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Sector coupling and hydrogen policies in Europe

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1. Introduction

Not long ago, energy policy used to be neatly compartmentalized into individual industries. Transportation, power generation, heat production, and so on each had their own distinct material structure, rules, and behavior-governing norms and practices. With rising climate change concerns, energy policy has effectively merged with climate policy and the transition to low-carbon energy has become a priority. This paradigm shift has spurred rapid technological development, introduced new rules and practices and generally redefined the energy landscape. Along the way, the existing borders between industries were disrupted as the decarbonization of one tends to be closely tied with the decarbonization of others. The construction of an all-encompassing integrated energy system is now underway.

Conceptually, this process has been understood as "sector coupling", i.e., bringing individual industries closer together to optimize the energy transition as well as the deployment of enabling technologies such as energy storage and hydrogen. This book is intended to reflect on this process. It was written as a part of a larger research project aimed at developing a Europe-wide sector coupling model. The model optimizes the deployment of renewable energy and the use of the existing natural gas infrastructure, while the presented book contextualizes the model's environment and its results. Specifically, it sets out to answer the following research questions:

1. What is sector coupling and how is it understood across different political and analytical contexts?
2. What role will hydrogen play in the development of sector coupling?
3. What are the current and expected hydrogen policies in Europe, USA, and China?

The book is organized as follows: First, a general overview of approaches towards sector coupling and hydrogen is presented (Section 2). Second, sector coupling and hydrogen policies in the European Union are discussed (Section 3). Third, the policies of six front-runners (Denmark, France, Germany, Spain, China, and USA) are introduced in depth. We conclude by summarizing the main challenges and debates which will shape the future development of sector coupling and hydrogen within the energy transition.

2. General overview of sector coupling and hydrogen policy

2.1 Sector coupling and the energy transition

The role of renewable energy sources in achieving the set climate goals is indisputable. However, the nature of these sources means that the respective electricity generation is not dispatchable, directly affecting the entire electricity system, not only in the long term but also within a single day (Ramsebner et al., 2021). The concept of sector coupling (SC), whose popularity has risen along with the German energy transition, the so-called *Energiewende* (Fridgen et al., 2020), is believed to be the answer and the right path to achieving an efficient and reliable energy system based on renewable energy (Ramsebner et al., 2021).

However, what SC refers to differs across the existing literature, as some authors use a narrower and some a broader definition of SC. While Schaber et al. (2013) briefly present SC as the "interconnection of the power, heat, hydrogen, and natural gas sector," Ramsebner et al. (2021) define SC as a solution that would support "establishing 100 % renewable energy systems, adding flexibility and improved storage and distribution options to the use of renewable electricity. Still other authors offer more complex definitions.

Robinius et al. (2017) lean towards an understanding that sees SC as connecting the sectors of electricity, heat, mobility, and industrial processes along with their infrastructures. According to the authors, the objective of SC is "decarbonization, while simultaneously increasing the flexibility of energy use in the sectors of industry and commercial/trade, households and transport under the premises of profitability, sustainability and security of supply" (Ibid.).

Münster et al. (2020) offer an interesting definition of SC as an "energy conversion process towards an adjacent industrial sector," where the converted energy may go in three different directions. It can be either "stored more easily outside than inside the electric system […], consumed in another sector […] or transported (in form of heat or gas/liquid)" (Ibid.). This makes SC a "complex multi-variables optimization problem with the objective of minimizing design and operational cost" (Ibid.) with regard to "decarbonization targets, system-inherent boundary conditions, and operational constraints" (Ibid.).

The study by van Nuffel et al. (2018) explains that at the beginning SC was mainly discussed in the matter of electrification of end-use sectors, such as transport or heating, with the goal of more effective integration of renewable energy in these sectors and "providing balancing services to the power sector" This broad definition of SC is then similar to energy system integration (ESI), which is defined as "the process of coordinating the operation and planning of energy systems across multiple pathways and/or geographical scales to deliver reliable, cost-effective energy services with minimal impact on the environment" (Ibid.). Nonetheless, the authors remark that the concept's understanding has recently expanded to include the supply side as well. Integration of the supply side is then tightly associated with the integration of gas and power sectors, using technologies such as power-to-gas, which will be discussed in later sections of this chapter.

Furthermore, Fridgen et al. (2020) associate the concept of SC also with so-called *smart energy systems* or *multi-energy systems* (MES). Concerning the latter, there is a vast amount of literature (e.g., Guelpa et al., 2019; Ma et al., 2018; Mancarella, 2014; Mazzoni et al., 2019). Mancarella (2014), for example, highlights the advantages of MES, namely vis-à-vis its technical, economic, and environmental performance in comparison to "independent or separate energy systems".

Returning to the concept of SC itself, in recent years the literature on SC has grown with studies examining the concept at national or otherwise geographically defined scales, providing several case studies, modeling frameworks, and simulations (Edtmayer et al., 2021; Gils et al., 2022; Nasimul Islam Maruf, 2019; Rinaldi et al., 2021). While a significant amount of research is dedicated to the initiator, Germany (Kanngießer et al., 2021; Maruf, 2021; Palzer & Henning, 2014; Robinius, Otto, Syranidis, et al., 2017), other countries, such as Ireland (Connolly et al., 2011), Denmark (Skov et al., 2021) or Brazil (Gils et al., 2017), are also featured.

Great attention is also paid to individual technologies. This is because one of the main positive aspects of SC is that it enables indirect electrification of energy processes that cannot be electrified directly (e.g., high-temperature industrial processes using green hydrogen) (Olczak & Piebalgs, 2018). SC also creates new possibilities in linking energy carriers and transport infrastructure. For example, excess electricity can be used for water electrolysis to produce hydrogen or for the process of methanation to achieve synthetic methane. Those can then serve for technologies that fall under the common designation “Power-to-X” (P2X), such as Power-to-Gas (P2G), Power-to-Liquid(s) (P2L) or Power-to-Heat (P2H) (Ibid.). Not surprisingly, there is an extensive amount of literature concerning the use of these technologies in SC.

To briefly introduce P2G technology, Sterner and Specht (2021) describe it as the “conversion of renewable energy to renewable gas”. This conversion is done by combining two crucial processes—water electrolysis and carbon dioxide (CO_2) methanation. During the electrolysis, water is split into hydrogen (H_2) and oxygen (O_2) using renewable electricity (generated by renewables). The resulting hydrogen is then converted with CO_2 into methane (CH_4) during the methanation process. Since methane is the main component of natural gas, the generated renewable gas is a “substitute natural gas (SNG) that can be fed and stored 1:1 in the natural gas grid” (Ibid.). P2L technology is associated with P2G as it comes from the described P2G processes but the resulting product is in liquid form (Varone & Ferrari, 2015).

Another P2X technology that is gaining progressively more attention is P2H. The reason is, as Bloess et al. (2018) explain, the fact that in many industrialized countries decarbonizing the heating sector would mean substantial progress toward achieving the set climate targets. The reason is that space heating is, in many countries, responsible for a significant portion of final energy demand and greenhouse gas emissions while still being far behind other sectors regarding renewable energy utilization.

The P2H concept is based on converting renewable electricity to heat through heating resistors, electrode boilers, and heat pumps. The associated strategies can then be applied at both centralized and decentralized levels. The centralized level refers to district heating, where the heat is produced centrally using either electric boilers alone or combining them with large-scale heat pumps. In this approach, the energy for the generation of heat is provided by the grid. Decentralized heat production refers to heat generation at the residential level and therefore does not involve using a heating network (Rehman et al., 2021). As the authors emphasize, most P2H options at both levels are associated with an energy storage mechanism.

As already mentioned, one of the biggest challenges regarding implementing renewable energy sources in energy systems is their questionable stability and reliability, which stems from their intermittent nature. The answer to such a challenge lies in integrating energy storage systems into the power grid. Such storage systems would ensure the regulation of renewable energy generation and the overall flexibility of the energy system (Wade et al., 2010). For instance, Steinmann et al. (2019) present one of the possible energy storage technologies from the P2H perspective, pumped thermal energy storage (PTES), as a “versatile concept for sector coupling in future scenarios with high penetrations of heat and electricity delivered by renewable energy sources”. Liu et al. (2020) offer a complex modeling framework for combined cooling, heat, and power (CCHP) long-term planning while accounting for energy demand variations, costs of technologies, resources, emissions, and selection of energy storage technologies.

Nevertheless, several authors raise questions about the restraints of various P2X technologies. While, for example, Schnuelle et al. (2019) present a socio-economic assessment discussing the potential and limitations of integrating P2X technologies into the German energy system. The authors point out that both on the centralized and decentralized levels, the given P2X concepts are realizable from a technical perspective. The main difficulties and limitations are tied to high capital expenses and disadvantageous legal framing conditions, at least when it comes to extensive integration of P2X technologies into energy systems. Decourt (2019) underlines that another crucial weaknesses of the employment of P2X technologies is social acceptance. The author explains that since most applications of these technologies are often invisible to end-users, the "ability to leverage the social recognition associated to clean-technology promotion and adoption" is limited.

2.2 Hydrogen and its role in sector coupling

Hydrogen has become one of the most discussed possibilities to tackle climate change and successfully achieve energy transition. For some hydrogen has a crucial role and its use is often described as inevitable (Griffiths et al., 2021), while for others it may also be a rather controversial topic (Cheng & Lee, 2022). This section presents the basic techno-economical aspects of hydrogen production and use as well as its role in SC.

Hydrogen has been used for decades primarily as a feedstock in chemical industries, e.g., ammonia and methanol production, steel industry, and petroleum refineries (Böhm et al., 2021). In terms of its sourcing, hydrogen can be produced in a variety of ways, each having its own energy, material, and carbon intensity. The hydrogen community labels these with colors (see Table 1).

Table 1. The colors of hydrogen

Hydrogen type	Technology	Fuel or feedstock	Carbon intensity
Grey	Steam methane reforming	Natural gas	High
Black or brown	Gasification	Coal	High
Blue	Steam methane reforming + carbon capture and storage	Natural gas	Low (about 10% of "grey" hydrogen)
Green	Electrolysis	Water + renewable energy	Zero
Pink	Electrolysis	Water + nuclear energy	Zero
Yellow	Electrolysis	Water + power grid mix	Depends on the mix
Turquoise	Methane pyrolysis	Natural gas + high temperature heat	Zero

Sources: GasConnect, 2020; World Economic Forum, 2021

One of the most used production methods is steam methane reforming. Such a method is applied when operating with natural gas or biogas. During this thermochemical conversion, a reaction between the steam and methane is produced, leading to the creation of synthetic gas that consists predominantly of hydrogen (Office of Energy Efficiency & Renewable Energy, 2022).

Another method is water electrolysis, a process of separating water into hydrogen (H_2) and oxygen (O_2) using electricity. Using an electrolyzer consisting of a cathode and an anode that are immersed in an electrolyte, an electrical current is applied which then splits the water molecules, with hydrogen at the cathode and oxygen at the anode (Nikolaidis & Poullikkas, 2017). To produce green hydrogen, the electricity used for electrolysis must come from renewable sources. Such hydrogen then has no directly connected carbon dioxide (CO_2) emissions (Nebel et al., 2022). Since green hydrogen is produced by renewable power, this process is also called "Power-to-Hydrogen".

The major benefit of green hydrogen deployment is its technical potential "to channel large amounts of renewable electricity to sectors for which decarbonization is otherwise difficult" (IRENA, 2018). Industry is one such sector. As previously mentioned, chemical industries constitute a significant portion of CO_2-intensive industries. Such sectors are urrently using grey hydrogen and thus producing GHG emissions. It is, however, possible to substitute grey hydrogen with green hydrogen and thus decarbonize the respective industrial processes (Ibid.).

The steel industry can serve as an example. This industry mainly depends on coal or coke, which serves as a reducing agent and heat provider and ensures the "mechanical stability of the different layers of coke and iron ore inside the furnace" for a conventional blast furnace (Otto et al., 2017). Using green hydrogen as a substitute in these processes would then be the answer for this industry to reduce its carbon emissions (Böhm et al., 2021). As Liu et al. (2021) explain, there are two aspects to the application of hydrogen in the steel industry. The first option for using H_2 is using it as a reducing agent to reduce iron oxide during the blast furnace production process or the gas-based direct reduction iron process. The second option is to use hydrogen as a "fuel for heating, including assistant sintering production, palletizing process, or heating ladle furnace" (Ibid.).

Hydrogen also has considerable potential to decarbonize the transport sector (e.g., Ajanovic and Haas, 2021, 2018; Ehret and Bonhoff, 2015; Kendall, 2015). This sector is responsible for approximately a third of total energy use and more than a quarter of total GHG emissions (Ajanovic & Haas, 2021). The advantage of hydrogen-fueled mobility, i.e., using fuel cell electric vehicles (FCEVs), is its comparability to conventional vehicles in the sense of driving performance and, therefore, driving range and refueling time. This is where battery electric vehicles (BEVs) fall short. Hydrogen, however, is primarily seen as a solution where the use of electric batteries is currently limited—i.e., long-range or heavy-duty vehicles (e.g., trucks, trains, aviation, shipment) (IRENA, 2018).

H_2 is also seen as a solution to lower the carbon footprint of the entire gas sector value chain. Using hydrogen in a gas grid is possible either by blending hydrogen into natural gas or via the aforementioned methanation (converting H_2 and CO_2 into methane). According to Cavana et al. (2021), electricity–gas SC via blending hydrogen within the existing gas infrastructure is thus considered an effective decarbonization option for the emerging hydrogen economy development.

Hydrogen also has many prospects for energy storage. Nebel et al. (2022) explain that after water electrolysis the hydrogen is stored in low- or high-pressure vessels or in geological (underground) storage. The latter is the most suitable option for large capacity and long-term storage and would store hydrogen under high pressure, making it possible to withdraw when necessary. Such solutions would provide an energy system with the needed resiliency as well as flexibility, for example, by making it possible to store excess renewable energy and "balancing peaks and troughs in demand" (Hydrogen Council, 2021b).

If hydrogen is to fulfil its promise, targeted policies will be required to de-risk it. De-risking can be understood as a series of actions aimed at mitigating uncertainty around a specific decarbonization activity or technology (CEER, 2022). There are several interrelated reasons why de-risking is important for the diffusion of emerging technologies. First, it communicates government's interest in developing the technology, which may bring public (co-)financing or other means of public support in the early stages of implementation. Second, it provides enabling institutions such as banks and insurance companies with information about which technologies are preferred and therefore “politically sustainable” in the long term. This makes such technologies potentially less risky and, consequently, less costly to co-finance and insure. Third, government support and more accessible financing and insurance create a more attractive investment environment and incentivize private actors to invest in the new technology and take an active part in its development. Examples of de-risking new technologies or politically desirable projects include the Europe-wide rollout of feed-in tariffs, which featured fixed price and guaranteed offtake for producers of renewable energy (Karneyeva & Wüstenhagen, 2017), and the EU’s “Projects of Common Interest”, i.e., a regularly updated list of gas and electricity infrastructure which is considered important for the development of the European common energy market and which is eligible for minor financial support (Marshall, 2014).

In the case of hydrogen, uncertainty stems mainly from its sourcing and its use. With regards to the use of hydrogen, a large variety of applications have been contemplated. Hydrogen has been nicknamed “the Swiss army knife of the energy transition” and a debate has emerged whether the use of hydrogen will be restricted to applications where there is no other viable decarbonization option or whether its supply chain will be interwoven with all sorts of industries and applications (Hydrogeninsight, 2022b).

Over time, as it has become more widely understood what a ramp-up of hydrogen production would entail, the hydrogen community has progressively abandoned some of the most ambitious hydrogen applications, such as passenger transportation, low-temperature heat in industries, and small-scale heating. These may not be the last casualties of the rapid development of competing technologies. The progress in battery technology, for example, has rendered the use of hydrogen in automobiles, and recently also light trucks, impractical and expensive. Similarly, heat pumps have become the technology of choice for many households seeking an alternative to natural gas. The reasons why hydrogen fights uphill battles are energy efficiency, capital intensity, and technological maturity. Furthermore, the competing technologies have already achieved significant economies of scale, providing investors with less uncertain investment environments and users with more predictable products and services. In short, the marketing for future hydrogen has been a moving target throughout recent years and many envisaged applications have become controversial or outright wrong idea (Hydrogeninsight, 2022c) (see Table 2).

Table 2. Hydrogen applications

Application	Industry	Transport	Power sector	Buildings
Uncontroversial	Reaction agents (DRI steel); feedstock (ammonia, chemicals)	Long-haul aviation; maritime shipping	Long-term storage for variable renewable energy back-up	District heating (residual heat load)
Controversial	High-temperature heat	Trucks and buses; short-haul aviation and shipping	Absolute size of need given other flexibility and storage options	
Wrong idea	Low-temperature heat	Cars; light-duty vehicles		Individual buildings

Source: (Bock et al., 2020)

Aside from the uncontroversial applications, the main source of demand for the years to come will stem from the existing use of hydrogen. Currently, over 90 million tons of predominantly unabated fossil fuels-sourced hydrogen are being used on a yearly basis in oil refining and production of ammonia and methanol (IEA, 2022). This amount is by no means small. The IEA's Net Zero Emissions scenario assumes a total hydrogen consumption of 180 tons in 2030 (IEA, 2022), which means that more than half of the envisaged 2030 market already exists. The uncertainty around future applications thus affects the concerned sectors and industries rather than hydrogen producers themselves.

With regards to the sourcing of hydrogen, the main uncertainties are associated with the choice of production technology and respective fuels and feedstocks, the question of hydrogen imports, and the future shape of the hydrogen market. Currently, about 99% of hydrogen produced is grey or comes as a byproduct of (mainly) the petrochemical industry. Future production, according to the IEA, should shift to zero or low-carbon alternatives, of which green hydrogen now appears the most viable (IEA, 2022). However, there are a few challenges on the way. First, the electrolyzer capacity needs to be scaled up fast. More precisely, to meet the Hydrogen Council's vision of a 2050 hydrogen market ten times bigger than today's, capacity has to grow by more than 30% per year starting 2021. While certainly a "huge undertaking", the Council points out that solar PV and offshore wind managed to grow at a comparable or even higher pace (Hydrogen Council, 2021a). In fact, there have been voices warning against oversupply in hydrogen capacity throughout the 2020s (Hydrogeninsight, 2022a).

Second, these electrolyzers will require a lot of (renewable) power. The mere replacement of current hydrogen production with green hydrogen will require around 140% of the wind and solar capacity installed to date (Hydrogeninsight, 2022b). This raises the question whether the development of hydrogen would not hinder the transition to renewable energy rather than enable it (Bellona, 2021). Since there are considerable capital and operational costs associated with storing electricity via hydrogen, it can be expected that until we develop significant renewable energy surpluses direct electrification will be preferred wherever possible. It remains an open question which hydrogen applications will by that time cease to be "uncontroversial".

Sourcing hydrogen is closely associated with the questions of international trade and the designing of emerging hydrogen markets. While domestic sourcing will be a priority for many European countries, regional differences in access to renewable energy will cause the formation of hydrogen production clusters where energy surpluses can be taken advantage of. Depending on the pace and scale of such development, the hydrogen trade will generate highly selective economic growth, create new interdependencies, and introduce new security of supply concerns (IRENA, 2022). The fallout of the 2022 gas market crisis in particular can be expected to shape the perspectives of key players.

Finally, the development of hydrogen trade will raise regulatory questions. New standards and certification schemes, e.g., for tracking and reporting carbon footprint, will need to be developed, agreed on, adopted, and enforced across jurisdictions. Similarly, a suitable market design will need to be adopted (IEA, 2022). The experience with natural gas market liberalization and integration can be useful in preventing the monopolization of local hydrogen clusters and in mobilizing competition among hydrogen producers while keeping an eye on security of supply (Tanase & Anchustegui, 2022).

3. Sector coupling and hydrogen policies in the European Union

The sector coupling (SC) debate on the European Union (EU) level has its roots in the energy transition debate and the discussion about the role of gases in decarbonizing the EU´s energy sector, potential contribution of gas infrastructure, and potential of SC in general.

The European energy transition towards climate neutrality in 2050 is supposed to represent the gradual transformation of the European energy sector from its fossil fuel past toward a fossil-free and sustainable future, which will be primarily electrical. Nonetheless, gas plays an essential role within the European energy mix, and thanks to its flexibility it combines well with intermittent renewable sources of energy. Therefore, natural gas was for a long time considered a suitable transition fuel on the EU's path to decarbonization in 2050. It was a logical option as its burning produces only half of the CO_2 emissions as coal, it was cheap and accessible, and there was already existing infrastructure. Also, natural gas was and still is crucial for some industries, where some production processes are technologically dependent on gas and cannot transfer to electricity only.

However, due to geopolitical tensions wherein natural gas can be taken hostage by Russia, the EU and its Member States (MS), realizing their vulnerability and how much they underestimated energy security, are giving second thought to their original plan to rely on gas as a transition fuel. Therefore, the time may come much sooner than initially expected for renewable fuels of non-biological origin (RFNBO), particularly hydrogen. While there are several unknowns and questions to be addressed first, clearly the current energy crisis is forcing MS and European industry to search for available and affordable alternatives to natural gas from Russia. At such times of high gas and electricity prices, RFNBO emerge as a competitive alternative.

3.1 Energy transition and European climate and energy policy

As history keeps proving, energy systems are in constant development and under the scrutiny of many challenges and trends continuously appearing around us—"[a] long-term process of change that results from the economic, social, technological, institutional and/or ecological development" (Williams & Doyon, 2019). All those changes have a significant impact on society and are reflected in relevant policies. There are four fundamental technological milestones of energy transitions—industrial/coal, electrification, nuclear, and now decarbonization via renewables (RES). At the same time, observing changes in the energy discourse within society is also interesting, especially the changes in the 1990s and first decade of the 21st century when a growing emphasis on environmental policy and the negative impacts of energy on the climate began to be reflected also in energy policies. Today, the goal of decarbonization appears to be the standard, and with it a growing emphasis on decentralized resources.

Let us look at the concept of transition more broadly. It is a relatively clearly definable term understood as a process of change (Cambridge Dictionary, 2022) or as "a process or period of transition from one state or condition to another" (Oxford Dictionary, 2022). In an energy context, however, it constitutes an essentially contested concept (Gallie, 1955) due to its multidisciplinary overlap and debate regarding what to include under the concept and what not. In general, it can be defined as a change in the energy system, usually to a specific fuel source, technology, or driving force (Sovacool, 2016), or as a transformation towards a more sustainable system of energy production and demand (Bartiaux et al., 2019).

According to Verbong and Geels, the European energy transition has its roots in the 1960s and 1970s, when the central defining movements were liberalization and Europeanization

(Verbong & Geels, 2007). Environmental aspects only gradually became part of the transition, but not the main motive. In this context, Ottinger also claims that "the true transition of the energy system is not only based on new technologies but must also be accompanied by a proactive and collaborative decision-making process" (Ottinger, 2013), which is significant for the EU itself. The EU has long recognized the importance of tackling and limiting the impact of climate change. The energy-climate package set the first climate goals on the EU level in 2008, and its key objective was to reduce emissions by 20% by 2020. In 2014, the EU decided to go further and increased its target for 2030 to reduce greenhouse gas emissions by at least 40%. The decarbonization of the energy sector and the associated energy savings and consumption reduction trends form the development framework of the European Union and set the direction for research, investors, and industry. They represent the technological and social change that supports a sustainable system, and the aim is for Europe to become a leader in this direction and in the field of renewable technologies globally (European Commission, 2022b).

The current position of the European Commission and the European Parliament accelerates this approach even more. The key document is the Green Deal for Europe, presented in December 2020 and setting the binding target of net domestic reduction of at least 55% in greenhouse gas emissions by 2030 compared to 1990. Overall, the EU aims to be climate-neutral by 2050. European climate policy is thus the main driver of the energy transition in Europe as it significantly shapes the energy mix of MS and their strategies.

In response to the 2021–2022 energy crisis and the forecast of low future availability of natural gas, the EU introduced REPowerEU: A plan to rapidly reduce dependence on Russian fossil fuels and fast forward the green transition. Energy savings, diversification of energy supplies, and accelerated rollout of renewable energy all play significant roles within this plan (European Commission, 2022e). What is also important is that natural gas is no longer seen as a transition fuel. Where possible, MS are returning to their domestic energy sources (often coal) or more available sources like oil, emphasizing that such steps are only temporary. For some, this situation offers justification for nuclear power plants, though they do not offer a fast-fix solution, while others are planning to jump straight from fossil fuels to low-carbon sources.

3.2 Sector coupling debate: main features

In Europe, the SC idea is closely linked to the significant moment of the 21st Conference of the Parties (COP21), which culminated in the 2015 Paris Agreement, and with the German *Energiewende* policy, for which SC represented flexibility, storage, and transition. Both were crucial for accelerating the energy transition and helped launch the deployment of various renewable energy sources.

Early in the debate, SC was perceived as an essential concept and path toward cost-efficient decarbonization of energy systems. Thus, it soon gained prominence in political discussions among European institutions, EU MS, and other relevant actors from the energy sector. It gained momentum for the first time as a part of the EU energy policy debate on the agenda of the Madrid Forum in 2018. There it was agreed that the energy transition requires a mix of energy sources and technologies and that "renewable and low-carbon gases, in particular biogas, biomethane, and hydrogen, should play a significant and growing role" (European Gas Regulatory Forum, 2018). Thus, RFNBO have been part of the debate ever since, with a tightening linkage between the electricity and gas sectors. More specifically, such linkage is found when the synergies between the two sectors are used to maximize our usage and effectivity of electricity produced from renewable sources of electricity and when we can transform it to renewable gas and effectively store it using existing gas infrastructure.

However, it is important to highlight that SC also implies new circumstances and interconnections in the energy sector and not merely creating a substitute for the natural gas sector. The European energy transition has its clear order—the main emphasis shall be placed on electrification and only those sectors that cannot be electrified or where it would be otherwise inefficient to do so shall transfer to RFNBO. As the transformation process of electricity to RFNBO always entails significant losses and is more expensive than electricity production alone, it does not make economic sense to transform electricity to renewable gas for use at a higher price in areas and sectors where electricity can be used directly, unless there is a surplus of electricity which cannot be used and thus needs to be stored. Nevertheless, even in the case of maximal electrification, there will still be high demand for RFNBO, especially in industry and heavy transport. This demand is expected to be higher than what is currently being produced, and what is currently being produced does not represent a competitive energy source. Nevertheless, as the urgency for a quick transition increases with the current energy crisis and geopolitical situation, we might see faster developments in SC.

