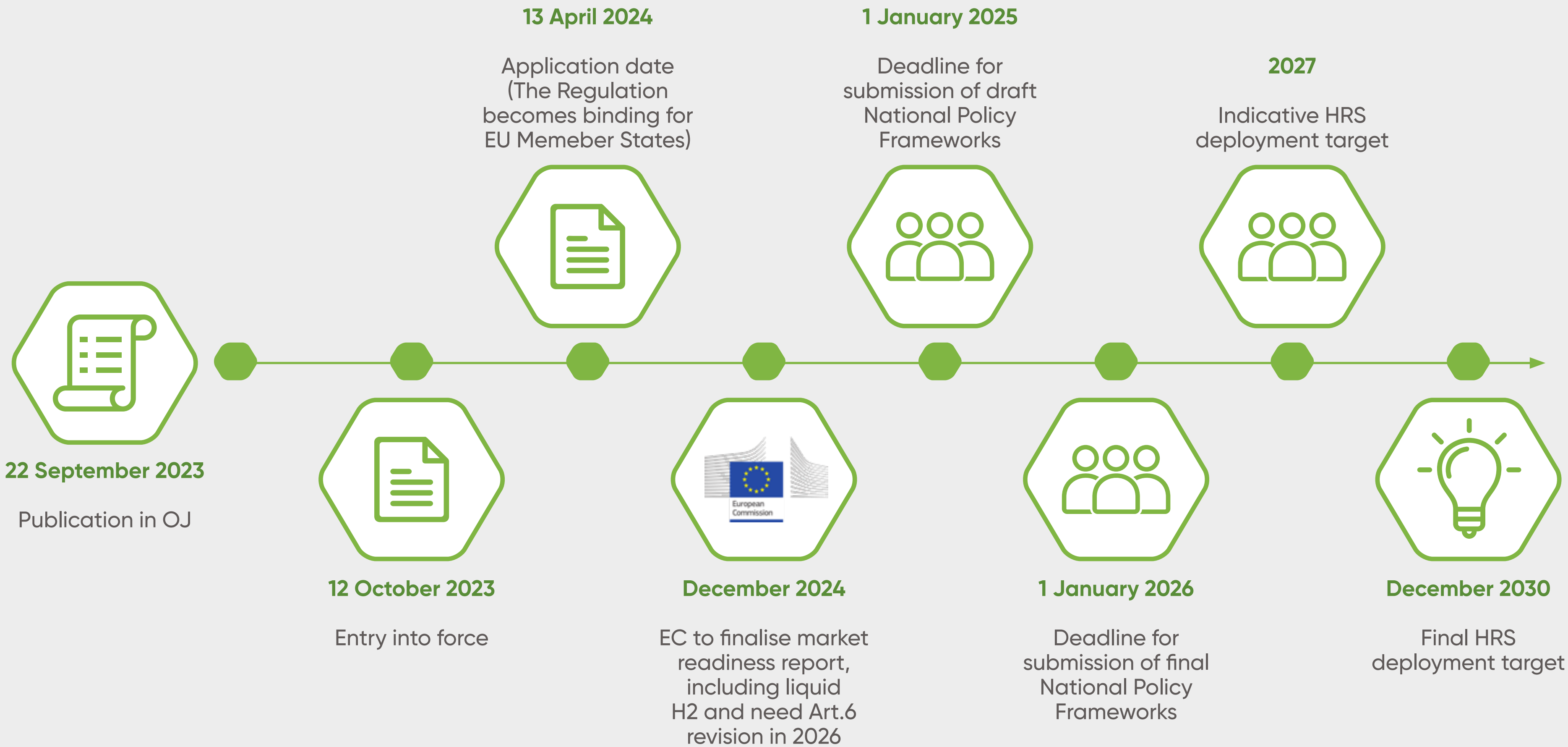
Article 6 of the Regulation mandates the construction of hydrogen refuelling stations for road transport. By the end of 2030, Member States must deploy at least one hydrogen refuelling station every 200km on the TEN-T core network and at least one in every urban node (as defined by the TEN-T Regulation). For example, this roughly translates into a target of 32 HRS across the core TEN-T network for Germany, 29 in Spain and 19 in Poland. Most importantly, the minimum cumulative capacity at every location must be 1 tonne per day. The Regulation leaves an option to halve the daily capacity of HRS on roads whose average daily heavy-duty traffic is below 2000 vehicles and in case of justified socio-economic cost-benefit terms. Outermost regions and islands can also be exempted under certain conditions.

The Regulation was proposed in July 2021 as part of the Fit for 55 package and was finally adopted in July 2023. Member States are expected to indicate a 2027 interim deployment target as part of their National Policy Frameworks, which must be submitted to the European Commission by the end of 2025. In the meantime, the European Commission will prepare a market readiness report, due by December 2024, which will inform the need to adjust the targets under Article 6 as part of the planned revision of the Regulation in 2026.

The ultimate ambition of the Regulation is to finalise the HRS network in the EU by the end of 2030.

FIGURE 6.7

AFIR timeline



Source: Hydrogen Europe.

Driving the demand for hydrogen in the transport sector

There is a regulatory drive for decarbonisation of road, maritime, and aviation transport sectors with zero-emission solutions including hydrogen due to CO2 emissions standards regulation for light and heavy duty vehicles, FuelEU Maritime, and ReFuel EU Aviation.

The FuelEU Maritime and the ReFuel EU Aviation aim to decarbonise the maritime and aviation sectors by encouraging alternative fuels.

FuelEUMaritime

FuelEU Maritime seeks to steer the EU maritime sector towards decarbonisation by limiting the average carbon intensity of the energy used on board from 2025 to 2050, considering GHG emissions from the whole supply chain ('well-to-wake'). The Regulation's targets apply to energy used on board a ship in or between EU ports but to only 50% of the energy used by ships arriving or departing from EU ports on voyages to or from a third country. Regardless of their flag, commercial vessels above 5,000 gross tonnages are covered. The Regulation establishes the obligation for containerships and passenger ship owners to use on-shore power supply for all electricity needs when moored at quayside (not anchorage) in TEN-T ports by 2030 and in 2035 for all other ports if equipped.

The Regulation also includes specific provisions to incentivise ship owners to use renewable fuels of non-biological origin (RFNBOs). First, until 2033, a multiplier of two can be used on RFNBOs to reward their use by early movers: this means that every ton of e-fuels used will have their GHG savings counted twice towards the GHG intensity reduction target. Additionally, an RFNBO 'sunrise clause' was introduced in Article 4: if in 2031 the share of RFNBOs in the yearly energy used on-board ships is less than 1%, a mandatory quota of 2% RFNBOs shall apply by 2034.

FIGURE 6.8

FuelEU Maritime annual average carbon intensity reduction

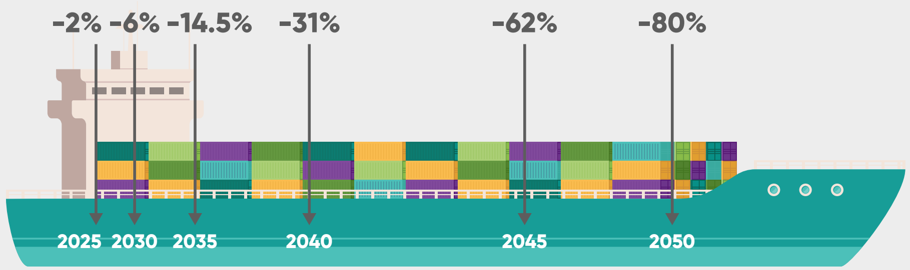


FIGURE 6.9

RFNBO specific provision in FuelEU Maritime

Multiplier of 2 for RFNBOs can be used until 2033 to reward their use by earlymovers: every ton of e-fuel used will have their GHG savings counted twice towards the GHG target.

"Sunrise clause": Mandatory quota of 2% RFNBO shall apply in 2034 if the share of RFNBO used in yearly energy used is less than 1% in 2031.

Furthermore, several flexibility mechanisms are introduced for ship owners to comply with the Regulation, among which:

- the possibility of banking and borrowing of compliance surpluses over the next period.

- the possibility of pooling compliance for the GHG intensity limit between two or more ships of the same company or from different companies - to reward and incentivise overachievers and encourage rapid deployment of the most advanced options to cut GHG emissions.

The Regulation also introduces a financial penalty in case of non-compliance with its requirements. The penalty has been set at 2,400 EUR per tonne of Very Low Sulphur Fuel Oil (VLSFO) consumed over the limit set by the maximum carbon intensity of energy the ship uses – an equivalent of around 7 EUR/kg of hydrogen. The revenues from penalties will go to Member States' budgets, which must re-allocate them towards support for rapid deployment and use of renewable and low-carbon fuels in the maritime sector.

The Regulation was adopted in July 2023 and will enter into force on the 1st of January 2025.

ReFuel EU Aviation

ReFuel EU Aviation aims to decarbonise the aviation sector by setting minimum obligations for all fuel suppliers to gradually increase the share of sustainable aviation fuels (SAFs) in the fuel supplied to operators at EU airports. A sub-obligation is also set for synthetic aviation fuels within this SAF requirement. Synthetic aviation fuels are defined in the Regulation as RFNBOs complying with the lifecycle emissions saving threshold of 70%. ReFuel EU Aviation also opens the possibility to reach the mandatory shares of SAFs and synthetic fuels when using renewable fuel for aviation (for direct use in aircraft) or low carbon-fuels for aviation, including low-carbon hydrogen. Additionally, the Regulation will establish an obligation for aircraft operators to ensure that the yearly quantity of aviation fuel uplifted at a given EU airport is at least 90% of the annual aviation fuel required to prevent fuel tankering practices where aircrafts are refuelled at the origin airport with more fuel than necessary for the flight to avoid refuelling partially or fully at a destination airport where aviation fuel is more expensive.

The Regulation was adopted in September 2023, and will enter into force on the 1st of January 2024 (2025 concerning SAFs mandates). By January 2027 and every five years after that, the European Commission will have to report to the co-legislators on its application and assess the potential need to revise the mandate and the SAF definition.

This first-of-a-kind mandate for green aviation fuel will allow SAF projects to be deployed at a larger scale, adding certainty on the definition of those fuels for investors and suppliers and establishing a European supply-chain for these sustainable aviation fuels. ReFuel EU Aviation will help to de-risk current investments and increase fuel suppliers' production goals, as political conditions make them more attractive.

FIGURE 6.10

REFuelEU Aviation targets

	REFUELEU AVIATION TARGETS Minimum SAF share within fuel supplied, and additional sub-quota for synthetic fuels	
2025	2% SAF	
2030	6% SAF	1.2% (2030-31) 2% (2032-34) synthetic fuels
2035	20% SAF	5% synthetic fuels
2040	34% SAF	10% synthetic fuels
2045	42 % SAF	15% synthetic fuels
2050	70% SAF	35% synthetic fuels

CO2 emission standards for light duty and heavy-duty vehicles

The revised Regulation on CO2 Emission Standards for light duty vehicles was enacted in April 2023. New standards will require new cars and vans to reduce their CO2 emissions at tailpipe, compared to 2021 levels. In detail, this means that from 2030 to 2034, emissions from cars will have to be reduced by 55% (50% for vans). From 2035 onwards, a 100% reduction is planned for both cars and vans. Carmakers could also benefit from less stringent targets if they meet certain benchmarks for the sale of Zero- and Low-Emission Vehicles, namely 25% for cars and 17% for vans. Following a last-minute opposition from Germany at the ratification stage, a political debate sparked around the definition and use of carbon-neutral fuels in conventional combustion engines. The initial stalemate was solved when the European Commission pledged to propose registering vehicles running exclusively on CO2-neutral fuels after 2035; the institutions are currently working on such a proposal. The Regulation will be assessed and reviewed in 2026.

Stricter standards are positive news for the scale-up of hydrogen solutions in the light-duty segment, as there is no carbon emission at the tailpipe. Carbon-neutral fuels would also pave the way for a higher demand for hydrogen in the sector. However, significant obstacles persist, some being the definition of what a carbon-neutral fuel entails and its certification, production capacity of e-fuels, as well as the availability of detection devices that would stop the car in case it is not running on a carbon neutral fuel.

In February 2023, the European Commission published a proposal to revise the existing CO2 emission standards for heavy-duty vehicles. The Regulation aims to progressively switch to zero-emission vehicles and reduce carbon emissions from the heavy-duty transport sector, whose levels are still on the rise. The proposed Regulation includes a 100% zero-emission target for city buses for 2030 and a 90% CO2 reduction target for trucks for 2040. The European Commission proposed a staggered approach to 2040, with the following milestones for new trucks and most bus classes (% reduction compared to 2019 emissions): **Figure 6.11**.

Hydrogen fuel cell trucks and buses will play a key role in this respect, as their CO2 emission at tailpipe is zero. Zero emission heavy-duty vehicles are defined in the Regulation as those emitting below the threshold of 5gCO2/tonne-kilometre. The proposal considers some types of hydrogen combustion engines as zero emission. However, this is one of the most debated issues of the proposal in the European Parliament. The Parliament is discussing further lowering the threshold to 1gCO2/tonne-kilometre. Lowering the threshold would exclude all dual fuel hydrogen combustion engines, even those which only use diesel as a pilot fuel. In that case, the "zero emission" category would only include battery electric, fuel cells and monofuel hydrogen combustion engines.

Once adopted in 2024, the proposed Regulation is expected to incentivise manufacturers to integrate an increasing share of low- and zero-emission vehicles in their fleet to meet their average CO2 emission reduction targets. The first due date by which manufacturers must reach their emission reduction target is set for 2025. This means that their decarbonisation efforts will have to start as of now to be compliant in 2025.

FIGURE 6.11

Share of zero-emission vehicles in new sales

	From 1 January 2030	From 1 January 2035	From 1 January 2040 onwards
HEAVY TRUCKS AND COACHES	45%	65%	90%
CITY BUSES	100%	-	-

Source: Hydrogen Europe.

Europe's response to the Inflation Reduction Act

In February 2023, the European Commission published the Green Deal Industrial Plan, the European industry masterplan for deploying and manufacturing clean technologies. The Green Deal Industrial plan was a response to the US Inflation Reduction Act (IRA), offering $369 billion in tax breaks over ten years for clean energy production and technologies, including hydrogen. It aims to create a more favourable environment for manufacturing clean technologies in Europe by providing a predictable and simplified regulatory framework, speeding up access to finance, enhancing skills, and working on open trade for resilient supply chains.

FIGURE 6.12

Four pillars of the EU Green Deal Industrial Plan

A predictable and simplified regulatory environment

- Net-Zero Industry Act
- Critical Raw Material Act
- Electricity Market Design reform

Boosting investments and financing

- Adaptation and softening of state aid rules
- Targeted aid for production facilities in strategic sectors (e.g., tax breaks)
- Hydrogen Bank
- Strategic Technologies for Europe Platform (STEP)

Enhancing Skills

- European Hydrogen Academy

Trade

- Ambitious EU trade agenda
- Global agreements to be ratified
- Unfair practices in the Foreign Subsidies Regulation

Source: Hydrogen Europe.

NZIA sets a target for the manufacturing capacity of strategic net-zero technologies to at least 40% of the EU's annual deployment needs by 2030. As a result, it is expected to directly contribute to an electrolyser manufacturing capacity of 25 GW/year from 2025.

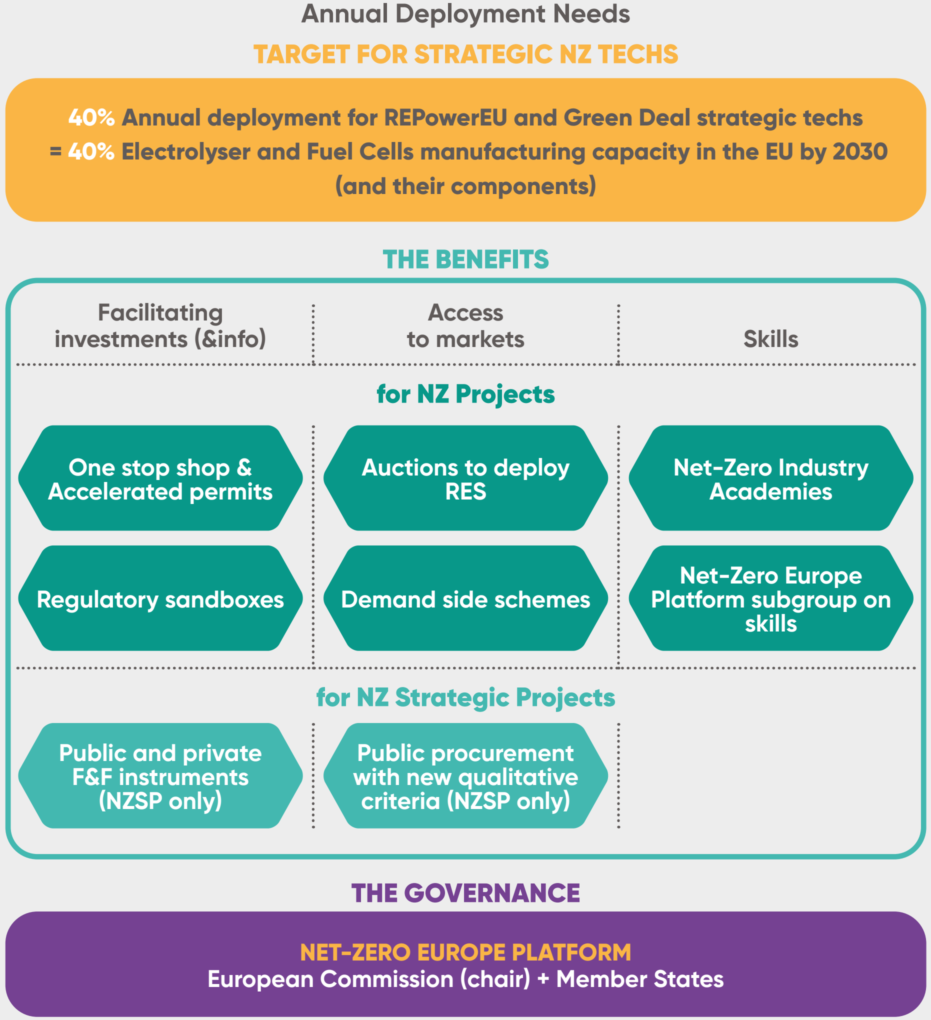
European Net-Zero Industry Act (NZIA)

The Net-Zero Industry Act (NZIA) is one of the cornerstones of the Green Deal Industrial Plan. Published in March 2023, it is key to ramp up the manufacturing of net-zero technologies in Europe. The measures in the NZIA proposal aim to provide investment certainty and lower administrative burdens through simplified and accelerated permitting by, for example, setting a one-stop-shop in Member States and access to information. The proposal will also facilitate market access through public procurement, auctions to deploy renewable energy sources and schemes to support private demand by consumers. The Regulation would also allow Member States to set up regulatory sandboxes to test innovative net-zero technologies in a controlled environment and for a limited amount of time. Finally, to underpin the manufacturing and deployment of clean technologies, NZIA will address the availability and quality of skills in net-zero sectors by creating European net-zero industry academies to develop learning programmes and credentials to provide skilling and reskilling of the workforce for the clean transition throughout Europe.

The NZIA proposal distinguishes between net-zero technologies and strategic net-zero technologies. The latter are defined as those making a significant contribution to decarbonisation by 2030 and are commercially available or will soon enter the market. All net-zero technologies will benefit from measures outlined in NZIA. However, strategic net-zero technologies will enjoy additional benefits, such as the possibility of becoming Net-Zero Strategic Projects. Pending the fulfilment of several criteria, including technology readiness level, contribution to decarbonisation and competitiveness and resilience of the energy system, such projects could receive priority status and benefit from faster permitting. Given that electrolysers and fuel cells have been identified as net-zero strategic technologies, projects involving the manufacturing of these technologies could be granted Net-Zero Strategic Project status. Clean manufacturing projects in Europe's less developed and transition regions and Just Transition Fund Territories can be considered of strategic importance upon request from project promoters; the same status can be granted to projects awarded by the EU ETS Innovation Fund, Important Projects of Common European Interest (IPCEIs), Hydrogen Valleys and Hydrogen Bank (if the received support was CAPEX only).

FIGURE 6.13

Structure of Net Zero Industry Act from Commission's proposal



Source: Hydrogen Europe.

Additionally, NZIA sets a target for the manufacturing capacity of strategic net-zero technologies to at least 40% of the EU's annual deployment needs by 2030. As a result, it is expected to directly contribute to an electrolyser manufacturing capacity of 25 GW/year from 2025.

To oversee its implementation, the European Commission proposes the creation of a Net Zero Europe Platform composed of Member States' representatives and the Commission. The Platform would focus on coordinating Member States actions, advisory services to companies and national authorities, and identification of financial needs, among others.

Adoption of NZIA is expected to happen at the beginning of 2024. Currently, the proposal is being negotiated, with some changes expected compared to the initial Commission proposal, for example, removing the distinction between net-zero and strategic net-zero technologies or simplifying the criteria to be awarded the status of a Net-Zero Strategic Project.

FIGURE 6.14

Net-zero vs strategic net-zero technologies

NET-ZERO TECHNOLOGIES*

- Renewable energy technologies (as per RED II)
- Electricity and heat energy technologies
- Grid technologies
- RFNBOs technologies
- Electrolysers and Fuel Cells
- Sustainable alternative fuels technologies (ReFuelEU Aviation/ FuelEUMaritime)
- Advanced nuclear technologies
- Small Modular Reactors, and related best-in-class fuels
- CCUS
- Heat pumps
- Energy-system related energy efficiency technologies

General benefits for all NZ Techs

- One stop shop/online info (permit, F&F)
- Accelerated permitting & envi assessment
- Planning
- Market support measures (auctions for RES, demand side measures...)
- Skills
- Innovation (regulatory sandboxes)

STRATEGIC NET-ZERO TECHNOLOGIES

- Solar photovoltaic and solar thermal technologies
- Onshore/offshore renewable technologies
- Battery/storage technologies
- Electrolysers and Fuel Cells
- Sustainable biogas/biomethane technologies
- CCS technologies
- Grid technologies

Additional benefits for strategic qualified projects (MS)

- Fast track permitting
- Mobilisation of public & private investments
- Public interest
- Sustainable & resilient public procurement

Source: Hydrogen Europe. Notes: Final products, specific components & specific machinery primarily used for the production of those products + TRL of at least 8.

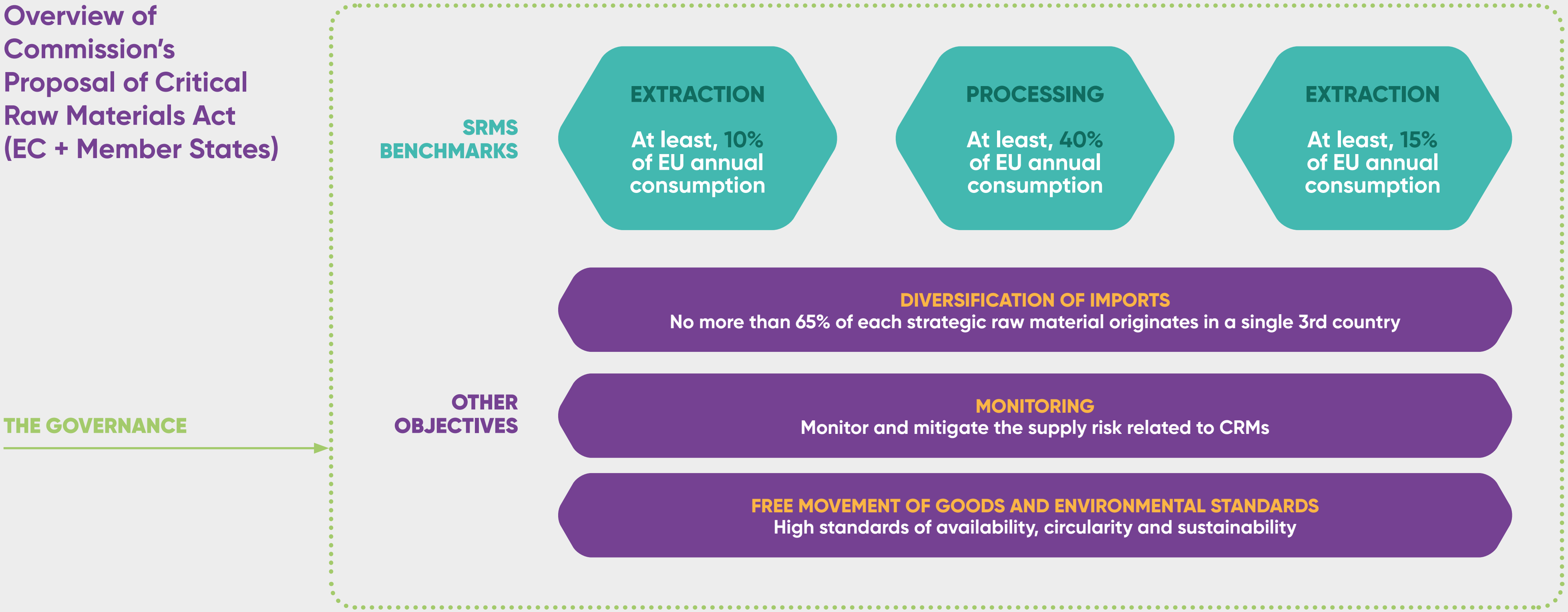
Critical Raw Materials Act

The Critical Raw Materials Act (CRMA), published in March 2023, aims to renew the European approach to the use of raw materials and the revival of Europe's sustainable materials market, focusing on the extraction, processing, recycling, monitoring and diversification of critical ores, minerals, and concentrates. The proposed regulation targets several issues related to critical raw materials, such as low diversification of EU supply sources, the untapped potential of local supply, weak monitoring, and risk management capacity to anticipate and prevent supply disruptions of critical raw materials (CRM), adverse social and environmental impacts of CRM production, insufficient support for circularity and insufficient research and innovation.