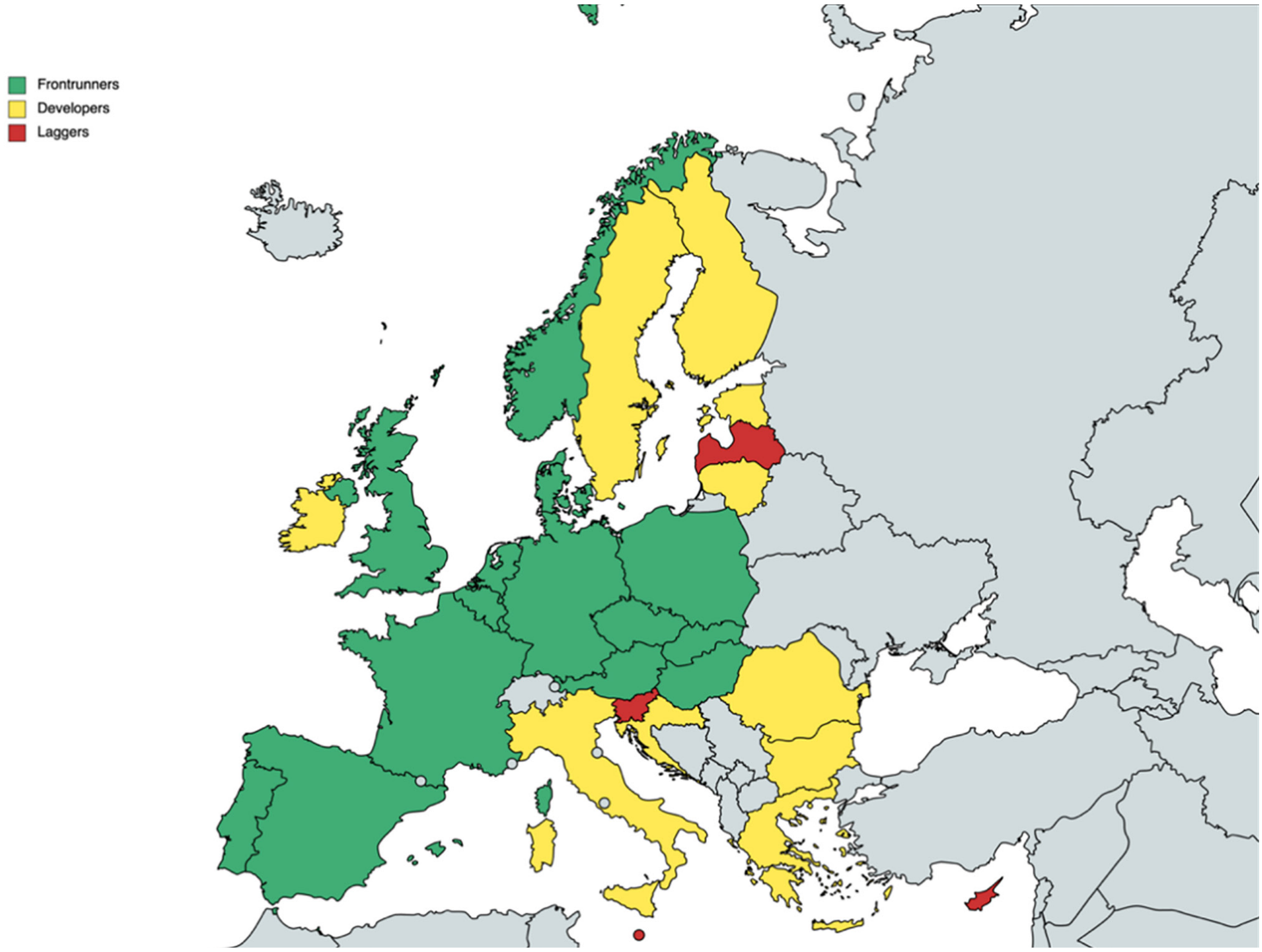
3.3 Main actors

Among the main actors in the EU is the European Commission (EC), which creates the framework for RFNBOs and sets the direction. The EC has also called for a climate-neutral Europe by 2050 to achieve the Paris Agreement goals and, under President Ursula von der Leyen, has decided to accelerate the green transition (see the European Green Deal). Sector coupling together with sector integration were broadly discussed by the EC during 2018–2020 when creating the framework for further transition and the role of gas. Building on these, the EC has paid further attention to legislative and budgetary steps and focused on specific technologies rather than on SC as a whole. The Green Deal emphasizes "the smart integration of renewables, energy efficiency and other sustainable solutions across sectors," which "will help to achieve decarbonisation at the lowest possible cost" (European Commission, 2019a)—i.e., the acceleration of renewables and a focus on renewable fuels of non-biological origin, especially hydrogen. This effort has increased in response to the energy crisis and security of supply issues, and we can see the same emphasis in the REPowerEU plan and investment plans.

The European Parliament´s (EP) view on European climate policy is highly ambitious and drives progress. The EP also supports SC as it "can contribute to the cost-efficient decarbonisation of the energy system by valuing synergy potentials and interlinkages between different parts of the energy system" (van Nuffel et al., 2018b). The EP has "distinguished two types of sector coupling: end-use sector coupling and cross-vector integration. End-use sector coupling involves the electrification of energy demand while reinforcing the interaction between electricity supply and end-use. Cross-sector coupling involves the integrated use of different energy infrastructures and vectors, particularly electricity, heat, and gas." (van Nuffel et al., 2018b).

However, it is the Member States (MS) who will have to do the work. They have shown increasing interest in sector coupling and sector integration in the last couple of years. However, each differs in their level of involvement (political proclamation, strategies, investment, R&D). So far, the most extensive development can be seen in Germany (the pioneer), Denmark, the Netherlands, and Belgium. However, SC is also evolving in France, the UK, Spain, Finland, and Italy. Currently, it is possible to mix hydrogen with natural gas in Belgium, Denmark, Germany, the Netherlands, and the UK. Yet, this is still a very small number. In general, all MS share the same climate objective and see it as an important part of the energy sector transition. However, they differ in their levels of ambition and in their opinions on how to achieve it. Many are still skeptical about the future role of RFNBO, as most of the related technologies are still in the initial state of development and highly costly. Thus, MS differ in their views on what the EU policy and regulatory framework should look like, and many do not anticipate a fast rollout by 2030. They also have diverse expectations regarding the "realistic" broader development of the hydrogen economy (Figure 1) and differ in their views on where hydrogen should be sourced (domestically or via imports), how it should be produced (green or low-carbon), whether at the beginning we should allow some transition period to help the sector develop, and how and when to count the percentage of green energy that will eventually feed electrolyzers with grid-borne electricity.

Figure 1. Hydrogen strategy adoption



Source: authors

Currently, there are 15 states with already published strategies. Another 10 are in the preparation process, some of which (Greece, Italy) have already outlined their strategy drafts. Only a few are lagging behind with no strategy announced. More information on each country can be found in the Appendix.

The majority of countries (see Table 3) are counting with hydrogen imports, except for those which have a high potential for renewable energy (e.g., Spain, Portugal) or natural gas (Norway). Countries that are currently serving as European LNG hubs (Belgium, Netherlands, Greece) intend to preserve such a position on hydrogen markets as well.

Table 3. Hydrogen sourcing preferences

Import	Export	Only domestic production
Austria Belgium Czech Republic Germany Greece* Italy* Luxemburg Netherlands Slovakia	Denmark Norway Portugal Spain UK	France Hungary Poland

* Based on the published strategy draft.

Three countries, namely France, Poland, and Hungary, have stated no clear position on potential hydrogen export or import in their strategies. Only domestic production capacity build-up is being considered there. The primary driver for such position is a broader energy security focus where hydrogen is seen as a way to strengthen energy independence (Dragan, 2021). In 2021, at the Energy Council meeting the aforementioned countries, joined by Estonia, they clearly spoke out against hydrogen imports instead advocating local hydrogen production in Europe (Kurmayer, 2021).

Disagreement on hydrogen supply sourcing is exacerbated by Europe's two major economies—Germany and France—taking opposing stances (Simon et al., 2022). The dispute also concerns the preferred hydrogen production technology and its eligibility to be called "low-carbon" or "renewable". Germany calls for looser EU rules to count as "renewable" hydrogen produced in locations such as Africa, Canada, or the Middle East, even if it is not entirely derived from renewable energy. Nevertheless, within the EU Germany strictly advocates green hydrogen production in order to lead by example, avoid lock in effect, and to boost their green hydrogen technology development.

France, on the contrary, argues that European and foreign producers must follow the same rules and standards, with priority given to hydrogen produced domestically from "low-carbon" sources of electricity, not just renewables. Apparent self-interest can be seen in both stances. Germany is trying to attract as much hydrogen at the lowest price possible to satisfy the expected high demand emerging as the country transitions to a low-carbon, nuclear-free economy (*Energiewende*). France, in turn, wishes to secure a role for nuclear energy-based hydrogen to ensure its fit into the country's broader energy strategy focused on energy security.

Despite advocating "renewable" hydrogen imports, Germany appears to be flexible on hydrogen production technologies, at least in the short term and outside Europe (German Federal Government — Federal Ministry for Economic Affairs and Energy, 2020). It considers low-carbon hydrogen (such as blue and turquoise) imports relevant if available at the global or European market. Overall, most countries (see Table 4) adopt a rather technology-neutral approach, supporting domestic electrolyzer capacity growth alongside advancing alternative production technologies.

Table 4. Hydrogen production preferences

Only green	Low-carbon
Belgium Denmark Greece* Luxemburg Portugal Spain	Austria Czech Republic France Germany Hungary Italy** Netherlands Norway Poland Slovakia UK

* Based on the published strategy draft.

** In the long-term, green only.

As for application, all countries aim primarily on hard-to-abate sectors (so-called no-regrets options), such as industrial processes and heavy-duty transport. Secondary priority areas are the use of hydrogen to increase the flexibility of the power system and the heating sector. Immediate industrial applications include reducing and replacing current fossil hydrogen in refineries and ammonia production, as well as partially replacing fossil fuels in steel production. In transportation, hydrogen is intended for use in the short term mainly in city buses, on certain sections of the railway network where electrification is not possible, and in heavy road vehicles. In the longer term, countries see a role for hydrogen in decarbonizing the aviation and maritime sectors.

Concerning infrastructure, most countries plan to repurpose existing gas infrastructure for H_2 needs. Some (e.g., Hungary, Portugal) also plan to blend hydrogen with natural gas to “green” their current gas consumption. To make hydrogen application in transport possible, several countries (e.g., Spain, Hungary, Portugal) have presented targets for the number of hydrogen refueling stations.

3.4 Development of policies

With environmental policies aiming at carbon neutrality in 2050, the EU has bound itself to transform its sectors and practices to be more sustainable. The transition policy has developed gradually, building on a broader and more general notion of integrational strategies and moving towards more specific plans, legislation, and regulation for specific technologies. Though the main aim of the green transition in the energy sector is to achieve complete electrification, this will be a long-term process as electricity currently covers only 23% of energy consumption in Europe (Eurostat, 2022a). Furthermore, a solution needs to be found for hard-to-abate sectors (specific industries, aviation, and maritime transport), which cannot easily decarbonize through electrification and must instead use gas. Similarly, related policies and legislation first started developing slowly from mentions of sector coupling (or the broader notion of sector integration) in strategies early in the debate to create the respective framework between 2018 and 2020. More legislation and regulation on specific technologies representing particular aspects of sector coupling, such as renewable fuels of non-biological origin or simply hydrogen, has subsequently developed. However, the regulatory framework is still being created.

Sector integration is a general term for coupling within the whole system, while sector coupling specifically refers to the coupling of the electricity and gas sectors (European Commission, 2019b).

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The Commission defined sector coupling as a process of "closely linking the electricity and gas sectors, both in terms of their markets and infrastructure" (European Gas Regulatory Forum, 2018). Sector integration is understood in a "broader notion as a strategy to provide greater flexibility to the energy system so that decarbonization can be achieved more cost-effectively" (van Nuffel et al., 2018b), and energy system integration as "the coordinated planning and operation of the energy system 'as a whole', across multiple energy carriers, infrastructures, and consumption sectors… the pathway towards an effective, affordable and deep decarbonization of the European economy in line with the Paris Agreement and the UN's 2030 Agenda for Sustainable Development" (European Commission, 2020c). Sector integration was presented as the main topic of the new European strategy by Kadri Simson, the EU's energy commissioner, to the European institutions on 8 July 2020 in the document *An EU Strategy for Energy System Integration*. The strategy sets out a vision to accelerate the transition towards a more integrated energy system with a central role for hydrogen. It proposes concrete policy and legislative measures at the EU level to gradually shape a new integrated energy system (European Commission, 2020c). At the same time, the Commission presented the EU Hydrogen Strategy, which focuses on creating a European hydrogen economy, more specifically on the production and usage of hydrogen and its role in EU decarbonization in line with the Green Deal (European Commission, 2020a).

The EU Hydrogen Strategy sets the basis for the EU policy framework in this area. Furthermore, the framework is also shaped by the Fit for 55 Package, the hydrogen and decarbonized gas market package, EU taxonomy, the Renewable Energy Directive, the REPowerEU plan, Important Projects of Common European Interest (IPCEI) on hydrogen, national strategies, and industry initiatives. Nevertheless, it is still under development, and hydrogen currently accounts for less than 2% of present energy consumption in the EU (European Commission, 2022c).

Starting with investments, the EU is generally putting emphasis on creating incentives for investors through climate policy. As an EU system for classifying sustainable economic activities, the EU taxonomy for sustainable activities offers important direction for investors and is supposed to help the EU to accelerate investments in renewable energy and thus achieve decarbonization goals aiming at six environmental objectives[1]. At the same time, it creates certainty for investors and the market. It entered into force on 12 July 2020. The relevance to hydrogen and RFNBO is that one of the two Delegated Acts sets criteria for sustainable hydrogen activities and emission thresholds. Moreover, the taxonomy rules will be reflected and followed in other EU and national legislation and, more importantly, by financial institutions.

Other valuable tools are IPCEI, a framework for important projects and cooperation between MS on common interests, which significantly contributes to strategic EU objectives and has a possible spill-over effect. IPCEIs on hydrogen were established in 2020 with the signature of a manifesto between EU MS and Norway. It began the path towards a clean hydrogen value chain "from renewable and low-carbon hydrogen production to hydrogen storage, transmission and distribution, and hydrogen application notably in industrial sectors" (European Commission, 2020b). Furthermore, the European Clean Hydrogen Alliance focuses on investments in faster infrastructure rollout, production, and use. For example, the EU is also supporting strategic investments in clean hydrogen under the Recovery plan through the Strategic European Investment Window of InvestEU and in transport through the Sustainable and Smart Mobility Strategy as well as through the recent creation of the European Hydrogen Bank,[2] which will invest three billion euro in order to boost the development of the hydrogen economy and market. As is apparent, other alternatives to natural gas and relevant technologies are being rather downplayed.

[1] 1) Climate change mitigation, 2) climate change adaptation, 3) sustainable use and protection of water and marine resources, 4) transition to a circular economy, 5) pollution prevention and control, and 6) protection and restoration of biodiversity and ecosystems (European Commission, 2020d).

[2] Announced in September 2022.

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Additionally, there are two recent decarbonization packages, the Fit for 55 Package and REPowerEU Plan. The Fit for 55 Package—the EU's plan for a green Europe—was presented in July 2021. It is a set of legislative proposals increasing targets and ensuring that EU policies align with climate neutrality in 2050. The main target is to increase the greenhouse gas emission reduction plan to at least 55% by 2030. For sector coupling and RFNBO together with hydrogen, this represents a significant moment when their increased role was acknowledged. Their role has further been acknowledged in the revision to the Renewable Energy Directive, ReFuelEU Aviation, Fuel EU Maritime, revision of the Energy Tax Directive, and the gas package from December 2021, thus significantly increasing the importance of renewables across sectors and emphasizing sector integration.

The REPowerEU Plan presented by the Commission in May 2022 further developed the Fit for 55 Package. It was prepared following the Russian invasion of Ukraine, with the aim to end the EU's dependence on Russian fossil fuels at the latest by 2027. The package consists of the Communication on REPowerEU, two legislative proposals (the revision of the Recovery and Resilience Instrument and proposal for a complementary Directive on the promotion of renewable energy, energy efficiency, and energy performance of buildings), delegated act on additionality, and seven non-legislative initiatives (among other things, a hydrogen accelerator and biomethane target). It goes on to list five areas through which to reduce dependence on Russia: energy savings, diversification of resources, substitution of fossil fuels and accelerating transition, smart investments, and strengthening preparedness.

The concept of a hydrogen accelerator for faster rollout involves scaling up the 2020 Hydrogen Strategy and 2021 gas market package, increasing the production target from 5.6 to 10 million metric tons (Mt) of renewable hydrogen in the EU by 2030, and setting a goal of hydrogen import of 10 Mt of renewable hydrogen from third countries (European Commission, 2022a). To accelerate this, the REPowerEU Plan proposes the EU Energy Platform, which the Commission and MS later established for the common purchase of gas, LNG, and hydrogen.

Finally, the Renewable Energy Directive (RED) sets goals for the usage of RFNBO in transport and industry, while the Delegated Act on Additionality creates a regulatory framework and sets the rules for the production of green hydrogen. The hydrogen and decarbonized gas market package creates a regulatory framework for the market and rules for integration of renewable and low-carbon gases, including hydrogen, into the existing gas system.

The RED Directive (EU) 2018/2001 on the promotion of the use of energy from renewable sources, which is currently in force, only briefly mentions the topic of renewable gases among eligible fuels for fulfilling transport obligations. However, its revision presented by the Commission under the Fit for 55 Package in July 2020 goes much further. First, it increases the overall goal from at least 32% of renewable energy sources in the overall energy mix to at least 40% by 2030. Under REPowerEU, the Commission wants to increase this target even further to 45%, while the European Parliament (EP) has mentioned at least 45%. The package also sets binding targets for RFNBO in industry and transport by 2030 and tasks the Commission to prepare a delegated act setting the criteria for the production of green hydrogen. As for sub-targets in RFNBO, the Commission's proposal for industry is a 50% share of hydrogen in final energy and non-energy purposes by 2030, while the general target quoted by the Council is 35% by 2030 and 50% by 2035. The EP wants 50% by 2030 and 70% by 2035. In transport, a binding new sub-target for renewable fuels of non-biological origin was set at 2.6%, while the Council changed it to a non-binding 5.2%. The EP advocates for a binding 2.6% by 2028 and at least 5.7% by 2030.

Regarding the delegated act, the Commission has prepared it based on its obligation under the adopted Renewable Energy Directive 2018/2001. The act aims to establish a methodology and detailed rules setting out the conditions and requirements that hydrogen produced in electrolyzer must meet to be certified as a fully renewable fuel of non-biological origin. Under the current Directive, the criteria should apply to renewable hydrogen consumed in transport. However, based on the revision of the Directive currently under discussion, the delegated act should apply to all renewable hydrogen consumed within all sectors and count towards RES targets. As part of the ongoing negotiations of the Directive, the final form of the act is still open, having been very restrictive in its original setting and, according to industry insiders, threatening the development, e.g., of a competitive hydrogen industry in Europe.

However, three important concepts which appear there are important to mention as they are crucial for the act—additionality, regionality, and temporality. These three concepts are meant to ensure that RFNBO are truly renewable and that there is no greenwashing. Additionality is the main principle and means that RFNBO should be made from additional energy sources to avoid increased production from fossil fuels. Regionality constitutes a constraint resulting from requirements for electrolyzer and renewable resource location. The original proposal included one bidding zone, possibly widened to other bidding zones if there is a similarly low price. The temporality criterion then states that the generation from the respective RES must coincide with the generation of the RFNBO at the electrolyzer, whether connected to the grid or separate from the RES. The act is crucial for investors and the future development of the hydrogen economy in the EU as its adoption will set the rules for the production of green hydrogen. Under its current wording, however, it is extremely strict, and many projects are losing their rentability and, thus, economic sense.

The hydrogen and decarbonized gas market package presented by the Commission in December 2021 represents a revision of EU gas market rules enabling a shift from natural gas towards new gases to ensure reaching the climate objectives of at least 55% reduction in greenhouse gas emissions by 2030 compared to 1990 levels and thus promoting demand for and production of renewable and low-carbon gases, including hydrogen. It consists of the Regulation on the internal markets for renewable and natural gases and for hydrogen and the Directive on common rules for the internal markets in renewable and natural gases and in hydrogen, which are both under preparation and discussion by the Council. They seek to facilitate the penetration of low-carbon and renewable gases into the energy system and create a regulatory framework for the market.

More specifically, the package "enables the market to decarbonise gas consumption and put forward policy measures required to support the creation of optimum and dedicated infrastructure and efficient markets. It removes barriers to decarbonisation and creates the conditions for a more cost-effective transition" (European Commission, 2022d). It also establishes rules for consumers, introduces a European Network of Network Operators for Hydrogen, and proposes a system of terminology and certification of low-carbon hydrogen and low-carbon fuels, complementing the revision of REDII (European Commission, 2022d). The package has also increased in importance as it strengthens energy security and the security of supply through measures to enhance transparency and access to LNG terminals and gas storage facilities. In response to the Communication and Toolbox on Energy Prices of 13 October 2021 and recent developments, it includes new requirements regarding storage, joint procurement of strategic stocks, market competitiveness, hydrogen infrastructure, network planning, and hydrogen markets.

Current discussions concern making the regulatory framework for the hydrogen market more flexible during the ramp-up phase, with more detailed rules applying from January 2031, but concerns about future market maturity by that time persist. An emphasis is placed on harmonized data and developing an efficient internal market. An essential part of the regulatory framework is tariffs for renewable and low-carbon gases and cross-border tariffs in the hydrogen network.

In the early stage, zero-level cross-border tariffs and appropriate cost-sharing mechanisms represent the proposed financial compensation mechanisms among hydrogen network operators to create fair conditions. Importance is also placed on blending, with the regulation obliging transmission system operators (TSOs) to accept hydrogen blending up to 5% at interconnection points between EU MSs from 1 October 2025. However, some MS prefer to have separate infrastructure or to postpone the date.

4. Hydrogen policies at the state level

To showcase different countries' approaches to hydrogen economy build-up with varying starting positions (e.g., economy structure, geography) and broader policy priorities, the following chapter presents several case studies in more detail. Among European countries, Denmark, Germany, France, and Spain were selected based on their varying positions on hydrogen sourcing and production technologies. Denmark appears to be an especially interesting example of a country that did not present a "hydrogen" but rather a "Power-to-X" strategy. Germany is considered an active hydrogen imports advocate, counterbalanced by France with its special attitude to pink (nuclear energy-based) hydrogen. Finally, Spain represents the group of potential renewable hydrogen exporters.

To offer a more global perspective on emerging hydrogen policies, two non-European examples are also included. The first case, the USA, sheds light on a very recent joiner to the hydrogen frontrunners club with ambitious plans and funding made available. Its long-term export plans to its allies make the development of the US domestic hydrogen market important also for Europe. Another international player to monitor is China. The hydrogen share in its ever-growing energy demand is expected to rise in the coming decades, fueled by the country's decarbonization and energy independence aspirations. Although China is expected to cover its hydrogen demand largely from domestic sources, potential cooperation in research and development (R&D) in different parts of the hydrogen value chain should not be overlooked.

4.1 Denmark

4.1.1 Status quo

Denmark offers an impressive example of a robust energy transition. The country's energy system "shifted from nearly full fossil-fuel dependency" to a self-sufficient system with a significant share of renewable sources (Eikeland & Inderberg, 2016). Today's Danish energy sector is innovative and highly interconnected, with a notable share of wind resources (Johansen, 2021). Of the total 26 TWh of generated renewable electricity in 2021, 16 TWh came from wind sources, surpassing any other renewable source (BP, 2022c).

Additionally, Denmark has substantial offshore wind capacity potential, particularly in the North Sea. The Danish government sees these resources as a way to supply electricity to "innovative activities such as PtX production or energy storage" (Danish Ministry of Climate, 2021). Hydrogen development in Denmark can thus be built on a solid foundation consisting of a wind-powered energy system with constantly growing potential.

Aspirations for hydrogen

For Denmark, hydrogen plays a crucial role along with P2X technologies for achieving its CO_2-neutral and climate-neutral society. This overall goal underlies the Danish *Strategy for Power-to-X* published in December 2021. These technologies are then seen as the key to achieving Denmark's ambitious climate targets (Danish Ministry of Climate, 2021) demarcated by the *Climate Act* legislation passed in June 2020 and amended in December 2021. The main goals are to reduce Denmark's emissions by 70% in 2030 compared to the 1990 level and to achieve absolute climate neutrality by 2050 at the latest (Danish Ministry of Climate, 2020).

Beyond the stated objectives for H_2 and P2X application in industry, heavy transport, shipping and aviation, the Danish plan also relies heavily on the "utilization of carbonaceous products (Carbon Capture and Utilization - CCU)" and related carbon capture and storage (CCS) technologies (Danish Ministry of Climate, 2021). Denmark envisions becoming a global player in P2X, betting on its unique P2X knowledge backed up by several players and historically rooted know-how of green energy and considerable wind resources, which could potentially expand its offshore capacities in the North Sea. Consequently, Denmark envisages itself becoming an exporter of P2X products and technologies, mainly for Germany (Ibid.).

Demand forecast

The production of "fossil hydrogen" in Denmark has been minimal, and the same goes for consumption, which in this case is remarkably low. Thus, unlike in other countries, the agenda is not to replace this hydrogen with green hydrogen but to create an entirely new demand.

Considering Denmark's starting position, combined with the fact that the country is a small market, national demand should not serve as a point of reference. Instead, Denmark should concentrate on the demand for green hydrogen of its neighboring countries and the consumption driven by international developments and trends. Thus, the country is dependent on EU regulation and international cooperation (Dansk Energi, 2020).

4.1.2 Policies and objectives

National Hydrogen Strategy (NHS)

While other countries focus on hydrogen in their national strategies, Denmark has focused its strategy on Power-to-X (P2X). The strategy understands P2X as a "crucial technology for a green, CO_2-neutral future" that will "boost indirect electrification so that Denmark can become a climate-neutral society" (Danish Ministry of Climate, 2021). The Danish government formulates four objectives to achieve the "development and expansion of green hydrogen and green PtX products", namely:

1. Power-to-X must be able to contribute to the realization of the objectives in the Danish Climate Act.
2. The regulatory framework and infrastructure must be in place for Denmark to utilize its strengths and allow Power-to-X to perform on market terms in the long run.
3. The integration between Power-to-X and the Danish energy system must be improved.
4. Denmark must be able to export Power-to-X products and technologies. (Ibid.)

Regarding specific targets, Denmark specifies only the one regarding electrolysis capacity—the country anticipates building up to 4–6 GW. Other targets remain unquantified. The Danish strategy underlines the need for robust and transparent regulation regarding all parts of hydrogen and other P2X fuel value chains. To achieve an efficient hydrogen market, especially internationally, it is also "necessary to ensure that the green value – i.e. climate neutrality – of both hydrogen and other PtX fuels can be documented" (Danish Ministry of Climate, 2021). One of the first steps to achieve this goal was taken in April 2022 when *Energinet*, the Danish Transmission System Operator (TSO), started working towards developing guarantees of origin (GOs) for renewable hydrogen. The scheme will provide the documentation needed for "green hydrogen-based fuels" and

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"may become an important foundation in a market model for a future hydrogen infrastructure" (Energinet, 2022a). The scheme's development is carried out in cooperation with the *Danish Energy Agency* and should be in its final form in Summer 2023 (Ibid.).

The strategy calls for major review of legislation in relation to hydrogen to define obstacles to the "development of a hydrogen market and establishment of a hydrogen infrastructure" (Danish Ministry of Climate, 2021). Such infrastructure would support not only Danish but also international companies to produce and use PtX-related technologies. However, there is currently no hydrogen infrastructure, i.e., "gas pipelines and gas storage facilities for transporting and storing hydrogen" in Denmark (Ibid.). Yet, Energinet and the Danish Energy Agency have established a dialogue with market actors that could establish such infrastructure. Moreover, Energinet selected two gas pipelines connecting the Danish and German gas systems as possible candidates for conversion and their use for hydrogen export (Ibid.).