Hydrogen technologies such as electrolysers and fuel cells depend on CRMs. Thus, their availability and future prices will be a crucial aspect affecting the speed at which the

FIGURE 6.15

Overview of Commission's Proposal of Critical Raw Materials Act (EC + Member States)



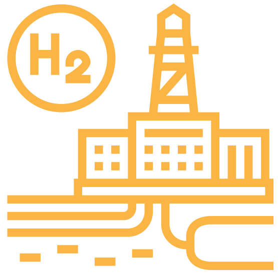
Source: Hydrogen Europe.

hydrogen market can grow. Certain technologies are heavily dependent on Platinum Group Metals (PGMs, such as platinum and iridium), which are fundamental for manufacturing key components like membranes and stacks. PGMs may represent a bottleneck for the EU supply chain as they are concentrated in specific geographies (South Africa, Russian Federation, etc.) and are precious, and scarce. Europe's goal to produce 10 Mt of renewable hydrogen by 2030 will require more than 100GW of electrolyser capacity by 2030. This could increase demand for platinum group metals (e.g., platinum, iridium) and other base metals such as nickel and copper that may be subject to shortages and price spikes due to competition with other clean tech sectors (electric motors, batteries, photovoltaic, wind...).

The Critical Raw Materials Act (CRMA) is expected to be approved by the end of 2023. However, several crucial points continue to be a subject of intense debate. These include the level of transparency in the compilation of the Strategic Raw Material List, the definition of purity criteria for these materials, comprehensive declarations of their environmental footprints, and the dynamic nature of targets set for producing, processing, and recycling strategic raw materials. It is worth noting that these targets tend to fluctuate consistently based on the perspectives of different institutional players.

PFAS restriction proposal

In January 2023, five countries (Denmark, Germany, Norway, Sweden, and the Netherlands) tabled a proposal under the EU's REACH (the EU/EEA's chemicals framework) aiming to ban all types of PFAS (per-and polyfluoroalkyl) substances. The group covers over 10 thousand substances most of which are problematic from an environmental and animal and human health standpoint, and whose production and availability needs to be regulated. However, the PFAS grouping also includes the subgroup fluoropolymers and perfluoropolyethers. These do not present significant toxicity concerns, cannot degrade into other PFAS and are not "bioavailable", "bioaccumulative" or water soluble. As such, they are considered polymers of low concern according to the OECD's criteria. Additionally, they are essential to a variety of net zero sectors, including the entire value chain of the hydrogen industry from various key electrolyser and fuel cell technologies to the infrastructure and grids to storage and offtake applications imperative to achieve the EU's energy and digital transition and have no viable and available alternatives. The five countries' restriction proposal could have detrimental effects to the ramping up of the hydrogen industry, effectively stopping and redirecting investments to other regions, crippling the European industry. The proposal is now being evaluated by the European Chemicals Agency (ECHA), which, given the unprecedented size of the PFAS restriction dossier, could take months to years. The ECHA will give its evaluation of the proposal to the European Commission, based on which the Commission has the prerogative to draft a restriction (under the REACH framework) that will be voted in by the Member States. Given the size of the file, the timeline is currently unclear, causing legislative uncertainty to the sector, and in turn putting strain on the ramp up of the European hydrogen (and other net-zero) industries.



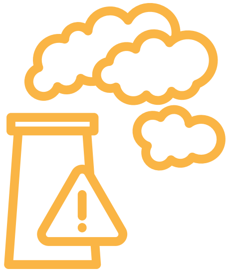
Electricity Market Design Reform – The role of hydrogen in the power system

In 2022, the European Commission was tasked with the structural reform of the electricity market in response to exceptionally high and volatile energy prices and serious concerns about security of supply for European consumers. In March 2023, the Commission came forward with a proposal to revise the rules for electricity market design. The aim of the proposal is to make the EU energy market more resilient as well as to detach the energy bills of European companies and citizens from the short-term market price of electricity. This can be done by using more long-term contracts, such as power purchase agreements (PPA) and investment support structured as two-way contracts for difference (CfD). These CfDs, which are market-based and voluntary, are introduced with the objective to bolster the roll out of renewable energy sources. Moreover, the PPAs are strengthened by streamlining of PPAs contracts, facilitating offtaker pooling and public financial guarantees. A new product – a peak shaving tool is introduced as a part of better and reinforced demand response mechanisms, which from now on can fully participate in the market via flexibility schemes and capacity mechanisms. Consumer protection is also at the heat of the reform, with numerous measures, including the mandatory establishment of suppliers of last resort and revenues from CfDs to be used to counterbalance retail tariffs. Finally, to streamline state intervention in case of an energy crisis, Article 66a introduces provisions and conditions to ensure energy affordability during price surges. Despite several adjustments, the proposal does not change the heart of the EU market functioning that is the merit-order principle and marginal pricing formation. Instead, it promotes the trading of electricity in the long term to reduce fluctuations.

Although the electricity market design is not a topic directly related to hydrogen, the inclusion of provisions for long term and seasonal flexibility targets in the reform (through Article 19c) strengthens the role of hydrogen in the power sector as a flexibility option to balance supply and demand variations. The reform also addresses the challenges of the integration of RES intermittency through the introduction of national flexibility targets. Along with the new targets, comes an obligation for Member States to assess flexibility needs, considering public feedback and ACER's periodic assessments. The flexibility needs will be assessed for different timeframes: short term, medium term, and seasonal flexibility needs. Furthermore, the Commission intends to ask Member States to define a national (non-binding) objective for controlling demand and storage, based on the assessment of the need for flexibility in the electricity network for a 5-year period done by the national regulator. This target should then be integrated into National Energy and Climate Plans (NECPs). Hydrogen could potentially play a significant role in the achievement of the seasonal flexibility targets as it provides balancing services for seasonal variation of supply and demand between summer and winter. Capacity markets are also reformed, even if they remain optional for Member States.

The work on the proposed reform is ongoing. Member States are particularly in disagreement on the issue of Contracts for Difference (CfD), with Germany and France discussing whether or not the CfDs could be applied to existing nuclear power plants and the level of supervision for the state's of the revenues from CfDs (when market prices are above the level set in the contracts guaranteed by the state) to industries. The proposal is expected to be approved by the beginning of 2024.

Industrial Emissions Directive



In April 2022, the European Commission published its proposed update of the Industrial Emissions Directive (IED), which had been in force since 2010. This revamp is necessary to align the EU's framework of dealing with harmful industrial emissions with the increasingly better knowledge of these pollutants and with the bloc's ambitious decarbonisation and environmental goals. Electrolysis-based hydrogen production is not explicitly included in the current IED framework since hydrogen production on an industrial scale was almost exclusively based on steam methane reforming. This raised a question for current electrolyser developers and Member State authorities: should they group the electrolyser developments with all other types of hydrogen production and condemn them to lengthy and expensive permitting procedures, even when electrolysers do not have industrial emissions? This legal grey area resulted in differing implementation in various Member States, causing an uneven playing field in the EU for electrolyser developers. Although the Commission's proposal did not address this issue, both the Council and the European Parliament recognised the problem. They attempted to address it in their respective legislative positions in the first half of 2023. The Council proposed an exemption from having to comply with the IED's excessive permitting and reporting obligations for electrolysers with a daily production capacity below 60 tonnes. The Parliament chose a similar approach, exempting electrolyser plants under 50 MW electricity input. Although these thresholds are far apart, the recognition of the issue is very welcome by the hydrogen industry.

The proposal is still in negotiations, with the adoption expected in 2024.

National Hydrogen Strategies

National economic characteristics such as renewable energy availability, critical raw materials and industry sector structure, together with political ambition are the key determinants shaping the content of national hydrogen strategies.

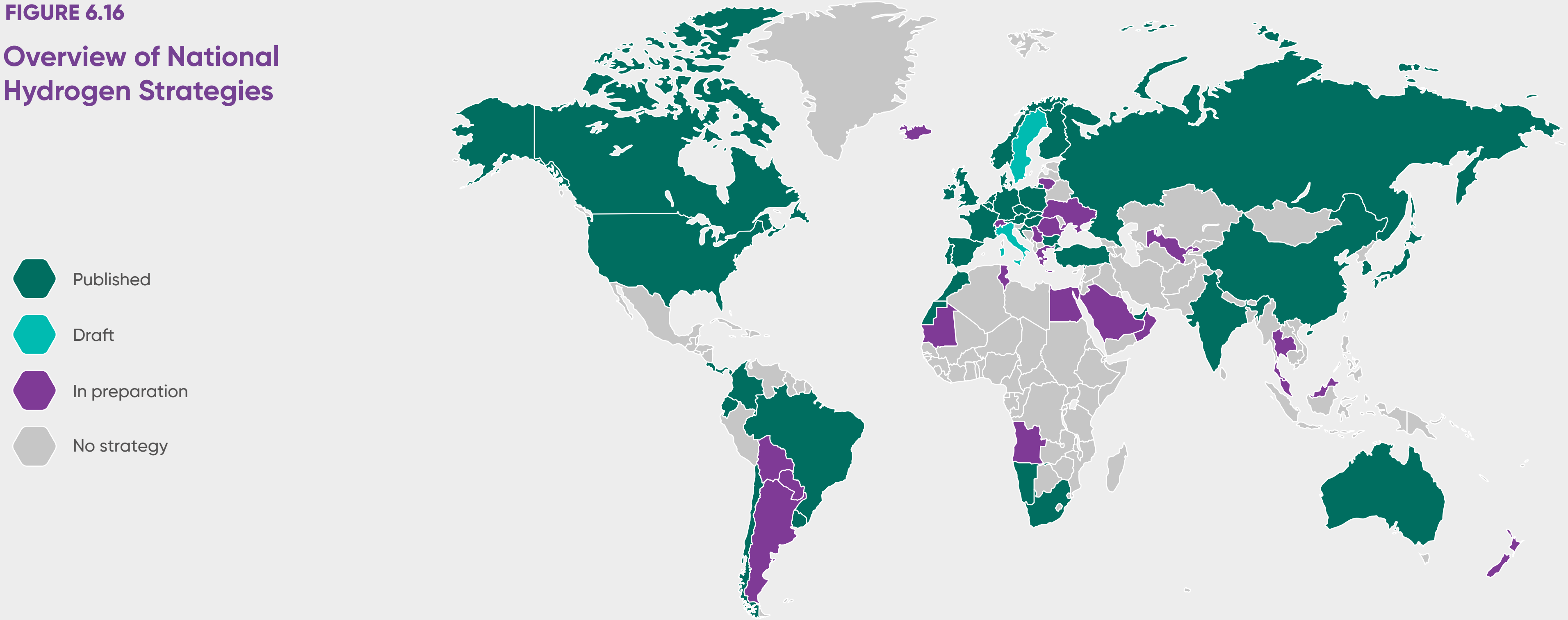
Since September 2022, globally, 16 countries have adopted national policy documents for the hydrogen sector, raising the number of hydrogen strategies adopted to 43. Looking at **Figure 6.16**, hydrogen has become a global phenomenon. In almost every region except for Central Africa, countries have adopted or are preparing their national hydrogen strategies. While Europe and East Asia were first movers, North and South America, as well as south of Africa, are emerging as important regions for hydrogen.

An overview of these national policy documents shows that specific country characteristics remain the key determinant for national policies on hydrogen. As an example, the high renewable production potential in South Africa will enable the decarbonisation of transport, energy-intensive industry, and exports of hydrogen. At the same time, the locally available critical raw materials will enable the development of local components manufacturing. In neighbouring Namibia, the renewable energy potential will be used for green hydrogen derivatives and hot-briquetted iron oriented towards exports. As a result, different localised hydrogen markets will likely develop before the emergence of a fully global hydrogen market. For the EU, which is looking to achieve its REPowerEU target of 10 Mt of imported renewable hydrogen, it means that it will face competition even within localised hydrogen markets. The first mover advantage and the regulatory clarity, thanks to the adoption of the majority of the files under the Fit for 55 package, are enablers of success. However, willingness to pay for hydrogen and the support for reducing transport costs will be key factors in determining whether the targets can be achieved.

One of the most important strategies to be published in 2023 was the US National Clean Hydrogen Strategy and Roadmap, adopted in June. The Strategy has three key priorities: targeting strategic uses of clean hydrogen (i.e., in industry, heavy-duty mobility and long-term energy storage); reducing the cost of clean hydrogen and focusing on Regional

FIGURE 6.16

Overview of National Hydrogen Strategies



Source: Hydrogen Europe. Data as of 07/08/2023.

Clean Hydrogen Hubs. In line with the Inflation Reduction Act, the Strategy focuses on clean hydrogen, defined as hydrogen produced irrespective of the production pathway, with carbon intensity equal to or less than 2kgCO2eq/kgH2 at the production site. It puts forward ambitious goals for hydrogen production, reduction of costs (reducing the cost of hydrogen to USD 1 per 1 kg of clean hydrogen in 1 decade) and establishing six to ten Clean Hydrogen Hubs by 2028, with a total backing of USD 9.5 billion to achieve them. This way, the US is a key player in the global hydrogen market. That said, the success of the US Hydrogen Strategy will be determined by how national policymakers tackle the issue of additionality, temporal and geographical correlations, and the selection of the locations for the regional hydrogen hubs.

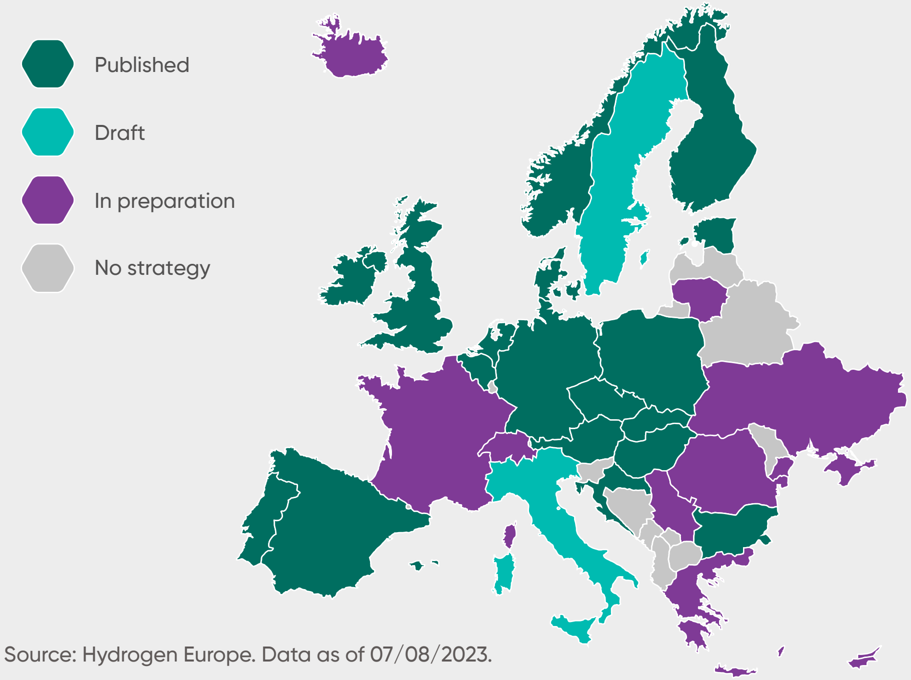
In the US and globally, regional hydrogen ecosystems (also called valleys, hubs, and clusters) are becoming a fundamental building block for developing national hydrogen economies. Regional hydrogen ecosystems are a relevant feature in the US, Brazilian, Namibian, South African and draft Israeli hydrogen strategies, to name a few. According to Mission Innovation, there are 83 hydrogen valleys already across the world, of which 55 are in Europe. For the European Union, the upcoming Hydrogen Valleys Roadmap (due in Q4 2023) represents a unique opportunity to outline the vision and actions to develop hydrogen valleys, both concerning achieving the target of 10 Mt of renewable hydrogen production internally and in the context of 10 Mt of renewable hydrogen imports target and the role of local hydrogen ecosystems in the development of a global hydrogen market.

In Europe, there are now 20 countries with national hydrogen strategies or roadmaps. Since September 2022, four new strategies have been adopted: Bulgaria, Estonia, Finland, and Ireland. By the end of 2023, four additional strategies are expected: those of Lithuania, Cyprus, Romania, and Greece. In the same period, Belgium, the United Kingdom and most recently, Germany have updated theirs, while France is preparing its strategy update to be published in December 2023.

Several trends have been identified in the recently adopted strategies. Firstly, strategies are moving away from quantitative indicators such as targets and goals in favour of more detailed qualitative descriptions of the actions to be undertaken by governments. An example is the strategies of Bulgaria, Estonia, and Finland, which contain no quantitative targets. The German updated strategy also reiterates the previously defined 10 GW electrolysis capacity from the ruling coalition's agreement, as opposed to the 2020 strategy, which contained electrolysis capacity targets for 2025, 2030 and 2040. Secondly, in terms of infrastructure development, most strategies foresee that hydrogen will be firstly produced at the site of consumption or transported via compressed tanks. In contrast, infrastructure development will start with connections between production and consumption and only later develop into national grids (2030 – 2040), which aligns with the European Hydrogen Backbone vision. The exception regarding this case is Germany, where the strategy significantly emphasises hydrogen infrastructure development before 2028. Thirdly, strategies remain technologically neutral by not excluding any end-use for hydrogen, however, governmental support is prioritised on hydrogen applications in hard-to-decarbonise sectors, such as industry, heavy-duty mobility, and energy production.

FIGURE 6.17

Overview of hydrogen strategies in Europe



Source: Hydrogen Europe. Data as of 07/08/2023.

Germany - Update of the National Hydrogen Strategy (NWS 2023)

The update to the 2020 Hydrogen Strategy was adopted on 26th July 2023. The updated Strategy aims to accelerate the hydrogen market ramp-up, ensure sufficient quantities of hydrogen and derivatives, establish an efficient infrastructure, establish hydrogen applications, make Germany the leading provider of hydrogen technologies by 2030 and create suitable framework conditions. Two principles are introduced in the document: 1) direct use of electricity should be prioritised whenever possible to benefit from the overall system efficiency, and 2) direct financial support will be limited to only green hydrogen production, although other production pathways will also be used, such as low-carbon hydrogen production.

Four fields of action are defined with short, medium, and long-term measures. The first field, "Ensuring availability of sufficient hydrogen", focuses on domestic production and imports. For domestic production, the Coalition Agreement target of 10 GW of electrolysis by 2030 is restated, but the significant emphasis is put on system-friendly electrolysis. In other words, most electrolysers to be installed by 2030 must be located and operated in a way that serves the system. The criteria for implementing this principle are under

TABLE 6.1

Comparison between targets and estimates in the 2020 and the 2023 German Hydrogen Strategy

	2020 NHS	2023 Update
Electrolyser capacity 2030	5 GW	10 GW
Hydrogen demand 2030	90-110 TWh	95-130 TWh
H2 Pipelines 2028		1,800 km
H2 demand for industry 2050	102 TWh (refining & steel only)	290-440 TWh

Source: Hydrogen Europe.

development. It is considered that imports will cover the greater part of national demand. Until 2030, hydrogen imports will be mostly ship-based in the form of ammonia. Afterwards, imports of green methane, synthetic methanol, LOHC and liquid hydrogen will play a more important role. The expansion of pipeline-based imports of green hydrogen from Europe and the neighbouring countries will increase after 2030.

The second field – "Expanding hydrogen infrastructure"- concerns establishing efficient infrastructure. The aim is to have 1,800 km of new or repurposed hydrogen pipelines by 2027-2028. To achieve this, the Government will continue developing the hydrogen network plan (see Chapter 4) and is looking into financing models via network charges to avoid frontloading the initial users of the network. On the imports' infrastructure side, partnerships with neighbouring countries are to be developed to enable the European Hydrogen Backbone by 2030. All new LNG facilities will be hydrogen-ready to enable later conversion to hydrogen or derivatives.

Moving to end-uses in the third field of action, "Establishing hydrogen applications", the guiding principle is that hydrogen use should not be limited to certain applications. However, the Strategy also notes that increasing the demand for hydrogen will increase its price. This will make the decarbonisation of users with no alternatives costlier. As such, support will focus on end-uses for which it is necessary or without alternatives. Singled out sectors for the application of hydrogen include steel production, chemical industry, aviation and maritime (through PtL) and development of HRS infrastructure according to AFIR. For the energy sector, the main goal is to achieve a climate-neutral electricity system, with the already announced initiatives to build 4.4 GW of hydrogen sprinter plants and 4.4 GW of renewable hydrogen hybrid power plants. Requirements for "system-compatible" electrolysis will also be developed to guide electrolyser locations and modes of operation that are compatible with the system. For heating, hydrogen is not expected to have a major role, and the economic viability of the conversion of natural gas distribution grids must be examined, which is to be done through municipal heating plans.

The last field of action – "Creating good framework conditions", aims to establish an effective framework for the hydrogen market ramp-up. The key priority is to simplify the regulatory framework across the value chain. Work will also be carried out to establish uniform sustainability standards and certification systems, especially in the European and international contexts. Lastly, priorities in terms of Education, Research and Development are also set in the strategy with a view making Germany a leading exporter of hydrogen technologies.

The strategy generally does not commit any specific funding towards the sector, contrary to its ambitious predecessor, which committed EUR 11 billion in non-exclusive funds. For the most part, it sets guiding principles for Governmental action, yet a significant part of the measures following those guiding principles are already ongoing initiatives. Lastly, the strategy leaves the details on important questions to a multitude of documents yet to be adopted, namely: Hydrogen Import Strategy, Carbon Management Strategy, National Ports strategy, System Integration Strategy, Master plan for hydrogen and fuel cells in transport, National Action Plan for Climate Friendly Shipping and Hydrogen Technology Innovation Roadmap.

Ireland – National Hydrogen Strategy

The Irish strategy was adopted in July 2023. It has three strategic goals: decarbonising the economy, where renewable hydrogen can replace fossil fuels in hard-to-decarbonise sectors; enhancing energy security, where green hydrogen from indigenous offshore wind provides a significant opportunity for Ireland to reduce its energy import dependence; and creating industrial and export opportunities, where again the offshore wind potential can enable Ireland to be an exporter of hydrogen for Europe, while also creating high skilled jobs in the renewable energy sector. As there is no existing hydrogen industry to be decarbonised, such will need to be developed, and it will be based on offshore wind.

Before 2030, it is foreseen that electrolysers will be produced from grid connections, using surplus renewable energy. The strategy reinstates the existing target of 2GW of offshore wind to produce renewable hydrogen by 2030. It also strongly emphasises hydrogen safety. A Safety roadmap and appropriate regulatory framework will be developed across the value chain. The certification issue is high on the list of priorities, to integrate guarantees of origin for hydrogen with those for renewable electricity to avoid double-counting. To better understand the business cases for hydrogen, deployment projects will be supported to identify regulatory, permitting and supply-chain issues.

Hydrogen deployment will focus on hard-to-decarbonise sectors where energy efficiency and direct electrification are not feasible. As such, heavy-duty transport is expected to be one of the first end-use sectors, followed by industry and flexible power generation. In mobility, hydrogen is expected to have a significant role in freight and intercity transport, with aviation and maritime to develop at a later stage. In industry, hydrogen will be in medium and high-heat applications. Should a market for green ammonia develop favourably, the possibility of producing such might be developed. Lastly, in the energy sector, hydrogen is expected to enable flexible power generation through the decarbonisation of conventional generation and by enabling energy storage.

In relation to green hydrogen exports, the first step will be to assess the competitiveness of green hydrogen produced in Ireland compared to international benchmarks and the benefits of hydrogen trade. The Government has already partnered with Germany, the UK, and Northern Ireland. Possible export routes are the interconnectors with the UK, through which hydrogen can be directed towards Europe.

FIGURE 6.18

Estimated hydrogen demand for Ireland for 2050

IRELAND HYDROGEN STRATEGY	
Total Estimated Hydrogen Demand	19.8 - 74.6 TWh
Flexible power generation or Integrated Energy Parks for Large Energy Users	3.6 - 13.3 TWh
Commercial and Residential	0 - 1.5 TWh
Industry and Processing	0 - 14.9 TWh
Road and Rail Transport	1 - 9.3 TWh
Aviation	13 - 26 TWh
Maritime	2.2 - 2.6 TWh
Other Potential Non-Energy Uses	0 - 7 TWh

Source: Ireland National Hydrogen Strategy 2023.

Hydrogen Certification and Standards

Hydrogen certification and standards are unclear, complex, or under development posing challenges for production and consumption project developers.

The discourse on hydrogen certification and standards is marked by a complex landscape that poses challenges for both producers and consumers (**Figure 6.19**). That is why it is crucial to highlight the importance of digitalisation and highlight the crucial role of incorporating automation tools into certification practices. These not only automate and simplify processes but also support different sustainability frameworks and carbon accounting methodologies, ensuring that hydrogen markets are sustainable and adhere to global rules and regulations, ensuring safety, reliability and trust among consumers and stakeholders alike. This strategic combination of standardisation, quality infrastructure and digitisation will be key to managing the complexities and maximising the potential of the hydrogen economy.