In June 2022, Energinet also launched the first phase of its feasibility study of hydrogen transmission infrastructure in Jutland, intending to present it in March 2023. In this feasibility study, the focus is not only on converting existing natural gas pipelines for H_2 transportation but also on establishing new hydrogen infrastructure. Furthermore, the TSO emphasizes the need to develop hydrogen and power infrastructure to ensure the full use of the "socioeconomic value of PtX in Denmark" (Energinet, 2022b). Consequently, Energinet and Gasunie Deutschland signed a memorandum of understanding (MoU) in September 2022 to strengthen their collaboration concerning hydrogen infrastructure (Energinet, 2022c).

To boost research and innovation in the field, another new partnership was launched in June 2022. The *MissionGreenFuels* partnership has emerged as one of the public Danish *Innovation Fund*'s Inomissions, bringing together 60 partners from universities, industry, SMEs and other spheres. The focus of the project's three strategic areas are technologies, infrastructure/P2X plants/sector coupling, and business and market development and acceptance (MissionGreenFuels, 2022).

4.1.3 Actors and funding

Actors and projects

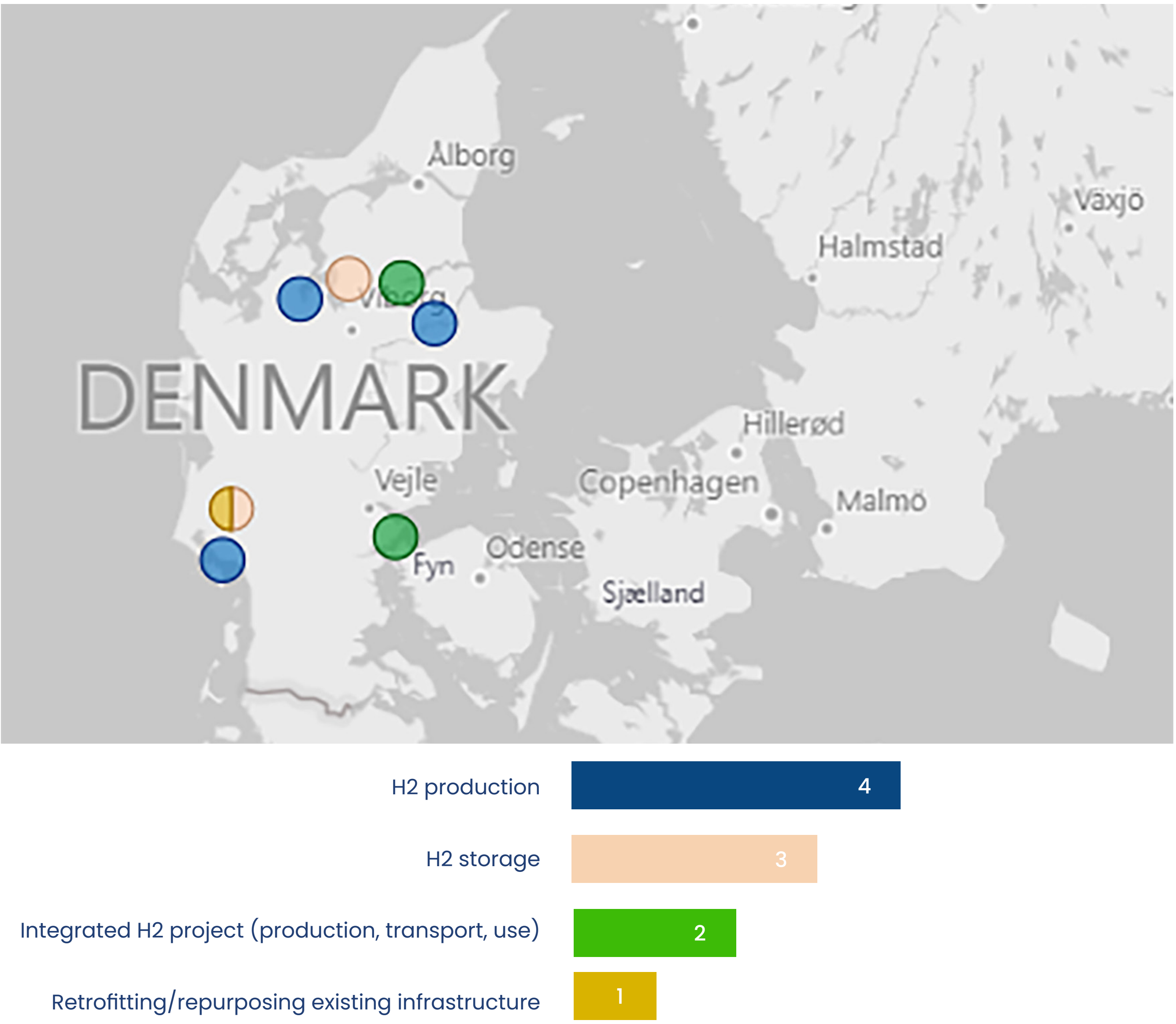
One of the key Danish hydrogen players is undoubtedly *Brintbranchen: Hydrogen Denmark*, an industry association representing all actors of the Danish hydrogen and P2X value chain (Brintbranchen, 2022) and covering all active Danish hydrogen and P2X projects, including already launched projects and those still in the phase of preliminary talks between the actors. Figure 2 presents a visualization by ENTSO-G mapping ten existing hydrogen projects in Denmark. Among these, most are focused on H2 production.

When it comes to H_2 production, Denmark's ambitions are not negligible. For instance, the country will be home to the world's largest 1 GW electrolyzer project, known as *Plug Power* and announced in May 2022. This project, commissioned by *H2 Energy Europe*, will take place near Esbjerg and will use offshore wind energy to produce up to 100,000 metric tons of green hydrogen per year. This hydrogen will then find its use primarily in the energy and transportation sectors across northern Europe. Moreover, it will also serve to fuel at least 250 H_2 refueling stations in Denmark, Germany, and Austria, which will be the outcome of a joint venture between H2 Energy Europe and Phillips 66 that emerged at the beginning of 2022. The technology is expected to deploy in 2024, with green hydrogen production commencing in 2025 (Plug Power, 2022).

The *HySynergy* project led by *Everfuel* has similar aspirations. Its purpose is to establish a large-scale production and storage facility of green hydrogen with the support of 6.5 million euros provided by the Danish Energy Agency. To fulfil its goals, the project is planned in three phases—20 MW by the end of 2022, 300 MW in 2025, and 1 GW in 2030 (Everfuel, 2022).

The *Green Hydrogen Hub Denmark* is a complex project focusing on large-scale green hydrogen production, storage, and compressed-air energy storage (CAES). The project is expected to establish a “350 MW electrolysis plant, 200,000 MWh hydrogen storage and a 320 MW CAES facility, which as the final link in the chain can reconvert the green hydrogen to electricity” (Eurowind Energy, 2022). One of the main goals of this project is to combine “seasonal hydrogen storage and daily storage in CAES” to provide consumers with “100% green electricity 24-7 all year” (Ibid.).

Figure 2. Hydrogen projects in Denmark



Source: ENTSO-G (ENTSO-G, n.d.)

Funding

In March 2022, the Danish Parliament agreed to support the development of P2X technologies and thus raise the cost competitiveness of green hydrogen production. The total amount of approved funding at this stage is more than 167 million euros. This support is planned to be granted as "operational support and payable according to the quantity of produced green hydrogen" (DLA Piper, 2022). The tender is also expected to be "carried out as market-based, aiming at the least costly and largest hydrogen production within the budget" with over 10 years of granted support. The first tender is expected to take place in 2023 (Ibid.)

4.1.4 International cooperation

Denmark relies heavily on international cooperation regarding hydrogen. Such collaboration occurs on both multinational and bilateral levels.

Nordic Hydrogen Partnership

Established in 2006, this partnership, originally named the *Scandinavian Hydrogen Highway Partnership*, connects research institutions, industrial actors, and local and national authorities while the national networking bodies of the Nordic countries—in the case of Denmark, *Brintbranchen*—act as the partnership coordinators. This cooperation aims to "create one of the first regions in Europe where hydrogen is available and used in a network or refueling stations" concentrating on the dialogue with manufacturers in various areas of the transportation sector or relevant policy bodies (Nordic Hydrogen Partnership, 2022).

Green Hydrogen Compact Catalogue

This initiative was launched in connection with the UN Energy Summit in September 2021 by Denmark, Germany, and Chile in cooperation with IRENA, the World Economic Forum and others (United Nations, 2022). The main goal of the Catalogue is to promote dialogue and partnership between countries, international organizations, and private sector actors to undertake "ambitious goals within the green hydrogen value chain in the form of Energy Commitments", i.e., a voluntary commitment to action (Green Hydrogen Catalogue, 2022a). Today, additional partners include the Republic of Namibia, Colombia, and the Basque Region as well as 27 partner companies and 6 knowledge partners with the commitment of employing 283,800 MW of renewable energy and 133,700 MW of electrolyzer capacity (Green Hydrogen Catalogue, 2022b).

Green Power Plant of Europe

In May 2022, a joint declaration was signed by the representatives of Denmark, Germany, Netherlands, and Belgium with the intention to become the "Green Power Plant of Europe". While this agreement emerged primarily in the context of cooperation in offshore wind energy generation, the potential of green hydrogen also plays a role. The four countries have committed to further green hydrogen cooperation "with plans to expand related infrastructure in the region" (Euractiv, 2022b).

Germany

As already mentioned, Germany is one of Denmark's critical partners for hydrogen development. Not only did Energinet and Gasunie Deutschland sign the aforementioned MoU, but the two countries have also collaborated in the development of offshore wind energy. For example, Germany and Denmark decided to cooperate on the renewable energy island project of Bornholm, equally sharing the investment costs and future profits (Reuters, 2022c). Such partnerships are, in the Danish context, indisputably substantive for hydrogen development as well.

Scotland

In November 2021, representatives of Denmark and Scotland agreed an MoU in the green transition of the energy system. Even though the areas of cooperation were focused on heating networks and energy efficiency in buildings and industry, the fields of wind power and hydrogen were determined as prospective areas of cooperation. The two parties envision identifying shared interests and potential for cooperation concerning hydrogen as well as encouraging commercial investment in this technology (Scottish Government, 2021).

India

In January 2022, India and Denmark agreed to initiate joint R&D in green fuels, including hydrogen (Government of India, 2022).

Japan

Denmark and Japan's cooperation focusing on renewable energy emerged with an MoU in 2019. The respective authorities cooperate primarily in the "deployment of offshore wind energy regulation through exchange of experience and knowledge sharing" (Danish Energy Agency, 2022). In 2021, the two countries decided to expand their collaboration to the area of green hydrogen (State of Green, 2021).

4.2 France

4.2.1 Status quo

The French energy sector builds on historical legacies formed mainly during the 1970s and 1980s in response to the first oil shock of 1973. As the preceding economic growth induced increased energy consumption, particularly oil, the impact of the oil crisis was substantial, raising many questions about the country's energy policy goals, particularly concerning energy independence, security of supply, and cost competitiveness (Millot et al., 2020). The answer was clear—to reinforce the French nuclear program. What followed was a rapid and successful transition, supported mainly by the French technocratic elite coordinating the program between the French government and the institutions commanding the nuclear power reactor deployment (Ibid.). The French nuclear program is thus considered to be the most successful "scaling-up of a complex and capital-intensive energy technology system in the recent history of industrialized countries" (Grubler, 2010).

Today, France is the second largest energy consumer in the EU, consuming 2,614 TWh of energy in 2021. Following its historical path, this energy consumption is dominated by nuclear energy, representing 952.78 TWh, followed by oil and natural gas. By contrast, coal has the smallest share in the French energy mix with only 63.89 TWh. However, the position of renewable sources is not strong either, totaling 202.78 TWh of total energy consumption (BP, 2022c).

Aspirations for hydrogen

France is considered one of the early leaders in the climate change agenda (IEA, 2021b), as the country has "gradually changed its doctrine" and began to focus on the energy transition

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(Andriosopoulos & Silvestre, 2017). The energy transition, however, did not gain significant visibility until 2012 with the then presidential elections and victory of François Hollande (Mauger, 2018) and the publication of the national *Transition Énergétique* program in 2012–2013 (Andriosopoulos & Silvestre, 2017).

Despite this, France falls short of its climate targets. IEA recommendations support the revision of the French *National Low-Carbon Strategy* (lastly updated in 2020) to clarify and stabilize the country's climate goals and therefore achieve the needed progress in this area. As part of these revisions, the French government should also reflect on the latest developments in selected technologies and reassess their expected contributions. In doing so, it should focus particularly on hydrogen (IEA, 2021b).

Since publishing its national hydrogen plan in 2018, and therefore being the first European country to do so, France has become one of the most ambitious EU members regarding the development of the hydrogen sector (Lambert & Schulte, 2021). Its *National strategy for the development of decarbonized and renewable hydrogen in France* published in 2020 establishes three main priorities for hydrogen deployment: decarbonization of industry, development of hydrogen-based heavy-duty mobility, and support for research and innovation (French Ministry for the Ecological Transition, 2020b). The aspirations for supporting the national hydrogen sector are then rooted primarily in environmental, economic, energy sovereignty, and technological independence concerns.

Demand forecast

To date, hydrogen is primarily consumed in non-energy industrial uses, such as oil refining or chemical sectors. This hydrogen thus comes from fossil fuels, with up to 95% produced from natural gas, oil, and coal. As the French strategy indicates, one key priority is to decarbonize industry or as RTE, the French TSO, states, to "convert the conventional production of industrial hydrogen to a carbon-free production method" (RTE, 2020). The target for the share of decarbonized hydrogen in industry was set at 20–40% in 2028 (French Ministry for the Ecological Transition, 2018).

4.2.2 Policies and objectives

NHS and other relevant policies

Looking at the legislative framework, a very important milestone for the development of the hydrogen sector in France was Law No 2015-992 on Energy Transition for Green Growth, also known as the *Energy Transition Law*. Its Article 121 states that the government shall establish a "development plan for the storage of renewable energies using decarbonated hydrogen" (Law No 2015-992, 2015). This article then promotes the implementation of an economic model for hydrogen storage, as it would encourage "renewable energy producers to participate in the availability and implementation of the reserves necessary for the operation of public energy transmission and distribution networks, as well as the conditions for the valuation of these services" (Ibid.). This law also emphasizes the need to develop fuel cells and, therefore, also hydrogen mobility and the necessary hydrogen infrastructure as well as the need for regulations to support the deployment of new hydrogen technologies, such as power-to-gas (Ibid.).

This law was followed in 2018 with the adoption of the French hydrogen plan, also known as the 2018 *Hulot Plan*[3], which defined three main axes of hydrogen development, identified the main

[3] Named after the then Minister of Ecological Transition, Nicolas Hulot.

objectives for the French hydrogen sector, and offered eighteen measures to achieve these objectives (French Ministry for the Ecological Transition, 2018).

The first phase in the development of the hydrogen sector in France is to provide decarbonized hydrogen for French industry. French industry, particularly the refining and chemical industries, is a large consumer of hydrogen, but this hydrogen is produced by technologies that are responsible for large quantities of greenhouse gases and, therefore, a significant negative impact on the environment. It is thus necessary to provide these and other industries in France with hydrogen produced using a different technology, namely water electrolysis. The plan is to promote this technology, both in the development of different types of electrolyzers and in R&D. The aim is to reduce the cost of this technology, which is the key to enabling decarbonized hydrogen to compete with hydrogen produced from fossil fuels and consequently to reduce French industry's carbon footprint. (French Ministry for the Ecological Transition, 2018).

The plan then highlights two types of industries to target—those that consume hydrogen as an input raw material (e.g., glass and steel industry) and those that are highly CO_2 intensive (e.g., cement industry). The target for decarbonized hydrogen production in industrial hydrogen use was set to reach 10% in 2023 and 20–40% in 2028. Another defined goal was to introduce by 2020 a traceability system for the origin of hydrogen to ensure that the actors in the French hydrogen industry can valorize the decarbonized hydrogen (French Ministry for the Ecological Transition, 2018).

The second axis identifies the need to develop hydrogen mobility to complement battery-based mobility. The main objective identified in this area is to deploy territorial hydrogen mobility ecosystems, based particularly on fleets of professional vehicles. In this regard, in 2023 France should introduce 5,000 light commercial vehicles and 200 heavy vehicles (incl. buses, trucks, rail transport, and boats) as well as construct 100 stations fueled by locally produced hydrogen. In 2028, the target is for 20,000–50,000 light commercial vehicles, 800–2,000 heavy vehicles, and 400–1,000 stations (French Ministry for the Ecological Transition, 2018).

The third axis identifies hydrogen as an "element of stabilization of energy networks in the medium-long term" (French Ministry for the Ecological Transition, 2018). This stance highlights the potential of decarbonized hydrogen to solve a structural problem—the efficient integration of renewables into the electricity grid—as it is the most promising means for energy storage. However, the authors of the Hulot plan also mention power-to-gas technologies and hydrogen injection into the gas grid as strategies for reducing CO_2 emissions in the gas system (French Ministry for the Ecological Transition, 2018).

Hydrogen is also the subject of Law No 2019-1147 on Energy and Climate. This law reflects the goals of the National Hydrogen Plan, regulates and defines related terminology of different types of hydrogen, and empowers the government to adopt measures through legal decrees allowing the production, transport, storage, and traceability of hydrogen as well as defining a support framework applicable to low-carbon hydrogen (Law No 2019-1147, 2019).

In 2020, the French Ministry for Ecological Transition published the new version of the *Multiannual Energy Program*, setting targets for the hydrogen sector for 2023 and 2028. These targets closely reflect those set out in the 2018 plan. Additionally, the program emphasizes the need for financial support (French Ministry for the Ecological Transition, 2020a). As already mentioned, 2020 was also the year when the *National strategy for the development of decarbonized and renewable hydrogen in France* was launched. This strategy also mirrors the hydrogen plan of 2018 and sees the development of hydrogen technologies as "an opportunity to speed up the ecological transition and create a dedicated industrial sector, both at local/regional level as well as on a European scale" (French Ministry for the Ecological Transition, 2020b). The strategy defines three goals: "to install enough electrolyzers to make a significant contribution to the decarbonization of the economy; [...] to develop clean mobility, in particular for heavy-duty vehicles; [...]" and "to build a French industrial sector that creates jobs and guarantees our technological prowess." To achieve these targets, France committed to allocate 7 billion euros towards hydrogen development until 2030, including 2 billion euros from its National Recovery and Resilience Plan (Ibid.).

Finally, in 2021 Law-Decree No 2021-167 related to hydrogen provided several significant changes to the legal framework. Not only did it alter a few key definitions (e.g., those of *renewable hydrogen*, *low-carbon hydrogen*, and *carbon-based hydrogen*), but it also establishes two traceability systems for hydrogen and a support mechanism for green or low-carbon hydrogen production. According to the decree, this support can be in the form of "either operating aid or a combination of financial aid for investment and operating aid" (Law-Decree No 2021-167, 2021).

France, therefore, has established a strong legal foundation. The policies are based on clear terminology and definitions reflecting the needs for developing the French hydrogen industry. Together, they formulate an ambitious aim to make France a global leader in this sector (see Ministry for the Ecological Transition, 2020a). The identified objectives show that France has the ambition to operate in all parts of the hydrogen value chain, with special emphasis placed on producing decarbonized hydrogen by electrolysis and using hydrogen in industry and transport.

4.2.3 Actors and funding

One of the crucial players in French hydrogen development is undoubtedly the French Agency for Ecological Transition—ADEME—working under the supervision of the Ministry for Ecological Transition and Territorial Cohesion, Ministry of Energy Transition, and Ministry for Higher Education and Research. ADEME is responsible for the implementation of public policies "related to the environment, energy, and sustainable development through funding programs, including for innovation/demonstration, monitoring, and evaluations" (IEA, 2021b).

ADEME and its calls for tenders have been the driving force behind the development of hydrogen projects since 2016. These calls for tenders have involved key industrial players, local operators, public actors and specialized manufacturers, therefore ensuring their cooperation in favor of the hydrogen sector development.

In October 2020, ADEME launched two calls for tenders as part of the French National Hydrogen Strategy to accelerate the sector's development and move closer to the set targets. These two calls are currently the main source of government funding for hydrogen development, deriving finances from the national *Future investments program*[4] (French Ministry of Ecological Transition, 2021).

The first call for projects under ADEME was called "Territorial hydrogen ecosystems" and built on the foundations of the first ever in France—"Hydrogen territories" from 2016. The call aimed "to deploy structuring ecosystems in the territories that are associating production, distribution and uses of carbon-free and/or renewable hydrogen" and to "support the change of scale allowing the structuring of the industrial sector and lowering the costs" (French Ministry of Economy, 2020). Project applications were open to companies and local authorities that wanted to be involved in the introduction of hydrogen technology and invest in its production and distribution on their territory. Based on this call, ADEME presented in May 2022 a selection of 18 projects that will undergo closer scrutiny and receive funding. Funding for these projects has been designated for the period 2021–2023 with an allocation of 275 million euros, part of which comes from the *France Relance* program (Actu Environment, 2022; ADEME, 2022; French Ministry of Economy, 2022).

[4] Programme d'Investissements d'Avenir.

The second call for tenders, "Technological bricks and hydrogen demonstrators", is still open until the end of 2022 and aims to "develop and improve components and systems related to the production and transport of hydrogen and its uses such as transportation or energy supply applications" (French Government, 2020b). This call is then targeted mainly to pilot or first commercial projects in France, as it aims to develop new solutions and industry structure. It is open to innovative and demonstrative projects (over 20 MW) realized by either individual companies or partnerships between companies and/or research actors (French Government, 2020b). These projects must correspond to at least one of the four defined categories—Axis 1: Technological bricks: innovative components and systems; Axis 2: Innovative industrial and network pilots; Axis 3: design and demonstration of new vehicles; and Axis 4: Large electrolysis demonstrators. The minimum value of these projects should be 2 million euros in the case of Axis 1–3 and 5 million euros for Axis 4 (French Government, 2020a). The total value of the funding allocated to these projects is 350 million euros.

At the beginning of 2021, a new player emerged on the French hydrogen scene—the *National Hydrogen Council*,[5] which was established to ensure the effective implementation of the National Hydrogen Strategy. The main role of this authority is to mediate communication between the State and hydrogen stakeholders, particularly industrial actors, and to ensure a seamless progression toward set goals. The Council's overall objective is thus to "contribute to the development of a competitive French low-carbon hydrogen industry and encourage the emergence of collective projects aimed at structuring a complete value chain on [French] territory or in the framework of European cooperation" (French Ministry of Ecological Transition, 2021). The Council is composed of representatives of leading French companies active in the hydrogen sector, such as Air Liquide, EDF, Engie, and others.

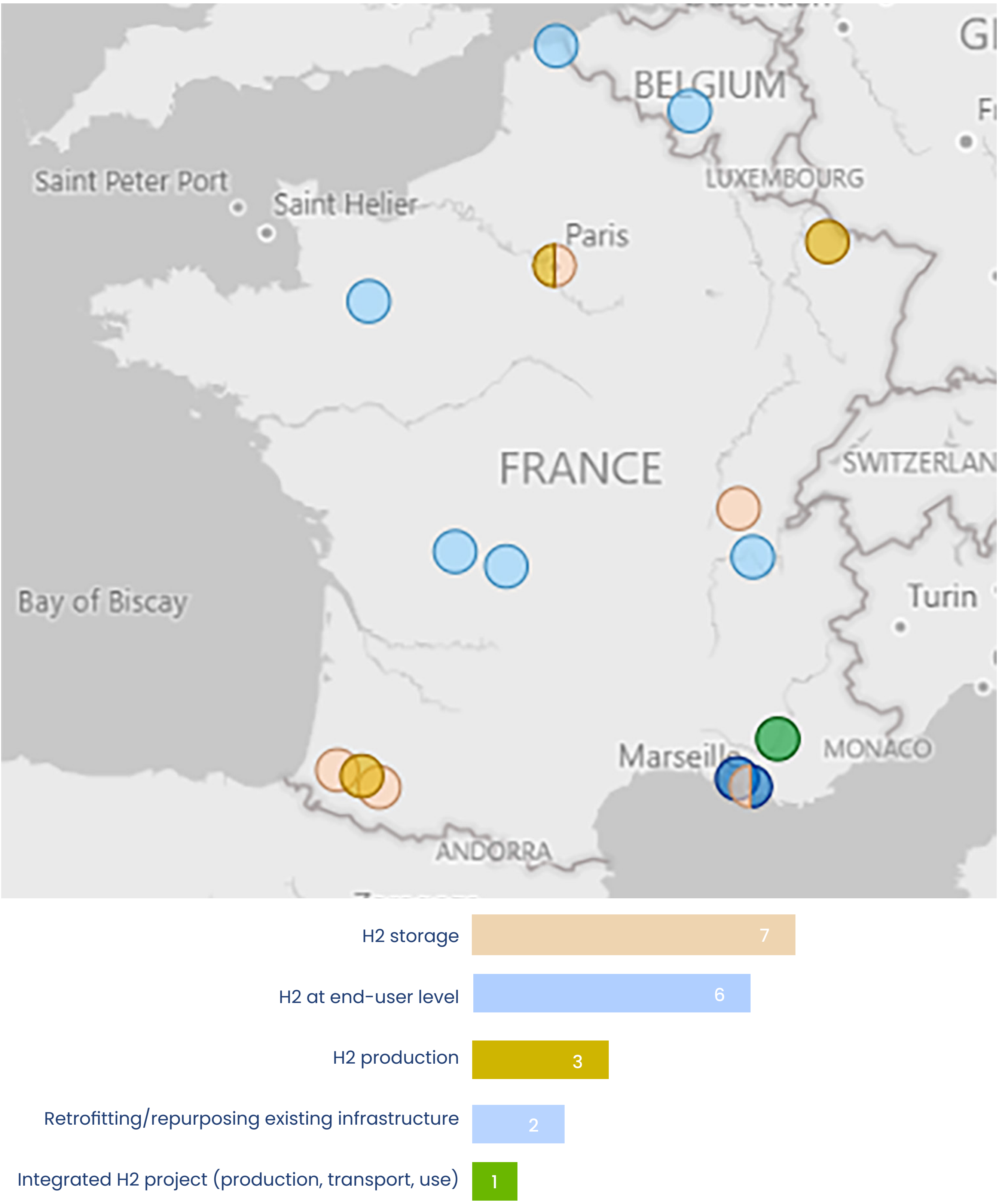
These leaders continue to push the French hydrogen sector forward and include several traditional industrial players and new entrants that have emerged in the last decade. Moreover, they can be found across the entire hydrogen value chain. Several long-standing industrial companies are now turning to hydrogen, either by participating in hydrogen projects (for example, *storengy*, a specialist in natural gas storage, is now involved in projects of large-scale hydrogen storage—e.g., *Emil'Hy* with *GazelEnergie*) or by creating their own hydrogen-specialized subsidiaries or joint ventures (e.g., *Symbio*, specializing on fuel cells and created by *Michelin* and *Faurecia*).

Projects across different sectors

As France has ambitions to dominate virtually the entire value chain of hydrogen, it is possible to find several projects in France in several areas where hydrogen is produced or used. As the map from ENTSO-G indicates (see Figure 3), most French H2 projects are dedicated to energy storage. For example, the project *Hypster*, the first EU-supported large-scale green H_2 underground storage demonstrator, launched in January with the aim "to use salt cavern storage to connect hydrogen injection by electrolysis to industrial and mobility uses" (HyPSTER, 2022). With a total budget of 13 million euros, the goal is to construct an electrolysis unit for on-site green hydrogen production in 2022 and ultimately be able to store the hydrogen using the salt caverns in 2023 to demonstrate the technical feasibility, safety, and positive environmental impact of such storage (Ibid.).

[5] Established by the agreement of Barbara Pompili (Minister of Ecological Transition), Bruno Le Maire (Minister of Economy, Finance and Recovery), Frédérique Vidal (Minister of Higher Education, Research and Innovation) and Agnès Pannier-Runacher (Minister Delegate for Industry).

Figure 3. Hydrogen projects in France



Source: ENTSO-G (ENTSO-G, n.d.)

In the case of Power-to-Gas, Jupiter 1000 is the first project deploying this technology in France. It demonstrates the P2G technology “with a power rating of 1Mwe for electrolysis and a methanation process with carbon capture” (“Jupiter 1000 - Power-to-Gas - Le Projet,” n.d.). With planning having started in 2014, the project should reach the end of trials in 2023. Using two electrolyzers and producing hydrogen from 100% renewable energy, this project sets the pace and blazes a trail for the development of P2G technology in France. The ultimate goal is then to launch the P2G system in the country, with the potential to have more than 15 TWh of gas produced by this system each year in 2050 (Ibid.).

Several projects focus on using hydrogen in mobility, from light vehicles and trains to marine and air mobility (e.g., HyPORT, NavibusH2, Alerion M1h & Alcyon M3c, CATHYOPE). These are also connected to the need for hydrogen infrastructure and hydrogen refueling stations. The French company *Hydrogen Refueling Solutions*, founded in 2004, has 55 working refueling stations with a total capacity of 8,900 kg of hydrogen per day (Hydrogen Refueling Solutions, 2022).

4.2.4 International cooperation

United Arab Emirates

France and UAE decided to seal their partnership by signing an energy cooperation deal in July 2022. The start of this cooperation, directed at not only hydrogen but also renewable and nuclear energy, was announced already in November 2021 (Reuters, 2021, 2022b).

India

In October 2022, France and India adopted their Joint Roadmap on Green Hydrogen. To achieve their shared goal of becoming world leaders in decarbonized hydrogen, the two countries decided to establish "a regulatory framework for developing a decarbonized hydrogen value chain, covering production, storage, transportation, and consumption"; focus on R&D of hydrogen technologies; support other industrial partnerships between the countries; and create "robust carbon-content certification methods to certify the carbon content of decarbonized hydrogen throughout its life-cycle" (French Ambassy in India, 2022).

USA

Hydrogen is also present in the United States–France bilateral clean energy partnership launched at the end of 2021. Representatives of both countries agreed to explore potential synergies in clean energy technologies. Besides hydrogen, the focus is also, for instance, on small modular reactors and energy storage solutions, including batteries (French Ministry for Europe and Foreign Affairs, 2021).

Germany

The cooperation between the two EU hydrogen powerhouses was announced in February 2022 when France and Germany decided to work on common industrial projects, i.e., electrical networks, batteries, and hydrogen. Nevertheless, concerning hydrogen, the countries show significant differences, notably when it comes to the origin of hydrogen. While for Germany the only way is to deploy RES-based hydrogen, France plans on using nuclear power to achieve its hydrogen goals (Euractiv, 2022a)

4.3 Germany

4.3.1 Status quo

Germany is Europe's largest energy consumer at 3,511 TWh in 2021 (BP, 2022a). For comparison, it consumes 30% more energy than the second-largest industry powerhouse—France. In 2021, the German economy accounted for over 20% of the EU's GDP, and its value of sold industrial production was equivalent to 27% of the EU total (Eurostat, 2022b). At the same time, Germany is also the higher CO_2 emitter in Europe, with 74% of the energy consumed coming from fossil fuels (BP, 2022a).

Aiming to become climate neutral by 2045, Germany has set preliminary targets to cut emissions by at least 65% by 2030 and 88% by 2040 compared to 1990 levels (BMUV, 2021). To achieve these targets, currently used fossil fuels need to be replaced with alternative carbon-free options. This especially applies to energy sources in the form of gases and liquids, which are expected to continue to be a crucial part of the German energy supply.

Aspirations for hydrogen market build-up

The key role of hydrogen in the German decarbonization strategy was envisioned in the National Hydrogen Strategy (NHS) in June 2020. Especially after the country's decision to phase out coal (BMWK, 2020), hydrogen has become essential in meeting the goals of reducing emissions from the country's large industrial sector, parts of the transportation sector, and potentially also emissions from the heating sector in the long term.

Though the strategy is primarily focused on achieving climate goals, the economic opportunities of growing the hydrogen market are also in the spotlight. Supporting national R&D projects, Germany seeks to become a leading hydrogen technology provider globally. The government has supported hydrogen research activities since the 1980s, due to which the current German research landscape is rather advanced (Huber, 2021). Siemens Energy is already the largest electrolyzer manufacturer, responsible for over 50% of the global market (GlobalData, 2022). Another three German manufacturers are in the top 12 major companies.

Hydrogen demand forecast

As stated in its NHS, current domestic hydrogen consumption in Germany amounts to roughly 55 TWh (German Federal Government — Federal Ministry for Economic Affairs and Energy, 2020). Its use is largely limited to the industrial sector (refinery and ammonia production). Moreover, the dominant method of hydrogen production is the steam reforming of natural gas without capturing GHG gases in the process (i.e., grey hydrogen). German hydrogen demand is expected to reach 90–110 TWh by 2030. To cover at least part of this demand, the strategy proposes to build a total generation capacity of up to 5 GW by 2030, corresponding to 14 TWh of green hydrogen production. This target would result in an additional renewable electricity demand of 20 TWh. An extra 5 GW of capacity should be added, if possible, by 2035 and no later than 2040. In November 2021, the new German coalition government announced plans to double the original hydrogen capacity target for 2030 (FuelCellsWorks, 2021).

Domestic production of green hydrogen will not be sufficient to cover the expected demand. Therefore, most of the hydrogen required will be imported. To establish a secure supply, Germany will intensify its cooperation with other European Member States, particularly those bordering the North and Baltic Sea, but also with the countries of southern Europe. The use of offshore wind energy is expected to play an important role. Apart from EU countries, Germany also plans to strengthen energy cooperation with third countries (see section 4.3.4).

4.3.2 Policies and objectives

The National Hydrogen Strategy states that for hydrogen to become an enabler of the energy transition, the entire value chain—technologies, production, storage, infrastructure, and use, including logistics and important aspects of quality infrastructure—must be considered. To accelerate the domestic hydrogen economy, the strategy proclaimed EUR 7 billion available for hydrogen and hydrogen-related projects, along with a further EUR 2 billion for international partnership development. Although it focuses on green hydrogen in the long term, other colors of hydrogen were not taken off the table.

The strategy includes an action plan consisting of 38 measures the government plans to take in the first phase of domestic market ramp-up by 2023. In a second phase starting in 2024, the domestic market will be consolidated, and the European and international dimensions will be established. In September 2021, a report tracking the progress of the implementation of the abovementioned measures was published (BMWK, 2021). One of the core measures that is stated as addressed is the exemption of renewable electricity used for hydrogen production from the EEG surcharge. In this way, domestic green hydrogen production is expected to become more economically attractive. Another important achievement was made in securing funding for 62 hydrogen projects under the Important Projects of Common European Interest (IPCEI) label. The state aid will amount to €8 billion, which is expected to be matched with an additional €33 billion of private investment. Together, the projects comprise more than 2 GW of green hydrogen production capacity and are expected to result in the rollout of some 1,700 km of hydrogen pipelines. On the off-takers side, steel and chemical industries are in focus. Fuel cell systems, hydrogen-powered engines, and fueling stations networks should also be backed to promote hydrogen use in the transportation sector.

Apart from project support, to make the switch to climate-friendly industrial processes more attractive for investors, the government plans to introduce the Carbon Contracts for Difference (CCfD) funding program. The scheme is intended to guarantee a fixed carbon price needed to make the implementation of low-carbon technologies economically viable. The program primarily targets the steel and chemical industries where hydrogen is seen as a way forward as profound emission reductions cannot be achieved simply by replacing fossil fuels with renewable energy sources. Instead, entirely new methods of production are required. Agora Energiewende estimates that with the introduction of CCfDs German basic material industries could cut their emissions by about 20 million tons per year (Wehrmann, 2022).

As regards the transportation sector, to stimulate the deployment of green hydrogen and hydrogen-based fuels the EU's RED II has been implemented into national law. The German provision to reduce greenhouse gases by 25% for fuel by 2030 even exceeded EU requirements. Furthermore, additional funds were made available to continue incentives for the National Innovation Programme for Hydrogen and Fuel Cell Technology (NIP). Recent calls have covered such areas as the procurement of fuel-powered garbage collection and street cleaning vehicles, green intralogistics and vehicle parks, and the creation of electrolysis plants for hydrogen production for the transportation sector. Moreover, approximately EUR 630 million were allocated for power-to-liquid applied development and demonstration projects.

As for hydrogen applications in heating, support for high-efficiency fuel cell heating systems was expanded in the building sector (both residential and non-residential). For combined heat and power (CHP) generation, the government considers "hydrogen-readiness" as a condition for installation funding. Overall, the government appears rather reserved with regard to hydrogen in the heating sector compared to other application areas.

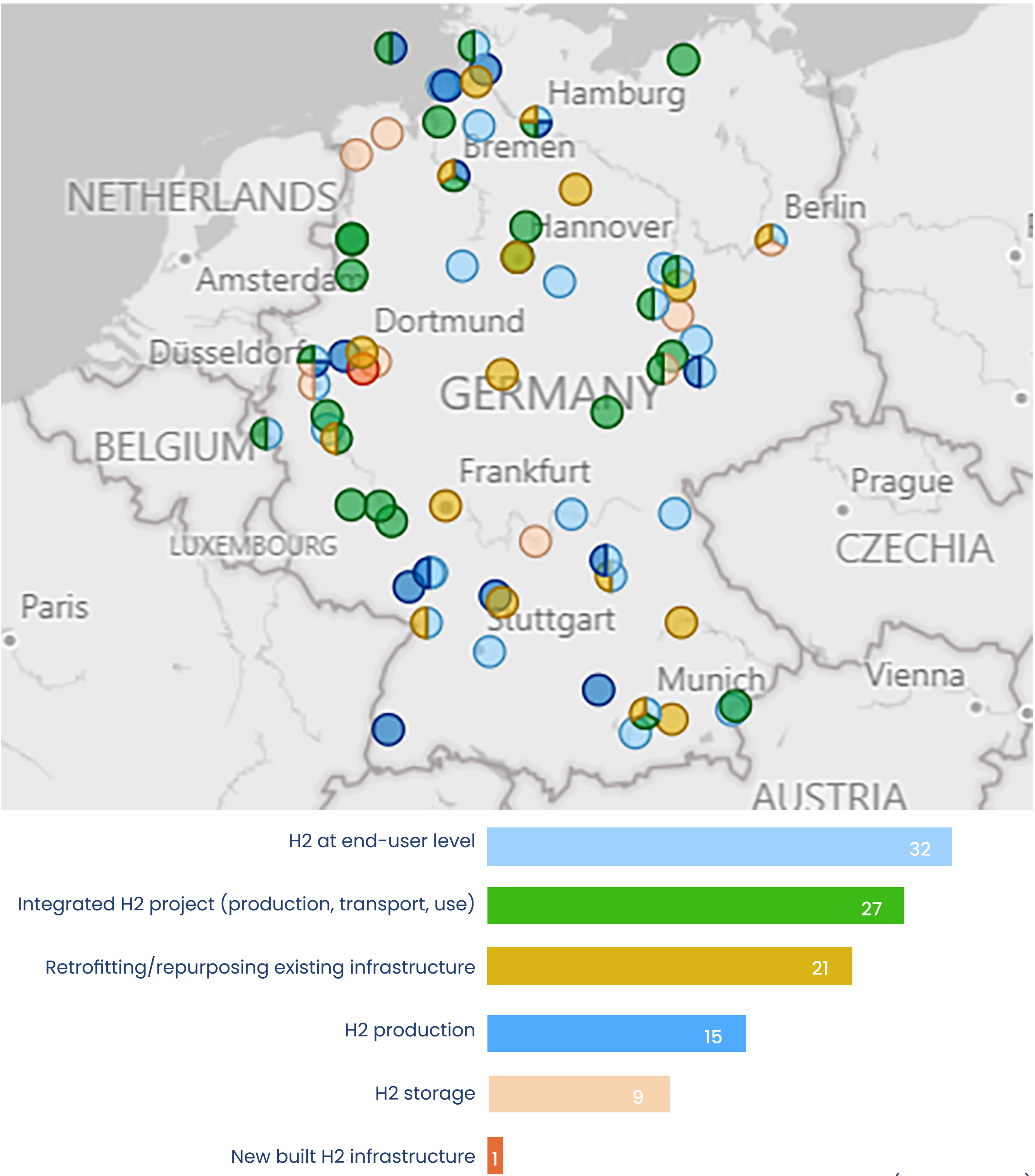
Concerning governance, the strategy envisions a cross-sectoral approach to the further development and implementation of the hydrogen policy. The main policy-shaping actors are the State Secretaries' Committee for Hydrogen and the National Hydrogen Council. The latter is an independent advisory board that consists of 25 members representing business, industry, research institutions, and civil society organizations. The main idea of the board is to assist the committee in the further development and implementation of the NHS (NWR, n.d.). This way, all types of actors have a chance to be part of the political debate on hydrogen and influence the final policy outcome. Despite the disruptive effect of hydrogen on the day-to-day activities of some private sector actors, they can increasingly be seen as active proponents and drivers of the hydrogen market build-up as global excitement about hydrogen technology rises.

After the change of government in September 2021, a plan to update the strategy was outlined (BMBF, 2022). A new version is expected by the end of 2022 and should lead to even more ambitious and binding targets (Wiedemann, 2022). The Ministry of Economics outlined that instead of doubling the total green hydrogen capacity target that was stated in the coalition agreement earlier, there are to be more precise specifications for each sector. The agreement also outlined the requirement for new gas-fired power generation installations to be "hydrogen-ready". With the decision to phase out both coal and nuclear power capacities in the near future and simultaneous intermittent renewable capacities expansion, gas-fired generation was assigned to play a curtailing role. In response to the war in Ukraine, the contribution of low-carbon gases (such as biomethane and hydrogen) is being reassessed.

4.3.3 Actors and funding

According to the ENSTO-G database, there are currently 86 projects in Germany, most of which are focused on the end-user level (Figure 4). Hydrogen use across various applications is being researched or tested. For instance, ArcelorMittal, the world's second-largest steelmaker, plans to convert its Hamburg plant to climate-neutral steel production, including developing a hydrogen-powered demonstration plant for the direct reduction of iron ore (H2First) and upgrading the direct-reduction plant by 2030 (H2Ready) (Mandel, 2021). As another example, BASF, the largest chemical producer in the world, intends to replace fossil fuel-based processes for basic chemicals production with green electricity and hydrogen at the Ludwigshafen site (Offshore-to-X project) (RWE, n.d.). In cooperation with RWE, an offshore wind park will be built in the Northe Sea to supply the required electricity. Other end-use projects cover district heating, CHP, and the transportation sector (heavy-duty trucks, aircraft, and conventional gas engines for vehicles).

Figure 4. Hydrogen projects in Germany



Source: ENTSO-G (ENTSO-G, n.d.)

The second largest projects category—integrated projects—includes complex and often international projects covering multiple parts of the hydrogen supply chain. An example here is the project Blue Danube, which aims to transport green hydrogen produced in southeast Germany to Austria and the rest of Germany in a liquid state by barges on the River Danube (Verbund, 2020). The listed projects are not limited only to green hydrogen. Norwegian energy company Equinor in cooperation with ThyssenKrupp and German gas and electricity TSOs are working on creating a blue hydrogen ecosystem (project H2morrow) (OGE, n.d.). Norwegian natural gas should serve as the feedstock, and CO_2 produced in the steam reforming process should be captured and safely stored under the seabed in the Norwegian North Sea. Also, existing German gas pipelines should be converted to pure hydrogen ones to deliver the low-carbon hydrogen to off-takers across the country.

Existing infrastructure repurposing projects are driven mainly by German gas TSOs and DSOs, alongside energy utilities and LNG terminal owners. Gas storage operators also plan on hydrogen storage construction by retrofitting existing caverns. Hydrogen production projects are developed primarily by energy utilities, oil and gas companies, and technology providers.

4.3.4 International cooperation

The strategy recognizes that in the medium and long term, the German economy will be dependent on hydrogen imports due to the expected enormous demand hardly being met indigenously. Thus, the German Federal Government is seeking to establish hydrogen partnerships with countries that demonstrate the largest potential for cost-effective green hydrogen production and can thus contribute to long-term security of supply. The country also takes part in global hydrogen initiatives promoting global hydrogen market creation.

Clean Hydrogen Mission

In June 2021, the European Commission, together with Australia, Austria, Canada, Chile, Germany, India, Italy, Morocco, Norway, Saudi Arabia, South Korea, the United Kingdom, and the United States, launched the "Clean Hydrogen Mission" (Mission Innovation, n.d.). The idea is to accelerate the creation of a global clean hydrogen economy by reducing the total cost of clean hydrogen to USD 2 per kg by 2030. This would be a tipping point in ensuring that clean hydrogen is competitively priced compared to other energy sources. To achieve this goal, Mission members have committed to creating at least 100 large-scale, integrated clean hydrogen valleys worldwide by 2030.

CEM Hydrogen Initiative

The CEM Hydrogen Initiative (CEM H2I) is a voluntary intergovernmental initiative that seeks to promote policies, programs, and projects that accelerate the commercialization and deployment of hydrogen and fuel cell technologies in all areas of the economy (Clean Energy Ministerial, n.d.). It operates under the auspices of the Clean Energy Ministerial (CEM), involving non-binding arrangements among participating national government ministries. Germany is one of the participating governments, along with Australia, Austria, Brazil, Canada, Chile, China, Costa Rica, the European Commission, Finland, India, Italy, Japan, the Netherlands, New Zealand, Norway, Portugal, Saudi Arabia, South Africa, South Korea, the United Kingdom, and the United States. In addition to governments, some large industrial companies have also partnered with the initiative, including German electrolyzer manufacturer ThyssenKrupp Nucera (part of ThyssenKrupp AG).

H2 Global

The H2Global Foundation was established in June 2021 to facilitate the launch of the green hydrogen industry and its international market ramp-up. Through the foundation, green hydrogen and its derivates will be purchased from non-EU suppliers under long-term fixed-price contracts and resold to German industry via annual auctions (H2Global Stiftung, n.d.). The idea behind this is to provide certainty for low-carbon hydrogen developers through long-term contracts at an adequate price while creating early demand for these products by offering competitive prices on the demand side. Since the cost of producing green hydrogen is likely to exceed buyers' willingness to pay in the short term, the intermediary will sell at a loss. This price difference will be covered by public funds. The German Federal Ministry of Economics and Energy has approved a grant of EUR 900 million for the purpose of ensuring a fast and sustainable build-up of the market for hydrogen products (BMWI, n.d.).

The first supply contracts are due to be concluded in 2022, and the first deliveries of hydrogen-based fuels to Germany and Europe will take place in 2024. One contract each for the sale of ammonia, methanol, and kerosene products derived from green hydrogen is expected to be awarded in the first round of tenders (BMWK, 2022).

Australia

In June 2021, the "Germany Australia Hydrogen Accord" was signed. It included the three following initiatives:

- *HyGate*: creation of a German-Australian H_2 incubator for applied research and pilot projects along the entire hydrogen supply chain.
- *Demonstration projects*: support for and the promotion of industrial cooperation in German–Australian demonstration projects in Australian hydrogen hubs.
- *Hydrogen trade cooperation*: development of measures to support the import of hydrogen and its derivatives from renewable energy sources from Australia to Germany (part of H2Global).

Canada

In March 2021, the two countries signed an MoU. The announced energy partnership is rather general. So far, no specific projects have been announced. However, cooperation in green hydrogen production is planned.

Chile

An MoU on cooperation in the field of hydrogen was signed in June 2021. It established a *Hydrogen Task Force* under the German–Chilean Energy Partnership framework. The goal is to further intensify cooperation between the two countries, to identify opportunities for the creation of consortiums and for investments, to create suitable framework conditions for the development of a hydrogen economy, and to identify concrete joint pilot and demonstration projects.

Japan

In June 2021, a framework announcement on the topic of green hydrogen cooperation with Japan was published by the German Federal Ministry of Education and Research. The aim is to promote research cooperation, which generates added value for the participating research and cooperation partners.

Morocco

An MoU was signed in June to cooperate in the field of renewable energies. Within this framework, the joint development of green hydrogen production technologies and the construction of a hydrogen production plant with a capacity of 100 MW is planned (BMZ, n.d.). The infrastructure needed to export the hydrogen by tank ships is also being expanded, with Hamburg and Tangier agreeing in October 2020 to expand their respective port infrastructures.

Saudi Arabia

Hydrogen cooperation was officially established in March 2021. In this context, a bilateral innovation fund will be established to promote clean hydrogen. Furthermore, the use of German technologies and the involvement of German companies in the implementation of clean hydrogen projects in Saudi Arabia are planned. The import of clean hydrogen and its downstream products, such as electricity-based kerosene, from Saudi Arabia to Germany is also intended.

South Africa

On behalf of the German government, the German Development Bank (Kreditanstalt für Wiederaufbau) has initiated a program of up to EUR 200 million to boost green hydrogen projects in South Africa and has issued a formal request for information to identify opportunities for projects to produce, consume, transport or store green hydrogen and its derivatives in South Africa (CSIR, 2021). These projects may include the production, transportation, export, and/or storage of green hydrogen and hydrogen-based products, as well as projects in existing materials and chemicals value chains that support the transition from fossil fuel-based processes to green hydrogen-based processes. The German Federal Ministry for the Environment, Nature Conservation, and Nuclear Safety have also launched the *PtX Pathway Project*, which promotes the development of sustainable hydrogen/PtX markets as a building block for the energy transition in South Africa and elsewhere.

West and Southern Africa

Besides the aforementioned partnerships, the Federal Ministry of Education and Research (BMBF) intends to focus in the future on strategic partnerships with various states in West and Southern Africa since these states have a high potential for green hydrogen production. For this purpose, the BMBF is financing the creation of a *Hydrogen Potential Atlas* for the region, for which 31 countries, such as Nigeria, Niger, Mali and Senegal, have already been analyzed. The analysis of these states is intended to serve as a basis for future hydrogen partnerships.

4.4 Spain

4.4.1 Status quo

With an energy consumption of 1,553 TWh in 2021, Spain is the fourth largest energy consumer in the EU. Considerably dependent on energy imports (Energy Commission, 2022), the country is fueled primarily by oil and natural gas (BP, 2022c). Still, the country has significant ambitions when it comes to its 2050 climate goals—Spain aims to reach "100% renewable energy in the electricity mix and 97% renewable energy in the total energy mix" (IEA, 2021). It has great potential in renewable energy and already boasts the second largest renewable energy generation in the EU with 95.8 TWh in 2021. The most significant RES are wind (62.4 TWh) and solar sources (26.8 TWh) (BP, 2022c).

However, the energy transition and transformation of the existing Spanish energy sector pose various challenges, mainly regarding the country's energy security. The current energy system relies on “massive stocks of oil, gas, and coal that can be dispatched in a flexible way” (IEA, 2021a). In contrast, the new system, powered primarily by renewable energy, will need “other forms of longer-term backup, on top of short-term flexibility” (Ibid.). Thus, the Spanish *Long-term decarbonization strategy* published in 2020 clearly suggests that climate and energy security questions go hand in hand and are planned to be tackled as such. The long-term strategy also defines targets for diminishing the country’s energy dependence—to 61% in 2030 and 13% in 2050. The year 2050 is also when Spain aims to achieve climate neutrality (Spanish Ministry for Ecological Transition and the Demographic Challenge, 2020a).

Aspirations for hydrogen

To achieve its ambitious climate targets, Spain counts on significant development of renewable energy, energy efficiency, electrification, and “renewable hydrogen” (IEA, 2021a). In its national *Hydrogen roadmap*, Spain formulates several environmental, business, economic and social benefits of the development of the renewable hydrogen sector. In addition to the more widely applicable opportunities for hydrogen, such as energy storage or stabilization of the electricity systems built on renewable sources, other benefits of hydrogen deployment arise from the country’s position. Owing to its geographical location and climatic conditions, Spain has the potential to become one of the “European powers in renewable energy generation” and to be an exporter of renewable energy, including renewable hydrogen (Spanish Ministry for Ecological Transition and the Demographic Challenge, 2020b). The country also positions itself as an evident option for Europe’s green hydrogen hub (Euractiv, 2021).

Hydrogen is also an opportunity for Spain and its island territories. These territories represent isolated energy systems with several physical and energy access restrictions. Not only could hydrogen solve such problems as temporary energy storage, but it could also be used for mobility and thus make these islands more sustainable tourist destinations (Spanish Ministry for Ecological Transition and the Demographic Challenge, 2020b).

Demand forecast

Today, hydrogen consumption in Spain is up to 500,000 metric tons/year, covered mainly by grey hydrogen. It is used primarily in refineries and the chemical industry. The Spanish NHS envisions that in 2030 at least 25% of the hydrogen consumed in industries will be renewable.

Nonetheless, the NHS does not specify any forecasts related to the future demand of hydrogen. Still, Spain emphasizes the need to create and promote a favorable environment for the supply and demand of renewable hydrogen. The creation of “hydrogen valleys or clusters” is a key concept in this area. Such territories will concentrate the “production, transformation and consumption” of renewable hydrogen to develop pilot projects linked to, for instance, isolated energy systems or the transport sector (Spanish Ministry for Ecological Transition and the Demographic Challenge, 2020b).

4.4.2 Policies and objectives

Spain introduced its *Hydrogen Roadmap: A Commitment to Renewable Hydrogen* in October 2020, joining other European countries that have already presented their ambitions concerning the hydrogen sector. This roadmap extends the Spanish *Integrated National Energy and Climate Plan* 2021–2030 (INECP) from January 2020. In INECP, hydrogen is discussed primarily in the context of renewable gases, one of the key measures for achieving decarbonization of the Spanish energy sector. That is also why this climate plan stresses the need for 100% renewable hydrogen. The main advantages of hydrogen discussed in INECP are its use in the transport sector, in industry, as energy storage, and as a means for synthetic natural gas production (Spanish Ministry for Ecological Transition and the Demographic Challenge, 2020c).

The Spanish *Hydrogen Roadmap* envisions Spain concentrating on the whole hydrogen value chain and formulates 60 measures to achieve the set targets of this hydrogen strategy. These measures are divided into four groups—regulatory instruments, sectoral instruments, cross-cutting instruments, and promotion of R&D.

Regarding regulatory instruments, the authors address several regulatory barriers arising from existing legislation that impede the development of green hydrogen activities. The main barrier is the categorization of hydrogen production as an industrial activity, which is restricted to be situated on land classified as industrial and must be subject to a rigorous environmental impact assessment.