However, there are many challenges to establishing green hydrogen and its derivatives as a sustainable energy carrier. One glaring issue is the global inconsistency of certification schemes, which hampers cross-border hydrogen trade and regulation. Given the developing nature of the industry, standards and regulations are still evolving, creating a certification paradox where operations and certification are intertwined in a cyclical dilemma. Different methodologies across regions and organisations lead to inconsistencies in hydrogen certification, while life cycle gaps, particularly in stages such as transport, provide an incomplete emissions picture. Regulatory ambiguity, exemplified by regulations such as the EU's RFNBO and the US's 45Q, hampers project development. At the same time, the additionality puzzle and confusion over scope and thresholds lead to debate and confusion over what qualifies as 'low carbon' or 'renewable'. Sectoral hurdles, investor reluctance due to prevailing ambiguity, and a race against time to address these challenges before key events such as COP28 further complicate the path to a green hydrogen economy. Addressing these challenges will require a harmonised, global approach to standardisation and regulation to ensure consistency, clarity and comprehensive coverage across the entire hydrogen production and use lifecycle.

LACK OF STANDARDISATION

One of the most outstanding issues is the absence of a unified certification scheme. Given the industry's embryonic state, it is perhaps unsurprising that certification standards are underdeveloped. However, this lack of standardisation complicates cross-border trade and hampers the growth of a global hydrogen market.

COMPLEXITY OF CERTIFICATION LANDSCAPE

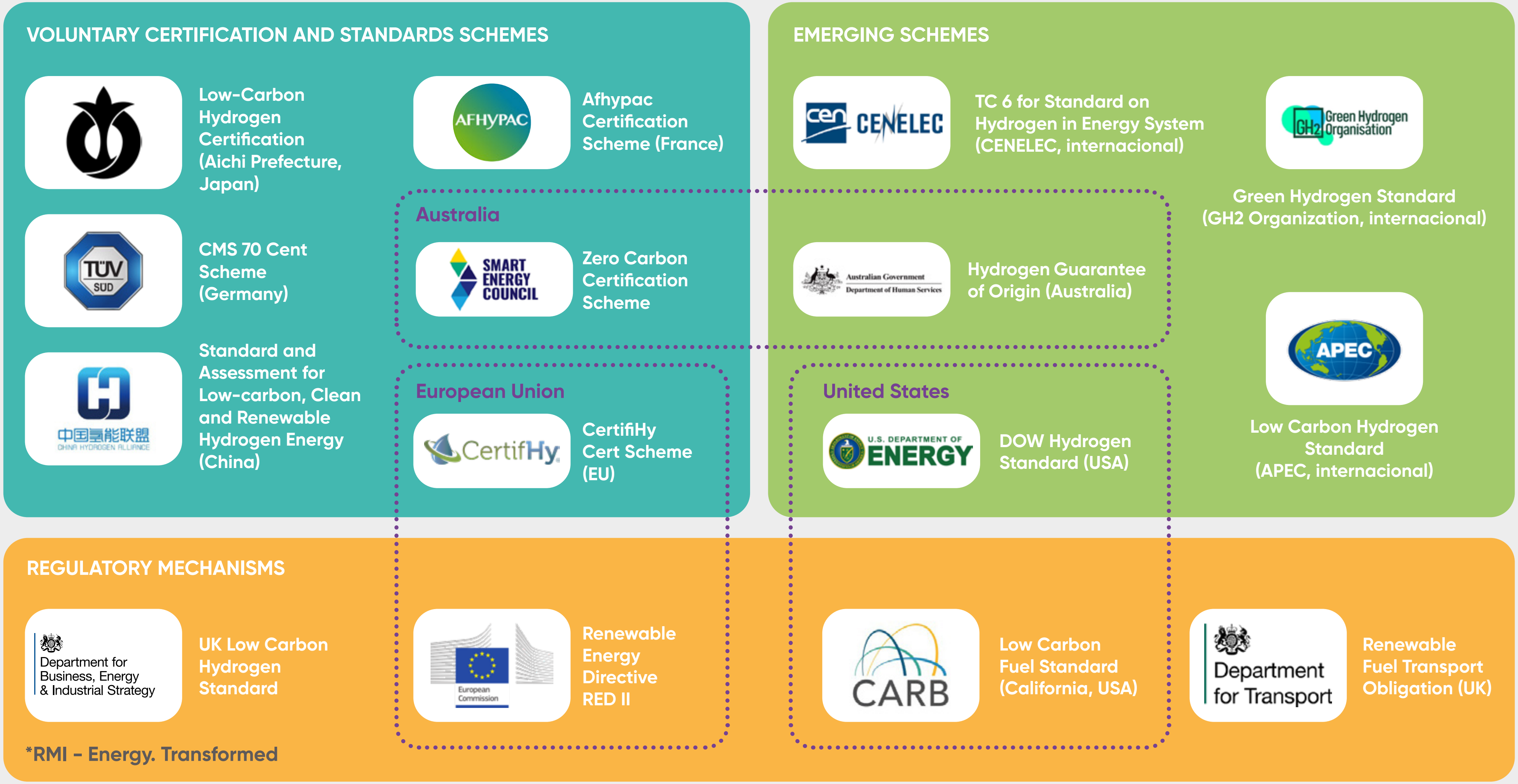
The certification landscape is characterised by a plethora of both voluntary and mandatory schemes, each with its own set of criteria and methodologies. This complexity makes it difficult for stakeholders to navigate the certification process, slowing project development and market entry.

LIFECYCLE ANALYSIS GAPS

Current certification schemes predominantly focus on emissions at the point of production, often neglecting a complete lifecycle analysis. This omission is problematic, especially for projects that aim to export hydrogen across borders. For instance, a project in Brazil aiming to export to Europe would need to account for transportation emissions to qualify as green hydrogen under European standards, creating a chicken-and-egg dilemma for project developers.

FIGURE 6.19

Global "Zoo" of Standards, Schemes and Regulations



Source: Hydrogen Europe based on IRENA.

Proposed Solutions

There are several innovative solutions to streamline the hydrogen industry's approach to climate mitigation and facilitate global trade. Among the solutions proposed are:

1 "COMMON DENOMINATOR" APPROACH:

Recognizing the diverse standards and regulations across different regions, Hydrogen Europe proposed adopting a "Common Denominator" approach. This strategy is designed to bridge the gaps between various regulatory frameworks, making it easier for stakeholders to navigate the complex landscape of hydrogen production and trade on a global scale. Necessary information can be transposed via a Digital Product Passport (DPP).

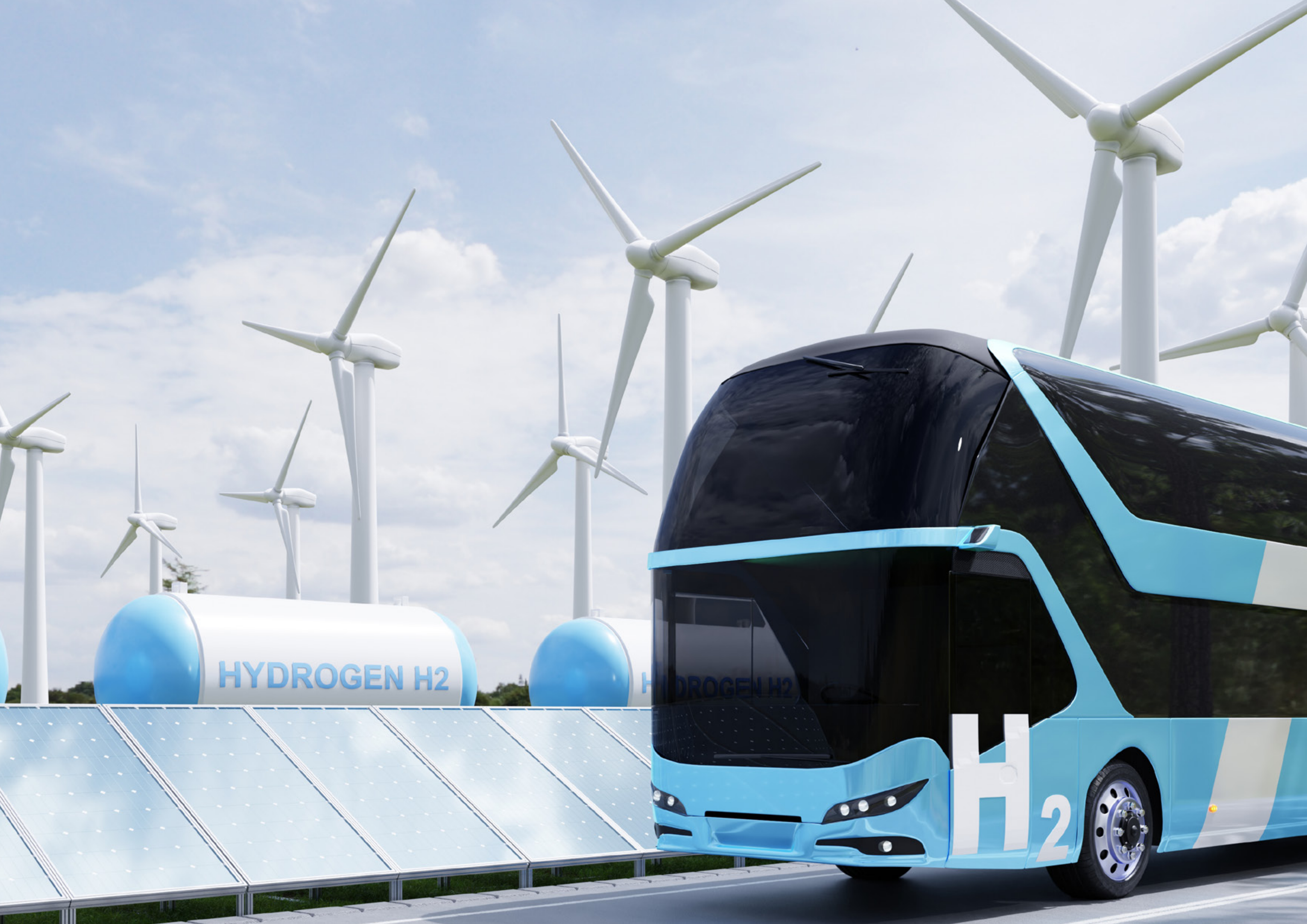
2 DIGITAL PRODUCT PASSPORT (DPP):

To enhance transparency and ensure that all stakeholders have access to accurate and up-to-date information, Hydrogen Europe introduced the concept of a Digital Product Passport (DPP) for hydrogen. This digital tool will provide a comprehensive overview of a hydrogen product's lifecycle, from production to end-use, ensuring that all involved parties can make informed decisions based on reliable data. It fosters interoperability and data exchange while making traceability and transparency key.

Additionality, in a collaborative effort with the H2Global Foundation, Hydrogen Europe presented a detailed vision of the future of hydrogen certification in the joint paper on standardizing hydrogen certification. The joint paper, titled "Standardizing Hydrogen Certification: Enhance Traceability, Transparency, and Market Access"[1] delves into the potential of a digital-driven approach to automated certification. The paper emphasizes the importance of traceability and transparency in the hydrogen market and outlines strategies to ensure that hydrogen products meet the highest quality and sustainability standards.

These proposed solutions underscore Hydrogen Europe's commitment to fostering collaboration, promoting transparency, and driving innovation in the hydrogen industry. By adopting these strategies, we aim to pave the way for a more sustainable and efficient hydrogen market that benefits all stakeholders.

1 / https://hydrogeneurope.eu/wp-content/uploads/2023/09/H2Global-Stiftung-Policy-Brief-05_2023-EN.pdf


HYDROGEN H2
H2

07

Funding and financing ecosystem

The clean hydrogen sector still requires significant public support and incentives to mitigate risks, attract the whole private finance value chain and unlock the sector's economic and decarbonisation potential.

- USD 6 to 30 trillion will need to be invested in the global clean hydrogen economy by 2050. In Europe, EUR 1.2 to 2.6 trillion must be mobilised, and a substantial funding gap remains.

- Equity investing is dominant in the sector. Lenders are still not funding projects through non-recourse financing, although they expect hydrogen to be a significant part of their portfolio by 2030.

- To fully unlock the sector's potential, public sector support and the timely implementation of innovative market-making instruments will be imperative to mitigate risk and attract the whole private finance value chain.

Investment needs in Europe

USD 6 to 30 trillion will be needed to be invested in the clean and renewable hydrogen economy worldwide to reach global decarbonisation goals.

EUR 1.2 to 2.6 trillion will have to be deployed in Europe, equivalent to EUR 50 to 100 billion of yearly investments until 2050, with higher investments through the 2030s.

USD 100 billion of cumulative funding by 2030 announced in Europe towards hydrogen, covering only between 11 to 20% of the funding needed.

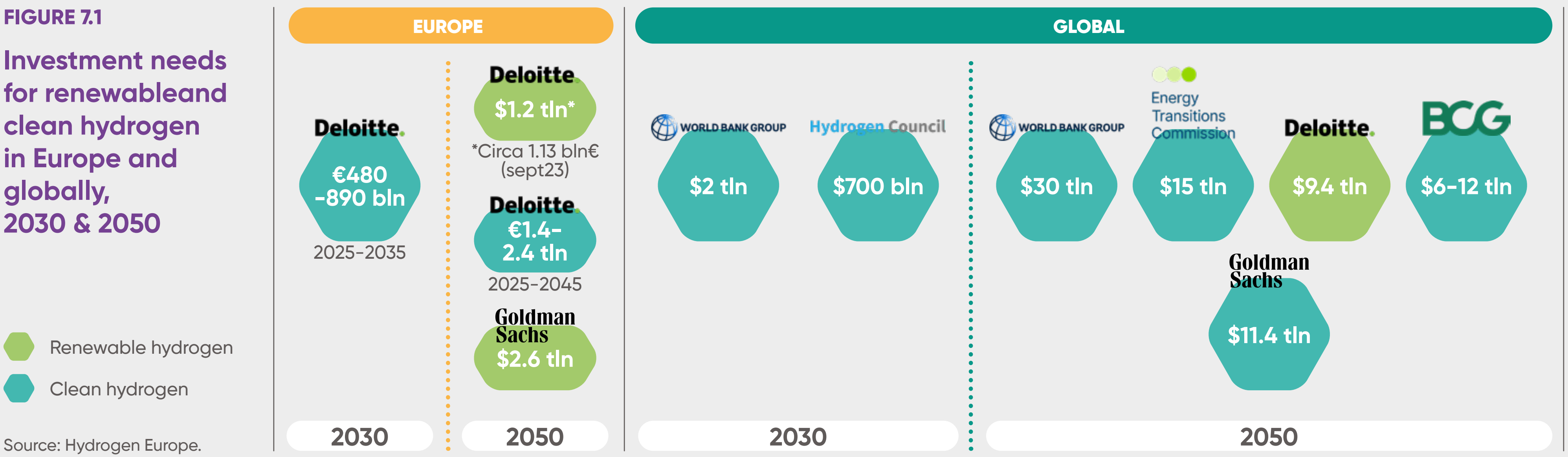
Meeting the investment needs of Europe's developing hydrogen sector is critical for the region's transition to a sustainable and low-carbon energy landscape. Leading stakeholders and consulting companies have been working in the last couple of years to try to assess the hydrogen market's size and the associated opportunity with various approaches and results. The exercise is quite complex due to the divergences in the scoping of the market, the underlying definitions, and standards, and the difficulty to forecast the development of new usages.

According to the most prominent studies, the global investment requirements by 2050 range from USD 6 to 30 trillion globally, with Europe's market accounting between EUR 1.4 to 2.4 trillion (**Figure 7.1**). To put this into perspective, this would mean that Europe needs an annual investment ranging from EUR 50 to 100 billion until 2050. On top of this, with the recognition that the hydrogen industry operates on an extended investment cycle, the biggest spending should occur during the period between 2025 and 2030. Projections suggest a potential peak in global investment needs in the late 2030s, reaching as high as USD 800 billion per year.

In the meantime, BNEF assesses the cumulative announced public funding dedicated to the sector to be USD 100 billion in Europe in 2023 (including EU Member States' support), while the World Bank is even more conservative with an identified USD 100 billion in subsidies identified for OECD countries and China. If we consider these numbers on currently available subsidies and the results of the studies presented in **Figure 7.1**, this amounts to approximately 14% of the EU 2030 investment[1] and 5% of global needs. The funding gap is still huge, and until the market is more mature and competitiveness against fossil fuels projects increases, debt and project finance will not be able to take their place fully.

FIGURE 7.1

Investment needs for renewableand clean hydrogen in Europe and globally, 2030 & 2050



Source: Hydrogen Europe.

1 / Under Deloitte's assessment of investment needs between EUR 480 billion - 890 billion by 2030, an average of EUR 700 billion is taken as a reference for Europe. Under the World Bank assumption of a need of 2 trillion global investment by 2030, we assume that subsidies for China and OECD countries are a good proxy for global subsidies.

International financing and trade

EU and MS development finance institutions have committed to mobilising around EUR 300 billion globally, of which around EUR 200 billion is to support Africa and Latin America's green energy transition through financing and de-risking hydrogen projects.

Substantial support for hydrogen uptake in developing countries is also coming from multilateral banks, financial institutions, and organizations such as the World Bank, IFC and UNIDO.

Global Gateway

Global Gateway is the EU strategy to support smart, clean, and secure investments in quality infrastructure worldwide. Via the Team Europe approach, which brings together the Commission, the European Investment Bank (EIB), the European Bank for Reconstruction and Development (EBRD), EU Member States and their financial and development institutions, it aims to mobilise up to EUR 300 billion in public-private investments by 2027.

Africa is a key focus, with the Strategy aiming to mobilise up to EUR 150 billion under the EU-Africa Investment Package. Its Africa-EU Green Energy Initiative announced in November 2022 will foster the region's renewable hydrogen potential by supporting massive deployment of clean hydrogen production, targeting at least 40 GW_{el} of electrolyser capacity and 300 GW_{el} of renewable energy by 2030. The Strategy also commits EUR 45 billion to the Latin American and Caribbean region (LAC). It supports hydrogen projects in third countries with concessional finance, guarantees to facilitate risk-sharing with local banks, direct financing through debt or equity, and quasi-equity instruments to share investment risks. Strategic orientations are discussed and developed in the Global Gateway Business Advisory Group (BAG), an informal expert group of which Hydrogen Europe is a member, supporting the Commission in developing innovative financing tools and access to EU instruments to fund projects on the ground.

Multilateral Development Banks and International Financial Institutions

The increased international attention to hydrogen and the potential for developing countries, often benefitting from a large share of renewables in their energy mix, to produce at a competitive cost and export has brought multilateral development banks (MDBs) and international financial institutions (IFIs) to try reducing regulatory offtake and operational risks of hydrogen projects.

Announced at COP27, the World Bank (WB) Hydrogen for Development Partnership (H4D) aims to enable third countries and project promoters to access concessional finance as well as technical assistance on projects. In late June 2023, the WB provided a USD 150 million loan for renewable hydrogen projects in Chile via its Green Hydrogen Facility and a USD 1.5 billion loan to India.

The International Finance Corporation (IFC), the private sector financial arm of the WB, is active across the renewable hydrogen value chain both at the pre-investment and investment stage. IFC provides investments via equity, senior and subordinated loans, and blended instruments with institutional partners and mobilises capital via bond issuance.

Hydrogen Europe has been a partner since June 2023 with the United Nations Industrial Development Organization (UNIDO), with which we works on capacity-building, promotion of hydrogen technologies and project development in third countries. UNIDO, supported by Austria, Germany, Italy, and China launched the Global Programme for Hydrogen in Industry in 2021. It is a multi-donor program financing renewable hydrogen in developing countries. Via its Global Environmental Facility (GEF), which received a pledge of EUR 4.9 billion (USD 5.33 billion) from 29 donor countries in June 2022, it will support hydrogen manufacturing in the MENA region, with new operations expected to start in early 2024.

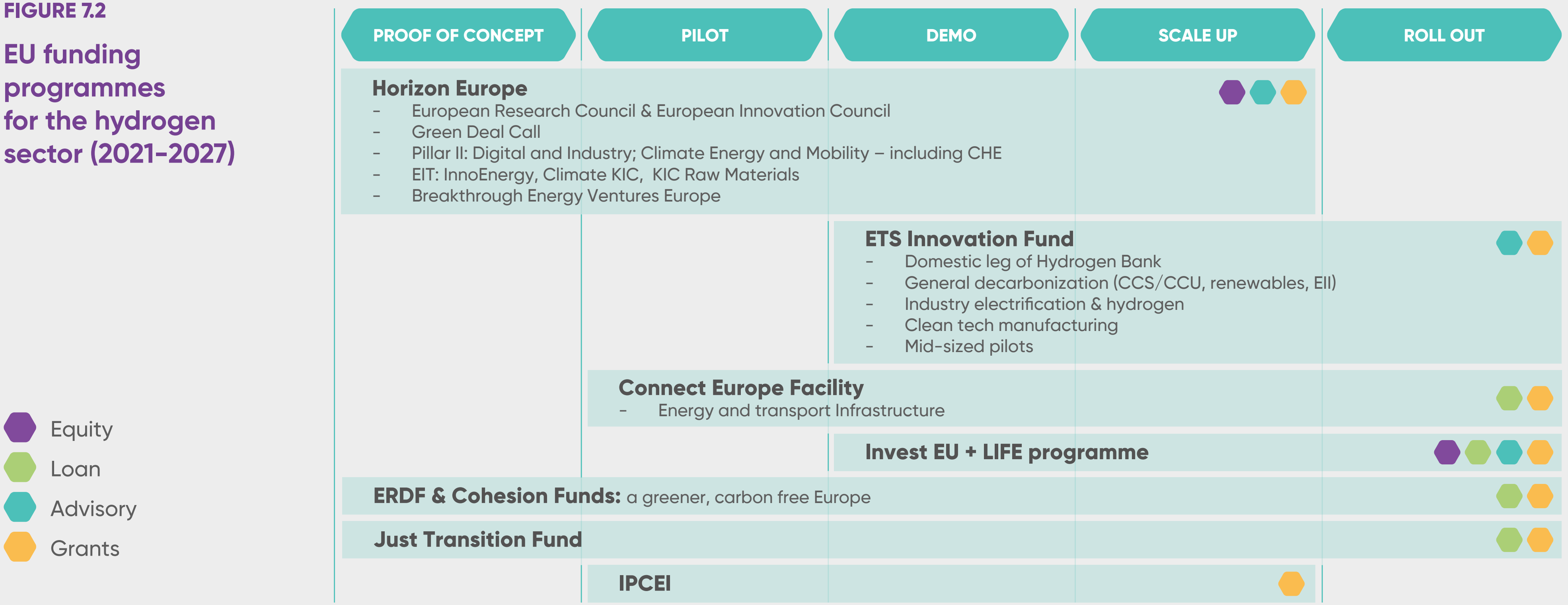
EU funding opportunities

The EU funding ecosystem for hydrogen is complex, with multiple programs dedicated to different sectors of the value chain.

An overview of the different EU funding programs in support of hydrogen and related technologies can be found in **Figure 7.2**. 2023 Has also seen the launch of market-making mechanisms and other support schemes launched at the EU level. Such as the European Hydrogen Bank and its pilot auction under the Innovation Fund, coupled with announcements at the Member State level and EU-led initiatives at the international level. This edition of the Clean Hydrogen Monitor will cover all of the aforementioned instruments.

FIGURE 7.2

EU funding programmes for the hydrogen sector (2021-2027)

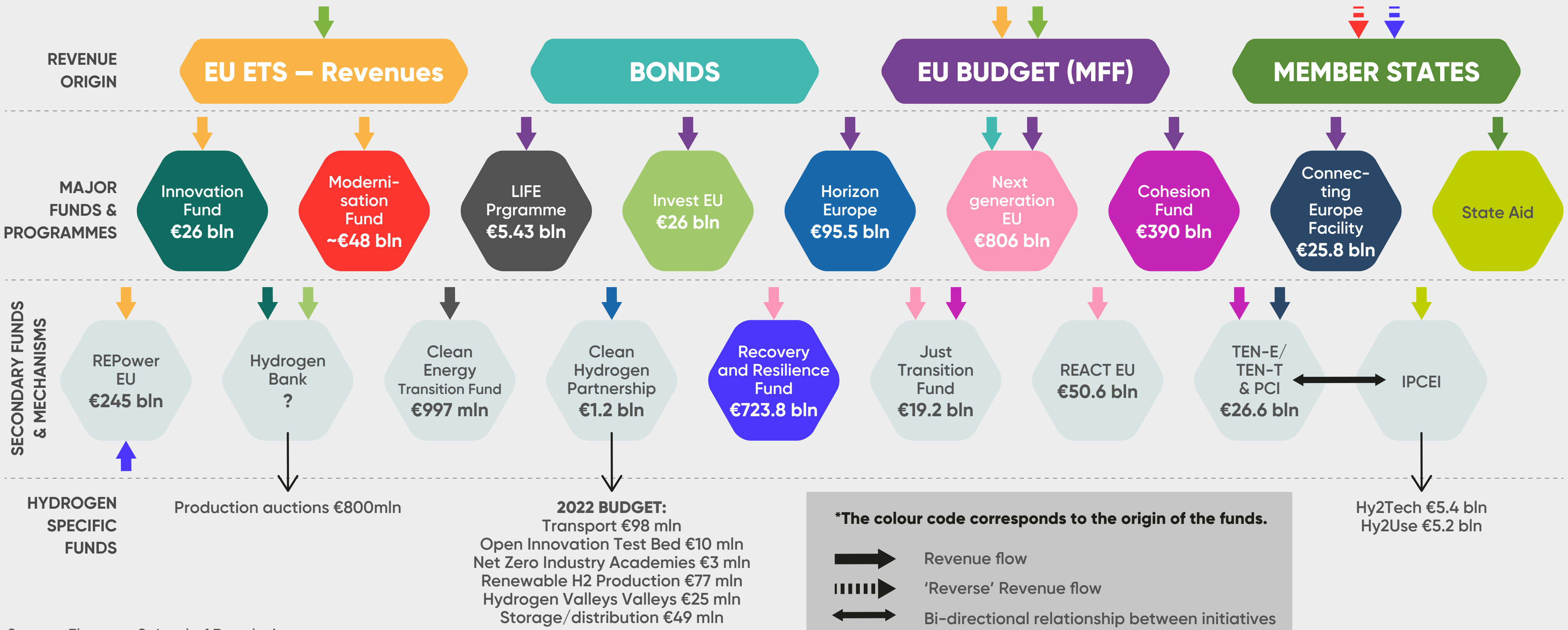


Source: Hydrogen Europe.

The structure presented in **Figure 7.3** follows a top-down logic to trace EU funding and private financing through the different macro-level mechanisms dedicated to hydrogen and related technologies, with respective budgets. The EU funding ecosystem is highly complex, with multiple instruments covering different sectors of the hydrogen value chain, some of these sharing a common budget pool. The EU's main funding sources come primarily from the EU budget (MFF) and the ETS. Funding from the MFF is channelled into various programmes which support different sectors of the hydrogen value chain, such as Horizon Europe, the Connecting Europe Facility (CEF), InvestEU, LIFE and the Cohesion Funds. ETS allowances are used to fund the Innovation Fund and Modernization Fund.

FIGURE 7.3

Overview of EU and national funding mechanisms

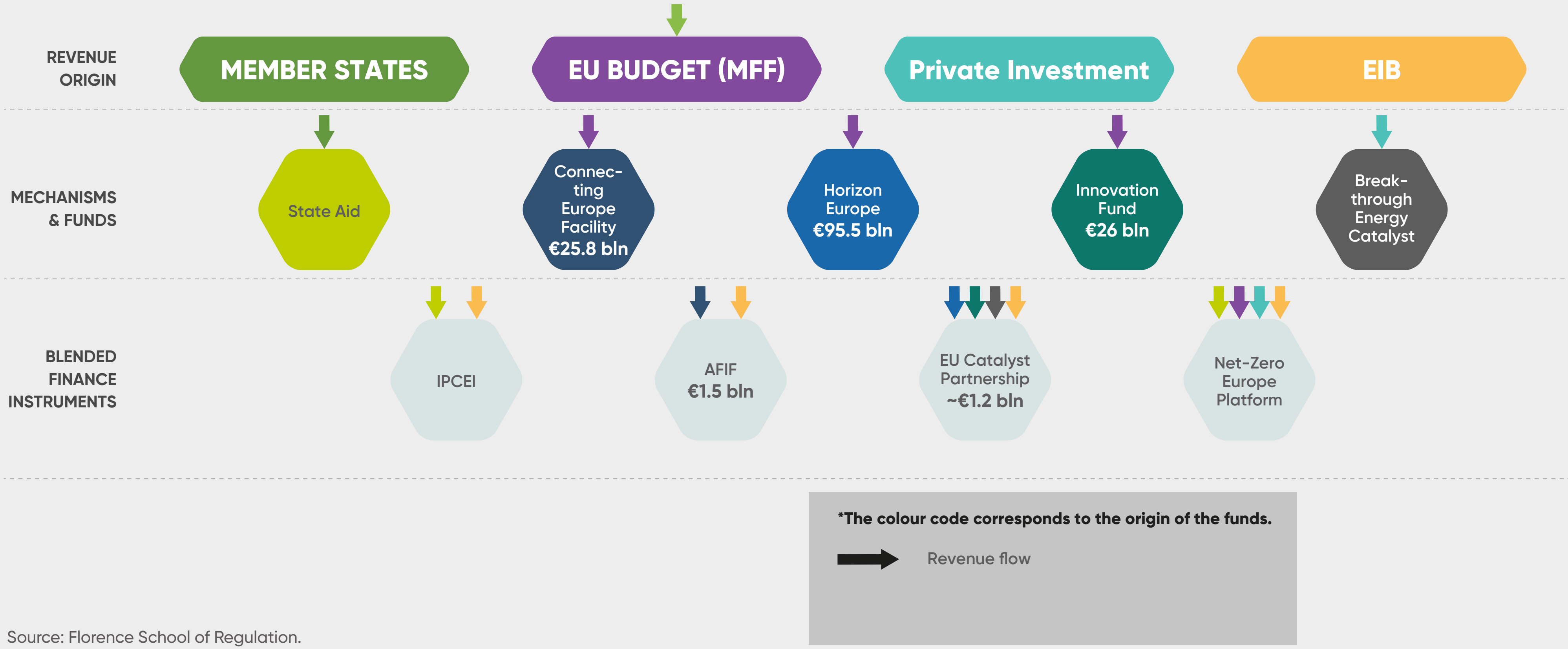


Source: Florence School of Regulation.

EU institutions also use investment vehicles to partner with major investors, one example being the Breakthrough Energy Catalyst. Which partners with the Commission and the EIB in providing blended finance to key clean technologies including green hydrogen. There is also a significant role for the EIB and others to contribute to strategic infrastructure, particularly for projects that are earmarked as strategically important within Europe's IPCEI framework. A mapping of these blending mechanisms is provided in **Figure 7.4**.

FIGURE 7.4

Overview of blended financing mechanisms



Source: Florence School of Regulation.

EU funding programs

As mentioned, funding from the MFF is channelled to different EU funding programs with different budgets, each one dedicated to different hydrogen applications. An overview of all EU funds targeting hydrogen and related technologies, with indicative amounts dedicated to the sector in 2023 compared to their original budget capacity, can be found in **Figure 7.5**.

FIGURE 7.5

Overview EU funding instruments dedicated to hydrogen and related technologies as part of the MFF 2021-2027

	Hydrogen Applications	Budget	Climate/clean tech dedicated budget (relevant for H2)	Approximate budget used/committed (2023)	Approximate budget used for H2 (2023)
Horizon Europe (2021-2027) **Among which: Clean Hydrogen Partnership (2021-2027)**	R&I projects, testing, demo and validation of H2 technologies, innovation & market deployment, Open Innovation Test Beds for H2 technologies.	€95.5 bln €1.2 bln	€33.4 bln €1.2 bln	€43.2 bln €495 mln	N/A €495 mln
LIFE (2021-2027)	Innovative frameworks & capacity building on H2 technologies.	€5.4 bln	€1.94 bln for climate action	€ 1.82 bln	N/A
ETS Innovation Fund (2020-2030)	Breakthrough H2 technologies, CCUS, ELYS manufacturing, H2 use in applications.	€40 bln* (carbon price of €75/tCO2)	€40 bln	€6.7 bln (3.1 bln signed, 3.6 bln 2023 grant preparation)	€1.19 bln
Breakthrough Catalyst (2022-2027)	Clean Hydrogen, Sustainable Aviation Fuels, Direct Air Capture and Long Duration Storage	€820 mln	€410 mln (clean hydrogen & SAFs streams)	N/A	N/A
CEF – E (2021-2027)	Cross-border H2 transmission & distribution projects, storage, electrolyser.	€5.84 bln	€3.5 bln (60% for climate objectives)	€2.537 bln	Circa 0, to change with eligibility of H2 in 2023 6th PCI list
CEF – T (2021-2027) **Among which: AFIF (2021-2023)**	HRS on TEN-T road and railway networks, dedicated to public transport in urban nodes and to deployment of H2 alternative fuels for TEN-T maritime and inland ports, inland waterways.	€25.81 bln €1.575 bln	€15,49 bln (60% for climate objectives) €1.575 bln	€18.12 bln €920 mln	€232 mln (September 2023) (AFIF, see below) €232 mln (September 2023)
InvestEU	H2 production, HRS & other H2-related infrastructure, storage, H2 technology equipment, supply at commercial scale.	€26 bln of guarantee (backed by €10.46 bln of budget through 40% provisioning rate)	€9.9 bln of guarantee for sustainable infrastructure stream, backed by €3.96 bln budget)	€21.4 bln (backed by €8.5 bln budget)	N/A
ERDF	HRS, H2 transmission & distribution, H2 innovative projects for territorial integration.	€191 bln	€57.3 bln (30% target for entrepreneurship for climate transition)	€ 5.7 bln	N/A
Cohesion Fund	HRS & other H2-related infrastructure on TEN-T networks.	€43 bln	€15.91 bln (37% for entrepreneurship for climate transition)	€1.1 bln	N/A
Modernisation Fund	Production & use of green hydrogen from renewable electricity; assets like green H2 fueled trains/ trucks / cars; high-efficiency hydrogen CHP.	€48 bln (carbon price of €75/tCO2)	€33.6 bln (70% for priority investment, mostly focused on renewable energy and energy efficiency)	€7.5 bln	€372 mln

Source: Hydrogen Europe.

Under the Clean Hydrogen Partnership, nine Hydrogen Valleys have been selected in 2023 with a total funding of EUR 105 million, expected to mobilize five times as many investments. Funding dedicated to the sector under the Partnership will amount to EUR 115 million in 2024.

As the primary funding instrument for research and innovation (R&I) with a budget of EUR 95.5 billion for 2021-2027, Horizon Europe is composed of three pillars - namely Pillar I 'Excellent Science', Pillar II 'Global Challenges and European Industrial Competitiveness' and Pillar III 'Innovative Europe'. Under Pillar II 'Global Challenges and European Industrial Competitiveness', the Commission co-invests a total of EUR 13.1 billion in European Partnerships (European Commission, 2023)[2].

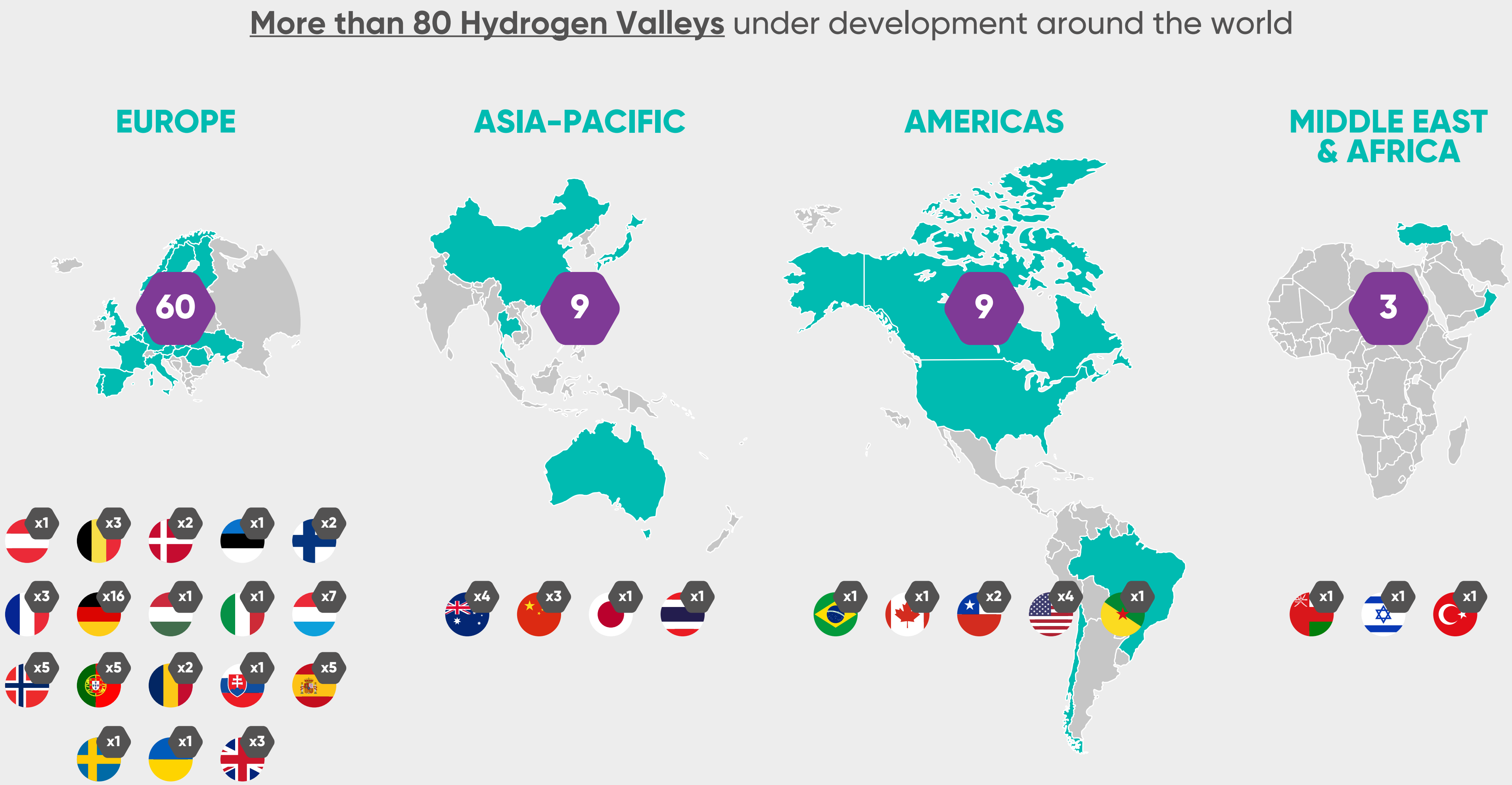
The Clean Hydrogen Joint Undertaking (Clean Hydrogen Partnership or CHP) supports hydrogen R&I to develop the European renewable hydrogen value chain with a budget of EUR 2 billion, provided by the EU and private sector investments respectively. The CHP, whose budget was topped up with EUR 200 million as part of REPowerEU to double the number of Hydrogen Valleys by 2025[3], announced the results of the 2022 call for proposals in January 2023. Nine Hydrogen Valleys[4] were selected with a total funding budget of EUR 105.4 million. The Clean Hydrogen Partnership published its annual call for proposals, the Annual Work Programme 23 (AWP23), in January 2023, it will run until April 2023. The call included 26 topics, from R&D and demonstration projects in hydrogen production, distribution/storage/transmission to end-use applications and overarching subjects, for a total funding budget envelope of EUR 195 million. Projects are expected to start in early 2024, following the signature of Grant Agreements. The call of the following year (AWP24) will likely have a budget around EUR 115 million. Topics are currently under development and are expected to be published in January 2024. Following its call for proposals in 2022, the CHP announced in January 2023 the nine Hydrogen Valleys selected under its 2022 call for proposals. Together they have a total requested funding amounting to EUR 105.4 million, which is expected to mobilise five times that amount in additional investment. As one of the first two planned valleys, the North Adriatic Hydrogen Valley (NAHV) (**Figure 7.7**), a transnational project comprising Slovenia, Croatia and the Italian Region of Friuli Venezia Giulia was approved for implementation in September 2023. NAHV is being developed by a consortium of 37 organisations and is set to feature 17 pilot projects in various locations. With the production of more than 5,000 tonnes of renewable hydrogen per year, this project will target end uses such as steel and cement production and transport. The leading partner in the project, Holding Slovenske Elektrarne (HSE), signed a contract with the CHP which co-founded the project with a EUR 25 million grant for a total budget of EUR 344 million.

The second planned valley is the BalticSeaH2 Project, a cross-border hydrogen valley between southern Finland and Estonia led by the Finnish CLIC Innovation, which kicked off in June 2023 for a duration of five years. The project, which is being developed by a consortium of 40 partners from nine Baltic Sea region countries, will produce hydrogen and derivatives to be either used or sold by different applications such as, among others, the maritime and heavy transport sectors. With a total value of EUR 33 million, of which EUR 25 million comes from the EU, the project will involve 25 demonstration and investment cases, expected to bring up over EUR 4 billion in total investments.

2 / The Clean Hydrogen Partnership is the successor of the Fuel Cells and Hydrogen 2 Joint Undertaking. Its three members are the European Commission, Hydrogen Europe and Hydrogen Europe Research.
3 / Out of the EUR 200 million topped-up by REPowerEU, EUR 60 million were provided in 2023.
4 / The development and mapping of the 88 Hydrogen Valleys within and outside Europe can be tracked in the Mission Innovation Hydrogen Valley Platform.

FIGURE 7.6

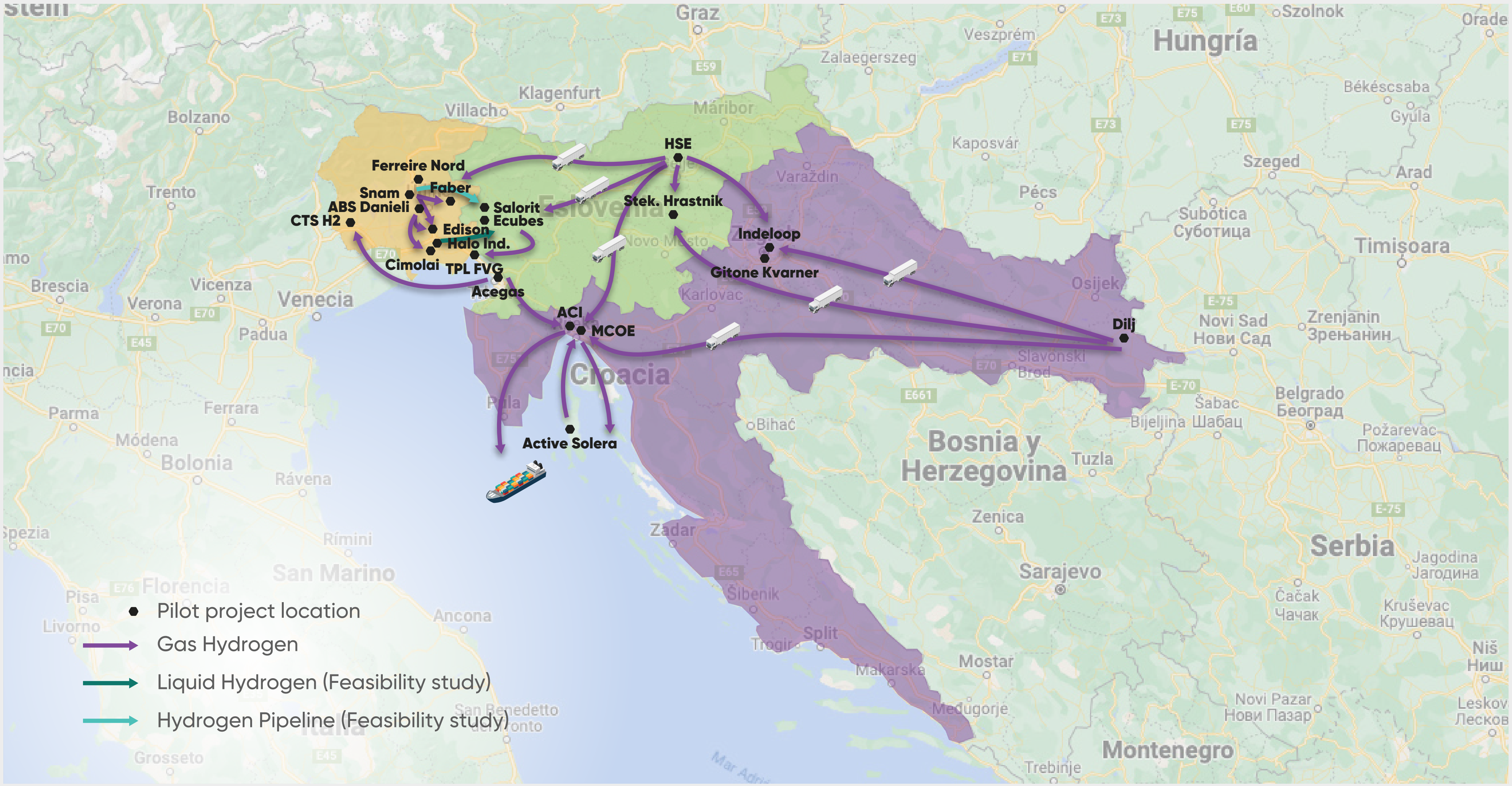
General map of hydrogen valleys in world's regions



Source: https://h2v.eu/

FIGURE 7.7

North Adriatic Hydrogen Valley (NAHV)



Source: HSE.

In 2022 EUR 3.1 billion have been allocated under the Innovation Fund to clean technologies with significant funding dedicated to renewable hydrogen projects.

The Innovation Fund has so far provided more than EUR 1.1 billion to large-scale and small-scale low carbon hydrogen projects, constituting an important funding instrument for the sector.

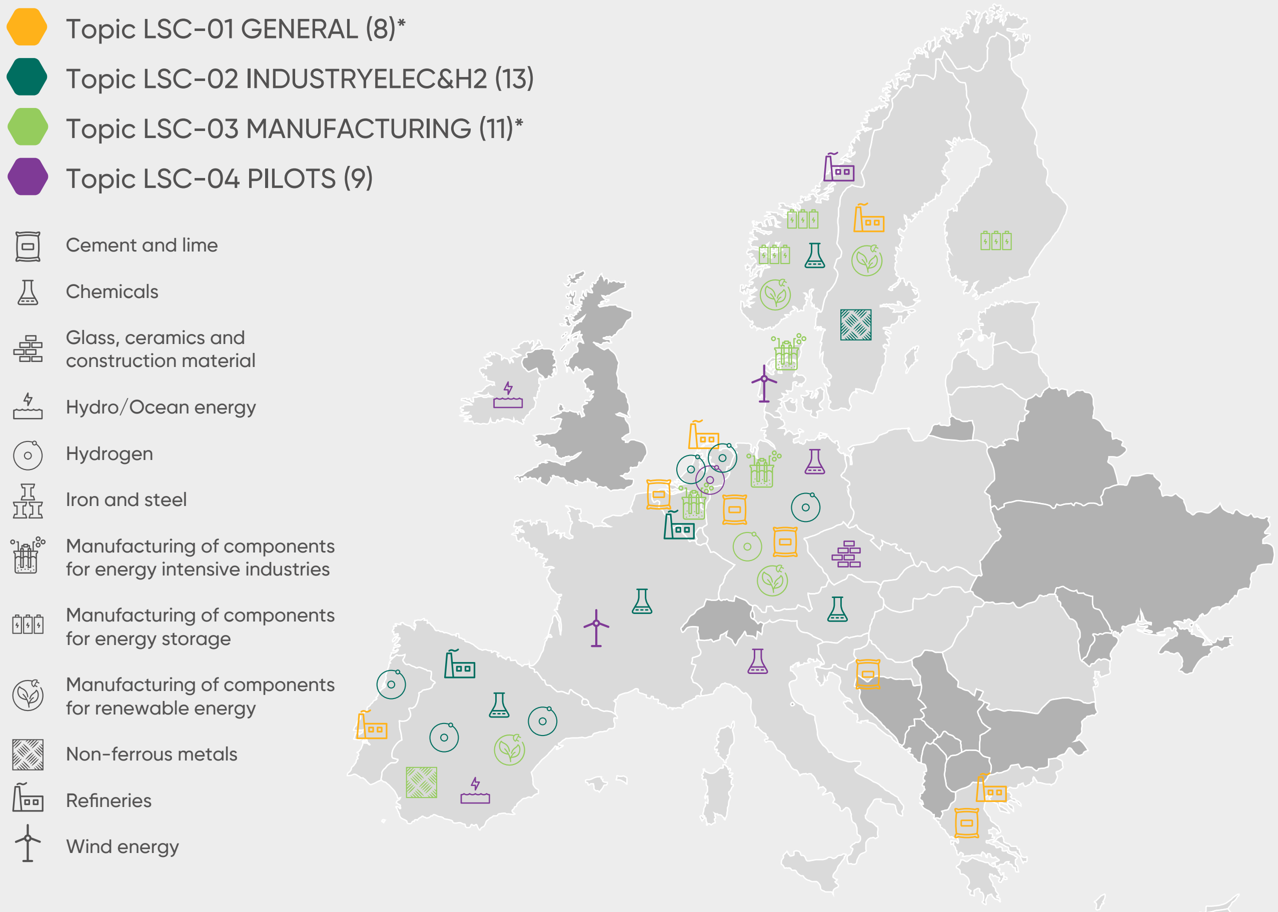
Two Innovation Fund new large-scale and small-scale calls have been launched since last year. The third large-scale call had a budget of EUR 3 billion, doubling the previous year. The call results were announced in July 2023, with 41 projects selected and a total grant amount of EUR 3.6 billion. 23 out of the 41 projects selected for grant agreement preparation were hydrogen projects (**Figure 8**), in the following categories:

- **General decarbonisation:** 3 projects
- **Innovative electrification and hydrogen applications in industry:** 13 projects
- **Innovative clean tech manufacturing:** 4 projects
- **Mid-sized pilot projects:** 3 projects

Hydrogen Europe has collaborated with the European Commission by organising dedicated workshop with its members and DG CLIMA to prepare the GHG emission savings and costs calculation methodologies for the electrolysers and fuel cell manufacturing subcategory. This enabled the gathering of views from the industry and supported the drafting of the simplified relevant costs and GHG emissions saving calculation methodology for this sub-window. Four hydrogen-related manufacturing projects, which benefitted from this simplified methodology, have been selected. Overall, the pre-selected projects account for an additional 2.5 GW electrolysis installation and over 300 kt/y clean hydrogen production and consumption in nine EU MS.

FIGURE 7.8

Pre-selected projects for the ETS IF third Large-Scale Call (July 2023)



*The number of symbols is higher than the number of projects, as some projects are implemented in multiple locations.

Source: CINEA.

Examples of selected projects under the Clean Tech Manufacturing window:

TopSOEC: The project, Led by TOPSOE AS, consists of building and operating a factory in Denmark for innovative solid oxide electrolyser cell (SOEC) stack modules used for electrolysis in renewable hydrogen production. The technology enables higher energy (electrical) efficiency as compared to conventional electrolysis.

ELYAS: This project will be developed in Germany and led by Bosch and will industrialise the novel Smart Electrolysis Module (SEM), which combines the ELY stack with cost-efficient, robust, and highly available automotive-based power electronics, control units and sensors including global service offerings.