Among the regulatory instruments, the Guarantees of Origin system is established in collaboration with European institutions. This system and a given responsible body would define procedures and requirements for renewable hydrogen and thus guarantee its green origin. Consequently, the Spanish government approved this system's proposal on a national level in May 2022 via Royal Decree. Moreover, this system is applicable not only for hydrogen but also for renewable gases as such. The new decree also aims to create a *Census of Installations for the Production of gas from renewable sources* and a *Producers Committee* (Spanish Ministry for Ecological Transition and the Demographic Challenge, 2022b, 2022a).

As regards sectoral instruments, the roadmap envisions, for instance, establishing a national statistical system of hydrogen consumption and production in Spain differentiated by different hydrogen types and by consumption sectors, the design of financial instruments to "support hydrogen-intensive industries to adapt processes and infrastructure for the continuous supply of renewable hydrogen", and the identification of current hydrogen consumption locations to encourage the creation of the aforementioned hydrogen valleys or clusters (Spanish Ministry for Ecological Transition and the Demographic Challenge, 2020b).

The hydrogen roadmap formulates two visions of hydrogen development for 2030 and 2050. The Spanish goals for 2030 are as follow:

> *4 GW of installed capacity of electrolyzers; 25% of the total hydrogen consumed in the industry will be of renewable origin; 100–150 publicly accessible hydrogen stations; 150–200 fuel cell buses; 5,000–7,500 light and heavy-duty fuel cell vehicles for freight transport; 2 commercial train lines powered by H_2; Operation of commercial hydrogen projects for electricity storage and/or use of surplus renewable energy (Spanish Ministry for Ecological Transition and the Demographic Challenge, 2020b).*

The vision for 2050 corresponds with the approach to deploying green hydrogen technologies as formulated in the *EU Hydrogen Strategy*. The overall target for 2050 is to make Spain a decarbonized society with a fully developed green hydrogen economy and with renewable energy having the prime share in the country's energy mix. The final ambition is to become an exporter of renewable hydrogen to the rest of Europe (Spanish Ministry for Ecological Transition and the Demographic Challenge, 2020b).

Relevant legislation

A crucial milestone for the development of the Spanish hydrogen sector was the approval of the *Strategic Project for the Recovery and Economic Transformation*[6] (PERTE) plan for *Renewable Energies, Renewable Hydrogen and Storage* (ERHA) in December 2021 (Spanish Government, 2021).

Concerning the application of renewable hydrogen, the Spanish hydrogen plan envisages the first uses to be selective and gradual considering the economic demands of initial green hydrogen production projects. Therefore, renewable hydrogen should be used mainly in sectors with no alternative option for decarbonization or direct electrification. Thus, there are two main directions for hydrogen application. The main focus is on industries, particularly those that are already heavy consumers of grey hydrogen (i.e., iron, steel, and chemical industries). Not only will it help to decarbonize these emissions-heavy industries, but since these sectors provide reliable demand and favor the increased use of hydrogen, such efforts could also boost the economic viability of Spanish decarbonized hydrogen production and thus its competitiveness. That is also one of the objectives of the Spanish hydrogen strategy— to lower the costs of producing renewable hydrogen and ensure the competitiveness of renewable hydrogen relative to other, non-decarbonized options.

4.4.3 Actors and funding

Funding

Regarding the funding of hydrogen development, the Spanish *Hydrogen Roadmap* refers to the possible contribution of already existing financing instruments. Such funding is directed primarily at supporting initiatives and projects where R&D plays a major role. The first mechanism mentioned, CIEN *projects*, is managed by the Spanish Center for Industrial Technological Development (CITD) “in the form of partially reimbursable aid, aimed at large industrial research and experimental development projects” (Spanish Ministry for Ecological Transition and the Demographic Challenge, 2020b). The budget of such projects must range from 5 to 20 million euros, of which 50% is allocated to industrial research activities (Spanish Ministry for Ecological Transition and the Demographic Challenge, 2020b). Other suggested possibilities of already existing funding include *Science and Innovation Missions* (also managed by CITD) with total allocation of 70 million euros, the MOVES *II Plan* with total allocation of 100 million euros, and the Programs of the General Secretariat for Industry and Small and Medium-Sized Enterprises for Financial Support to Industry (Ibid.).

Projects across different sectors

Indisputably one of the most significant projects of the Spanish hydrogen development (see Figure 5) is planned to take place in Mallorca under the name of *Green Hysland*. This complex project aims to “deploy a fully-functioning Hydrogen ecosystem in the island of Mallorca [...], turning the island into Europe’s first H2 hub in Southern Europe” (GreenHysland, 2022a). Behind this project is a multi-disciplinary consortium of 30 entities from 11 countries covering the whole hydrogen value chain. The involved members include, for instance, *Enagás* (an independent transmission system operator), the Spanish *National Hydrogen Centre*, *Spanish Hydrogen Association*, and international actors such as *Enercy* (an “international engineering consultancy specialized in the Clean Energy Transition through the development and deployment of Green Hydrogen Hubs”) and *European Marine Energy Centre* (GreenHysland, 2022c). The vision of *Green Hysland* is to fully utilize the geographical potential of Mallorca and produce green hydrogen from solar energy and deploy it to various end uses, e.g., transport, industry, but also in gas grid injection for heat and power and for sector coupling (GreenHysland, 2022b).

[6] Proyecto Estratégico para la Recuperación y Transformación Económica.

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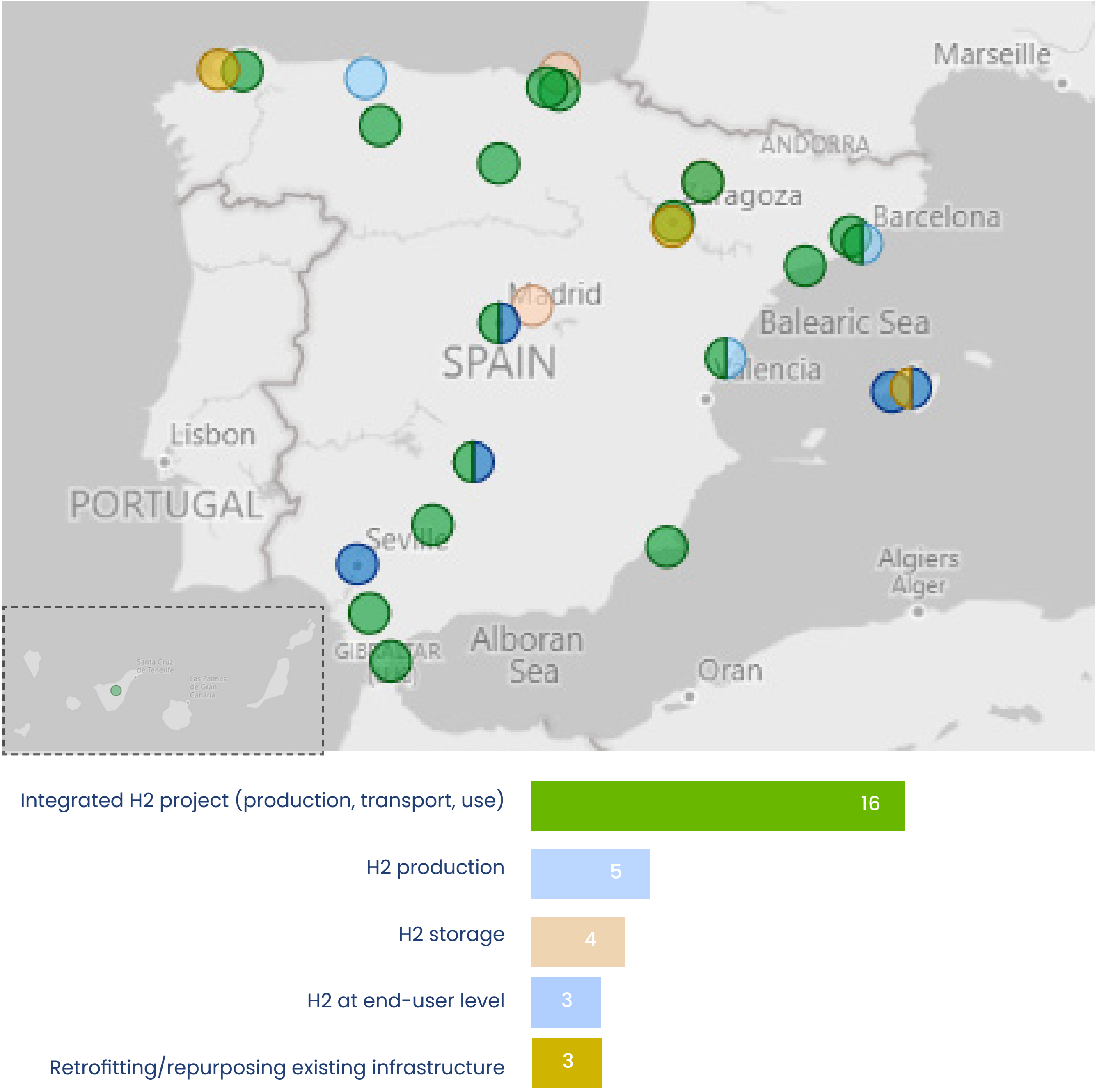
Figure 5. Hydrogen projects in Spain



Source: ENTSO-G (ENTSO-G, n.d.)

Under the patronage of the *Green Hysland* project, the consortium led by Enagás and Acciona Energía started commercial production at Spain's first industrial renewable hydrogen plant in Mallorca in March 2022. This project, named The Power to Green Hydrogen Mallorca and established in 2020, "will produce 330 tons of green hydrogen a year powered by the nearby 8.5 MW Llosseta and 5.9 MW Petra solar arrays" (Recharge, 2022).

In May 2022, Iberdrola, the Spanish multinational energy company, commissioned the largest green hydrogen plant for industrial use in Europe. The *Puertollano* plant "consists of a 100 MW photovoltaic solar plant, a lithium-ion battery system with a storage capacity of 20 MWh and one of the largest electrolytic hydrogen production systems in the world (20 MW)" (Iberdrola, 2022). With investments of 150 million euros, the produced green hydrogen will be used in a local ammonia plant, making its operator, Fertiberia, the first European company with expertise in green ammonia production (Ibid.). The plant is said to be able to produce up to 3,000 tons of green hydrogen per year and thus avoid the emission of 78,000 tons of CO_2 annually (Iberdrola, 2022a).

With the goal to promote innovation in the efficiency and sustainability of seaports, *H2Ports* is the first project to apply hydrogen technologies in port handling equipment in Europe. This project, situated at the Port of Valencia, introduces two innovative solutions based on fuel cell technologies and a hydrogen mobile supply station (H2 Ports, 2022).

4.4.4 International cooperation

Regarding hydrogen, Spain plans on international cooperation rather in the form of joint projects among individual companies. To name a few examples, Spanish companies Naturgy, Enagás, and Fertiberia formed a partnership at the beginning of 2022 with the Danish Copenhagen Infrastructure Partners and Vestas, the wind turbine manufacturer. Together, these firms decided to work on the Catalina Phase I project, which will consist of a 500 MW electrolyzer powered by solar and wind energy. This project, with the first phase of construction starting in late 2023, will be able to generate more than 40,000 tons of green hydrogen per year (CNBC, 2022).

Staying with Denmark, an interesting alliance has been forged between the Spanish government and Maersk, the Danish giant in the logistics sector. This partnership, emerging with the goal to "explore large-scale green fuels production", including hydrogen, envisages the potential to "deliver up to 2 million tons of green fuels per year" (Maersk, 2022).

In October 2022, Spanish energy company Cepsa signed an MoU with the Port of Rotterdam aiming to "establish the first green hydrogen corridor between southern and northern Europe" by connecting the ports of Rotterdam and Algericas (Cepsa, 2022). Strategic collaboration was also established between Spanish Iberdrola and British BP. With investments up to 1 billion euros, the companies plan to expand EV public charging infrastructure and develop large-scale production of green hydrogen in Spain, Portugal, and the United Kingdom (BP, 2022b).

Hydrogen also plays a role in the cooperation among Spain, Portugal, and France. These countries announced a common intention to build a subsea pipeline to carry primarily green hydrogen and other renewable gases between Barcelona and Marseille. This pipeline, called BarMar, should also be temporarily used to transport a "limited amount" of natural gas to help abate the impacts of the energy crisis in Europe. A more concrete project plan is expected to be presented in December 2022 (Reuters, 2022a). This project will replace another collaboration between France and Spain, the MidCat project, which was intended to be a gas interconnector between the two countries (Euractiv, 2022c).

A new transatlantic alliance has also emerged. Spain and the USA agreed to a joint declaration where, among other commitments, an emphasis is placed on "joint action to improve Europe's energy security and reduce dependence on Russian fossil fuels". Spain and the USA have committed to collaborate in this area to promote, for instance, developing renewable energy, offshore wind power, and renewable hydrogen (White House, 2022).

4.5 China

4.5.1 Status quo

Since 1980, China has been the fastest-growing economy in the world, with industrialization being the main diver of its transformation (World Bank, n.d.). In 2021, China accounted for 30% of global manufacturing output (The State Council Information Office the People Republic of China, 2022). It is the leading producer of steel, cement, aluminum, chemicals, electronics, and textiles (IEA, 2021c). More than half of the world's cement and steel is being produced by Chinese industry (The European Cement Association, 2021; World Steel Association, 2021). Due to rapid production growth coming from energy-intensive industries, in 2009 China became the largest energy consumer. At the same time, reliance on coal has put China at the top of the world's energy-related CO_2 emitters since 2005 (same IEA). In 2021, its primary energy consumption of 157.65 EJ resulted in 10,523.0 million tons of CO_2 emitted (BP, 2022a).

China is by far the largest producer of hydrogen at around 33 million tons, most of the which (about 80%) comes from fossil fuels as feedstock for refineries and chemical plants. The coal gasification method contributes 60% of the supply, while steam methane reforming adds another 20% (Li et al., 2021). Green hydrogen, on the other hand, accounts for less than 1% of the current production.

Aspirations for hydrogen

The transition from grey to green hydrogen has not been at the forefront of China's energy agenda until recently. This changed in September 2020 when Xi Jinping announced that China would peak emissions by 2030 and achieve carbon neutrality by 2060 (Frangoul, 2020). As part of the strategy to reach these goals, a target of over 1,200 GW of wind and solar power by 2030 was set in December 2020. Moreover, the most recent five-year plan for 2021–2025 is set to add at least 570 GW of wind and solar, achieving the 1,200 GW target already in 2026, if realized (Myllyvirta & Zhang, 2022). Using low-carbon sources for hydrogen production and its subsequent application in various economic sectors (especially industry and transportation) would help reduce China's carbon footprint. The government estimates that a renewable hydrogen production target of 0.1–0.2 million tons per year could result in an emissions reduction of 1–2 million tons annually by 2025 (China National Development and Reform Commission, 2022).

Apart from emission cuts, hydrogen expansion is expected to help China to increase energy supply security, reducing overreliance on fossil fuels. China's reliance on overseas oil stood at 72% in 2021, while its dependence on natural gas imports was about 45% (BP, 2022a; Xin, 2022). Even coal imports are growing, with consumption outpacing the country's domestic production (EIA, 2022a). The current energy crisis as reflected in high price volatility and global supply turbulence adds even greater significance to the issue of energy security. Of course, hydrogen's ability to serve as a balancing tool for growing intermittent renewable energy sources and its application opportunities across various sectors are also highly desirable.

Another incentive for ramping up the hydrogen market is future economic opportunities. China already accounts for one third of the world's electrolyzer manufacturing capacity and is expected to become even more competitive as production increases (Brown & Grünberg, 2022). Chinese companies can produce all the core components needed domestically with few exceptions (such as hydrogen valves), and local producers are very competitive on price. However, they do not yet meet international standards in terms of efficiency and reliability, especially in large systems.

At the same time, the growing number of demonstration projects, as well as the steady inflow of investments, may allow China to become more competitive on the international market soon.

Demand forecast

The China Hydrogen Alliance, a government-supported industry group, estimates that by 2030 China's hydrogen demand should reach 35 million tons, which represents at least 5% of its energy system (Yujie et al., 2021). In turn, the IEA's Energy Sector Roadmap to Carbon Neutrality in China predicts a sharp increase in hydrogen demand after 2030 reaching 90 million tons by 2060 (IEA, 2021c). A recent Hydrogen Council report on Global Hydrogen Flows sees China as the future largest single market for clean hydrogen, with demand tending towards 200 million tons by 2050, followed by Europe and North America (Hydrogen Council, 2022).

In a recently published hydrogen industry development plan for 2021–2035, China aims to produce 0.1–0.2 million tons of green hydrogen annually and significantly increase the share of green hydrogen in energy consumption by 2025 (China National Development and Reform Commission, 2022). This target appears to be rather modest, given the strong outlook for renewable capacity growth. Also, projected hydrogen demand can hardly be met with the stated domestic production capacity expansion. However, despite modest national goals, many state-owned enterprises (SOEs) have shown interest in developing hydrogen projects, making ambitious pledges to expand their green hydrogen production. Moreover, several subnational governments have labeled hydrogen as their key economic priority or outlined their own hydrogen development plans (e.g., Beijing and Jiangsu province's hydrogen refueling infrastructure build-up plans) (Yujie et al., 2021).

4.5.2 Policies and objectives

Medium- and long-term plan for developing the hydrogen industry (2021–2035)

Since 2020, hydrogen has been included in several top-tier national energy and technology development strategies. To further boost hydrogen momentum, in March 2022 China's top economic leadership released a hydrogen development plan for the period 2021–2035, further accelerating the development of hydrogen energy in China. In line with the plan, by 2025 China should create favorable conditions for the development of hydrogen with appropriate systems and policies. By 2035, all necessary systems for hydrogen production, transportation, and application should be established (China National Development and Reform Commission, 2022).

Apart from the green hydrogen production target mentioned earlier, the plan outlines an aim to have about 50,000 hydrogen-fueled vehicles by 2025. It is worth mentioning that China already represents the third largest market for fuel cell electric vehicles (FCEV) and the world's leading market for fuel cell trucks and buses (Nakano, 2022).

14th Five-Year Plan (2021-2025)

China's 14th Five-Year Plan refers to hydrogen as a "frontier" area that the country commits to advance. The country's central and local governments have identified the hydrogen industry as one of China's six industries of the future. The plan is unique in that its renewable energy target was consumption-based rather than generation-based, which improves the likelihood of increasing actual clean energy consumption and changing demand-side behavior (Yin & Yep, 2022). This could also provide greater incentive for wider hydrogen use in sectors where direct electrification is not viable.

4.5.3 Actors and funding

There are more than 120 green hydrogen projects currently in various stages of development in China, with several gigawatt-scale projects announced in the past couple of years (Standaert, 2022). These projects are mostly located in inland regions, such as Inner Mongolia, Ningxia, and Xinjiang, where the potential for renewable energy is considerable (Figure 6).

Figure 6. Hydrogen projects in China

Source: (Brown & Grünberg, 2022)

Most green hydrogen projects to date have been financed by large energy SOEs (Brown & Grünberg, 2022). For instance, among the most recent key projects is the Chinese oil giant Sinopec's plan to build the world's largest green hydrogen production plant in Kuqa, Xinjiang province (Yihe & Collins, 2022). A 260 MW project should be powered by a dedicated 361 MW solar array and produce 20 thousand tons of hydrogen per year. In September this year, the largest hydrogen producer in China announced a plan to have over 60% of its hydrogen output be green by 2025. Assuming that its current production is unlikely to shrink, the output would amount to over 2 million tons. The company also aims to build about 1,000 fueling stations by 2050 to reach 120,000 metric tons yearly refueling capacity for vehicles.

To progress towards the set goals, Sinopec has formed a joint venture with Cummins, American electrolyzer manufacturing company Cummins called Cummins Enze (Collins, 2022). The cooperation should lead to 1 GW of polymer electrolyte membrane electrolyzer production in southern China. Another strategic partner is France's Air Liquide, one of the world's leading companies in gases, technologies, and services for industry and health, helping to develop the Chinese hydrogen infrastructure network.

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Private renewable energy companies are also increasingly including green hydrogen in their business plans. The solar project developer GCL New Energy has announced its intention to build 100 power plants with an annual production capacity of 0.4 million tons of green hydrogen by 2025 (Juan, 2021). It has also partnered with two financial companies to create a CNY 10 billion hydrogen investment fund.

China's steel manufacturers, the second largest contributors to the country's CO_2 emissions, have begun exploring hydrogen-powered metallurgy (Guoping & Zou, 2022). For instance, in May 2021 Hebei Iron and Steel Group, one of the world's largest steel producers, launched a demonstration project for hydrogen energy development and utilization in Zhangjiakou (Shahkar, 2021). The city itself aims to become the hydrogen capital of China, reaching an annual production of 50 thousand tons by 2035 (Xu & Singh, 2020).

4.5.4 International cooperation

According to many experts, China will be able to meet its own renewable hydrogen needs through competitive domestic production and thus not rely on imports (Hydrogen Council, 2022). Such situation would also be in line with its strategic objective of reducing energy import dependence.

From a European perspective, opportunities for establishing hydrogen trade connections with China appear to be rather limited due to China's immense domestic demand for energy and relatively long-distance transport constraints. However, this potentially large player in the global hydrogen market should not be neglected when making decisions about the hydrogen economy build-up. Thus, collaboration with China in R&D, trade of low-carbon hydrogen technologies and equipment, standard-setting, as well as joint projects in third countries should be considered.

An example of such an effort already taking place is the China-UK Hydrogen Energy Cooperation Forum held in April 2022 (Embassy of the People's Republic of China in the United Kingdom of Great Britain and Northern Ireland, 2022). The two countries showed a readiness to support local governments and businesses to establish closer cooperation in developing green hydrogen technologies. As a result, an MoU on hydrogen energy industry exchange and cooperation between Wuhan city and Manchester City was signed, with Wuhan University of Technology and Manchester Metropolitan University signing a letter of intent on hydrogen energy cooperation.

Cooperation efforts can also be seen among NGOs. For example, in November 2021 Agora Energiewende hosted a Europe–China workshop on the green hydrogen economy. The workshop was supported by GIZ and the Federal Ministry for Economic Affairs and Energy's Sino–German Energy Transition Project in partnership with the Shanghai Institute for International Studies (SIIS) and Energy Investment Professional Committee of the Investment Association of China (IAC) (Agora Energiewende, 2021). In the same month, the Rocky Mountain Institute organized the Europe–China Clean Hydrogen-based Steel Dialogue and Collaboration Workshop supported by the EU Delegation to China as well as the embassies of Sweden, the Netherlands, and Norway (Li et al., 2021).

4.6 United States

4.6.1 Status quo

The United States has been the second largest energy consumer in the world since 2009, when it was displaced by China. With less than 5% of the global population, it consumes nearly 17% of global energy and accounts for 16% of world GDP (EIA, n.d.). For comparison, the EU represents

6% of the global population, consumes 10.4% of energy, and accounts for 16% of GDP. In contrast, China has 18% of the global population, uses 25% of energy, and is responsible for 18% of the GDP.

Following the same pattern, the USA is also the second highest emitter (BP, 2022a). Since 2016, the transportation sector has been the main source of emissions (EIA, 2022b). For years, the energy sector was the largest contributor, but the transition to cleaner energy sources and the shift away from coal power have moved the sector to second place with an over 25% reduction compared to 2009. Meanwhile, emissions from transportation continue to rise, except for an unprecedented decline in 2020 caused by the pandemic.

As regards hydrogen, US industry currently produces about 10 Mt per year, mainly as a feedstock for methanol and ammonia production in the chemical industry and in refineries. Hydrogen also plays a growing role in the transportation sector (*Roadmap to a US Hydrogen Economy*, 2020). The number of FCEVs now exceeds 7,600 units, also complimented by a few dozen hydrogen buses and numerous hydrogen-powered truck prototypes. About 2,600 km of hydrogen pipelines are currently operational (DOE, n.d.). For comparison, in 2018 the European hydrogen network consisted of about 2,000 km (Ludwig et al., 2021). As for sourcing, 77% of produced hydrogen comes from natural gas (SMR) and 20% is a byproduct of refining, generating about 100 Mt of GHG per year.

Aspirations for hydrogen

In 2016, accounting for 18% of global emissions, the US formally ratified the Paris Agreement (Enerdata, n.d.). In November 2020, however, the Trump administration withdrew from the Agreement. The Biden administration, in turn, recommitted to it in January 2021.

After the official re-signing of the Agreement, hydrogen as a decarbonization tool has made its way onto the official policy agenda. Hydrogen plays a key role in the Biden administration's goal to achieve carbon-free electricity by 2035 and a net-zero economy by 2050. The US Department of Energy (DOE) expects that clean hydrogen use has the potential to reduce US emissions by approximately 10% by 2050 compared to 2005 (US Department of Energy, 2022b). Priority markets for clean hydrogen are expected to be hard-to-decarbonize sectors. Hydrogen is also seen as an enabling technology for renewable power expansion, providing flexibility and long-duration energy storage.

Demand forecast

Current hydrogen demand in the US amounts to 11.4 million metric tons. According to a study conducted by a coalition of major oil & gas, power, automotive, fuel cell, and hydrogen companies, demand could reach 14 million metric tons (Mt) by 2030, rising to 20 million by 2050 (*Roadmap to a US Hydrogen Economy*, 2020). The recently published draft DOE National Clean Hydrogen Strategy roadmap has estimated the US future hydrogen market as follows: 10 Mt/y by 2030, 20 Mt/y by 2040, and 50 Mt/y by 2050 (US Department of Energy, 2022b). These demand calculations reflect expected hydrogen competitiveness against the fuels and processes that hydrogen use would replace in each specific sector.

To allow hydrogen to become competitive and realize its potential, in June 2021 the DOE launched the Hydrogen Energy Earthshot (Hydrogen Shot)—an initiative to reduce clean hydrogen costs by 80% to $1 per 1 kilogram within 1 decade (Hydrogen and Fuel Cell Technologies Office, n.d.-a). In July 2021, $52.5 million in funding for R&D and scaling projects was announced.

4.6.2 Policies and objectives

US hydrogen policy has two main dimensions: the nationwide federal framework and state-level initiatives. The nationwide federal framework often suffers from changeable political attitudes, while individual state approaches vary greatly. To keep the level of analysis consistent, we focus on the federal level as creating the broader framework and setting the direction for regional policy development.

Bipartisan Infrastructure Law

In November 2021, the Infrastructure Investment and Jobs Act, also referred to as the Bipartisan Infrastructure Law (BIL), was passed by Congress and signed by the President (White House, 2021). This $1.2 trillion piece of legislation allocated $62 billion to the DOE for investments in energy infrastructure, of which $9.5 billion were dedicated to clean hydrogen. Funding is to be distributed among the following initiatives:

- Clean Hydrogen Electrolysis Program ($1 billion),
- Clean Hydrogen Manufacturing and Recycling RDD&D activities ($500 million), and
- Regional Clean Hydrogen Hubs ($8 billion).

The last initiative appears to be one of the largest investments in DOE history, aimed at enabling equitable and sustainable regional benefits along with market uptake. The initiative includes both green and fossil fuel-based hydrogen production coupled with CCUS technologies co-located with consumption points. The hubs need to be regionally dispersed across the US. The BIL also requires hydrogen hubs to target the power generation, industrial, heating, and transportation sectors to the maximum extent possible. At least 10 regional hubs are expected to be established (Office of Clean Energy Demonstrations, n.d.). Concept papers from applicants are due November 2022 and full applications by April 2023.