Examples of selected project(s) under the Innovative electrification and hydrogen applications:

EnergHys: The project in the Netherlands aims to establish a complete value chain of scalable renewable hydrogen production from renewable energies to end-users. The intention is to use the produced renewable hydrogen to help decarbonise hard-to-abate industrial customers and the mobility sector by replacing fossil-fuel-based hydrogen.

Examples of selected project(s) under the Mid-sized pilot projects:

- **CFCPILOT4CCS:** This project, led by Esso Nederland, will use carbonate fuel cells (CFCs) to capture and concentrate CO2 streams, aiming to reduce the effective cost of Carbon Capture and Storage, particularly in energy-intensive industries.

The Innovation Fund's small-scale call for projects was launched in March 2022 with a budget of EUR 100 million. Call results were announced in June 2023, with 3 out of 16 projects selected for grant agreement preparation being hydrogen-related. The third small-scale call for projects was published on 30 March and ran until 19 September 2023, with a budget of EUR 100 million and EUR 5 million for Project Development Assistance (PDA), with results expected to be announced at the beginning of 2024.

Since its first large-scale call in 2020, the Innovation Fund has provided more than EUR 1.1 billion to hydrogen applications, approximately one-third of its total disbursed budget so far (**Figure 7.9**), constituting an important funding instrument for the sector. As for the last large-scale call results announced in July, the allocation for each of the 23 hydrogen-related projects selected will be unveiled later in 2024 at the signature of the grants agreement, which will further increase the cumulative support envelope the Innovation Fund has mobilised for the sector.

Hydrogen Europe continues to collaborate with the European Commission and has participated in the stakeholder consultation on revising the Innovation Fund. At the time of writing, the updated Delegated Regulation has been published in mid-September and is expected to enter into force in mid-November of this year, provided EU co-legislators do not oppose it during the two months scrutiny period. Changes consist of an increase in the size of ETS allowances (from 450 to 530 million allowances), the introduction of a new 'medium-scale' category for projects (EUR 20 million – EUR 100 million), extending its scope to new sectors (e.g. maritime) and the use of financial instruments such as competitive bidding, fixed premiums, Contracts for Difference (CfDs) and Carbon Contracts for Difference (CCfDs) covering up to 100% of the project's funding gap.

FIGURE 7.9

Overview of Innovation Fund calls allocation to the hydrogen sector 2020-2023

Cut off date	Projects	H2 projects	% of H2 projects	Total funding	Funding for H2	% funding for H2
1st LSC (Oct20)	7	3	43%	€1.15 bln	€0.59 bln	51.1%
1st SSC (March21)	30	4	13.3%	€109.2 mln	€17.8 mln	16.3%
2nd LSC (Oct 2021)	16	6	37.5%	€1.78 bln	€0.57 bln	31.9%
2nd SSC (March22)	16	3	18.7%	€59.4 mln	€12 mln	20.2%
3rd LSC (Oct22)	41	23	56%	**€ 3.6 bln**	N/A	N/A
3rd SSC (March23)	N/A	N/A		€ 100 mln	N/A	N/A

Source: Hydrogen Europe.

Since 2021 approximately EUR 233 million of EU funding has been dedicated to hydrogen refuelling station projects. In 2023, the EU has dedicated EUR 750 million to hydrogen infrastructure for transmission, storage, and distribution.

CEF-Transport: The Alternative Fuel Infrastructure Facility (AFIF), which funds most of the CEF-T budget dedicated to hydrogen, closed its third cut-off call in November 2022. Out of 26 projects, 12 were hydrogen-related and will fund 63 hydrogen refuelling stations (HRS). Since the first cut-off call, AFIF funding for hydrogen has increased irregularly, with approximately EUR 233 million being dedicated to HRS, equivalent to an average of 25% of total AFIF resources used (**Figure 7.10**). AFIF, whose last rolling call will close in November 2023, will likely continue after 2023 as the Commission and CINEA are currently working on its future design and programming.

CEF – Energy: The first list of projects seeking to obtain the cross-border renewable energy (CB RES) status and receive 15% of the CEF-E budget was announced in August 2022, with one out of three projects being hydrogen-related (CEO-Alliance Cross-Border European Hydrogen Value Chain, between Italy, Spain, and Germany). In January 2023, the Commission launched the second call for projects seeking to obtain the CB RES status, a pre-condition to access future CEF-E CB RES calls for proposals. Selected projects will be officially published by the end of 2023, and projects will be eligible for funding under CEF in 2024.

In April 2023, the Commission launched a new CEF-Energy call for proposals for Projects of Common Interest (PCIs), with a total budget of EUR 750 million, to support key infrastructure projects to reach REPowerEU objectives. Only projects on the 5th PCI list were eligible to apply, with the funding rate reaching up to 75%. The application deadline closed on 5 September 2023, with results expected in January 2024. A consultation was also held on the 6th list of PCI-PMI candidates under the revised TEN-E Regulation until March 2023, and the list is expected to be announced in November of this year.

FIGURE 7.10

AFIF support to hydrogen projects since the first cut-off call

Cut off date	Number of projects	Selected H2 projects + number of HRS	Total funding	AFIF funding for HRS	% funding for HRS
1st (Jan. 2022)	15	3 projects – 3 HRS	€86.5 mln	€8 mln	9.3%
2nd (June 2022)	24	10 projects – 57 HRS	€292.5 mln	€99.1 mln	33.9%
3rd (Nov. 2022)	26	12 projects – 64 HRS	€188.8 mln	€98.3 mln	52%
4th (April 2023)	26	6 projects – 18 HRS	€352.1 mln	€27.2 mln	7.7%
Total funding (before last cutoff)	91	**31 projects – 142 HRS**	**€919.9 mln**	**€232.7 mln**	25.3%

Source: Hydrogen Europe.

INVESTEU

The InvestEU Fund expects to mobilise EUR 372 billion of public and private investment in 2022-2027 through an EU guarantee of EUR 26.2 billion. Specifically, InvestEU supports the hydrogen sector under its Fund's Sustainable Infrastructure window, backed by an EU guarantee of EUR 9.9 billion, through which it can fund hydrogen infrastructure and interconnection, transport, storage, development of energy systems, buildings' renovation, equipment of clean, innovative technologies. The EIB Group is responsible for implementing 75% of the Guarantee while other implementing partners (IPs) are responsible for the remaining 25%. As such, funding via InvestEU is channelled through the EIB and National Promotional Banks (NPBs). InvestEU resources can be blended with funding coming from other EU programs.

STRATEGIC TECHNOLOGIES FOR EUROPE PLATFORM

By adding EUR 10 billion to existing EU funds, the Strategic Technologies for Europe Platform (STEP) is expected to mobilize up to EUR 160 billion to support key technologies including green hydrogen projects across the value chain.

The Strategic Technologies for Europe Platform (STEP) was published in June 2023 as part of the Multi-Annual Financial Framework 2021-2027 mid-term review to support the development of hydrogen and fuel cells manufacturing and SAFs, as part of the Green Deal Industrial Plan (GDIP) announced by the Commission in February 2023. The Platform aims to increase the firepower of existing funds by adding EUR 10 billion in top-ups to existing funds, expected to leverage up to EUR 160 billion, bringing more flexibility and synergy across these and introducing a Sovereignty Seal and a Sovereignty Portal for strategic projects (**Figure 7.11**).

Under STEP, the InvestEU Fund budget is increased by EUR 3 billion, resulting in its guarantee available for the EU compartment reaching EUR 7.5 billion. The InvestEU Fund will have a new STEP investment window, and EU countries can transfer up to 10% (4% previously) of RRF resources to their InvestEU MS compartment. Additional flexibilities are added, for example in designing blending operations, with the objective of facilitating synergies between InvestEU and other Union programmes.

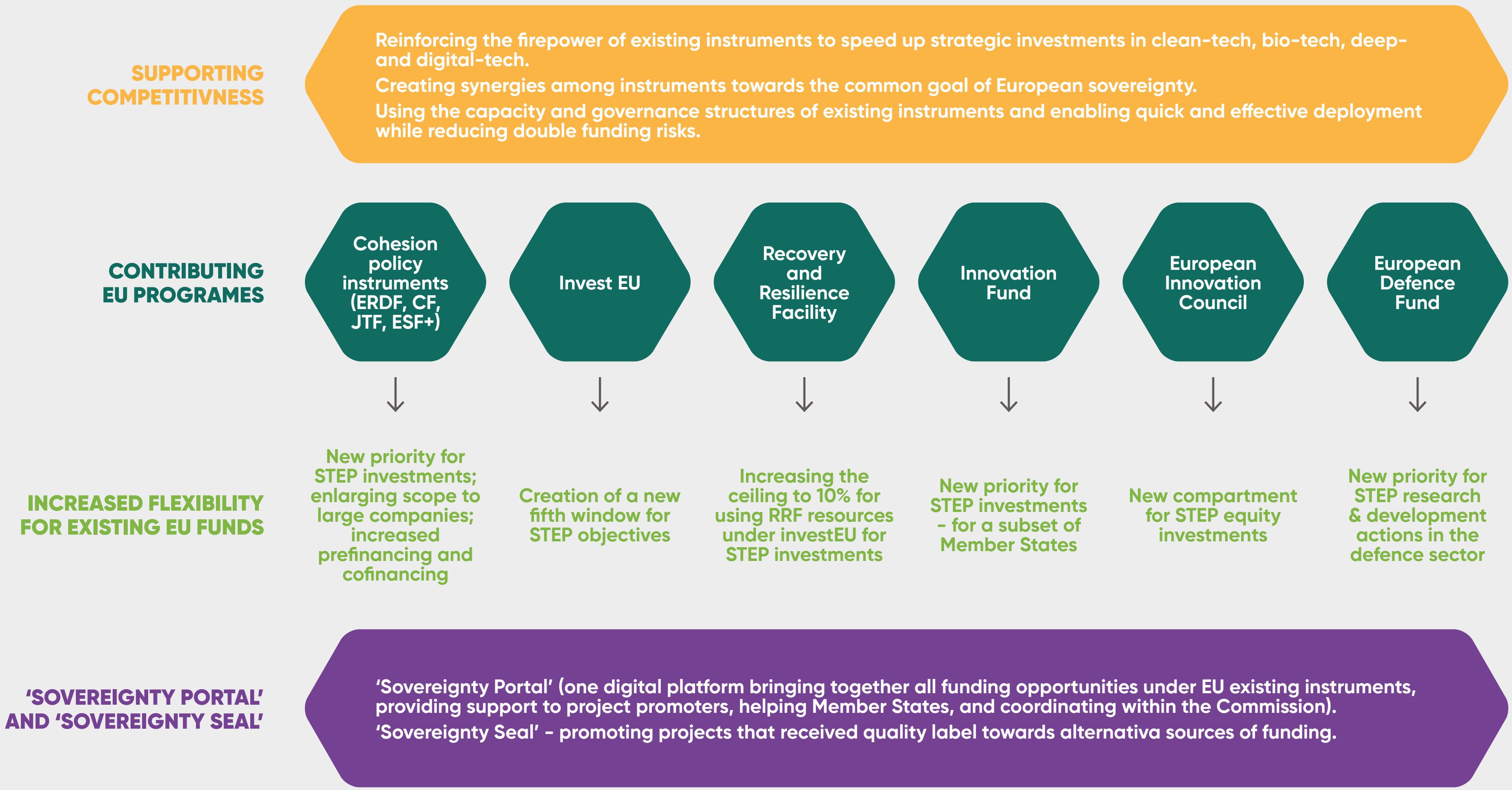
The Innovation Fund will also receive an extra EUR 5 billion in budget. The additional financial envelope shall be made available through calls for proposals for EU MS with an average GDP per capita below the EU-27 average. A new STEP priority will be added to the innovation fund's scope, with the budgetary top-up expected to result in overall investments of around EUR 20 billion.

The European Innovation Council Fund (EIC Fund), which supports the scaling up of breakthrough technologies developed by early-stage companies is topped up with an extra EUR 2.13 billion. The Fund will be able to invest between EUR 15 to 50 million in equity, participating in larger investment rounds of between EUR 50 to 250 million. This top-up is expected to lead to EUR 13 billion of new equity support to non-bankable SMEs and small mid-caps.

EU MS will also benefit in 2024 from up to 30% of pre-financing from cohesion policy instruments (ERDF, CF, JTF and ESF). STEP aims to streamline rules between EU funding and State aid, such as criteria and timing. Projects having achieved minimum quality requirements (in line with Horizon Europe or Innovation Fund call for proposals) and contributing to STEP objectives will be awarded a 'Sovereignty Seal' and listed in a 'Sovereignty Portal', connecting project promoters with the Commission, EU MS authorities and institutional financiers. The Seal will also enable these projects to benefit from fast-track access to financing, cumulation with RRF cohesion funding and visibility.

FIGURE 7.11

Strategic Technologies for Europe Platform (STEP)



Source: European Commission.

Auction mechanisms to kickstart the hydrogen economy

EUR 800 million will be provided under the first pilot auction of the domestic (EU) pillar of the Hydrogen Bank, with a green premium covering the cost gap between renewable hydrogen and conventional hydrogen production.

Market-making mechanisms for decarbonisation applications have been launched in some MS. We mapped some of the leading schemes relevant to the hydrogen sector among other clean technologies, reaching approximately EUR 100 billion.

2023 has seen several support schemes have been launched both at the EU and national level to leverage market mechanisms and build the hydrogen economy. The Commission launched the much-anticipated European Hydrogen Bank at the EU level while frontrunners like Germany, France and the Netherlands announced substantial packages to foster hydrogen production.

The European Hydrogen Bank

In March 2023, the Commission set up plans to launch a European Hydrogen Bank to support investments in clean hydrogen. This initiative includes two financing mechanisms and a coordination platform allowing the assessment of market needs and streamlining existing support mechanisms. The Bank is meant to address the so-called chicken-and-egg problem in ramping up a European hydrogen market. It will do so by supporting on the one hand European supply – the domestic pillar – while fostering on the other hand demand via imports from third countries – the international pillar.

Under the revised Innovation Fund, the Commission will launch a EUR 800 million auction on 23 November to support EU-domestic renewable hydrogen production. A fixed premium of up to EUR 4.5 per kilogram of hydrogen produced, covering the cost gap between renewable and fossil-fuel-based hydrogen, will be awarded to EU bidders. Hydrogen Europe has been collaborating closely with the Commission by providing feedback on the Terms and Conditions (T&Cs) for the first pilot auction under the Innovation Fund. This has led to improved and more supportive conditions for European hydrogen producers. The final T&Cs were published in late August 2023; an overview can be found in **Figure 7.12**.

In general, Hydrogen Europe mainly welcomes the conditions of this first pilot auction:

- **Ceiling price to support hydrogen production:** EUR 4.5/kg.
- **Completion bond for project promoters:** 4% of the total grant.
- **Required payment after entry into operation:** twice per year.
- **Maximum allocation per project:** one-third of the total budget, equivalent to EUR 266.67 million.

The lack of indexation on inflation and the very restricted possibility to cumulate Hydrogen Bank support with state aid are two main points of concern, whose impact will be followed closely by our association. Under the domestic pillar, the Bank could also serve as an Auction-as-a-Service (AaaS) for EU MS by using the future EU-wide auction mechanism. Under this AaaS offer, the Commission would run a single auction instead of multiple national auctions with different criteria, selecting the most competitive projects to be funded first with the Innovation Fund budget, complemented by national resources. This would further benefit the formation of an EU-wide hydrogen market, with EU MS being able to support specific projects in their territories.

At the end of May, the Commission announced it would be looking at using H2Global, the German double-side auction mechanism launched in 2021 as the instrument for import-side auctions of the Hydrogen Bank. To set up such an EU-wide mechanism, the possible options became either for EU MS to use H2Global to run their own import auctions in line with the provisions of the RED II and the Delegated Act – the so-called Team Europe approach – or for H2Global to become an EU-wide import instrument backed by the Commission and a common budget.

During the summer, the Commission and H2Global jointly invited EU MS to adhere to the initiative, meaning that the first Team Europe approach under H2Global could become the preferred option. At the time of writing, information on this design is in progress, and Hydrogen Europe is actively collaborating with the European Commission to ensure the future design of the international pillar of the Bank is effective in accelerating market maturation and best reflects the needs of the European hydrogen sector.

In the last twelve months, several initiatives have been launched in the last couple of years to accelerate technological development and ramp up the hydrogen market. We observed game-changing global announcements of supply-side support schemes, like the Hydrogen Bank domestic leg in response to the IRA production tax credit.

FIGURE 7.12

Hydrogen Europe's position on the Final Terms and Conditions for the pilot auction under the Innovation Fund for the Hydrogen Bank

Source: Hydrogen Europe.

Criterion	Terms	Assessment
Eligible H2	RFNBO hydrogen, compliant with REDIII and DAs	Satisfactory criteria
Minimum size for bidding	5MWe electrolyser	Point of attention
Electricity supply	No need to show procured power through PPA	Satisfactory criteria
Maximum allocation per project	1/3 of total budget (or 266,67 Mio EUR)	Point of attention
Time to commission	5 years from time of signature of grant agreement	Satisfactory criteria
Under delivering	Under delivery for 3 consecutive years – losing grant	Point of attention
Ceiling price	EUR 4.5/kg	Satisfactory criteria
Over delivering	Possibility to produce up to 140% of expected quantities/year and be remunerated until total grant amount is used	Satisfactory criteria
Completion bond	4% of the total grant	Satisfactory criteria
End use	No prioritization	Point of attention
Documen-tation	Details on electricity supply (at least 60% of production) + electrolyser manufacturing strategy	Unsatisfactory criteria
Cumula-tion with state aid	No cumulation possible for the same costs, but some flexibilities on offtakers and infrastructure	Unsatisfactory criteria
Indexation	No indexation to inflation	Unsatisfactory criteria
Payments	Twice a year after entry into operation	Satisfactory criteria

Satisfactory criteria | Point of attention | Unsatisfactory criteria

National auctions

Various EU MS launched schemes to fund production, including the SDE++ in the Netherlands and the PtX scheme in Denmark. However, these supply-side instruments need to be complemented by programs mitigating the demand-side market challenges, which could limit the developer's access to finance and their capacity to scale up production.

Significant demand-pull mechanisms are being set up to deal with market failures, like the German or the Austrian schemes, funding general industry decarbonisation. In September, France announced a supply-side scheme targeting industry and mobility applications (**Figure 7.13**).

Funding to ramp up the hydrogen market under the illustrated schemes amounts to approximately EUR 100 billion (non-exclusive to hydrogen), with additional market-support regimes expected to be launched in other Member States.

FIGURE 7.13

Overview of market-making mechanisms and auctions in EU MS

TOPIC	DE	DE	NL	FR	DK	AT
Name	Climate Protection Contracts	H2Global (first tender)	SDE++	Decarbonised hydrogen production for industry	Production of PtX in Denmark	Industry decarbonisation
Focus	**DEMAND**	**SUPPLY & DEMAND**	**SUPPLY**	**SUPPLY**	**SUPPLY**	**DEMAND**
Scope	Hydrogen as means of decarbonisation of industrial activities covered by ETS	Renewable ammonia, methanol & and e-kerosene produced outside of the EU	Low carbon production & heat, renewable electricity, renewable gas	Renewable and low carbon hydrogen production for industry & mobility	Production of renewable hydrogen and green fuels	Hydrogen as means of decarbonisation of industrial activities covered by the ETS
Budget (EUR)	50 billion total (TBC)	900 million 2023 4.5 billion total	38 billion total 13 billion 2022 8 billion 2023	4.2 billion total	167 million total	2.975 billion total
Selection process	Competitive auction	Double sided competitive auction	First come first serve upon eligibility	Competitive auction	Competitive auction	Competitive auction
Instrument	CfD	CfD	CfD	CfD	Fixed premium	CfD
Duration	15 years	10 years	12-15 years	15 years	10 years	10 years

Source: Hydrogen Europe.

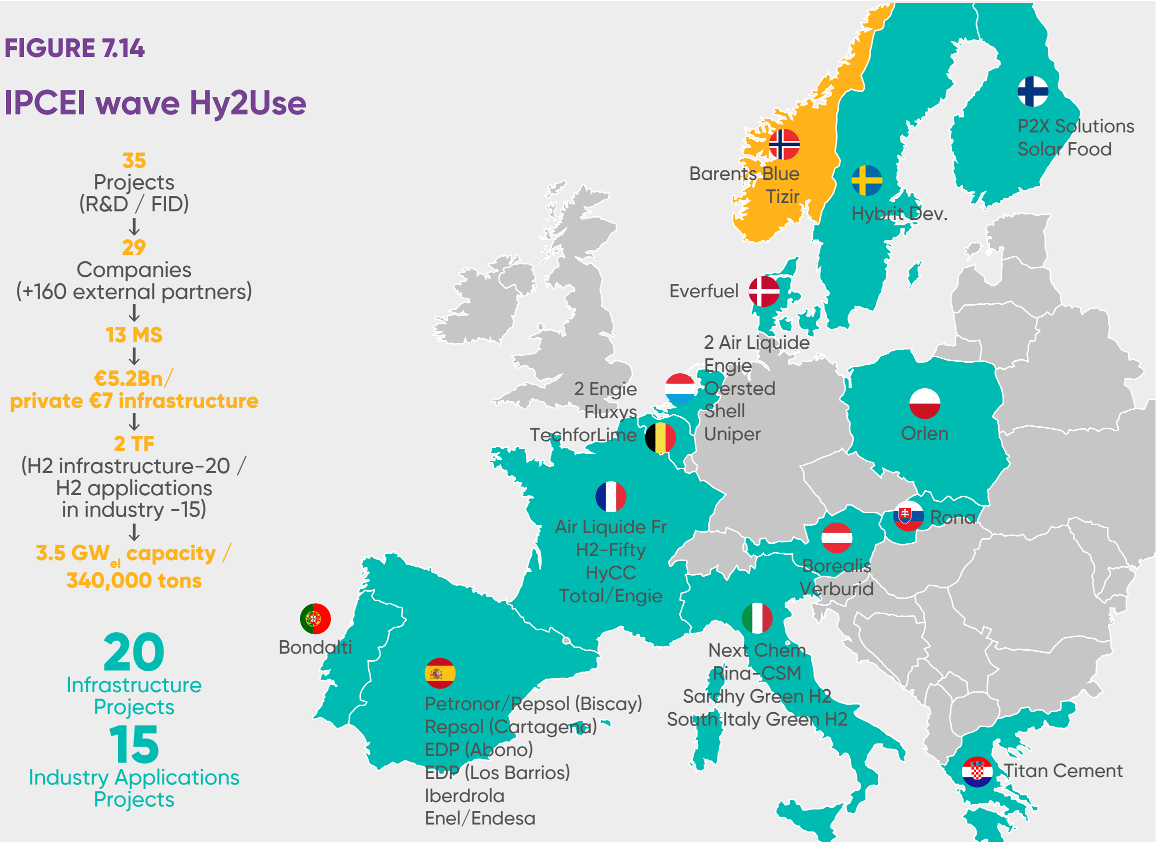
State aid

Important Projects of Common European Interest

More than EUR 10 billion have been allocated to the hydrogen sector under the recently approved IPCEI waves, which are expected to unlock EUR 15 billion in investments.
The following two waves are expected to support the hydrogen value chain further, however, the IPCEI process continues to generate uncertainty on timing and budget.

FIGURE 7.14

IPCEI wave Hy2Use



Source: Hydrogen Europe.

Since 2022 the European Commission (DG COMP) has approved two IPCEI waves, Hy2Tech and Hy2Use. The Hy2Tech wave is dedicated to supporting breakthrough technologies for renewable hydrogen production, with an overall budget of EUR 5.4 billion, expected to unlock EUR 8.8 billion, while Hy2Use will support technologies for hydrogen offtake in industry, with a budget of EUR 5.2 billion expected to mobilise EUR 7 billion in investments. Overall funding for the sector under these two IPCEIs therefore amounts to more than EUR 10 billion, with an additional EUR 15 billion expected to be unlocked with private investments. Together, the two approved IPCEI waves will support nearly 80 hydrogen projects, each with a budget ranging from a few to several hundred million euros. Meanwhile, EU MS are currently providing their resources as part of the IPCEI application to complement funding under the IPCEI waves. Nevertheless, the Hy2Use Chapeau is still not available to date.

The third IPCEI wave Hy2Infra and the fourth wave Hy2Move were notified to the Commission in April and September 2022 respectively. Hy2Infra is dedicated to hydrogen-related infrastructure (pipelines, ports, and storage facilities) while Hy2Move focuses on mobility. Information on timing and process for approval remains limited to date, and information on projects selected under these waves cannot be accessed until approval.

The European Commission expects to notify the Hy2Infra wave by the end of this year and early 2024 for the Hy2Move wave. The latter wave received its Chapeau Request for Information (RFI) in May 2023. The IPCEI process continues to generate uncertainties due to unclear timing and budget, an example of this being the delay in notification on the Hy2Move wave from the Commission to 2024.

Hy2Use" involves 37 projects. These projects were submitted by 13 EU MS plus Norway: Austria, Belgium, Denmark, Finland, France, Greece, Italy, Netherlands, Norway, Poland, Portugal, Slovakia, Spain, and Sweden. Thirty-five projects from 29 companies were approved by the European Commission (**Figure 7.14**).

Other State Aid Frameworks

Under the revised TCTF and GBER, support now can cover both CAPEX and OPEX for renewable hydrogen projects as well as 100% of funding gap via bidding processes.

The more flexible state aid rules have enabled around EUR 4 billion of investments for the sector, yet spending capacity is unevenly distributed due to national budgetary constraints.

The Green Deal Industrial Plan (GDIP) announced by the European Commission in February 2023 to counteract the US Inflation Reduction Act (IRA) will boost access to funding for hydrogen producers and manufacturers by strengthening State aid frameworks. In early March 2023, the European Commission adopted a new Temporary Crisis Transition Framework (TCTF) and a revised General Block Exemption Regulation (GBER).

The new TCTF offers more flexible rules than those established under the State Aid Guidelines on Climate, Environmental Protection and Energy (CEEAG) on investment and operation aid for renewable hydrogen production and storage, its use for industrial decarbonisation, support to electrolysers manufacturing, hydrogen-derived fuel production. The new Framework introduces new provisions including the maximum individual aid per undertaking limited to 10% of the overall State aid scheme budget, now capped at EUR 200 million; EU MS to cover up to 100% of the funding gap via competitive bidding; the scheme can cover support to both OPEX and CAPEX for renewable hydrogen production.

TCTF was extended until 2025, with notification to the European Commission still required. In parallel, the Commission put forward a revision of the General Block Exemption Regulation (GBER), which sets up thresholds and conditions under which aid to hydrogen projects is exempted from prior notification to the Commission, complementing the CEEAG. GBER now covers the entire hydrogen value chain, including renewable hydrogen production, infrastructure, hydrogen-powered fleets, and refuelling stations, and introducing the first-time different categories for support to hydrogen projects. Notably, the revised GBER allows for exemptions on operating aid for small-scale renewable hydrogen production. The Regulation complements existing hydrogen support schemes such as IPCEIs and may serve to streamline access to funding for hydrogen-related projects, where notification procedures from EU MS might delay accessing this type of support. The revised rules under CEEAG, TCTF and GBER have led to approval from the EC on substantive support packages for the sector in MS, just to name a few significant packages, for instance, EUR 167 million for PtX in Denmark (February 2023), EUR 450 million for renewable hydrogen production in Italy (March 2023) and EUR 246 million in the Netherlands (July 2023) and a EUR 3 billion scheme to support private investments in net-zero technologies including hydrogen in Germany (July 2023). Combined, these packages amount to almost EUR 4 billion in support across MS for the sector, although the EU-27 national spending capacity is uneven due to each MS' national budget-specific constraints.

Private Finance

Venture Capital and Private Equity

Global investment in the low-carbon energy transition totalled USD 1.1 trillion in 2022, a significant growth from the previous year, as the energy crisis and following regulatory actions accelerated the deployment of clean energy technologies, according to a new report from BloombergNEF (BNEF, 2023). Climate tech corporate finance totalled USD 119 billion (funding for innovation and scale-up).

Indeed, we can observe that the main type of financing being deployed for our sector currently is corporate finance, dominated by equity investing. Equity financing requirements are to be met by many different players: leading international industrial groups interested in the hydrogen sector building strategic partnerships with specialist players, para-public financial institutions, and venture capital investors.

FIGURE 7.15

Total Venture Capital investments in 2022

Data provider	Total VC investment in hydrogen ($, 2022)	Number of deals
Dealroom	3.6 bln	-
IEA	3.1 bln	-
Pitchbook	4.2 bln	192

Source: Hydrogen Europe.

In 2022, Venture Capital investment in hydrogen ranged between $3.1 billion to $4.2 billion while Private Equity investment in the sector reached approximately $5.6 billion.

40% of all investments are in electrolysis-focused companies, and most investment in project developers happens in Europe, which is leading regarding early-stage deals.

80% of non-electrolysis production and e-fuel investment occurs in the US, and 80% of fuel cell manufacturers deals happen in China, the two countries provide most of the growth capital opportunities.

VCs support disruptive technologies or highly scalable business models and have been the main supporters of clean tech manufacturing companies' development in the last decade in our sector. Similarly, to the market sizing exercise, different studies assess global VC investment in hydrogen differently due to our sector's wide range of applications and complexity. However, the figures tend to show that global venture funding in hydrogen peaked in 2022, ranging between $3.1 and 4.2 billion (**Figure 7.16**).

Investors are increasingly betting on early-stage enterprises operating within various segments of the hydrogen supply chain, reaching almost a total of USD 0.6 billion investment in 2022 (**Figure 7.16**). However, this heightened interest has not yet translated into substantial and balanced growth-stage funding, where the fuel cell sector has predominantly dominated investment trends over the past decade and counts in 2022 for almost one-third of late-stage investment.

Most VC investments into project developers and a little less than 40% of investment in electrolysis-focused companies are happening in Europe. Meanwhile, the US receives almost 80% of investment in hydrogen-based fuels, non-electrolysis production and non-hydrogen fuel cells. Finally, China is home to over 80% of investment in hydrogen fuel cells (**Figure 7.17**).

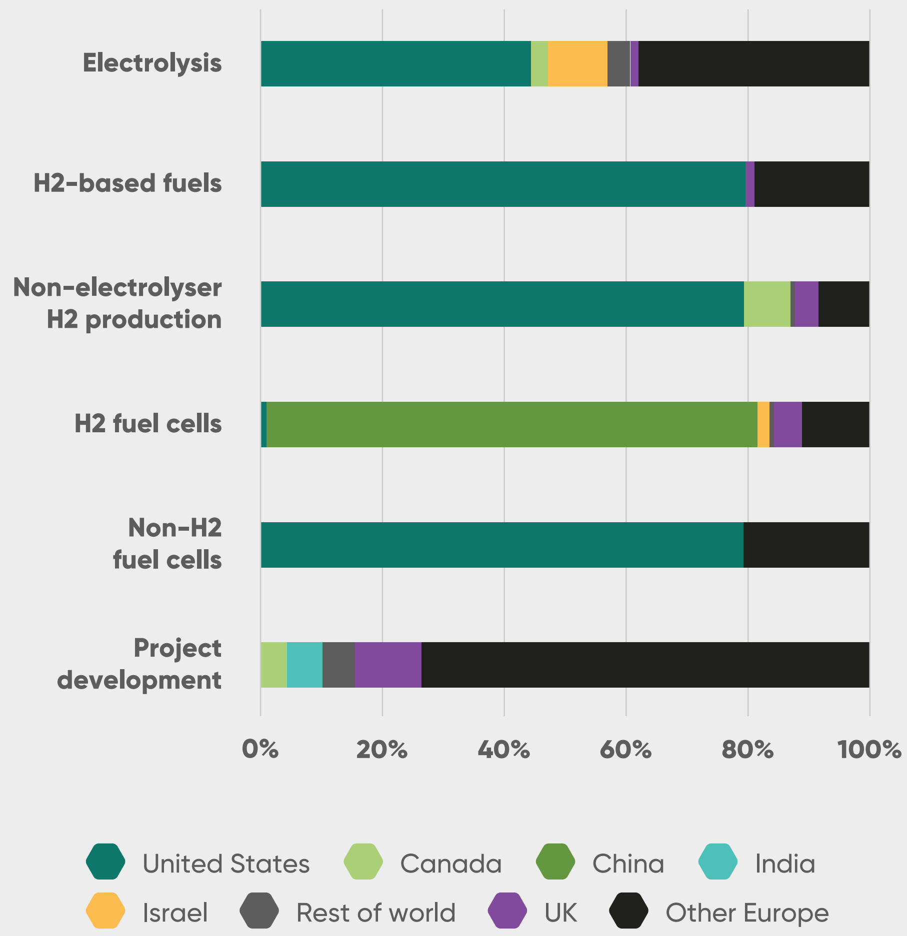
Unfortunately, this underlines the fact that cleantech companies in Europe often must tap into non-European investors given the dearth of growth stage equity funding in the region, often requiring relocation to markets where private finance is more abundant like China and the US.

Despite a sharp increase of venture fund investment in hydrogen between 2019 and 2022, as seen in **Figure 7.16**, both early and growth stage investment seem to be stalling in 2023, with fundraises in the first quarter of 2023 being approximately a third of what they were at the same time in 2022.

This is not restricted to our sector. Higher interest rates and inflation in 2022 are prompting a capital outflow from VC markets which introduces new risks for innovative companies. The ability of clean energy technologies to maintain adequate investment may hinge on the credibility of climate policies and corporate pledges. A good policy framework could help position these companies as a less risky investment than general technology start-ups, attracting scarcer capital in a complicated economic climate.

FIGURE 7.16

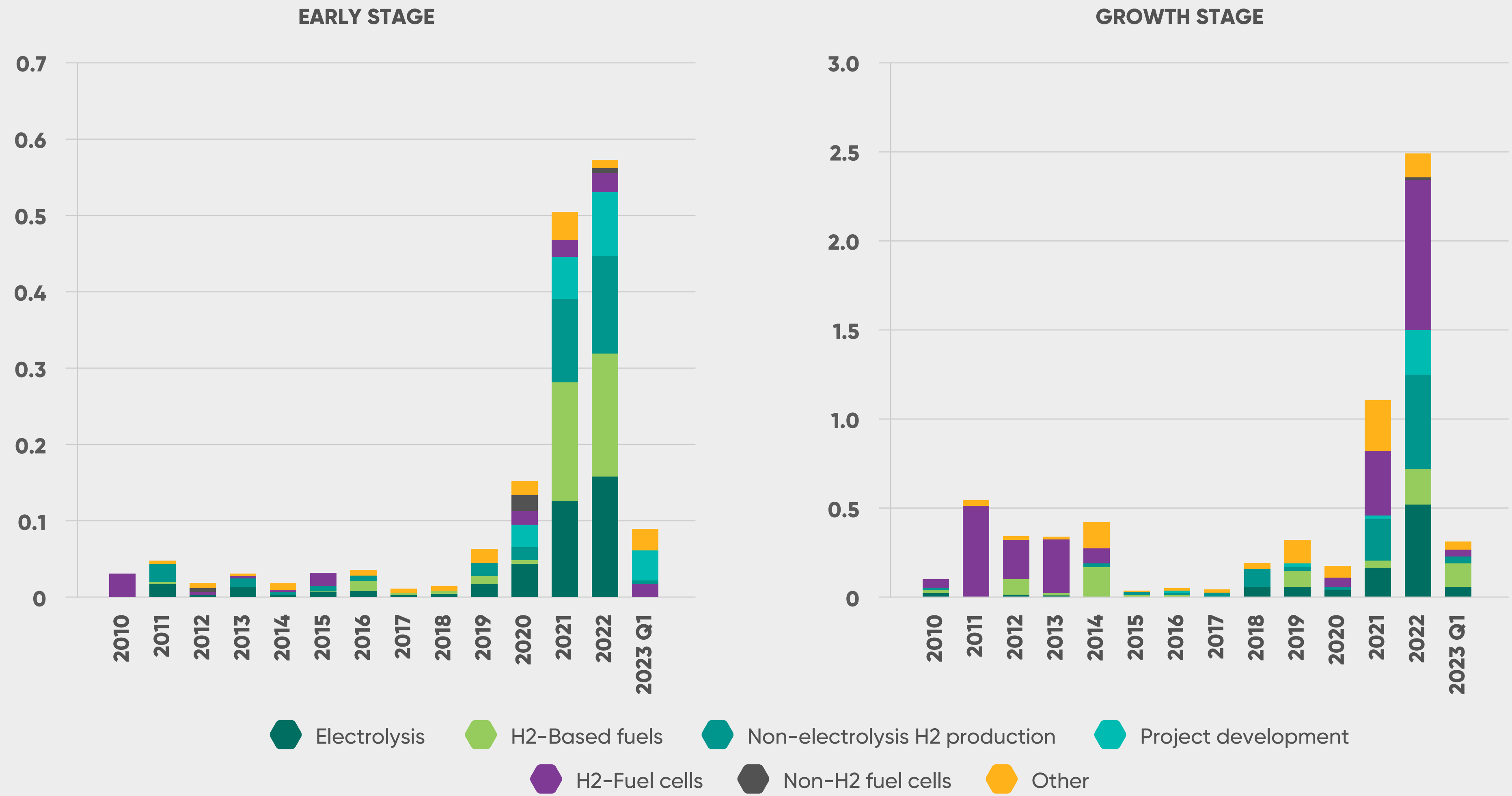
Early- and growth-stage equity investment in energy start-ups by region and technology area



Source: IEA.

FIGURE 7.17

Investment in energy startups in Hydrogen and Fuel Cells category, early stage and growth deals (USD bln)



Source: IEA World Energy Investment 2023.

Infrastructure investment

Infrastructure sector-owned assets have surged from USD 0.3 trillion in 2015 to USD 1.1 trillion in 2022, with infrastructure investors fundraising rising by an impressive 50% in 2022 compared to 2021.

The growth of non invested committed capital forces infrastructure fund to add flexibility to their mandate and look at applications still carrying merchant and technology risk.

Assets under management in the infrastructure sector surged from USD 0.3 trillion in 2015 to USD 1.1 trillion by 2022, marking an impressive growth rate of 21%. This remarkable expansion nearly doubled the 11% growth rate observed across all alternative asset investments. Furthermore, the largest infrastructure funds also experienced significant growth, with the top ten funds that closed in 2022 raising USD 36 billion more than they did the previous year. This popularity stems from its remarkable ability to withstand inflation and the ups and downs of demand. Infrastructure investors bring a valuable advantage by offering cost-effective funding to the sector and facilitating access to affordable debt and equity.

Highlighting the year 2022, infrastructure fundraising surged by an impressive 50% compared to the previous year. However, studies seem to show that non-invested committed capital, has reached record levels, too. This raises a critical question about the availability of investable projects and the alignment of risk/reward expectations between investors and project promoters. Considering the sector's inherent risk compared to traditional infrastructure assets, these funds are pioneering a novel approach to infrastructure investment, drawing inspiration from the risk strategies of Private Equity and Venture Capital.

Their strategy entails pursuing a higher Internal Rate of Return (IRR) while exhibiting a notable capacity for embracing comparatively higher levels of risk. A prime illustration of this trend occurred in 2022, with the successful closure of two remarkable funds: the Hy24 Clean Hydrogen Infrastructure Fund, boasting a substantial EUR 2 billion in commitments, and the Copenhagen Infrastructure Partners Energy Transition Fund I, securing an impressive EUR 3 billion (**Figure 7.18**). These funds are positioning themselves on hydrogen applications still carrying significant merchant and technology risk, which would deter traditional infrastructure funds. Notably, both funds were oversubscribed, underlying the robust appetite from investors to get involved in the hydrogen sector.

FIGURE 7.18

Main Infrastructure Funds raised 2022-2023

INFRA-STRUCTURE FUND	FUND SIZE (€)	SECTORS	TARGET	TARGET SIZE (€)
CIP Energy transition Fund I	3 bln	Renewables,Ptx, biofuels, CCUS, SAFs, hard to abate industries	Greenfield projects in OECD countries	Non disclosed
FiveT & Ardian Hy24	2 bln	Ptx, HRS, fleet deployment	Greenfield projects, global	15-150 mln
Cube Zero Carbon Fund (structuring/ fundraising)	1bln target	PtX, H2 storage and distribution, H2 based Heat and Power, HRS, fleets	Greenfield, Europe and North America	10-200 mln
EIP European Energy Infrastructure Fund	1 bln	Renewables, infrastructure to transport H2, pipelines	Brownfield and Greenfield, Europe	50 mln
Marguerite III (fundraising)	1-1.5 bln target	Renewables, Low carbon Hydrogen, CCS, Digital, Waste & Water, Alternative Fuels & transport infra	Greenfield, Europe	30-100 mln

Source: Hydrogen Europe.

Debt and non-recourse financing

Only 26% of interviewed banks in 2023 consider hydrogen and CCUS risk-adjusted return to equal or be higher than other sectors such as PV solar or wind.

By 2030, 67% of interviewees believe that by 2030, hydrogen returns would be at least equivalent to renewable energy projects, while 20% expect higher returns from the technology.

Commercial banks are incorporating low-carbon hydrogen into their mid-term sustainable lending strategies. However, they have not provided the necessary debt funding for the scale-up of the industry so far.For the hydrogen economy to scale up, equity will not be enough. Similar to how the LNG or renewable energy sectors developed, equity must be paired with bank debt or project finance debt. Only a mix of these two sources of capital can unlock the amount of funding required and ensure the returns expected by investors. In the last couple of years, banks, and debt finance providers developed hydrogen strategies and built expert groups to enhance their understanding of the sector. However, most if not all of them keep from funding large projects through non-recourse financing due to the high risks involved with renewable hydrogen projects.

Banks are dipping their toes with IPO mandates and advisory services and first publicly discuss supported FIDs. In early conversations around project finance for hydrogen, we see wariness among banks around the technology. While some equipment makers have seen their share prices surge in the past year, they generally do not have strong balance sheets, and banks may require major maintenance reserves, while manufacturer warranties may need to be backed by insurance or other financial instruments to provide credit support. These conditions are expensive for first-mover projects.

Various risks also limit hydrogen project finance: the cost of electricity or green premium, visibility on demand and offtake agreements as well as a mismatch between the length of offtake contracts and the duration of financing being requested. Manufacturers have started to expand their production capacity based on current market growth, but they need visibility on future demand to follow their expectations of future demand growth since the building of large manufacturing facilities is a long-term decision.

As seen with the emergence of other renewable asset classes like solar and wind, technological hydrogen advancements to drop hydrogen prices to levels competitive with traditional fossil fuels are needed. Projects are expected to be funded exclusively through equity or with the assistance of grant funding and/or concessional debt.

The Boston Consulting Group led a survey in early 2023 to understand the reasons behind the lack of availability of debt financing for hydrogen and CCS technologies, involving over 100 experts and interviewing more than 35 executives from commercial banks, development banks, private equity firms, asset managers, and energy companies. Between 75% and 80% of these banks anticipate that both hydrogen and CCUS technologies will constitute more than 10% of their energy-related portfolios by 2030. However, most banks are not extending non-recourse debt financing to hydrogen and CCUS ventures.

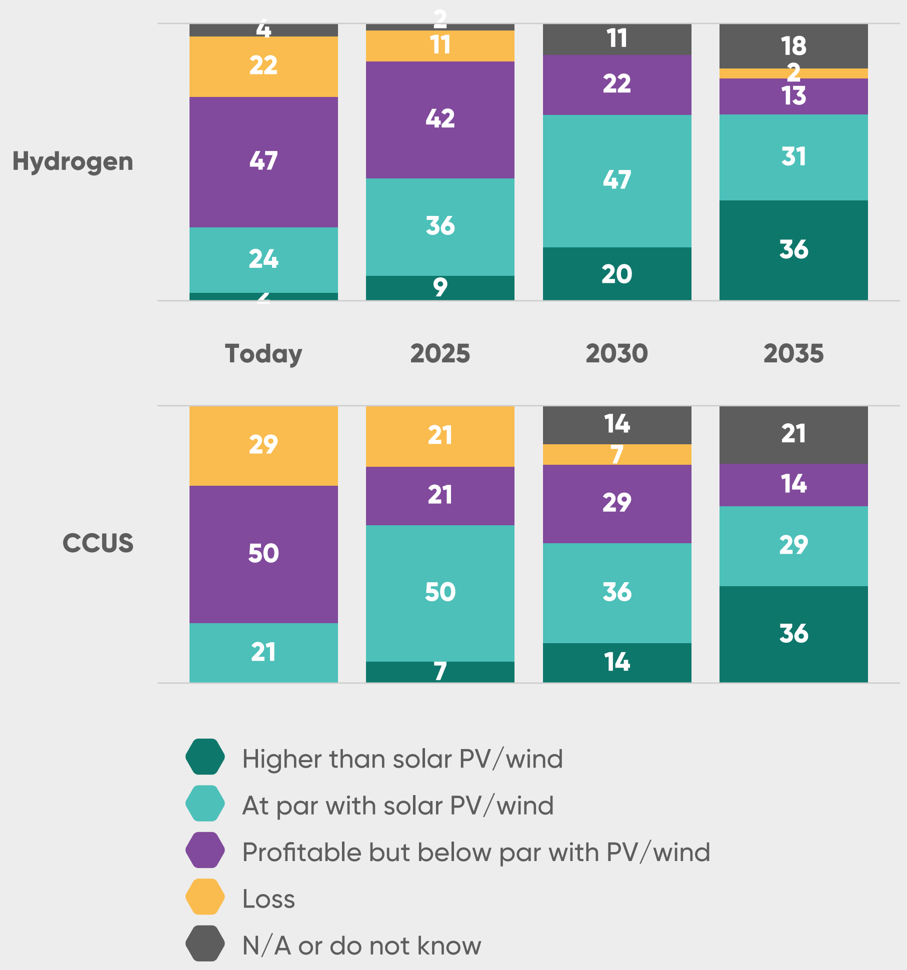
Their research indicates that numerous commercial banks are holding off on supporting these projects until they align with the same benchmarks and exhibit similar risk profiles as more established green initiatives, such as PV installations and wind farms. They will be looking for projects they fund to fulfil the following criteria:

- Possess long-term offtake agreements with reputable counterparties (addressing offtake risk);
- Use proven technologies (mitigating technological risk);
- Operate within a framework of clear regulatory and industry standards (reducing policy risk);
- Have the capability to sell their products or services in established markets (alleviating merchant risk).

In 2023, only 26% of interviewed banks expect hydrogen risk-adjusted returns to be at par or higher than solar PV or wind projects, and 2% of them believe that hydrogen yields could exceed solar or wind project returns. However, by 2030, 67% of interviewees believe that hydrogen returns would be at least equivalent to renewable energy projects, while 20% expect higher returns from the technology (**Figure 7.19**).

FIGURE 7.19

Expected hydrogen and CCUS returns from banks over time (% of responses)



Source: Boston Consulting Group (BCG).

Insurance

Insurers are starting to align their risk strategies to the nascent green economy market, yet only 27% have to date evaluated risks in their portfolios.

Green hydrogen could potentially generate commercial insurance premiums of EUR 406 billion for the utilities industry alone by 2050.

New hydrogen production methods, end usage applications, and the sector's quick scale-up are transforming the projects' risk profiles, making it more difficult for insurers to offer adequate insurance market provision to operators.

Similarly, as for energy or infrastructure projects, the lack of insurance policies aligned with the project risk profile might in the worst case stop these projects from happening, while in the best scenario, provoke lengthy delays and incur significant additional costs. The impossibility of sharing the risks between stakeholders increases the cost of capital and limits the involvement of private investors, especially providers of debt finance.

Some insurers are drawing from their experience in the construction, energy, infrastructure and oil and gas sectors to deliver standard policies for hydrogen producers which can cover well-known industrial risks in the short term:

- Engineering policies can manage risks like physical loss or damage to works during construction; delay in start-up (DSU) can broadly cover delays from physical damage caused by peril types; and construction liability insurance compensates for injury and damage.
- Standard property insurance can cover risks in the operational phase, including fire, explosion, malicious damage, and natural disasters.

However, existing risks are evolving, and new risks arise due to the complexity of emerging business models and the value chain deployment. For example, the interdependency between renewable energy and renewable hydrogen production, when structured and owned as distinctive projects, requires sophisticated coverage that considers interface agreements and project-on-project risk.

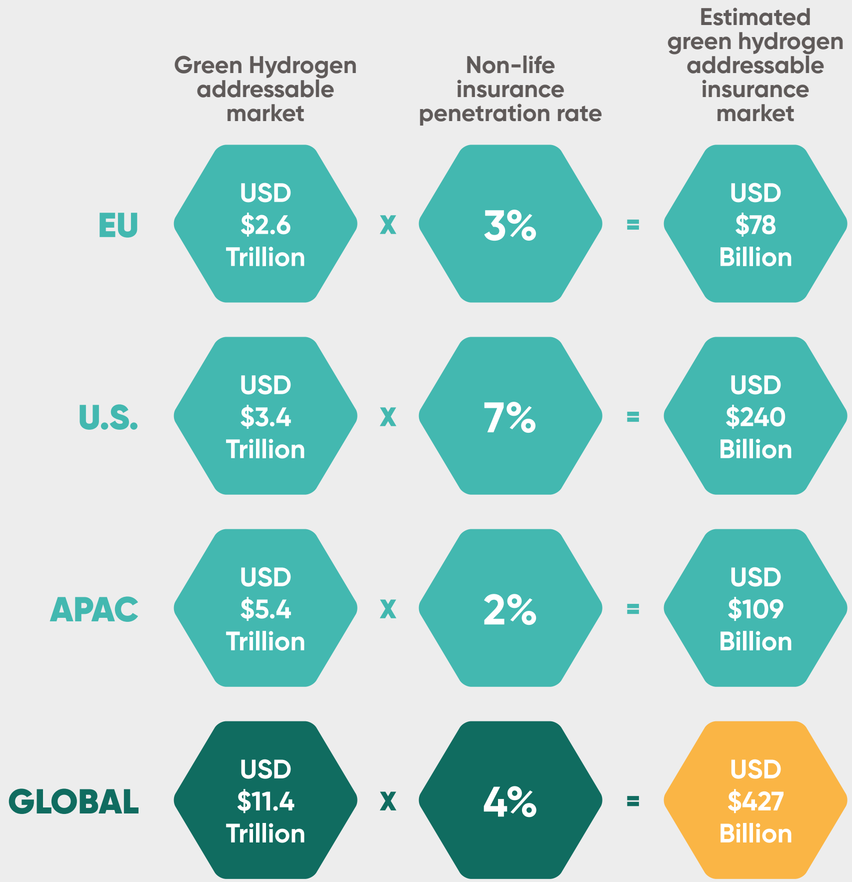
The business interruption risk is not yet well addressed by insurers, including disruption in the supply of renewable energy or the scale up of large-scale electrolyser plants. Similarly, the design risk associated with the lack of standards and best practices, the unproven nature of some technologies, and the risks linked to the early stage of testing and operating phase are still very novel to insurers, which will need to develop knowledge and new risk management processes, but only after they see several challenges addressed by regulators and first movers. Finally, lenders may require maintenance reserves, and manufacturer warranties may need to be backed by insurance or other financial instruments to provide credit support.