National Clean Hydrogen Strategy and Roadmap

The US is a relative latecomers to the party, with its draft National Clean Hydrogen Strategy and Roadmap published only in September 2022 (US Department of Energy, 2022b). The official strategy publication is expected by the end of 2022. The draft builds on three main strategies to ensure clean hydrogen nationwide development and adoption:

- Targeting strategic, high-impact uses (hard-to-abate sectors, long-term export);
- reducing clean hydrogen costs (the Hydrogen Shot initiative, addressing supply chain vulnerabilities and design imperfections); and
- focusing on regional networks (development of regional clean hydrogen hubs).

The strategy does not prioritize any one method of hydrogen production, even in the long-term perspective. Rather, it promotes “clean” hydrogen, which includes not just green (produced from renewable electricity) but also pink (from nuclear power) and blue (from fossil fuels with CCS application) hydrogen.

Clean Hydrogen Production Standard

The draft Clean Hydrogen Production Standard (CHPS) guidance was published together with the draft Strategy in September 2022 (US Department of Energy, 2022a). It proposed an initial target of a *lifecycle* GHG emissions rate of 4 kg of CO_2e per 1 kg of H_2. This target complements the one set in the BIL, where clean hydrogen is defined as having a carbon intensity equal to or less than 2 kg of CO_2e per 1 kg of H_2 *at the site of production*. The CHPS is intended to accommodate "some additional emissions from upstream and/or downstream processes", such as upstream methane emissions or downstream electricity usage for CCS application, while the BIL target is focused only on gate-to-gate emissions (Samji et al., 2022; US Department of Energy, 2022a).

The establishment of a lifecycle emission target allows the DOE to proceed with a technology-neutral approach, avoiding labeling hydrogen as green or blue and instead allowing the market to select any pathway that leads to the desired low-carbon footprint (Latham & Watkins Environment, 2022). The lifecycle emissions approach is also expected to provide stakeholders with more flexibility. For example, systems that use less carbon-intensive electricity or reduce fugitive emissions will have more flexibility at the production site.

CHPS is not to be understood as a legally binding regulatory standard but rather as a guideline for investment when considering clean hydrogen project support. Therefore, it does not mean that projects not meeting CHPS are not to be funded. As long as they "demonstrably aid the achievement" of the CHPS, they may be considered eligible (Latham & Watkins Environment, 2022).

Inflation Reduction Act

The Inflation Reduction Act (IRA), signed into law in August 2022, included $369 billion in energy and climate spending with an unprecedented emphasis on clean hydrogen. In particular, it introduced a clean hydrogen production tax credit (PTC) and extended the existing investment tax credit (ITC) to apply to hydrogen projects and off-grid hydrogen storage technologies. The Act further promotes the hydrogen economy by allowing taxpayers to aggregate bonus credits and capitalize on direct payment and transfer of hydrogen-related tax credits.

Clean hydrogen projects may qualify either for PCT based on the amount of hydrogen produced or ITC equal to a share of the cost to build or acquire the project. Both PTC and ITC rates vary based on the amount of CO_2 emitted per kilogram of hydrogen. To be eligible for either credit, the lifecycle emissions rate at the point of production should not exceed 4 kg of CO_2 equivalent per kg of hydrogen. While the ITC is a one-time benefit, the PCT can be claimed for 10 years in total.

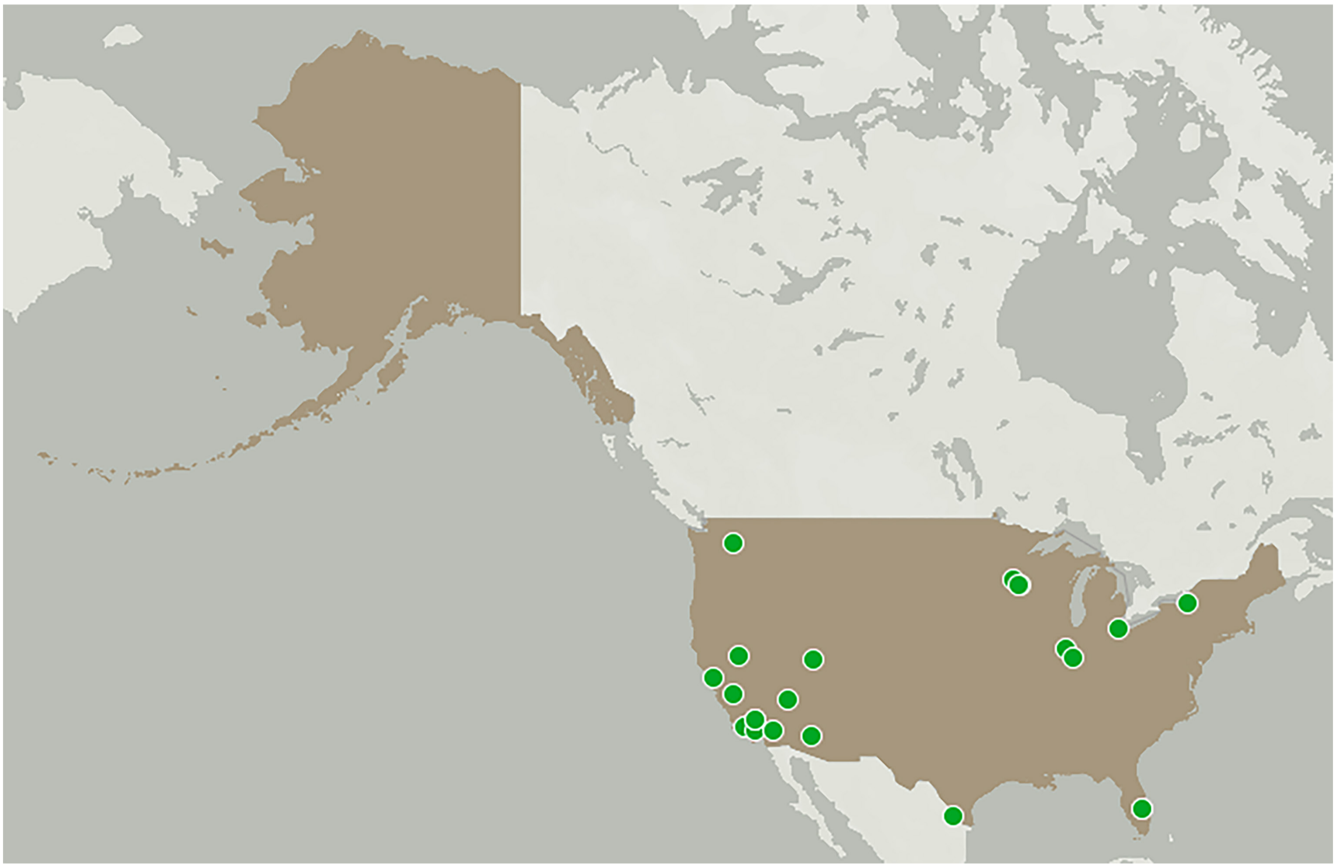
The PCT is expected to have a dramatic impact on hydrogen demand patterns. An analysis conducted by the Rhodium Group showed that thanks to these credits the cost of green hydrogen produced from solar energy could be $0.39 per kilogram in some US regions by 2030, while prices for grey hydrogen produced from natural gas could range from $0.99 to $1.54 per kilogram (Larsen et al., 2022). Thus, the timeline for green hydrogen to reach cost parity with grey hydrogen has probably been moved up by several years. In addition, the IRA may also open the door to pink hydrogen.

4.6.3 Actors and funding

According to Pillsbury Law's hydrogen map (Figure 7), there are currently around 20 low-carbon hydrogen projects in the US. All of them are labeled as green[7] hydrogen projects, with only 4 cited as operational. All currently functioning projects are located on the US west coast. Two are located in California: solar energy-powered hydrogen production (Heliogen, Bloom Energy) and a hydrogen-powered bus fleet (SunLine) (Bloom Energy, 2021; SunLine, n.d.). Another project, led by Douglas County Public Utility District, harvests hydrogen from the Wells Dam on the Columbia River in Washington state (FuelCellsWorks, 2022). The last one is a laboratory-scale reactor system for methane production from renewable hydrogen in Nevada (Hoekman et al., 2010).

[7] In this case, produced from renewable or nuclear energy.

Figure 7. Hydrogen projects in the USA



Source: Pillsbury (Pillsbury, n.d.)

As for non-operational projects, the highest concentration is yet again in California. For instance, the company SGH2 is focusing on the gasification of waste into hydrogen, planning to build its production facility in Lancaster (SGH2 Energy, n.d.). Another waste-to-hydrogen project was announced in Richmond, California, where Republic Services and Raven SR agreed to produce up to 2,000 metric tons of green hydrogen per year from organic waste (Raven SR, 2021).

In Ohio, New York, Minnesota, and Arizona, pilot projects are being funded by the DOE for hydrogen production from nuclear energy (Idaho National Laboratory, 2020; Nuclear Newswire, 2021). In Utah, Mitsubishi Hitachi Power Systems was awarded a contract to convert a coal-fired power generation plant into a renewable hydrogen-fired plant (Mitsubishi Power, 2020). Initially, the project will generate electricity from a mixture of hydrogen and gas, gradually moving to 100% hydrogen generation by 2045.

In Texas, US start-up Green Hydrogen International plans to create a hydrogen production, storage, and transport hub powered by 60 GW of wind and solar installations and capable of producing over 3 billion kg of hydrogen per year (Green Hydrogen International Corporation, n.d.). At the heart of the project is a hydrogen storage facility in the Piedras Pintas Salt Dome, located in Duval County. Pipelines will carry green hydrogen to Corpus Christi, where it will be converted into green ammonia, green jet fuel, and other products or piped directly to hydrogen power plants or other end-use customers throughout the state. Another hydrogen hub is being planned in Florida, where Florida Power & Light Company (FPL) wants to leverage solar power for hydrogen production (Business Wire, 2022). Once produced, green hydrogen is to be mixed with natural gas and used to power the existing internal combustion turbine at the nearby FPL Okeechobee Clean Energy Center.

Apart from the above hubs, the Center for Strategic & International Studies (CSIS) identified 19 more hydrogen hub proposals across the US that may compete for funding under the Regional

Clean Hydrogen Hubs program (Higman, 2022). All of them are still in the very early development stage and are mostly public–private partnerships. Such a partnership structure appears to be particularly beneficial for attracting investment and securing local economic benefits, offering benefits to all types of stakeholders. As for the feedstock, renewable energy appears to be the most common choice, followed by blue hydrogen projects. Pink hydrogen has received the least attention. As regards end-uses, most projects are targetting heavy industry and long-haul transportation.

4.6.4 International cooperation

The National Clean Hydrogen Strategy and Roadmap envisions the possibility to export clean hydrogen in the long term to enable energy security for US allies (US Department of Energy, 2022b). The US can already be seen initiating stronger relationships with allies on hydrogen. Already in 2003, the US was one of the founding members of the International Partnership for Hydrogen and Fuel Cells in the Economy (IPHE), which intended to accelerate progress in technologies development and provide a forum for sharing information on member country initiatives, policies, and technology status as well as safety, regulations, codes, standards, and outreach. The partnership now has over 20 members (Hydrogen and Fuel Cell Technologies Office, n.d.-b). The US currently serves as vice-chair of the steering committee and actively participates in IPHE's working groups.

Through the IEA, the US has also participated in several collaboration programs on hydrogen and fuel cell technologies (US Department of Energy, n.d.) and has supported the Hydrogen Initiative (see more in the German case study) launched under the Clean Energy Ministerial (Clean Energy Ministerial, n.d.). Apart from the US's co-leading role in the initiative, the American private sector is also represented by large industrial gases and chemicals provider Air Products. Other initiatives for close cooperation with specific countries can also be noted. For instance, in June 2018 Japan, the EU, and the US released a joint statement on future cooperation in hydrogen and fuel cell technologies, highlighting the importance of hydrogen cost reduction (US Department of Energy, 2019). The US also collaborates with the Netherlands on collecting, analyzing, and sharing information about hydrogen production and infrastructure technologies (Government of the Netherlands, 2020).

5. Concluding remarks

In this book, we set out to answer three research questions: What is sector coupling and how is it understood across different political and analytical contexts? What role will hydrogen play in the development of sector coupling? What are the current and expected hydrogen policies in Europe, the USA, and China?

The academic literature and policy realm approach sector coupling from a variety of perspectives, emphasizing different interconnections among components of supply (such as energy and heat) and end-use sectors (such as industry, households, transport) and considering energy system integration across multiple pathways and/or geographical scales. In Europe, the original understanding of sector coupling was primarily associated with the electrification of end-use sectors in one form or another (e.g., direct electrification or via hydrogen or synthetic fuels use). The focus has subsequently broadened to account for supply sector integration options through technologies such as power-to-gas. Thus, the current end goal of sector coupling can be summarized as comprehensive decarbonization of the economy alongside the establishment of an integrated pure renewable energy system that is sustainable, resilient, and cost-effective.

The role of hydrogen in sector coupling is still a subject of discussion. The challenge here is uncertainty with regard to its sourcing and use. These two issues are linked as the more energy- and cost-intense hydrogen production is, the less attractive it appears as a decarbonization tool competing with alternative technologies such as CCS and batteries. Thus, some hydrogen application options, such as low-temperature heat in industry, small-scale heating, and passenger transportation, have gradually been deprioritized by both market actors and policymakers. In contrast, hydrogen projects promoting its use in sectors where there is no other viable decarbonization option (e.g., steel making, chemical industry feedstock, maritime shipping) receive most of the attention. The priorities are still not fully set as both hydrogen and non-hydrogen technologies are constantly being researched and developed, potentially changing the parameters for selecting the most cost-efficient measure.

The development of hydrogen policies across different countries shows growing expectations from hydrogen the more the energy transition progresses. Europe currently has technology

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leadership but may soon lose the edge as other countries join the race and establish themselves on this promising emerging market. The position of European front runners (such as Germany and France) may be threatened by the more recent entry of major non-European countries with ambitious targets and game-changing support schemes, such as the USA's tax incentives for hydrogen projects. Policy ambiguity and delays in establishing a European hydrogen policy framework may decrease the region's attractiveness for further investments and delay current projects' final investment decision.

A very recent example is the postponement of several hydrogen projects' investment decisions after the European Parliament scraped the proposed additionality criteria, at the same time relaxing the accounting rules for matching renewable power with electrolysis projects (Burgess & Rathore, 2022). If a clear policy framework is not established soon, hydrogen developers' attention may shift to overseas markets, primarily the US market, which provides straightforward rules and guidance.

Apart from investments in hydrogen production projects, Europe's leadership may also shrink as China improves its innovation capabilities and strengthens its price competitiveness. Here, the potential economic benefits of shared ventures with Chinese manufacturers should be weighed against their potential development acceleration, creating aggressive competition for Western companies. Preventing the overexposure of hydrogen technology supply chains to China is necessary to prevent the formation of new dependences.

Another challenge that Europe must face is the unpredictable impact of the war in Ukraine, which apart from destabilizing the European energy system has crossed two potential hydrogen suppliers (Russia and, at least until the war is over and the energy system rebuilt, Ukraine) from the list of options. Nevertheless, in its efforts to reduce energy dependence, Europe has not only not abandoned but even raised its hydrogen targets and is pushing for closer cooperation with alternative suppliers such as the Middle East, Africa and American countries.

6. Literature

Actu Environment. (2022). *L'Ademe sélectionne 18 nouveaux écosystèmes territoriaux à hydrogène*. https://www.actu-environnement.com/ae/news/ademe-selection-18-projets-territoriaux-hydrogene-AAP-39634.php4

ADEME. (2022). *Appel à projets écosystèmes territoriaux hydrogène : 18 projets pré-sélectionnés*. https://presse.ademe.fr/2022/05/appel-a-projets-ecosystemes-territoriaux-hydrogene-18-projets-pre-selectionnes.html

Agora Energiewende. (2021, November 7). *Europa-China Workshop zu grüner Wasserstoffwirtschaft*. Agora Energiewende.

Ajanovic, A., & Haas, R. (2018). Economic prospects and policy framework for hydrogen as fuel in the transport sector. *Energy Policy*, 123, 280–288. https://doi.org/10.1016/j.enpol.2018.08.063

Ajanovic, A., & Haas, R. (2021). Prospects and impediments for hydrogen and fuel cell vehicles in the transport sector. *International Journal of Hydrogen Energy*, 46(16), 10049–10058. https://doi.org/10.1016/j.ijhydene.2020.03.122

Andriosopoulos, K., & Silvestre, S. (2017). French energy policy: A gradual transition. *Energy Policy*, 106, 376–381. https://doi.org/10.1016/J.ENPOL.2017.04.015

Bartiaux, F., Maretti, M., Cartone, A., Biermann, P., & Krasteva, V. (2019). Sustainable energy transitions and social inequalities in energy access: A relational comparison of capabilities in three European countries. *Global Transitions*, 1, 226–240. https://doi.org/10.1016/J.GLT.2019.11.002

Bellona. (2021). *Will Hydrogen Cannibalise the Energiewende?* https://bellona.org/publication/will-hydrogen-cannibalise-the-energiewende

Bloess, A., Schill, W. P., & Zerrahn, A. (2018). Power-to-heat for renewable energy integration: A review of technologies, modeling approaches, and flexibility potentials. *Applied Energy*, 212, 1611–1626. https://doi.org/10.1016/J.APENERGY.2017.12.073

Bloom Energy. (2021, July). Bloom Energy and Heliogen Join Forces to Harness the Power of the Sun to Produce Low-Cost Green Hydrogen. *Stockhouse*. https://stockhouse.com/news/press-releases/2021/07/22/bloom-energy-and-heliogen-join-forces-to-harness-the-power-of-the-sun-to-produce

BMBF. (2022, May 16). *National Hudrogen Strategy: Green hydrogen as energy source of the future*.
https://www.bmbf.de/bmbf/en/news/national-hydrogen-strategy.html

BMUV. (2021). *Lesefassung des Bundes-Klimaschutzgesetzes 2021 mit markierten Änderungen zur Fassung von 2019*. https://www.bmu.de/fileadmin/Daten_BMU/Download_PDF/Klimaschutz/ksg_aendg_2021_3_bf.pdf

BMWI. (n.d.). *What exactly is H2Global?* BMWI. Retrieved November 14, 2022, from https://www.bmwi-energiewende.de/EWD/Redaktion/EN/Newsletter/2022/01/Meldung/direkt-account.html

BMWK. (2020, July 3). *Final decision to launch the coal-phase out – a project for a generation*. https://www.bmwk.de/Redaktion/EN/Pressemitteilungen/2020/20200703-final-decision-to-launch-the-coal-phase-out.html

BMWK. (2021). *Bericht der Bundesregierung zur Umsetzung der Nationalen Wasserstoffstrategie*. https://www.bmwk.de/Redaktion/DE/Publikationen/Energie/bericht-der-bundesregierung-zur-umsetzung-der-nationalen-wasserstoffstrategie.html

BMWK. (2022). H2Global. Term Sheet: Hydrogen Purchase Agreements. Draft. In BMWK. https://www.bmwk.de/Redaktion/DE/Downloads/h2global/draft-term-sheet-hpa-market-consultation-h2global.pdf?__blob=publicationFile&v=2

BMZ. (n.d.). *Green hydrogen and Power-to-X*. BMZ. Retrieved November 14, 2022, from https://www.bmz.de/de/themen/wasserstoff/

Bock, N., Buck, M., Görlach, J., Graichen, P., Karcher, U., Maier, U., Matthes, F. C., Meyer, K., Hörmandinger, G., Peter, F., Rühring, A., Stam, C., & Witecka, W. K. (2020). *Making renewable hydrogen cost-competitive Policy instruments for supporting green H_2*. https://static.agora-energiewende.de/fileadmin/Projekte/2020/2020_11_EU_H2-Instruments/A-EW_223_H2-Instruments_WEB.pdf

Böhm, H., Moser, S., Puschnigg, S., & Zauner, A. (2021). Power-to-hydrogen & district heating: Technology-based and infrastructure-oriented analysis of (future) sector coupling potentials. *International Journal of Hydrogen Energy*, 46(63), 31938–31951. https://doi.org/10.1016/J.IJHYDENE.2021.06.233

BP. (2022a). *bp Statistical Review of World Energy* 2022. https://www.bp.com/content/dam/bp/business-sites/en/global/corporate/pdfs/energy-economics/statistical-review/bp-stats-review-2022-full-report.pdf

BP. (2022b). *Iberdrola and bp to collaborate to accelerate EV charging infrastructure and green hydrogen production | News and insights | Home*. https://www.bp.com/en/global/corporate/news-and-insights/press-releases/iberdrola-and-bp-to-collaborate-to-accelerate-ev-charging-infrastructure-and-green-hydrogen-production.html

BP. (2022c). *Statistical Review of World Energy* 2022.

Brintbranchen. (2022). *Home - Brintbranchen*. https://brintbranchen.dk/en/

Brown, A., & Grünberg, N. (2022). *China's Nascent Green Hydrogen Sector: How policy, research and business are forging a new industry*. https://merics.org/sites/default/files/2022-06/MERICS_China_Monitor_No_77_Green-Hydrogen_EN_final.pdf

Burgess, J., & Rathore, A. (2022, October 5). Policy headwinds for clean hydrogen in Europe temporary. *S&P Global*.

Business Wire. (2022, February 28). FPL Announces Cummins to Supply Electrolyzer for Florida's First "Green" Hydrogen Plant – Potential Key to Carbon-Free Electricity. *Business Wire*. https://www.businesswire.com/news/home/20220228005567/en/FPL-Announces-Cummins-to-Supply-Electrolyzer-for-Florida's-First-"Green"-Hydrogen-Plant---Potential-Key-to-Carbon-Free-Electricity

Cambridge Dictionary. (2022). *Transition* . https://dictionary.cambridge.org/dictionary/english/transition

CEER. (2022). *CEER Paper on Regulatory Sandboxes in Incentive Regulation Distribution Systems Working Group*. https://www.ceer.eu/documents/104400/-/-/72eab87d-9220-e227-1d26-557a63409c6b

Cepsa. (2022). *Cepsa and Port of Rotterdam will create a green hydrogen corridor*. https://www.cepsa.com/en/press/first-green-hydrogen-corridor

Cheng, W., & Lee, S. (2022). How Green Are the National Hydrogen Strategies? *Sustainability (Switzerland)*, 14(3). https://doi.org/10.3390/su14031930

China National Development and Reform Commission. (2022). *Medium- and Long-term Plan for the Development of the Hydrogen Energy Industry* (2021-2035). https://www.ndrc.gov.cn/xxgk/zcfb/ghwb/202203/t20220323_1320038.html?code=&state=123

Clean Energy Ministerial. (n.d.). *Hydrogen Initiative*. Clean Energy Ministerial. Retrieved November 14, 2022, from https://www.cleanenergyministerial.org/initiatives-campaigns/hydrogen-initiative/

CNBC. (2022). *Danish energy fund to lead massive green hydrogen project in Spain*. https://www.cnbc.com/2022/02/02/danish-energy-fund-to-lead-massive-green-hydrogen-project-in-spain.html

Collins, L. (2022). US-based Cummins to build 1GW hydrogen electrolyser factory in China with state-owned oil giant Sinopec. *RECHARGE*. https://www.rechargenews.com/energy-transition/us-based-cummins-to-build-1gw-hydrogen-electrolyser-factory-in-china-with-state-owned-oil-giant-sinopec/2-1-1139138

Connolly, D., Lund, H., Mathiesen, B. v., & Leahy, M. (2011). The first step towards a 100% renewable energy-system for Ireland. *Applied Energy*, 88(2), 502–507. https://doi.org/10.1016/J.APENERGY.2010.03.006

CSIR. (2021). Request for Information (RFI): Project opportunities for the production, consumption, transport or storage of green hydrogen and derivatives in South Africa. In *CSIR*. https://www.csir.co.za/sites/default/files/Documents/Green-hydrogen-RFI-2021.pdf

Danish Energy Agency. (2022). *Japan | Energistyrelsen*. https://ens.dk/en/our-responsibilities/global-cooperation/country-cooperation/japan

Danish Ministry of Climate. (2020). *Climate Act*.

Danish Ministry of Climate, E. and U. (2021). *Strategy for Power-to-X*.

Dansk Energi. (2020). *Recommendations for a Danish Power-to-X strategy*.

Decourt, B. (2019). Weaknesses and drivers for power-to-X diffusion in Europe. Insights from technological innovation system analysis. *International Journal of Hydrogen Energy*, 44(33), 17411–17430. https://doi.org/10.1016/J.IJHYDENE.2019.05.149

DLA Piper. (2022). *New political agreement to develop and promote Power-to-X | DLA Piper*. https://denmark.dlapiper.com/en/news/new-political-agreement-develop-and-promote-power-x

DOE. (n.d.). *Hydrogen Pipelines* . DOE. Retrieved November 14, 2022, from https://www.energy.gov/eere/fuelcells/hydrogen-pipelines

Dragan, D. (2021). Polish Hydrogen Strategy – regulatory challenges in the European perspective. *Polityka Energetyczna – Energy Policy Journal*, 24(2), 19–32. https://doi.org/10.33223/epj/135881

Edtmayer, H., Nageler, P., Heimrath, R., Mach, T., & Hochenauer, C. (2021). Investigation on sector coupling potentials of a 5th generation district heating and cooling network. *Energy*, 230, 120836. https://doi.org/10.1016/J.ENERGY.2021.120836

Ehret, O., & Bonhoff, K. (2015). Hydrogen as a fuel and energy storage: Success factors for the German Energiewende. *International Journal of Hydrogen Energy*, 40(15), 5526–5533. https://doi.org/10.1016/J.IJHYDENE.2015.01.176

EIA. (n.d.). *International Energy Data*. EIA. Retrieved November 14, 2022, from https://www.eia.gov/international/rankings/country/USA?pa=12&u=0&f=A&v=none&y=01%2F01%2F2019

EIA. (2022a). *Country Analysis Executive Summary: China*. https://www.eia.gov/international/content/analysis/countries_long/China/china.pdf

EIA. (2022b). *Monthly Energy Review*. https://www.eia.gov/totalenergy/data/monthly/pdf/mer.pdf

Eikeland, P. O., & Inderberg, T. H. J. (2016). Energy system transformation and long-term interest constellations in Denmark: can agency beat structure? *Energy Research & Social Science*, 11, 164–173. https://doi.org/10.1016/J.ERSS.2015.09.008

Embassy of the People's Republic of China in the United Kingdom of Great Britain and Northern Ireland. (2022, May 1). Ambassador Zheng Zeguang attends the Opening Ceremony of the China-UK Hydrogen Energy Cooperation Forum. *Embassy of the People's Republic of China in the United Kingdom of Great Britain and Northern Ireland*. http://gb.china-embassy.gov.cn/eng/tpxw/202205/t20220502_10681109.htm

Enerdata. (n.d.). *United States Energy Information*. Enerdata. Retrieved November 14, 2022, from https://www.enerdata.net/estore/energy-market/united-states/

Energinet. (2022a). *Energinet and Gasunie strengthen collaboration on hydrogen infrastructure | Energinet*. https://en.energinet.dk/About-our-news/News/2022/09/01/MoU-Brint

Energinet. (2022b). *Feasibility study of hydrogen transmission infrastructure | Energinet*. https://en.energinet.dk/Hydrogen/Feasibility-study

Energinet. (2022c). *Guarantees of origin for renewable hydrogen | Energinet*. https://en.energinet.dk/Hydrogen/Hydrogen-GOs

Energy Commission. (2022). *Spain Energy Snapshot*.

ENTSO-G. (n.d.). *Hydrogen project visualisation platform*. https://h2-project-visualisation-platform.entsog.eu

Euractiv. (2021). *Spain positions itself to be Europe's green hydrogen hub – EURACTIV.com*. https://www.euractiv.com/section/energy/news/spain-positions-itself-to-be-europes-green-hydrogen-hub/

Euractiv. (2022a). *France and Germany to work on 'common industrial projects' – EURACTIV.com*. https://www.euractiv.com/section/energy-environment/news/france-and-germany-to-work-on-common-industrial-projects/

Euractiv. (2022b). *Germany, Denmark, Netherlands and Belgium sign €135 billion offshore wind pact – EURACTIV.com*. https://www.euractiv.com/section/energy/news/germany-denmark-netherlands-and-belgium-sign-e135-billion-offshore-wind-pact/

Euractiv. (2022c). *Spain, France, Portugal abandon MidCat, agree on green energy, gas corridor – EURACTIV.com*. https://www.euractiv.com/section/energy/news/spain-france-portugal-abandon-midcat-agree-on-green-energy-gas-corridor/

European Commission. (2019a). A *European Green Deal*. https://ec.europa.eu/info/strategy/priorities-2019-2024/european-green-deal_en

European Commission. (2019b). *Potentials of sector coupling for decarbonisation: Assessing regulatory barriers in linking the gas and electricity sectors in the EU*. https://energy.ec.europa.eu/potentials-sector-coupling-decarbonisation-assessing-regulatory-barriers-linking-gas-and-electricity_en

European Commission. (2020a). A *hydrogen strategy for a climate-neutral Europe*. https://ec.europa.eu/commission/presscorner/api/files/attachment/865942/EU_Hydrogen_Strategy.pdf

European Commission. (2020b). *IPCEIs on hydrogen*. https://single-market-economy.ec.europa.eu/industry/strategy/hydrogen/ipceis-hydrogen_en

European Commission. (2020c). *Powering a climate-neutral economy*. https://ec.europa.eu/commission/presscorner/detail/en/ip_20_1259

European Commission. (2022a). *Commission launches consultations on the regulatory framework for renewable hydrogen | European Commission*. https://ec.europa.eu/info/news/commission-launches-consultation-regulatory-framework-renewable-hydrogen-2022-may-20_en

European Commission. (2022b). *Energy strategy*. https://energy.ec.europa.eu/topics/energy-strategy_en

European Commission. (2022c). *Hydrogen*. https://energy.ec.europa.eu/topics/energy-systems-integration/hydrogen_en#:~:text=The%20EU%20strategy%20on%20hydrogen,strategy%20for%20energy%20system%20integration.

European Commission. (2022d). *Hydrogen and decarbonised gas market package*. https://energy.ec.europa.eu/topics/markets-and-consumers/market-legislation/hydrogen-and-decarbonised-gas-market-package_en

European Commission. (2022e). *REPowerEU*. https://ec.europa.eu/commission/presscorner/detail/en/IP_22_3131

European Gas Regulatory Forum. (2018). *Thirty first meeting of the European Gas Regulatory Forum*. https://ec.europa.eu/info/sites/default/files/31st_mf_conclusions_final.pdf

Eurostat. (2022a). *What kind of energy do we consume in the EU?* https://ec.europa.eu/eurostat/cache/infographs/energy/bloc-3a.html?lang=en

Eurostat. (2022b, August). *Industrial production statistics*. https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Industrial_production_statistics#Industrial_production_by_country

Eurowind Energy. (2022). *New, large-scale hydrogen hub to support Denmark's green transition*. https://eurowindenergy.com/media/iifjyxik/green-hydrogen-hub-press-release-old-site.pdf

Everfuel. (2022). *HySynergy PtX facility*. https://www.everfuel.com/projects/hysynergy/

Frangoul, A. (2020, September 23). President Xi tells UN that China will be 'carbon neutral' within four decades. CNBC. https://www.cnbc.com/2020/09/23/china-claims-it-will-be-carbon-neutral-by-the-year-2060.html

French Ambassy in India. (2022). *France and India adopt Joint Roadmap on Green Hydrogen - La France en Inde / France in India*. https://in.ambafrance.org/France-and-India-adopt-Joint-Roadmap-on-Green-Hydrogen

French Government. (2020a). *Investissements d'Avenir, Appel à projets: Briques technologiques et démonstrateurs hydrogène*. https://agirpourlatransition.ademe.fr/

French Government. (2020b). *Stratégie nationale pour l'hydrogène décarboné: Lancement de deux appels à projets pour constituter des Écosystèmes territoriaux autour de l'hydrogène et développer les Briques technologiques et démostrateurs pour la production, le transport et l'usage de l'hydrogène*. https://entreprises.ademe.fr/dispositif-aide/20201014/ecosysh22020-165

French Ministry for Europe and Foreign Affairs. (2021). *Joint statement issued by the United States and France following the first meeting of the United States-France bilateral clean energy partnership (20 December 2021) - Ministry for Europe and Foreign Affairs*. https://www.diplomatie.gouv.fr/en/french-foreign-policy/economic-diplomacy-foreign-trade/news/article/joint-statement-issued-by-the-united-states-and-france-following-the-first

French Ministry for the Ecological Transition. (2018). *Plan de déploiement de l'hydrogène pour la transition énergétique*.

French Ministry for the Ecological Transition. (2020a). *Stratégie Français Pour l'Énergie et le Climat: Programmation Pluriannuelle de l'Énergie*.

French Ministry for the Ecological Transition. (2020b). *Stratégie nationale pour le développement de l'hydrogène décarboné en France*.

French Ministry of Ecological Transition. (2021). *Installation du Conseil national de l'hydrogène | Ministères Écologie Énergie* Territoires. https://www.ecologie.gouv.fr/installation-du-conseil-national-lhydrogene

French Ministry of Economy. (2020). *Plan de relance : lancement de 2 appels à projets pour la filière hydrogène | economie.gouv.fr*. https://www.economie.gouv.fr/plan-de-relance/lancement-appels-projets-filiere-hydrogene#

French Ministry of Economy. (2022). *Stratégie nationale pour le développement de l'hydrogène décarboné en France | economie.gouv.fr*. https://www.economie.gouv.fr/plan-de-relance/mesures/strategie-nationale-developpement-hydrogene-decarbone

Fridgen, G., Keller, R., Körner, M. F., & Schöpf, M. (2020). A holistic view on sector coupling. *Energy Policy*, 147, 111913. https://doi.org/10.1016/J.ENPOL.2020.111913

FuelCellsWorks. (2021, November 25). *Germany to Double 2030 Hydrogen Production Target to 10 gw*. https://fuelcellsworks.com/news/germany-to-double-2030-hydrogen-production-target-to-10gw/

FuelCellsWorks. (2022, March 17). Douglas County PUD to Aquire 409 Acres for Hydrogen Facility, Wells Dam Project. *FuelCellsWorks*. https://fuelcellsworks.com/news/douglas-county-pud-to-acquire-409-acres-for-hydrogen-facility-wells-dam-project/#:~:text=Douglas%20County%20PUD%20broke%20ground,the%20project%20in%20late%202019.

Gallie, W. B. (1955). Essentially Contested Concepts. *Proceedings of the Aristotelian Society*, 56, 167–198.

GasConnect. (2020). *The colours of hydrogen*.

German Federal Government — Federal Ministry for Economic Affairs and Energy. (2020). *The National Hydrogen Strategy*. Federal Ministry for Economic Affairs and Energy. https://www.bmwi.de/Redaktion/EN/Publikationen/Energie/the-national-hydrogen-strategy.pdf

Gils, H. C., Gardian, H., Kittel, M., Schill, W. P., Murmann, A., Launer, J., Gaumnitz, F., van Ouwerkerk, J., Mikurda, J., & Torralba-Díaz, L. (2022). Model-related outcome differences in power system models with sector coupling—Quantification and drivers. *Renewable and Sustainable Energy Reviews*, 159, 112177. https://doi.org/10.1016/J.RSER.2022.112177

Gils, H. C., Simon, S., & Soria, R. (2017). 100% Renewable energy supply for Brazil-The role of sector coupling and regional development. *Energies*, 10(11). https://doi.org/10.3390/en10111859

GlobalData. (2022). *Hydrogen Electrolyzers Market Size, Share and Trends Analysis by Technology, Installed Capacity, Generation, Key Players and Forecast*, 2021-2026. https://www.globaldata.com/store/report/hydrogen-electrolyzers-market-analysis/

Government of India. (2022). *India & Denmark agree to work together on green fuels including green hydrogen | Department Of Science & Technology*. https://dst.gov.in/india-denmark-agree-work-together-green-fuels-including-green-hydrogen

Government of the Netherlands. (2020, October 6). Collaboration Between the United States and the Netherlands Focuses on Hydrogen Technology. *Government of the Netherlands*. https://www.government.nl/latest/news/2020/10/06/collaboration-between-the-united-states-and-the-netherlands-focuses-on-hydrogen-technology

Green Hydrogen Catalogue. (2022a). *About - Green Hydrogen Catalogue*. https://greenhydrogencatalogue.com/about-2/

Green Hydrogen Catalogue. (2022b). *Home - Green Hydrogen Catalogue*. https://greenhydrogencatalogue.com/

Green Hydrogen International Corporation. (n.d.). *Hydrogen City*. Green Hydrogen International Corporation. Retrieved November 15, 2022, from https://www.ghi-corp.com/projects/hydrogen-city

GreenHysland. (2022a). *About Green Hysland - GreenHysland.* https://greenhysland.eu/about-green-hysland/

GreenHysland. (2022b). *About Green Hysland - GreenHysland.* https://greenhysland.eu/about-green-hysland/

GreenHysland. (2022c). *Who we are - GreenHysland.* https://greenhysland.eu/who-we-are/

Griffiths, S., Sovacool, B. K., Kim, J., Bazilian, M., & Uratani, J. M. (2021). Industrial decarbonization via hydrogen: A critical and systematic review of developments, socio-technical systems and policy options. *Energy Research & Social Science*, 80, 102208. https://doi.org/10.1016/J.ERSS.2021.102208

Grubler, A. (2010). The costs of the French nuclear scale-up: A case of negative learning by doing. *Energy Policy*, 38(9), 5174–5188. https://doi.org/10.1016/J.ENPOL.2010.05.003

Guelpa, E., Bischi, A., Verda, V., Chertkov, M., & Lund, H. (2019). Towards future infrastructures for sustainable multi-energy systems: A review. *Energy*, 184, 2–21. https://doi.org/10.1016/J.ENERGY.2019.05.057

Guoping, L., & Zou, M. (2022, February 11). China's steelmakers get 5 more years to reach peak carbon output. *NIKKEI Asia.* https://asia.nikkei.com/Spotlight/Caixin/China-s-steelmakers-get-5-more-years-to-reach-peak-carbon-output

H2 Ports. (2022). *About - H2PORTS.* https://h2ports.eu/about/

H2Global Stiftung. (n.d.). *Objective of the H2Global instrument*. H2Global Stiftung. Retrieved November 14, 2022, from https://www.h2global-stiftung.com/project/h2g-mechanism

Higman, M. (2022, July 14). Hydrogen Hubs Proposals: Guideposts for the Future of the U.S. Hydrogen Economy. CSIS. https://www.csis.org/analysis/hydrogen-hubs-proposals-guideposts-future-us-hydrogen-economy

Hoekman, S. K., Broch, A., Robbins, C., & Purcell, R. (2010). CO2 recycling by reaction with renewably-generated hydrogen. *International Journal of Greenhouse Gas Control*, 4(1), 44–50. https://doi.org/10.1016/j.ijggc.2009.09.012

Huber, I. (2021). Germany's Hydrogen Industrial Strategy. CSIS. https://www.csis.org/analysis/germanys-hydrogen-industrial-strategy

Hydrogen and Fuel Cell Technologies Office. (n.d.-a). *Hydrogen Shot*. DOE. Retrieved November 14, 2022, from https://www.energy.gov/eere/fuelcells/hydrogen-shot

Hydrogen and Fuel Cell Technologies Office. (n.d.-b). *International Partnership for Hydrogen and Fuel Cells in the Economy*. US Department of Energy. Retrieved November 15, 2022, from https://www.energy.gov/eere/fuelcells/international-partnership-hydrogen-and-fuel-cells-economy

Hydrogen Council. (2021a). *Hydrogen decarbonization pathways*. https://hydrogencouncil.com/wp-content/uploads/2021/01/Hydrogen-Council-Report_Decarbonization-Pathways_Part-2_Supply-Scenarios.pdf

Hydrogen Council. (2021b). *Hydrogen for Net-Zero*. www.hydrogencouncil.com

Hydrogen Council. (2022). *Global Hydrogen Flows*. https://hydrogencouncil.com/wp-content/uploads/2022/10/Global-Hydrogen-Flows.pdf

Hydrogen Refueling Solutions. (2022). *Hydrogen : HRS french refueling station manufacturer*. https://www.hydrogen-refueling-solutions.fr/?lang=en

Hydrogeninsight. (2022a). *"Hydrogen electrolyser makers will go bankrupt this decade amid brutal oversupply."* https://www.hydrogeninsight.com/electrolysers/exclusive-hydrogen-electrolyser-makers-will-go-bankrupt-this-decade-amid-brutal-oversupply/2-1-1343342

Hydrogeninsight. (2022b). *Liebreich: "Hydrogen is starting to look like an economic bubble — and here's why."* https://www.hydrogeninsight.com/analysis/liebreich-hydrogen-is-starting-to-look-like-an-economic-bubble-and-here-s-why/2-1-1334006

Hydrogeninsight. (2022c). *"Will no longer be considered" Hydrogen trains up to 80% more expensive than electric options, German state finds*. https://www.hydrogeninsight.com/transport/will-no-longer-be-considered-hydrogen-trains-up-to-80-more-expensive-than-electric-options-german-state-finds/2-1-1338438

HyPSTER. (2022). *About the Project | HyPSTER*. https://hypster-project.eu/about-the-project/

Iberdrola. (2022a). *His Majesty the King inaugurates Iberdrola's green hydrogen plant in Puertollano, the largest for industrial use in Europe - Iberdrola*. https://www.iberdrola.com/press-room/news/detail/his-majesty-the-king-inaugurates-green-hydrogen-plant-puertollano

Iberdrola. (2022b). *Puertollano green hydrogen plant - Iberdrola*. https://www.iberdrola.com/about-us/what-we-do/green-hydrogen/puertollano-green-hydrogen-plant

Idaho National Laboratory. (2020, November 9). Private-Public Partnership Will Use Nuclear Energy for Clean Hydrogen Production. *Idaho National Laboratory*. https://inl.gov/article/xcel-energy-inl-hydrogen-production/

IEA. (2021a). *Energy Policy Review Spain 2021*. www.iea.org/t&c/

IEA. (2021b). *France 2021: Energy Policy Review*. www.iea.org/t&c/

IEA. (2021c). *An Energy Sector Roadmap to Carbon Neutrality in China*. https://iea.blob.core.windows.net/assets/6689062e-43fc-40c8-9659-01cf96150318/AnenergysectorroadmaptocarbonneutralityinChina.pdf

IEA. (2022). *Hydrogen – Analysis*. https://www.iea.org/reports/hydrogen

IRENA. (2018). *Hydrogen from renewable power: Technology outlook for the energy transition*. www.irena.org

IRENA. (2022). *Geopolitics of the energy transformation: the hydrogen factor*. https://irena.org/publications/2022/Jan/Geopolitics-of-the-Energy-Transformation-Hydrogen

Johansen, K. (2021). Blowing in the wind: A brief history of wind energy and wind power technologies in Denmark. *Energy Policy*, 152, 112139. https://doi.org/10.1016/J.ENPOL.2021.112139

Juan, D. (2021, August 3). GCL New Energy unveils hydrogen energy plan. *China Daily*. http://www.chinadaily.com.cn/a/202108/03/WS6108abb8a310efa1bd666433.html

Jupiter 1000 - Power-to-Gas - Le Projet. (n.d.). Retrieved October 29, 2022, from https://www.jupiter1000.eu/projet

Kanngießer, A., Venjakob, J., Hicking, J., Kockel, C., Drewing, E., Beckamp, M., & Jaeger, S. (2021). Triggering local innovation processes for the implementation of sector coupling projects: An integrated approach. *Energies*, 14(5). https://doi.org/10.3390/en14051358

Karneyeva, Y., & Wüstenhagen, R. (2017). Solar feed-in tariffs in a post-grid parity world: The role of risk, investor diversity and business models. *Energy Policy*, 106, 445–456. https://doi.org/10.1016/J.ENPOL.2017.04.005

Kendall, K. (2015). *Hydrogen and fuel cells in city transport*. https://doi.org/10.1002/er.3290

Kurmayer, N. J. (2021). EU countries clash over scale of future hydrogen imports. *Euroactive*. https://www.euractiv.com/section/energy-environment/news/eu-countries-clash-over-scale-of-future-hydrogen-imports/

Lambert, M., & Schulte, S. 1987-. (2021). *Contrasting European hydrogen pathways an analysis of differing approaches in key markets*.

Larsen, J., King, B., Kolus Hannah, Dasari, N., Hiltbrand, G., & Herndon, W. (2022). *A Turning Point for US Climate Progress: Assessing the Climate and Clean Energy Provisions in the Inflation Reduction Act*. https://rhg.com/research/climate-clean-energy-inflation-reduction-act/

Latham & Watkins Environment, L. & R. P. (2022). *DOE Releases Draft Clean Hydrogen Production Standard, Draft Roadmap, and Hydrogen Hub Funding Opportunity*. https://www.lw.com/admin/upload/SiteAttachments/Alert-3021.pdf

Law No 2015-992. (2015). *LOI n°2015-992 du 17 août 2015 relative à la transition énergétique pour la croissance verte*.

Law No 2019-1147. (2019). *LOI n°2019-1147 du 8 novembre 2019 relative à l'énergie at au climat*.

Law-Decree No 2021-167. (2021). *Ordonnance n°2021-167 du 17 février 2021 relative à l'hydrogène*.

Li, L., Steinlein, A., Kuneman, E., & Eckardt, J. (2021, April). Factsheet on China, the world's largest Hydrogen producer and consumer. *Adelphi*. https://www.adelphi.de/en/publication/hydrogen-factsheet---china

Liu, W., Zuo, H., Wang, J., Xue, Q., Ren, B., & Yang, F. (2021). The production and application of hydrogen in steel industry. *International Journal of Hydrogen Energy*, 46(17), 10548–10569. https://doi.org/10.1016/J.IJHYDENE.2020.12.123

Liu, Z., Zhao, Y., & Wang, X. (2020). Long-term economic planning of combined cooling heating and power systems considering energy storage and demand response. *Applied Energy*, 279, 115819. https://doi.org/10.1016/J.APENERGY.2020.115819

Ludwig, M., Lüers, , Martin, Hegnsholt, E., Kim, M., Pieper, C., & Meidert, K. (2021, April 12). The Green Tech Opportunity in Hydrogen. *BCG*. https://www.bcg.com/publications/2021/capturing-value-in-the-low-carbon-hydrogen-market

Ma, T., Wu, J., Hao, L., Lee, W. J., Yan, H., & Li, D. (2018). The optimal structure planning and energy management strategies of smart multi energy systems. *Energy*, 160, 122–141. https://doi.org/10.1016/J.ENERGY.2018.06.198

Maersk. (2022). *Maersk and the Spanish Government to explore large-scale green fuels production | Maersk*. https://www.maersk.com/news/articles/2022/11/03/maersk-and-the-spanish-government-to-explore-large-scale-green-fuels-production

Mancarella, P. (2014). MES (multi-energy systems): An overview of concepts and evaluation models. *Energy*, 65, 1–17. https://doi.org/10.1016/J.ENERGY.2013.10.041

Mandel, E. (2021, April 26). Airbus, ArcelorMittal, MHI, Shell and eight others establish Hamburg Hydrogen Network. *H2 Bulletin*. https://www.h2bulletin.com/airbus-arcelormittal-mhi-shell-and-eight-others-establish-hamburg-hydrogen-network/

Marshall, T. (2014). The European Union and Major Infrastructure Policies: The Reforms of the Trans-European Networks Programmes and the Implications for Spatial Planning. *Https://Doi.Org/10.1080/09654313.2013.791968*, 22(7), 1484–1506. https://doi.org/10.1080/09654313.2013.791968

Maruf, M. N. I. (2021). Open model-based analysis of a 100% renewable and sector-coupled energy system–The case of Germany in 2050. *Applied Energy*, 288, 116618. https://doi.org/10.1016/J.APENERGY.2021.116618

Mauger, R. (2018). The voluminous energy transition legal framework in France and the question of its recognition as a branch of law. *Energy Policy*, 122, 499–505. https://doi.org/10.1016/J.ENPOL.2018.08.013

Mazzoni, S., Ooi, S., Nastasi, B., & Romagnoli, A. (2019). Energy storage technologies as techno-economic parameters for master-planning and optimal dispatch in smart multi energy systems. *Applied Energy*, 254, 113682. https://doi.org/10.1016/J.APENERGY.2019.113682

Millot, A., Krook-Riekkola, A., & Maïzi, N. (2020). Guiding the future energy transition to net-zero emissions: Lessons from exploring the differences between France and Sweden. *Energy Policy*, 139, 111358. https://doi.org/10.1016/J.ENPOL.2020.111358

Mission Innovation. (n.d.). Clean Hydrogen Mission. *Mission Innovation*. Retrieved November 14, 2022, from http://mission-innovation.net/missions/hydrogen/

MissionGreenFuels. (2022). *MissionGreenFuels*. https://missiongreenfuels.dk/

Mitsubishi Power. (2020, March 10). Intermountain Power Agency Orders MHPS JAC Gas Turbine Technology for Renewable-Hydrogen Energy Hub. *Mitsubishi Power*. https://power.mhi.com/regions/amer/news/200310.html

Münster, M., Sneum, D. M., Bramstoft, R., Bühler, F., Elmegaard, B., Giannelos, S., Zhang, X., Strbac, G., Berger, M., Radu, D., Elsaesser, D., & Oudalov, A. (2020). *Sector Coupling: Concepts, State-of-the-art and Perspectives*.

Myllyvirta, L., & Zhang, X. (2022, March 5). Analysis: What do China's gigantic wind and solar bases mean for its climate goals? *Carbon Brief*. https://www.carbonbrief.org/analysis-what-do-chinas-gigantic-wind-and-solar-bases-mean-for-its-climate-goals/

Nakano, J. (2022, March 28). China Unveils its First Long-Term Hydrogen Plan. CSIS. https://www.csis.org/analysis/china-unveils-its-first-long-term-hydrogen-plan#:~:text=China's%20push%20for%20clean%20hydrogen,in%20refineries%20or%20chemical%20facilities

Nasimul Islam Maruf, M. (2019). Sector coupling in the North Sea region—a review on the energy system modelling perspective. In *Energies* (Vol. 12, Issue 22). MDPI AG. https://doi.org/10.3390/en12224298

Nebel, A., Cantor, J., Salim, S., Salih, A., & Patel, D. (2022). The Role of Renewable Energies, Storage and Sector-Coupling Technologies in the German Energy Sector under Different CO2 Emission Restrictions. *Sustainability*, 14(16), 10379. https://doi.org/10.3390/su141610379

Nikolaidis, P., & Poullikkas, A. (2017). A comparative overview of hydrogen production processes. *Renewable and Sustainable Energy Reviews*, 67, 597–611. https://doi.org/10.1016/J.RSER.2016.09.044

Nordic Hydrogen Partnership. (2022). *About SHHP – Nordic Hydrogen Partnership*. http://www.nordichydrogenpartnership.com/shhp/about-shhp/

Nuclear Newswire. (2021, August 20). Nine Mile Point picked for hydrogen demonstration project. *Nuclear Newswire*. https://www.ans.org/news/article-3180/nine-mile-point-picked-for-hydrogen-demonstration-project/

NWR. (n.d.). *The German National Hydrogen Council* . Nationaler Wasserstoffrat. Retrieved November 14, 2022, from https://www.wasserstoffrat.de/en/national-hydrogen-council

Office of Clean Energy Demonstrations. (n.d.). *Regional Clean Hydrogen Hubs*. DOE. Retrieved November 14, 2022, from https://www.energy.gov/oced/regional-clean-hydrogen-hubs

Office of Energy Efficiency & Renewable Energy. (2022). *Hydrogen Production: Natural Gas Reforming | Department of Energy*. https://www.energy.gov/eere/fuelcells/hydrogen-production-natural-gas-reforming

OGE. (n.d.). *H2morrow – act today to be greenhouse gas neutral by* 2050. OGE. Retrieved November 14, 2022, from https://oge.net/en/sustainable/projects/our-hydrogen-projects/h2morrow

Olczak, M., & Piebalgs, A. (2018). *POLICY BRIEF Sector Coupling: the New EU Climate and Energy Paradigm?*

Ottinger, G. (2013). The Winds of Change: Environmental Justice in Energy Transitions. *https://Doi.Org/10.1080/09505431.2013.786996*, 22(2), 222–229. https://doi.org/10.1080/09505431.2013.786996

Otto, A., Robinius, M., Grube, T., Schiebahn, S., Praktiknjo, A., & Stolten, D. (2017). Power-to-steel: Reducing CO2 through the integration of renewable energy and hydrogen into the German steel industry. *Energies*, 10(4). https://doi.org/10.3390/en10040451

Oxford Dictionary. (2022). *Transition*. https://www.oxfordlearnersdictionaries.com/definition/american_english/transition

Palzer, A., & Henning, H. M. (2014). A comprehensive model for the German electricity and heat sector in a future energy system with a dominant contribution from renewable energy technologies – Part II: Results. *Renewable and Sustainable Energy Reviews*, 30, 1019–1034. https://doi.org/10.1016/J.RSER.2013.11.032

Pillsbury. (n.d.). *The Hydrogen Map*. Pillsbury. Retrieved November 14, 2022, from https://www.thehydrogenmap.com

Plug Power. (2022). *Plug Power Inc. | Plug Lands 1 GW Electrolyzer Order with H2 Energy Europe*. https://www.ir.plugpower.com/press-releases/news-details/2022/Plug-Lands-1-GW-Electrolyzer-Order-with-H2-Energy-Europe/default.aspx

Ramsebner, J., Haas, R., Ajanovic, A., & Wietschel, M. (2021). The sector coupling concept: A critical review. In *Wiley Interdisciplinary Reviews: Energy and Environment* (Vol. 10, Issue 4). John Wiley and Sons Ltd. https://doi.org/10.1002/wene.396

Raven SR. (2021, September 1). Raven SR's waste-to-hydrogen project with Republic Services could have implications beyond California. *Raven SR*. https://ravensr.com/raven-srs-waste-to-hydrogen-project-with-republic-services-could-have-implications-beyond-california/

Recharge. (2022). *Spain starts up flagship industrial green hydrogen plant – and first-ever "hydroduct" | Recharge*. https://www.rechargenews.com/energy-transition/spain-starts-up-flagship-industrial-green-hydrogen-plant-and-first-ever-hydroduct/2-1-1185088

Rehman, O. A., Palomba, V., Frazzica, A., & Cabeza, L. F. (2021). Enabling technologies for sector coupling: A review on the role of heat pumps and thermal energy storage. In *Energies* (Vol. 14, Issue 24). MDPI. https://doi.org/10.3390/en14248195

Reuters. (2021). *France to work with UAE on renewable and hydrogen projects -minister | Reuters*. https://www.reuters.com/business/energy/france-work-with-uae-renewable-hydrogen-projects-minister-2021-11-21/

Reuters. (2022a). *France, Spain and Portugal agree to build Barcelona-Marseille gas pipeline | Reuters*. https://www.reuters.com/business/energy/spain-france-portugal-agree-new-energy-route-pm-sanchez-says-2022-10-20/

Reuters. (2022b). *France, UAE sign energy cooperation deal | Reuters*. https://www.reuters.com/business/energy/france-uae-sign-energy-cooperation-deal-2022-07-18/

Reuters. (2022c). *Germany secures link to planned Baltic Sea renewable energy island | Reuters*. https://www.reuters.com/business/energy/germany-secures-link-planned-baltic-sea-renewable-energy-island-2022-08-29/

Rinaldi, A., Soini, M. C., Streicher, K., Patel, M. K., & Parra, D. (2021). Decarbonising heat with optimal PV and storage investments: A detailed sector coupling modelling framework with flexible heat pump operation. *Applied Energy*, 282, 116110. https://doi.org/10.1016/J.APENERGY.2020.116110

Roadmap to a US Hydrogen Economy. (2020). https://www.fchea.org/us-hydrogen-study

Robinius, M., Otto, A., Heuser, P., Welder, L., Syranidis, K., Ryberg, D., Grube, T., Markewitz, P., Peters, R., & Stolten, D. (2017). Linking the Power and Transport Sectors—Part 1: The Principle of Sector Coupling. *Energies*, 10(7), 956. https://doi.org/10.3390/en10070956

Robinius, M., Otto, A., Syranidis, K., Ryberg, D. S., Heuser, P., Welder, L., Grube, T., Markewitz, P., Tietze, V., & Stolten, D. (2017). *Linking the Power and Transport Sectors-Part 2: Modelling a Sector Coupling Scenario for Germany*. https://doi.org/10.3390/en10070957

RTE. (2020). *The transition to low-carbon hydrogen in France*.