In 2022, Marsh, the world's leading insurance broker and risk advisor, launched a first-of-its-kind insurance and reinsurance facility that provides dedicated insurance capacity for new and existing renewable and reforming carbon capture hydrogen energy projects. Developed by Marsh in collaboration with insurers Liberty Specialty Markets, part of Liberty Mutual Insurance Group, and AIG, the facility provides up to USD 300 million of cover per risk for the construction and start-up phases of hydrogen projects globally. This facility will provide risk transfer options for all construction and operational phase property damage risks and include marine cargo, business interruption, general third-party liability, and contingent delay-in-start-up insurance. In Europe, German leading insurer Munich RE has launched its hydrogen performance and product warranty insurance product against excessive repair and replacement costs for components and insolvency risks for suppliers. Yet according to infrastructure insurance broker Nardac, while the industry widely acknowledges the business potential of hydrogen for the insurance sector, to date, only about 27% of (re)insurers have evaluated the risks in their portfolio.

Insurers will play a key role in contributing to the bankability of hydrogen projects for investors. However, developing insurance products effectively covering risk transfer will require them to adapt their underwriting strategies and insurance policies thoroughly. The globally addressable market opportunity of green hydrogen is estimated to achieve USD 11.4 trillion in revenue by 2050 for the utility industry alone. Based on current (re) insurance penetration rates, green hydrogen could potentially generate commercial insurance premiums of USD 427 billion (EUR 406 billion) by 2050, with an estimated addressable insurance market of EUR 74 billion for Europe, USD 240 billion in the US and USD 109 billion across the APAC region (**Figure 20**). We can expect to see more and more exchanges between insurers and corporates active in the hydrogen sector to understand better the challenges they are facing in securing their coverage and consider how insurance policies may need to be segmented or consolidated for various risks carried by each part of the hydrogen value chain.

FIGURE 7.20

Estimated green hydrogen addressable insurance market, 2050



Source: AON.

Endnotes

a / Deloitte Center for Sustainable Progress, 2023.

b /Energy Transition Commission, 2021.

c / Bloomberg New Energy Finance, 2023.

d/ World Bank, 2022.

e / Hydrogen Europe, 2023.

f / European Commission, 2022.

g / European Commission, 2023.

h / European Commission, 2023.

i / Pitchbook Data, 2022.

j/ Nardac, 2022.

k / Goldman Sachs, 2020.

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Hydrogen in mobility

Hydrogen-powered mobility has a slow but steady uptake in Europe. Decarbonization efforts in maritime, road mobility, and aviation sectors all include clean hydrogen. However, main challenges remain insufficient infrastructure, expensive vehicles, and current prices of clean hydrogen.

- Total number of vehicles has increased by 32%, 20% and 75% from 2021 to 2022 for cars, buses and trucks, respectively, while number of vans remained the same.
- Maritime sector begins to slowly adopt clean hydrogen with the number of orders for low emission fuel cell and internal combustion powertrains, increasing from 11 in 2023 to 205 in 2028.
- Alternative Fuels Infrastructure Regulation sets the minimum goals for HRS deployment until 2030, which should significantly increase from the current 200 operational stations.

Hydrogen in mobility has seen increased uptake and shows significant potential in the zero-emission future. With infrastructure being the main bottleneck, OEMs have started providing turnkey solutions to customers, speeding up the transition.

Transportation of goods and people is essential to our economies, but it currently accounts for almost 25% of CO_2 emissions in Europe and causes air and noise pollution. The decarbonisation of this sector can be achieved by using electricity directly, hydrogen, or hydrogen derivatives.

Hydrogen as a solution in the mobility sector can be used directly through a fuel cell or fed into a hydrogen internal combustion engine (H2 ICE). Fuel cells generate electricity from hydrogen stored onboard the vehicle/vessel/aircraft within specifically designed tanks. In terms of H2 ICE, hydrogen is directly combusted in the internal combustion engine, producing lower emissions of CO_2.

Hydrogen can be stored in gaseous form at 350 to 700 bar and in liquid phase at atmospheric temperatures (with a low temperature of -253°C). Tanks with gaseous hydrogen at 350 bar are usually used for heavy-duty trucks and buses, while tanks with gaseous hydrogen at 700 bar are used for personal vehicles. Liquid hydrogen (LH2) will also play a role in the decarbonisation of heavy-duty applications. However, the application of the different technologies changes with their development, making each option available for different uses.

The other alternative to using hydrogen in the mobility sector is as a component necessary to produce other fuels, such as methanol, ammonia, and other e-fuels. These carriers have a higher energy density than hydrogen, resulting in lower spatial requirements, which is especially crucial for long distance, heavy-duty transport applications, where the possibility for frequent refuelling is limited. Aviation is not yet considered in this report, as the deployment of hydrogen-powered aircrafts is still in early development phases.

This chapter will focus on hydrogen-powered mobility and its deployment levels in Europe in 2022 and in previous years.

FIGURE 8.1

Different modes of mobility

Hydrogen in Road Mobility

The market is showing significant potential for hydrogen-powered trucks and buses, as OEMs and regions steer towards this powertrain solution.

Zero-emission vehicles (ZEVs) are widely regarded as an effective way to reduce CO_2 emissions and decarbonise the road mobility sector.

Considering the hydrogen mobility sector, this includes personal vehicles, light-duty (LDV) and heavy-duty vehicles (HDV), and also rail and off-road vehicles.

Regarding rail and off-road vehicles, these are still in early development or pilot phases and are not largely distributed on the market. However, their uptake is increasing by the year, and end-users are increasingly more interested, as they can provide high energy outputs required for these applications.

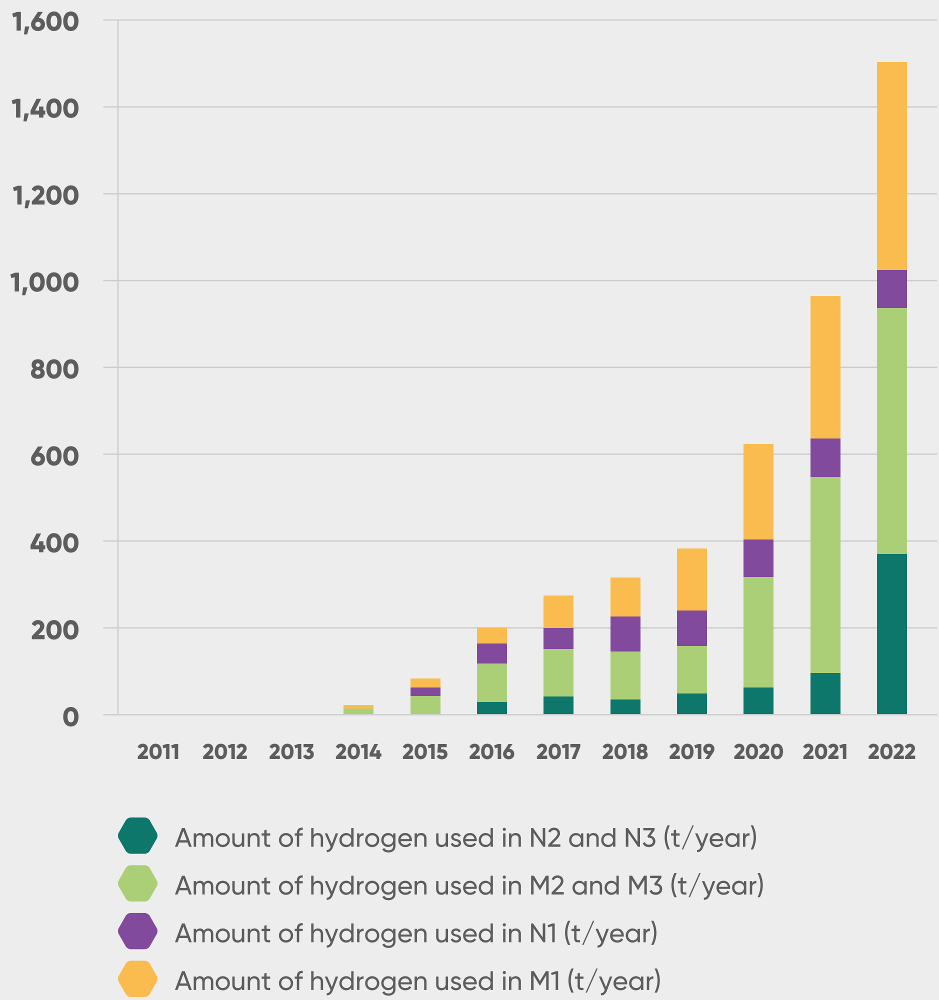
Personal vehicles, LDV and HDV (including trucks and buses) show steady growth over the years – as **Figure 8.2**[1] shows through estimated hydrogen demand for those vehicles. Moreover, 2022 has shown a significant increase in demand - mostly for heavy-duty trucks, which, to large extent, is a result of the H2Accelerate initiative.

Additionally, there are various other projects at EU level supporting the uptake of hydrogen-powered vehicles on the road, such as JIVE 2, ESCALATE and H2ME.

1 / Assumptions for the demand calculation: Annual mileage: 15,000 km/y for personal vehicles, 25,000 km/y for LDV, 42,000 km/y for buses and 90,000 km/y for trucks; Consumption: 0.01 kg H_2/km for personal vehicles, 0.01 kg H_2/km for LDV, 0.07 kg H_2/km for buses and 0.08 kg H_2/km for trucks.

FIGURE 8.2

Total amount of hydrogen used in road mobility (t/year)



Source: Hydrogen Europe, using data from European Alternative Fuels Observatory.

Personal vehicles

Hydrogen personal vehicles have seen steady growth over the years (**Figure 8.3**). Compared to the battery-electric vehicles (BEV) market, this growth is slow. However, it should be considered that BEV manufacturers are larger in number, containing a broader range of vehicles for various buyers (different car sizes, powers, types, etc.).

On the other hand, the EU market for hydrogen personal vehicles comprises only two models – Toyota Mirai and Hyundai Nexo. The two amounted to a total number of 4,000 units in 2022.

However, Toyota has announced a new model by the end of 2023, while BMW has launched an X5 Hydrogen, starting with a pilot fleet of 100 units, distributed globally for testing purposes. Other manufacturers have also announced their entrance into the fuel cell vehicles (FCEV) market, such as Range Rover, Ineos, Rolls-Royce, Pininfarina, and several others.

In terms of powertrains, fuel cells are most often considered the main solution for personal vehicles powered by gaseous hydrogen, stored at 700 bar pressure.

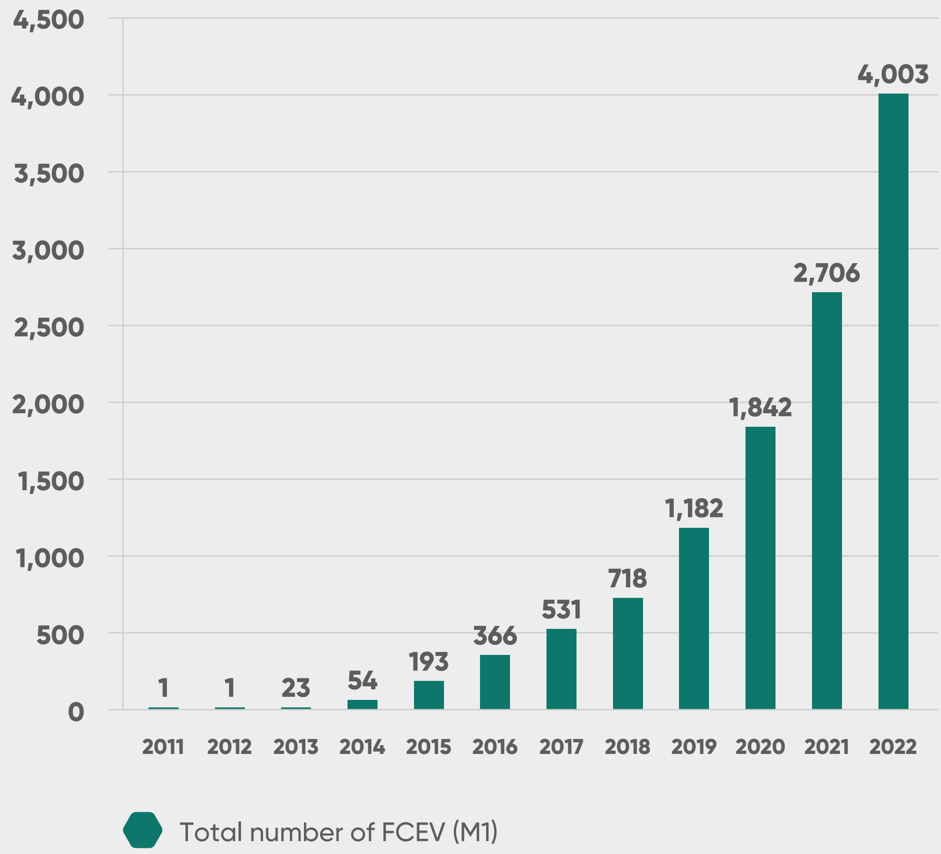
However, several manufacturers have been developing hydrogen internal combustion engines, while others have been developing liquid storage for personal vehicles.

As can be seen in **Figure 8.3**, hydrogen-powered personal vehicles are experiencing a steady but slow growth. One of the reasons is the slow development of refuelling infrastructure. The increase in vehicle numbers (and manufacturers) on the market, alongside with the build-up of hydrogen infrastructure[2], will lead to a potential increase in the total number of hydrogen personal vehicles. This can also be seen from **Figure 8.4**, where market distribution is more oriented towards developed EU countries with more developed infrastructure.

2 / Ensured by Alternative Fuels Infrastructure Regulation (AFIR).

FIGURE 8.3

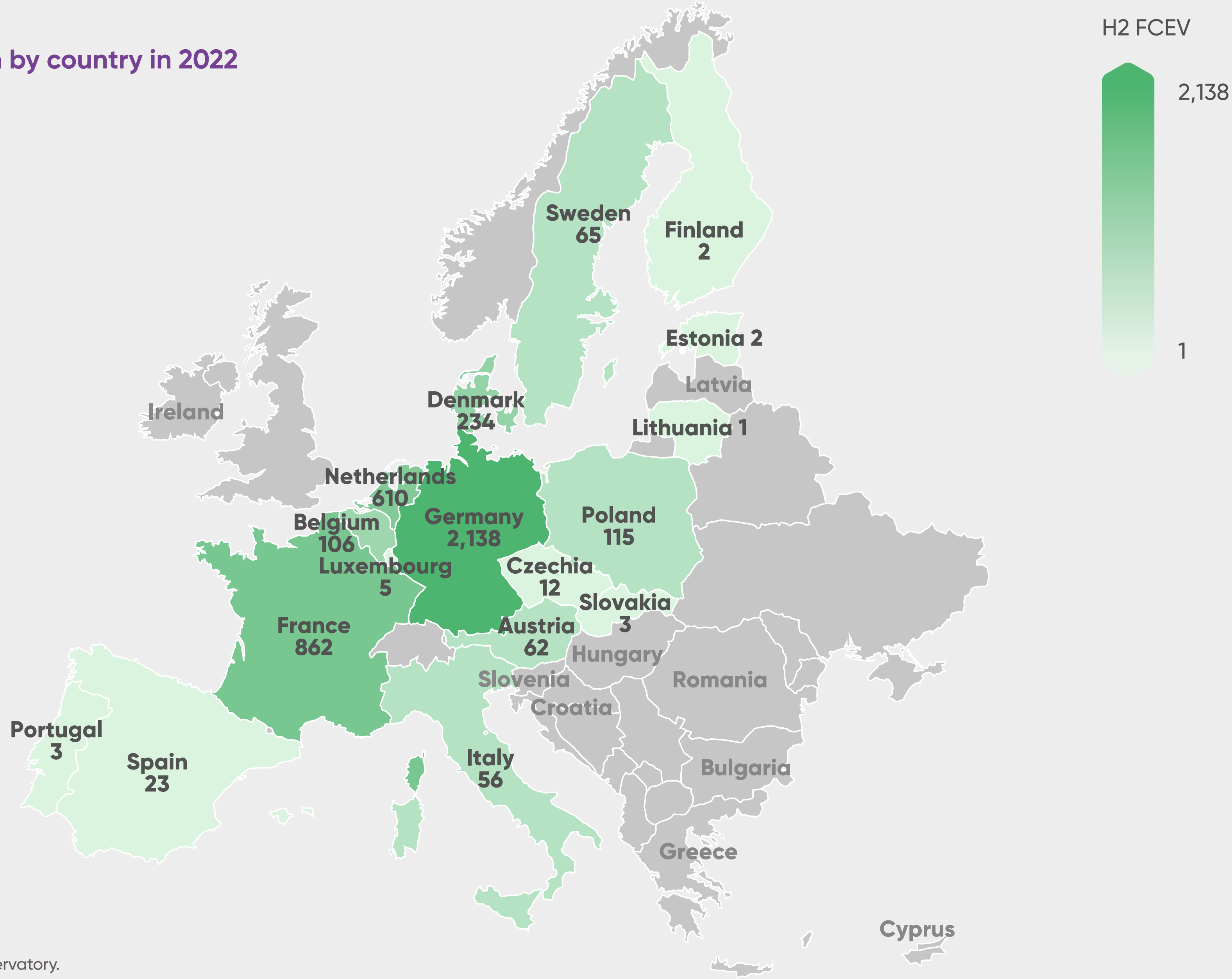
Number of FCEV in Europe



Source: European Alternative Fuels Observatory.

FIGURE 8.4

Map of FCEV distribution by country in 2022



Source: European Alternative Fuels Observatory.

Light-duty vehicles

Compared to personal vehicles, there are more models and manufacturers in the light-duty vehicles (LDV) market. Yet, the lack of refuelling infrastructure is having similarly negative effect, limiting the market growth rate (**Figure 8.5**). Furthermore, as almost 80% of commercial customers travel less than 200 km per day (on average), and around 40% never drive more than 300 km daily[b,c], hydrogen solutions in this sector face very strong competition from BEV alternatives.

They are more competitive with zero-emission alternatives as hydrogen-powered vans available on the market have up to 20 m^3 and 1,000 kg more storage capacity than their electric alternatives[d],[e].

Moreover, hydrogen LDVs have a range of around 400-500 km and a refuelling time of 3-5 minutes, which provides short stops and a quick continuation of the LDV's trip.

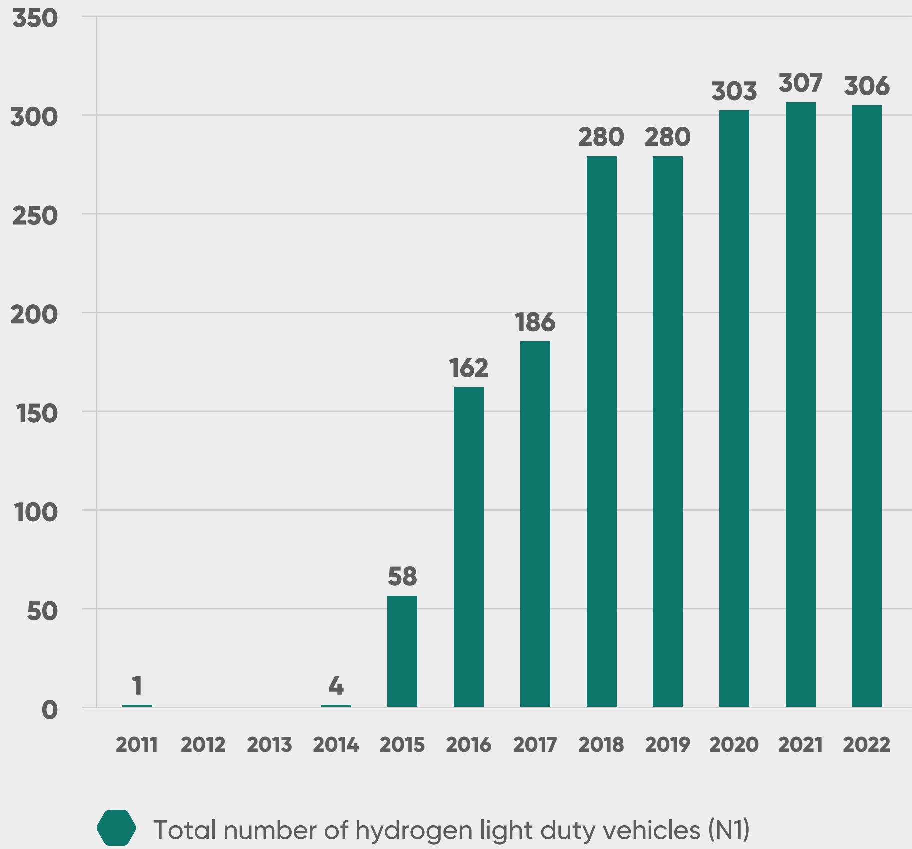
Those advantages create a favourable market outlook for hydrogen-powered LDVs, with many OEMs planning to enter the market with new models of vehicles. For example, the Stellantis group has been intensively working on deploying Peugeot, Opel and Citroen hydrogen-powered vans on the market – providing the end-users the option to choose between electric and hydrogen powertrains.

Some OEMs consider developing hydrogen-powered variants of their existing conventional models. Some examples are Hyvia[3], Ford[4] and Iveco[5], with other manufacturers intensively considering hydrogen-powered powertrains as an option within their model selection.

3 / Renault Master Van H2-TECH and Kangoo ZE hydrogen.
4 / Fuel cell E-Transit.
5 / Hydrogen e-Daily.

FIGURE 8.5

Number of hydrogen-powered LDV in Europe



Source: European Alternative Fuels Observatory.

Buses

Similarly to the LDV segment, the bus market is an arena of fierce competition between battery-electric and hydrogen-powered solutions (considering fuel cells, as well as hydrogen internal combustion engines) powertrains.

However, hydrogen-powered buses offer multiple benefits that make them quite similar to existing fleets, which are mostly run on diesel. This includes long range of up to 450 km on one refuelling. This is beneficial as it coincides with the buses daily route distance (300-400 km/day)[f].

Moreover, the refuelling time is less than 10 minutes, with further developments allowing to reduce that time to as short as 5-7 minutes[g]. FCEV buses do not require additional city infrastructure investments or permits other than a centralised hydrogen refuelling station (HRS) at the bus depot.

Hydrogen-powered buses provide consistent power delivery during the duty cycle, in heat and cold, which enables them to operate without issues during all seasons.

Hydrogen tanks are usually stored on the roof of the bus, while the fuel cell and electric engine are located at the back of the bus (**Figure 8.6**).

From environmental and social aspects, hydrogen-powered buses are silent and emit only water.

Due to aforementioned reasons, market uptake has increased significantly in 2022, as can be seen in **Figure 8.7**. This is mainly caused by the proactiveness of regions and cities which decided to select hydrogen as the fuel for their buses. Additionally, several project and proactive regions have promoted hydrogen-powered buses, including the JIVE project, which provides basic information on the various aspects, benefits and risks of hydrogen-powered buses in the city fleets.

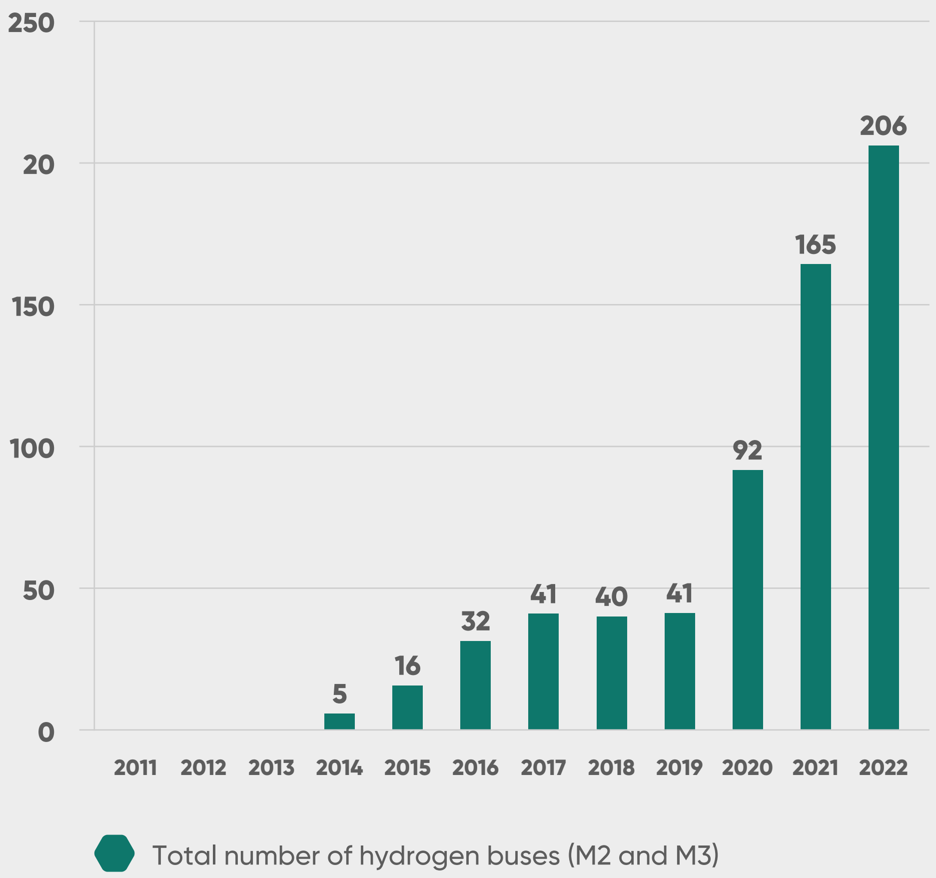
FIGURE 8.6

General schematics of fuel cell electric bus

Source: https//www.fuelcellbuses.eu

FIGURE 8.7

Number of hydrogen-powered buses in Europe



Source: European Alternative Fuels Observatory.

Heavy-duty vechicles

The heavy-duty vehicles (HDV) sector presents one of the most challenging sectors to decarbonise and bring to zero emissions. Emissions from lorries, buses and coaches are estimated to account for 6%[h] of total EU emissions, of which the vast majority comes from the trucking sector. The various zero-emission options include: hydrogen fuel cell trucks, battery trucks with stationary charging and battery trucks with catenary charging. Other options such as biofuels, H2 ICE and e-fuels, help reduce or eliminate GHG emissions, while still emitting NO_x and particulate emissions associated with internal combustion engines.

Fuel cell electric trucks have however many advantages over the competing solutions - most notably higher range and shorter refuelling times, achievable without compromising the cargo capacity of trucks. While fast charging for battery alternatives is technically feasible, this solution adds significant operating costs due to the cost of fast charging, resulting in a higher total cost of ownership when compared with hydrogen solutions in certain applications.

Even though most of the existing trucks models have working pressures in tanks of 350 bar, several OEMs are focusing on 700 bar (energy density at 1.3 kWh/l), are profiting from existing technology synergies and the need for long-distance driving without refuelling. Typically, type IV vessels are used to keep the weight as low as possible, which enables them to provide the end-user with more cargo area without reducing the FCEV range (**Figure 8.8**).

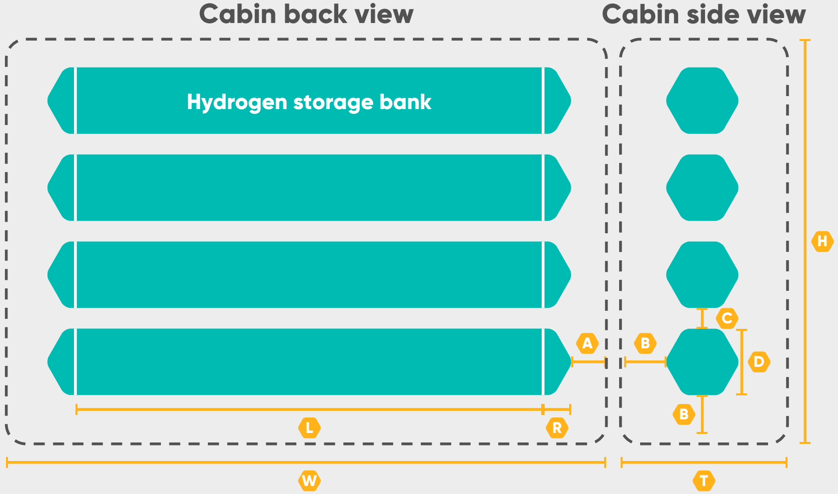
Moreover, Daimler Truck has announced a series of production starting in 2027 and is working on the first prototypes of the GenH2 Truck using subcooled LH2[6] technology (resulting in an energy density of 2.2 kWh/l[i]).

Due to the aforementioned advantages, hydrogen-powered trucks are getting a lot of interest in terms of heavy-duty zero-emission mobility, which can be seen in the increase of their number in 2022 (**Figure 8.9**), but also through the increased interest of OEMs in development of new models (Volvo, Iveco, Nikola, Toyota, etc.). Moreover, several EU-funded projects are currently ongoing, with the goal to provide data and information on the implementation of hydrogen-powered trucks, such as H2Haul and ZEFES.

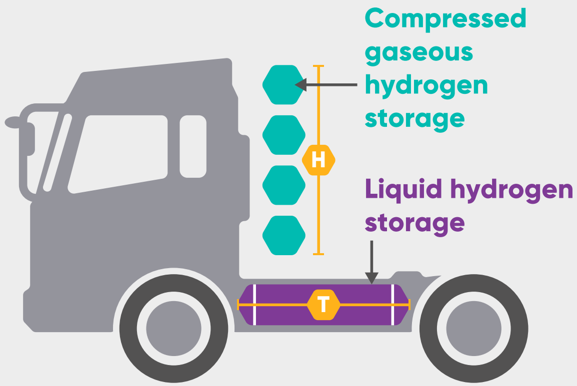
6 / Cooled to -247 degree Celsius.

FIGURE 8.8

Schematics of a hydrogen-powered trucks and positions of hydrogen tanks



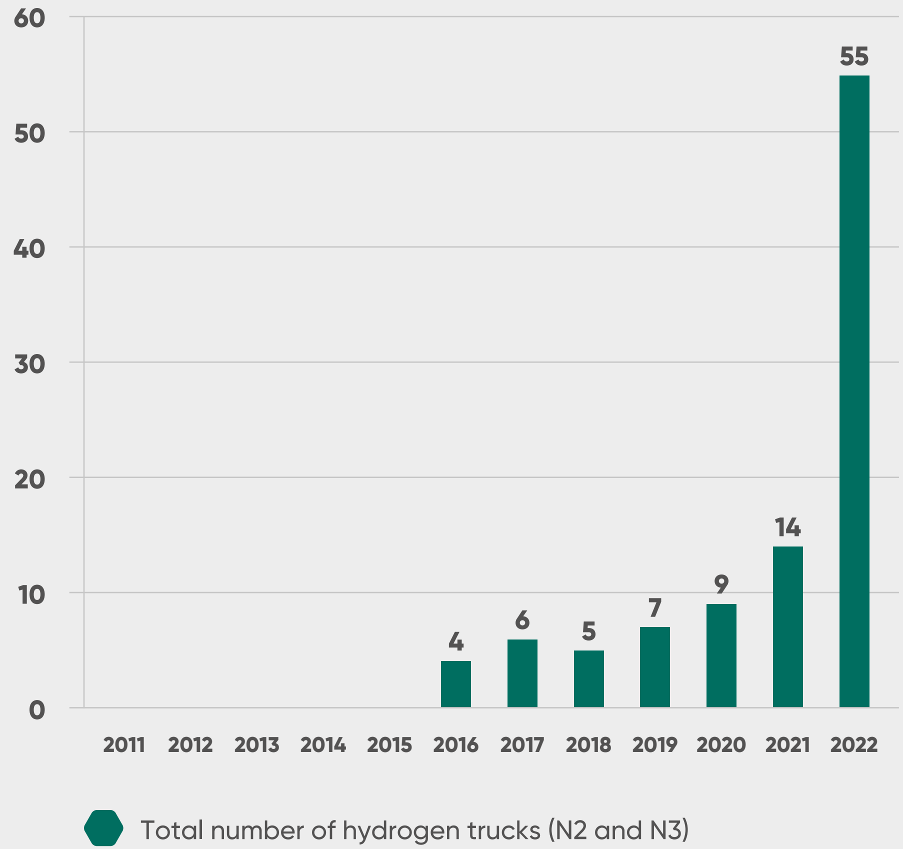
Dimension	Value (m)
W	2.2
H	2.25
T	0.9
A	0.09
B	0.05
C	0.05
R	0.1



Source: ICCT – Fuel cell electric tractor-trailers: Technology overview and fuel economy, 2022.

FIGURE 8.9

Total number of operational hydrogen trucks in Europe



Source: European Alternative Fuels Observatory.

Maritime Mobility

FuelEU Maritime sets ambitious goals to decarbonise the maritime sector. This could be achieved with liquid hydrogen and hydrogen vessels.

In accordance with Article 21 of Regulation (EU) 2015/757 on the monitoring, reporting and verification of CO_2 emissions from maritime transport, the European Commission provides the most comprehensive data via THETIS-MRV. Analysis of this data shows that the most common fuels causing the main emissions from the maritime sector are the following: diesel/gas oil, light fuel oil, heavy fuel oil, LPG (propane and butane), LNG, methanol and ethanol.

In order to reduce those emissions, a number of obligations through the FuelEU Maritime[7] regulation, which include the following targets for the reduction of GHG intensity of energy used on board of ships[8]:

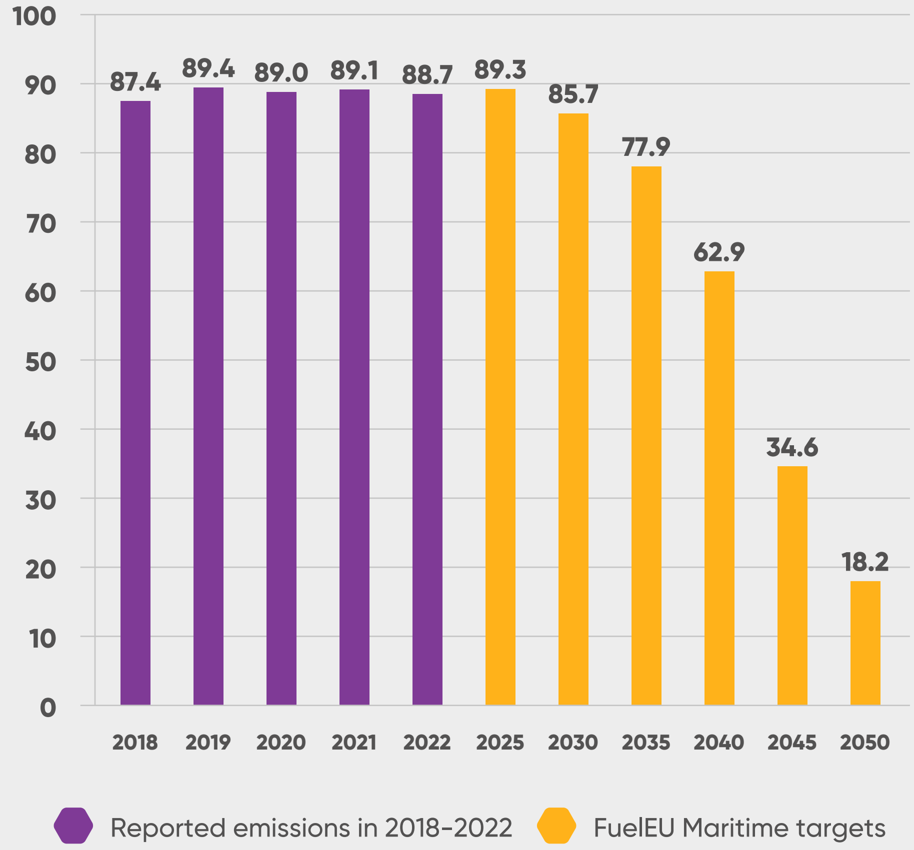
- 2% until 2025
- 6% until 2030
- 14.5% until 2035
- 31% until 2040
- 62% until 2045
- 80% until 2050

It can be seen that this demands a significant reduction in the following years[9] (**Figure 8.10**), in comparison to the current state-of-art, demanding gradual replacement of fossil fuels with their zero- or low-carbon alternatives.

7 / REGULATION OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL on the use of renewable and low-carbon fuels in maritime transport, and amending Directive 2009/16/EC
8 / In comparison to reference value of 91.16 g $CO2_{eq}$/MJ
9 / Calculations based on fuel consumption and total CO2 emissions for Well-to-Tank (EU 2023/1805) and Tank-to-Wake (EU 2015/757, Annex 1).

FIGURE 8.10

Average GHG intensity of energy used by ships above 5,000 GT (g CO_2/MJ)

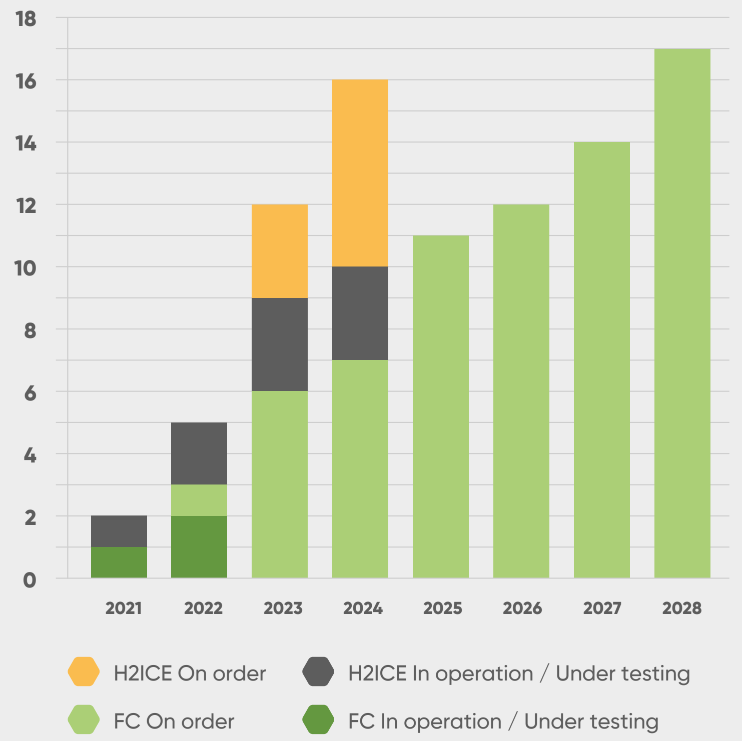


Source: Hydrogen Europe, using data from MRV (CO2 Emission Reports).

This represents quite a challenge, especially since this sector requires significantly high-power output[10] and fuel autonomy often measured in weeks, making battery-electric solutions not suitable for most application. Thus, there is a growing interest shown by ship-owners in using alternative fuels - including methanol, ammonia and hydrogen. For hydrogen as a fuel, both combustion engines as well as fuel cells remain a viable option.

FIGURE 8.11

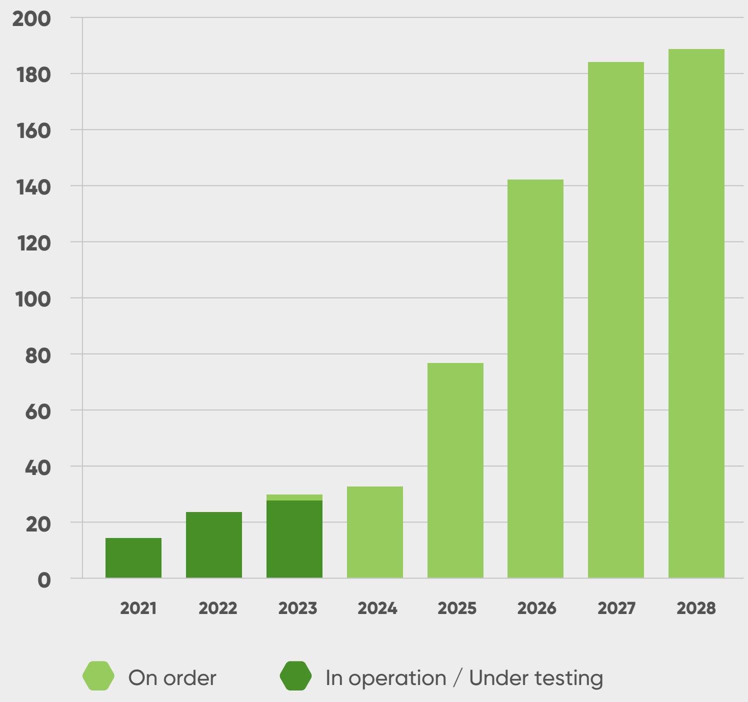
Number of hydrogen fuel cells and H2 ICE ships per year of delivery



Source: DNV – Alternative Fuels Insight.

FIGURE 8.12

Number of methanol ships per year of delivery



Source: DNV – Alternative Fuels Insight.

10 / Considering heavy-duty vessels (such as container ships, bulk carriers, tankers, cruisers, etc.).

Hydrogen Refuelling Stations (HRS)

AFIR will increase the deployment of hydrogen infrastructure and is set to increase the number of hydrogen-powered vehicles.

Hydrogen refuelling stations (HRSs) are one of the most critical parts of the distribution infrastructure required to implement hydrogen-powered mobility. Without a widespread hydrogen refuelling network, hydrogen vehicles are strongly limited in terms of operation, presenting the bottleneck in the wider distribution of hydrogen-powered vehicles and vessels.

Different modes of onboard hydrogen storage are feasible (liquid at -253°C, compressed gaseous at 350 or 700 bar), with different implications for refuelling architecture.

HRS number is steadily increasing in the EU, as shown in **Figure 8.13**, with a larger number of 700 bar HRS. Most stations are located in Germany, France, Denmark, the Netherlands and Belgium. The main end-users are personal vehicles, while 350 bar stations are focused more on buses and several deployed trucks.

With the implementation of AFIR[11], a specific number of HRS needs to be deployed by 2030 in the EU, making it an obligation for Member States to make the hydrogen infrastructure available for all end-users. This includes several specific points that need to be satisfied to achieve the minimum requirements, such as:

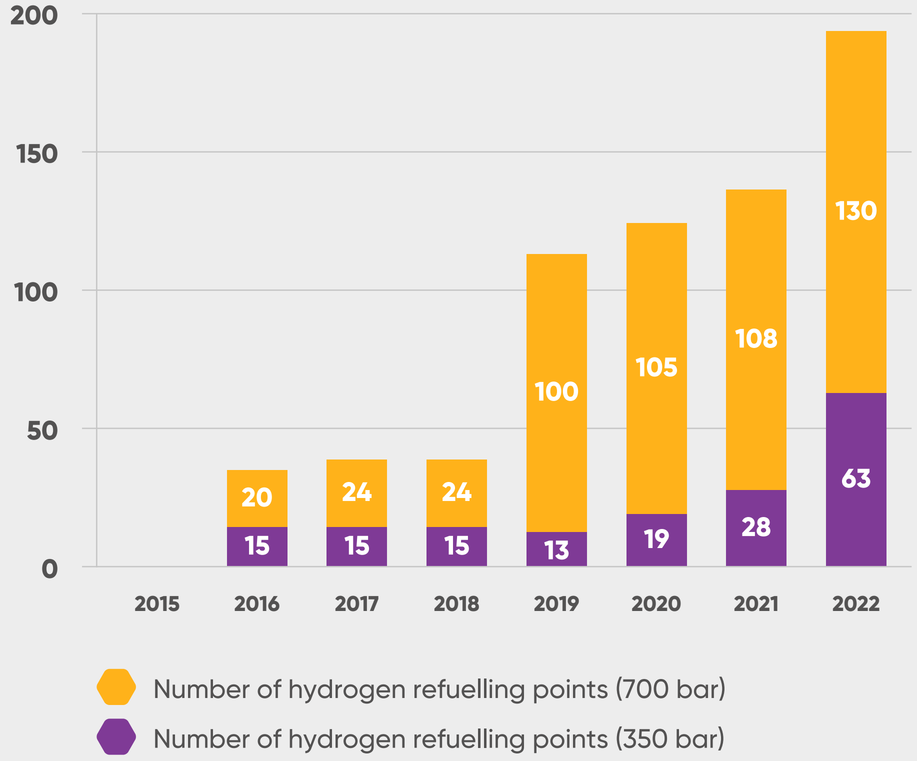
- One station each 200 km on the core TEN-T network and one station per each urban node.
- Minimum daily capacity: 1 t H_2/day (cumulative).
- Minimal pressure at stations: 700 bar.

The targets will be revised in 2024, with a possibility of ex anding them to cover LH2 at the HRS.

11 / Alternative Fuels Infrastructure Regulation

FIGURE 8.13

Number of HRS in Europe



Source: Hydrogen Europe, using data from European Alternative Fuels Observatory.

Hydrogen-powered mobility is still in its early phase of development. Yet, the future seems bright for faster uptake, as the regulatory framework is set to encourage HRS deployment, that will facilitate an acceleration of the growth of vehicle fleets.

The market for hydrogen mobility has been increasing year by year, as shown in previous chapters. OEMs are increasingly working on improving their hydrogen technologies and powertrains (both fuel cells and hydrogen internal combustion engines), which can cover the heavy-duty sector in particular, being viewed as the one with the most potential for uptake of hydrogen-powered vehicles and vessels. However, in terms of the maritime sector, additional low- or zero-emission solutions are needed to cover the energy demand this sector has – such as methanol, ammonia, and LPG. Additional solutions are also considered, including liquid organic hydrogen carriers (LOHC), which present a potential in the maritime sector, where high energy density is needed, while storage areas shouldn't be reduced.

Yet, research in efficiency, safety and emissions is ongoing. Especially in terms of the heavy-duty sector, two key financial barriers occur – developing a positive business case[12] and the high alternative fuel prices and electricity prices compared to fossil fuels.

However, to achieve this, the increase in hydrogen refuelling infrastructure deployment within EU and EU-neighbouring countries is crucial. The main bottleneck is the technological and standardisation approach (refuelling equipment, vehicle and vessel storage, etc.). Moreover, the various options (350, 500 and 700 bar, liquid, cryo-compressed) all have pros and cons, and different OEMs focus on different solutions. This brings disarray in the technology development process, as no general or standardised solution exists. AFIR offers a solution, determining the focus on 700 bar technology, with the potential for liquid hydrogen implementation. Additionally, there is a need for competitive hydrogen pricing at the HRS level and subsidies for hydrogen vehicles and vessels until the technology scales up to become price competitive on the market.

In conclusion, there is significant potential for hydrogen in the mobility sector, especially in heavy-duty transport (trucks, buses and vessels). Cost reduction through various research and development, but also commercial projects, is underway, enabling hydrogen and its carriers to become technically and economically feasible soon.

12 / Mainly focused on Total Cost of Ownership (TCO).

Endnotes

a / European Council, 2023.

b / Christensen, Klauenberg, Kveiborg, & Rudolph, 2017.

c / UK Department for Transport, 2021.

d / Opel, n.d.

e / Noble, 2021.

f / Ballard, 2021.

g / Ballard, 2021.

h / Clean Hydrogen in European Cities, 2015.

i / H2Accelerate, 2021.

j / H2 Mobility, 2021.

k / Hydrogen Europe, 2021.

l / DNV, 2022.

H2
HYDROGEN

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Commonly used abbreviations

AEL	Alkaline electrolysis/electrolyser
AEM	Anion Exchange Membrane
AFIR	Alternative Fuels Infrastructure Regulation
CAPEX	Capital expenditures
CBAM	Carbon Border Adjustment Mechanism
CCS/CCUS	Carbon capture and storage/utilization
CfD	Contracts for difference
CRMA	Critical Raw Materials Act
DA	Delegated act
DSO	Distribution System Operator
DRI	Direct Reduced Iron
ETS	Emission Trading System
ETS	EU Emission Trading System
FCEV	Fuel cell electric vehicle
FID	Final Investment Decision
GHG	Greenhouse gases
GW_{el}/year	Gigawatt of electrolysis per year
H2 ICE	Hydrogen internal combustion engine
HNO	Hydrogen Network Operator
HRS	Hydrogen Refuelling Station
IEA	International Energy Agency
IED	Industrial Emissions Directive
IPCEI	Important Projects of Common European Interest
IRA	Inflation Reduction Act
LCOE	Levelised cost of electricity
LCOH	Levelised cost of hydrogen
MS	Member state
NECPs	National Energy and Climate Plans
NZIA	Net Zero Industy Act
OEM	Original equipment manufacturer
OPEX	Operational expenditures
PE	Private Equity
PEM	Proton Exchange Membrane electrolysis/eletrolyser
PFAS	Per–and polyfluoroalkyl substances
PGM	Platinum Group Metals
PPA	Power purchase agreement
PtH	Power–to–hydrogen
RCF	Recycled carbon fuels
RED	Renewables Energy Directive
RES	Renewable energy source
RFNBO	Renewable Fuel of Non–Biological Origin
ROW	Rest of the world
RwCC	Reforming with carbon capture
SAF	Sustainable aviation fuels
SMR	Steam methane reforming
SO	Solid oxide electrolyser/electrolysis
STEP	Strategic Technologies for Europe Platform
TEN–T	Trans–European Transport Network
TYNDP	Ten-Year Network Development Plan
TPA	Third Part Access
TSO	Transmission System Operator
VC	Venture Capital
WACC	Weighted average cost of capital
ZEV	Zero–emission vehicle

Terminology

Clean hydrogen refers to power–to–hydrogen (electrolytic) and reforming with carbon capture projects/production methods. As we expand our project collection scope, this category will also include projects focused on gasification or pyrolysis of biomass, plastic waste, municipal waste, and other feedstocks if the emissions are below 3.38 kgCO2/kgH2.

Renewable hydrogen is used interchangeably with RFNBO hydrogen (Renewable Fuel of Non–Biological Origin) in this report and refers to hydrogen produced from renewable electricity and satisfying the conditions outlined in delegated acts of the Renewable Energy Directive.

Water electrolysis/power–to–hydrogen/electrolytic – This report uses the terms water electrolysis and power–to–hydrogen interchangeably. Water electrolysis or power–to–hydrogen (PtH) refers to electrolysers splitting water/solution with electricity with hydrogen being the main product. This excludes brine electrolysis.

Reforming (carbon capture)/Reforming with carbon capture refers to reforming, gasification, or partial oxidation of fossil fuels coupled with carbon capture of the emissions. In the operating plants, carbon capture rates are well below the ~95% that could be constituted to be low–carbon or clean hydrogen.

Non–abated fossil fuel–based hydrogen (fossil hydrogen) refers to hydrogen produced by steam reforming, partial oxidation, gasification, and autothermal reforming of fossil fuels without any CO2 abatement. Popularly referred to as "grey" hydrogen.

Reforming refers to hydrogen production from steam reforming, partial oxidation, gasification, and autothermal reforming of fossil fuels. These processes account for the largest hydrogen production capacity. This category also includes hydrogen produced in refineries as a by–product, e.g., during catalytic reforming.

By–product (ethylene, styrene) refers to the hydrogen production capacity as a by–product of ethylene and styrene production.

By–product (electrolysis) refers to by–product hydrogen production capacity from electrolytic chlorine and sodium chlorate production.

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