RWE. (n.d.). *Green electricity for a CO2-neutral chemical industry and green hydrogen*. RWE. Retrieved November 14, 2022, from https://www.rwe.com/en/research-and-development/project-plans/offshore-to-x

Samji, O., Feldman, D., Salinas, G., & Yazdani, H. Q. (2022, October 28). United States: Facilitating Clean Hydrogen In The US: The Draft Clean Hydrogen Production Standard. *Mondaq*. https://www.mondaq.com/unitedstates/renewables/1244862/facilitating-clean-hydrogen-in-the-us-the-draft-clean-hydrogen-production-standard-

Schaber, K., Steinke, F., & Hamacher, T. (2013). *Managing Temporary Oversupply from Renewables Efficiently: Electricity Storage Versus Energy Sector Coupling in Germany*.

Schnuelle, C., Thoeming, J., Wassermann, T., Thier, P., von Gleich, A., & Goessling-Reisemann, S. (2019). Socio-technical-economic assessment of power-to-X: Potentials and limitations for an integration into the German energy system. *Energy Research & Social Science*, 51, 187–197. https://doi.org/10.1016/J.ERSS.2019.01.017

Scottish Government. (2021). *MEMORANDUM OF UNDERSTANDING BETWEEN THE GOVERNMENT OF THE KINGDOM OF DENMARK AND THE SCOTTISH GOVERNMENT IN THE AREA OF GREEN TRANSITION OF THE ENERGY SYSTEM*.

SGH2 Energy. (n.d.). World's Largest Green Hydrogen Project to Launch in California. *SGH2 Energy*. Retrieved November 14, 2022, from https://www.sgh2energy.com/worlds-largest-green-hydrogen-project-to-launch-in-california

Shahkar, A. (2021, May 14). Chinese steelmaker HBIS launches hydrogen steelmaking pilot project. *Bulletin H2*. https://www.h2bulletin.com/chinese-steelmaker-hbis-launches-hydrogen-steelmaking-pilot-project/

Simon, F., Taylor, K., Kurmayer, N. J., & Romano, V. (2022). The Green Brief: Franco-German hydrogen fight is toxic for EU. *Euroactive*. https://www.euractiv.com/section/energy-environment/news/the-green-brief-franco-german-hydrogen-fight-is-toxic-for-eu/

Skov, I. R., Schneider, N., Schweiger, G., Schöggl, J. P., & Posch, A. (2021). Power-to-x in denmark: An analysis of strengths, weaknesses, opportunities and threats. *Energies*, 14(4). https://doi.org/10.3390/en14040913

Sovacool, B. K. (2016). How long will it take? Conceptualizing the temporal dynamics of energy transitions. *Energy Research & Social Science*, 13, 202–215. https://doi.org/10.1016/J.ERSS.2015.12.020

Spanish Government. (2021). *PERTE de Energías Renovables Hidrógeno Renovable y Almacenamiento*.

Spanish Ministry for Ecological Transition and the Demographic Challenge. (2020a). ESTRATEGIA A LARGO PLAZO PARA UNA ECONOMÍA ESPAÑOLA MODERNA, COMPETITIVA Y CLIMÁTICAMENTE NEUTRA EN 2050.

Spanish Ministry for Ecological Transition and the Demographic Challenge. (2020b). *Hoja de Ruta del Hidrógeno: Una apuesta por el Hidrógeno Renovable*.

Spanish Ministry for Ecological Transition and the Demographic Challenge. (2020c). PLAN NACIONAL INTEGRADO DE ENERGÍA Y CLIMA.

Spanish Ministry for Ecological Transition and the Demographic Challenge. (2022a). *El Gobierno aprueba el sistema de garantías de origen para los gases renovables*. https://www.miteco.gob.es/es/prensa/ultimas-noticias/el-gobierno-aprueba-el-sistema-de-garant%C3%ADas-de-origen-para-los-gases-renovables/tcm:30-540455

Spanish Ministry for Ecological Transition and the Demographic Challenge. (2022b). VICEPRESIDENCIA TERCERA DEL GOBIERNO DE ESPAÑA MINISTERIO PARA LA TRANSICIÓN ECOLÓGICA Y EL RETO DEMOGRÁFICO. www.miteco.gob.es

Standaert, M. (2022, May 9). China readies for post-2025 green hydrogen boom. *Energy Monitor*. https://www.energymonitor.ai/tech/hydrogen/china-readies-for-post-2025-green-hydrogen-boom

State of Green. (2021). *Japan and Denmark extend collaboration within renewable energy*. https://stateofgreen.com/en/news/japan-and-denmark-extend-collaboration-within-renewable-energy/

Steinmann, W. D., Bauer, D., Jockenhöfer, H., & Johnson, M. (2019). Pumped thermal energy storage (PTES) as smart sector-coupling technology for heat and electricity. *Energy*, 183, 185–190. https://doi.org/10.1016/J.ENERGY.2019.06.058

Sterner, M., & Specht, M. (2021). Power-to-gas and power-to-x—the history and results of developing a new storage concept. *Energies*, 14(20). https://doi.org/10.3390/en14206594

SunLine. (n.d.). *Clean Fleet Pioneers in fuel cell technology*. SunLine. Retrieved November 14, 2022, from https://www.sunline.org/projects/alternative-fuels/clean-fleet

Tanase, L., & Anchustegui, I. H. (2022). *The EU Hydrogen and Decarbonised Gas Market Package*. https://fsr.eui.eu/the-eu-hydrogen-and-decarbonised-gas-package-revising-the-governance-and-creating-a-hydrogen-framework/

The European Cement Association. (2021). *Activity Report* . https://cembureau.eu/media/03cgodyp/2021-activity-report.pdf

The State Council Information Office the People Republic of China. (2022, June 14). China accounts for 30% of global manufacturing output: Official. *China* SCIO. http://english.scio.gov.cn/pressroom/2022-06/14/content_78269516.htm

United Nations. (2022). *Green Hydrogen Compact Catalogue | United Nations*. https://www.un.org/en/energy-compacts/page/green-hydrogen-compact-catalogue

US Department of Energy. (n.d.). *International Hydrogen and Fuel Cell Activities*. US Department of Energy. Retrieved November 15, 2022, from https://www.hydrogen.energy.gov/international.html

US Department of Energy. (2019, June 18). Joint Statement of future cooperation on hydrogen and fuel cell technologies among the Ministry of Economy, Trade and Industry of Japan (METI), the European Commission Directorate-General for Energy (ENER) and the United States Department of Energy (DOE). US *Department of Energy*. https://www.energy.gov/articles/joint-statement-future-cooperation-hydrogen-and-fuel-cell-technologies-among-ministry

US Department of Energy. (2022a). *Clean Hydrogen Production Standard (CHPS) Draft Guidance*. https://www.hydrogen.energy.gov/pdfs/clean-hydrogen-production-standard.pdf

US Department of Energy. (2022b). *DOE National Clean Hydrogen Strategy and Roadmap Draft*. https://www.hydrogen.energy.gov/pdfs/clean-hydrogen-strategy-roadmap.pdf

van Nuffel, L., Gorenstein Dedecca, J., Smit, T., & Rademaekers, K. (2018a). *Sector coupling: how can it be enhanced in the EU to foster grid stability and decarbonise?*

van Nuffel, L., Gorenstein Dedecca, J., Smit, T., & Rademaekers, K. (2018b). *Sector coupling: how can it be enhanced in the EU to foster grid stability and decarbonise?* https://www.europarl.europa.eu/RegData/etudes/STUD/2018/626091/IPOL_STU(2018)626091_EN.pdf

Varone, A., & Ferrari, M. (2015). Power to liquid and power to gas: An option for the German Energiewende. *Renewable and Sustainable Energy Reviews*, 45, 207–218. https://doi.org/10.1016/J.RSER.2015.01.049

Verbong, G., & Geels, F. (2007). The ongoing energy transition: Lessons from a socio-technical, multi-level analysis of the Dutch electricity system (1960–2004). *Energy Policy*, 35(2), 1025–1037. https://doi.org/10.1016/J.ENPOL.2006.02.010

Verbund. (2020, November 17). *Green Hydrogen Blue Danube*. Verbund. https://www.verbund.com/en-at/about-verbund/news-press/press-releases/2020/11/17/greenhydrogenbluedanube

Wade, N. S., Taylor, P. C., Lang, P. D., & Jones, P. R. (2010). Evaluating the benefits of an electrical energy storage system in a future smart grid. *Energy Policy*, 38(11), 7180–7188. https://doi.org/10.1016/j.enpol.2010.07.045

Wehrmann, B. (2022, February 7). Carbon Contracts for Difference could kickstart German industry decarbonisation – think tank. *Clean Energy Wire*. https://www.cleanenergywire.org/news/carbon-contracts-difference-could-kickstart-german-industry-decarbonisation-think-tank

White House. (2021, November). *President Biden's Bipartisan Infrastructure Law*. White House. https://www.whitehouse.gov/bipartisan-infrastructure-law/

White House. (2022). *Joint Declaration Between the Kingdom of Spain and the United States of America | The White House*. https://www.whitehouse.gov/briefing-room/statements-releases/2022/06/28/joint-declaration-between-the-kingdom-of-spain-and-the-united-states-of-america/

Wiedemann, K. (2022, October 4). Federal government sets new hydrogen target. *Energate*. https://www.energate-messenger.com/news/227054/federal-government-sets-new-hydrogen-target

Williams, S., & Doyon, A. (2019). Justice in energy transitions. *Environmental Innovation and Societal Transitions*, 31, 144–153. https://doi.org/10.1016/J.EIST.2018.12.001

World Bank. (n.d.). *World Bank national accounts data, and OECD National Accounts data files*. World Bank . Retrieved November 16, 2022, from https://data.worldbank.org/indicator/NY.GDP.MKTP.CD?locations=CNhttps://data.worldbank.org/indicator/NY.GDP.MKTP.CD?locations=CN

World Economic Forum. (2021). *Grey, blue, green – why are there so many colours of hydrogen?*

World Steel Association. (2021). *World Steel in Figures*. https://worldsteel.org/wp-content/uploads/2021-World-Steel-in-Figures.pdf

Xin, Z. (2022, February 24). China's oil dependence on imports sees drop. *The State Council the People's Republic of China*. https://english.www.gov.cn/news/topnews/202202/24/content_WS6216e221c6d09c94e48a569e.html

Xu, M., & Singh, S. (2020, April 3). China's Hebei Approves $1.2 bln Hydrogen Production and Consumption Projects. *Fuel Cells Works*. https://fuelcellsworks.com/news/chinas-hebei-approves-1-2-bln-hydrogen-production-and-consumption-projects/

Yihe, X., & Collins, L. (2022, September 5). Sinopec to produce more than two million tonnes of green hydrogen annually by 2025. *RECHARGE*. https://www.rechargenews.com/energy-transition/sinopec-to-produce-more-than-two-million-tonnes-of-green-hydrogen-annually-by-2025/2-1-1290857

Yin, I., & Yep, E. (2022, September 23). China could exceed renewables generation target of 33% by 2025. *S&P Global* .

Yujie, B., Yukun, L., Simin, W., & Jia, D. (2021, June 21). China's hydrogen roadmap: 4 things to know. *NIKKEI Asia*. https://asia.nikkei.com/Spotlight/Caixin/China-s-hydrogen-roadmap-4-things-to-know

Reviews

Review by Lenka Kovačovská, independent energy consultant, former Executive Director of Czech Gas Association

The publication addresses the very topical issue of the potential of the hydrogen economy in Europe and worldwide. The authors have very well chosen their first research question focusing on what is actually "sector coupling" and how its definition has changed in the European narrative of the last few years. They also nicely portray the gradual reduction and some rationalization of the initial high ambitions of hydrogen in view of the real barriers to implementation—lack of self-sufficiency in production, high energy losses, and excessive costs. In this context I would perhaps highlight more the role of other colors of hydrogen, especially for some parts of the EU, although the European effort to promote and support pure green hydrogen is clearly dominant.

Personally, I was a little surprised by the authors' choice of countries to answer the third research question. I would probably have primarily included the most vocal hydrogen promoters in the analysis, such as the Netherlands, UK, Japan and, in the future, Australia. But in reading the specific chapters, I confirm the appropriateness of the chosen selection both in terms of diversity, type of support, pragmatism, and export/import potential.

Very appropriately and timely, the authors have drawn attention in the US to The Inflation Reduction Act (IRA), which may indeed deal a very heavy blow to European hydrogen ambitions if Europe is unable to respond quickly and pragmatically. From personal experience and interviews, I know that the concerns that the authors express about this development in the conclusion of their publication are very real and well-founded, and de facto the whole hydrogen and gas industry in Europe is sounding the alarm. It might be worth adding more specific recommendations to the conclusion on what Europe could do better and differently, following the example of China and the US (see, e.g., the ongoing discussions on the gas package and the hydrogen economy, unbundling rules, the regulatory framework, or even simply equating different shades of H2 based on their total emissions footprint).

To summarize, the publication is comprehensible, easy to read, and very up-to-date. After language correction, I definitely recommend it for publication.

Review by Petr Krejčí, researcher at Czech Technical University in Prague Faculty of Mechanical Engineering

The authors succeeded in the tasks they declared in the introduction of the book and delivered an up-to-date and very useful commented compilation of national, EU and intercontinental regulatory support mechanisms and political approaches.

To fully utilize the EU-level potential of the book, a more detailed explanation on the principle of additionality followed by the position of the authors would be appreciated.

From a technical point of view, the role of any energy infrastructure is to carry energy from points of production to points of consumption, therefore for security of supply it is vital if more than one energy carrier is used. Taking this point of view into account, I encourage the authors to elaborate their opinion on the role of gas infrastructure in the sense of cooperation between "electrons" and "molecules" in subsequent works based on the book.

Appendix: Country details

Country	Targets & Timeline		Expected hydrogen demand	Specific application areas	Particular steps proposed	Infrastructure development	Funds available	Policy Initiatives	Source
	Domestic production (electrolyzer capacity), GW	Hydrogen Imports/ Exports							
European Union	REPowerEU: 10 Mt of renewable hydrogen by 2030, at least 65 GW of renewable hydrogen electrolysers by 2030 Fit for 55: at least 44 GW of renewable hydrogen electrolysers by 2030 NHS: at least 40 GW of renewable hydrogen electrolysers by 2030 (+ production "up to" 10 Mt by 2030); at least 6 GW by 2024	REPowerEU: 10 Mt by 2030	Hydrogen Roadmap Europe: business-as-usual scenario - 780 TWh, ambitious scenario - 2,250 TWh in 2050	NHS: mobility (primaraly heavy duty transport, rail, maritime, aviation); industry (primaraly steel-making, refineries, chemical industry); energy (primaraly balancing); heating REPowerEU: demand is expected in refineries, industrial heat, transport, petrochemicals (ammonia), blust furnances, synthetic fuels, power generation, blending	NHS: A roadmap for the EU 1. 2020-2024, the strategic objective is to install at least 6 GW of renewable hydrogen electrolysers in the EU and the production of up to 1 Mt of renewable hydrogen, to decarbonise existing hydrogen production 2. 2025-2030, hydrogen needs to become an intrinsic part of an integrated energy system with a strategic objective to install at least 40 GW of renewable hydrogen electrolysers by 2030 and the production of up to 10 Mt of renewable hydrogen in the EU 3. 2030-2050, renewable hydrogen technologies should reach maturity and be deployed at large scale to reach all hard-todecarbonise sectors where other alternatives might not be feasible or have higher costs REPowerEU: 1. Scaling up the production and import of renewable hydrogen to 20 Mt by 2030 2. Scaling up the development of hydrogen infrastructure in the EU 3. Stepping up our international engagement on hydrogen to scale up renewable hydrogen imports	NHS: Initial hydrogen demand: production on-site in industrial clusters and coastal areas through existing "point-topoint" connections between production and demand Later: local hydrogen networks would emerge to cater for additional industrial demand After: TEN-E Regulation revision to account for hydrogen Repurposing in combination with (relatively limited) newly built hydrogen dedicated infrastructure REPowerEU Revised TEN-E Regulation (from June 2022) should enable coordinated and timely development of trans-European hydrogen networks by selecting key infrastructure projects of cross-border relevance (including hydrogen pipelines, storage facilities, electrolysers and hydrogen terminals, covering as well hydrogen embedded in other chemicals) - PCIs	REPowerEU: €27 bn is direct investment in electrolysers and distribution of hydrogen in the EU (CEF, InvestEU, HE, ETS Funds, RRF, ERDF, CF, JTF)	NHS July 2020 Fit for 55 July 2021 REPowerEU ('hydrogen accelerator') May 2022	https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52020DC0301&from=EN https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM%3A2022%3A230%3AFIN&qid=1653033742483 https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=SWD%3A2022%3A230%3AFIN&qid=1653033922121 "
Austria	1 GW electrolysis capacity by 2030	import expectated (cooperation partnerships will be developed)	Expected to be higher than production by 2040 (in climte--neutral Austria)	Graded possible uses of hydrogen from inefficient to priority. Priority: chemical and steel industry, air transportation, shipping, peak load balancing for volatile RES, storage and flexibility services Medium: long-distance trucks & buses, high-temperature processes (thermal recycling) Inefficient: low-temperature processes (thermal recovery), short-distance trucks, passenger cars, residential heat.	Action plan: 1. enable timely market ramp-up by means of showcase projects 2. create support and incentives for the production of renewable hydrogen 3. create incentives for market-based business models and the targeted use of hydrogen in industry hydrogen in industry 4. build infrastructure for hydrogen and create import opportunities 5. targeted further development of hydrogen technologies in mobility 6. intensify research and development 7. foundation of the hydrogen platform hydrogenAustria 8. Austria's priorities at European and international level	Gas infstrastructure gradual trnsformation for the purpuse of hydrogen. Construction of new hydrogen pipelines is being considered where there is a lack of appropriate infrastructure and where hydrogen infrastructure is necessary for decarbonization (+ in line with pan-European infrastructure development). The local development of a dedicated hydrogen infrastructure should also enable the supply of industrial clusters and other large-scale consumers.	125 million euros until 2026 (IPCEI) €40 million a year for electrolyzers construction"	NHS initiated in 2018. Finally published in June 2022.	https://www.bmk.gv.at/dam/jcr:0eb2f307-1e4d-41b1-bfd-8-22918816eb1b/BMK_Wasserstoff-strategie_DE_UA_final.pdf
Belgium	at least 150 MW of electrolysis capacity in operation by 2026	3-6 TWh in 2030 100-165 TWh in 2050	125-175 TWh/year by 2050	Industry Transport (not excluding cars, lets market to decide) Buildings (not a priority) Grid flexibility	4 pillars: 1. positioning Belgium as a hub for the import of renewable molecules for Europe; 2. consolidating Belgium's leadership in hydrogen technologies; 3. organising a robust hydrogen market; 4. focusing on cooperation.	The federal government plan to pursue the development of a hydrogen transport infrastructure by open-access pipeline. 1st phase will be started by the commissioning of minimum 100 to 160 km pipelines for hydrogen transport by 2026, partly supported by a budget of 95 million euros in the context of the national recovery and resilience plan. By 2030, Belgium has the ambition to connect the import hub to neighbouring countries via the open-access hydrogen network in order to realise its international positioning as an import and transit hub for renewable energy in Europe.	Energy Transition Fund until 2025: 20-30 million euros in support funding (not just hydrogen though) Federal budget of 60 million euros (including 50 million euros from the national recovery and resilience plan) to support various projects to scale up promising technologies (also not hydrogen specific)	NHS (October 2021)	https://economie.fgov.be/sites/default/files/Files/Energy/View-strategy-hydrogen.pdf
Bulgaria								NHS announced/ in preparation	
Croatia								NHS announced/ in preparation	
Cyprus								No NHS	
Czech Republic	7 kt of hydrogen/year by 2025 101 kt of hydrogen/year by 2030 284 kt of hydrogen/year by 2035	Given the limited possibilities for low-carbon hydrogen production in the Czech Republic, it is expected that a part of the consumption will have to be imported.	1 728 kt/year of lowcarbon hydrogen by 2050	Industry (chemical, iron and steal, rest) Transport (buses, cars, trucks) Production of electricity and heat Housholds (replacing natural gas) "	Strategic goals: • Reduce greenhouse gas emissions • Stimulate economic growth Specific goals to evaluate strategic goals fulfilment: 1. Volume of low-carbon hydrogen consumption that can replace fossil fuels in transport, chemical production, metallurgy, industry, heat and power generation. 2. Volume of low-carbon hydrogen production. 3. Infrastructure readiness for hydrogen transport and storage so that we can connect the points of production and consumption and import low-carbon hydrogen from abroad. 4. Progress in R&D and production of hydrogen technologies	Existing gas infrastructure modification for hydrogen purposes 3 dimentions of hydrogen transport: - domestic transport - hydrogen imports into the Czech Republic - transit transport of low-carbon hydrogen through the Czech Republic	Modernisation fund (not hydrogen specific) - Just stransition fund (stretegic and complex ematoc projects) - 1.6 bn EUR hydrogen technology: - applications in the production process - to existing renewable energy sources - in transport - in research and development	NHS (July 2021)	https://www.mpo.cz/assets/cz/prumysl/strategicke-projekty/2021/9/Hydrogen-Strategy_CZ_2021-09-09.pdf https://www.mpo.cz/assets/cz/prumysl/strategicke-projekty/2021/11/Vodikova-strategie_CZ_MSV-11-11-2021_prezentace.pdf
Denmark	4-6 GW 2030	Aims to be an exporter of Power-to-X (incl. hydrogen) products and technologies	Export plans	Different applications potential for emission reduction is estimated Most potential of P2X is seen in shipping and aviation. Also hydrogen for trucks and buses, industry	4 objectives: - P2X must cobtribute to Danish Climate Act realisation - Regulatory framework & infrastructure must be established to allow Denmark potential utilisation - Denmark must be able to export P2X products and technologies - Improvement of P2X and energy systems integration Patticulat Goverment actions to reach each objective listed	Extensive part of the NHS covers infarstructure development (transport , storaging, repurposing of existing gas infastructure, suitable locations)	CEF (EU), REACT-EU, JTF, IPCEI, Daish Investment Fund (p.5-6)	Power-to-X Strategy Dec 2021	https://ens.dk/sites/ens.dk/files/ptx/strategy_ptx.pdf
Estonia								NHS announced/ in preparation	
Finland								NHS announced/ in preparation	
France	6.5 GW capacity to produce decarbonised hydrogen using electrolysis by 2030			Industry (refinaries, chemical industry, sectors such as electronics or food processing where hydrogen is used too) Mobility (Initial phase: light and heavy trucks, buses, hydrogen-powered train; Pilot projects for hydrogen-powered river shuttles and ships, as well as the acceleration of innovation efforts to develop a decarbonised hydrogen-powered aircraft that could come into service in the 2030s)	1. To install enough electrolysers to make a significant contribution to the decarbonisation of the economy 2. Decarbonising industry by replacing fossil hydrogen 3. To develop clean mobility, in particular for heavy-duty vehicles; 4. Developing large-scale regional projects by encouraging the pooling of uses 3. To build a French industrial sector that creates jobs and guarantees technological prowess	hydrogen represents a definite potential in the medium term for the decarbonisation of the gas sector (liquid hydrogen, reuse in the gas network)	With a significant budget of €2bn under the recovery plan, the strategy for the development of decarbonised hydrogen extends beyond 2020-2022 and sets a trajectory that runs until 2030 with a total of €7bn in public support	NHS (Sep 2020)	https://www.bdi.fr/wp-content/uploads/2020/03/PressKitProvisionalDraft-National-strategy-for-the-development-of-decarbonised-and-renewable-hydrogen-in-France.pdf

Country	Targets & Timeline		Expected hydrogen demand	Specific application areas	Particular steps proposed	Infrastructure development	Funds available	Policy Initiatives	Source
	Domestic production (electrolyzer capacity), GW	Hydrogen Imports/ Exports							
Germany	5 GW by 2030; 10 GW by 2035 (2040 the latest) (NHS) 10 GW by 2030 (expected in ""Summer package"")	A 5 GW production capacity corresponds to about 14 terawatt-hours (TWh) and thus only covers about a 7th of the projected German hydrogen demand by 2030 With increase of target to 10 GW still around 3/4 of hydrogen demand will be covered by imports	90 to 110 TWh by 2030	Hard-to-abate sectors as a priority. A particular focus is on areas that are already close to economic viability and where greater path dependency is avoided or which cannot be decarbonized in any other way, for example to avoid process emissions in the steel and chemical industries or in certain areas of transport (aviation, shipping). +heating sector (highly efficient fuel cells systems)	Action Plan cosmists of 38 measures (divided into groups focused on production, application, infrastructure/supply, research&eduction&innovation, European level action, international hydrogen market and external economic partnerships)		7 billion EUR for speeding up domestic market rollout; another 2 billion EUR for fostering international partnerships (June 2020 'package for the future')	NHS (June 2020)	https://www.bmwk.de/Redaktion/EN/Publikationen/Energie/the-national-hydrogen-strategy.pdf?__blob=publicationFile&v=6
Greece	3.5 GWh domestic production capacity by 2030 (750 MW electrolyzers)				The Greek plan includes four stages. 2022-2027: uncertainty in investments, due to the high costs. State aid will be needed for infrastructure development. 2025-2030: pilot projects will begin, as well as upgrades and adaptation of gas pipelines, hydrogen storage planning, with the role of the state remaining giving aid and tax incentives 2027-2035: first hydrogen-only networks to facilitate mainly cross-border transactions, development of large-scale hydrogen storage, etc. 2030-2045: completion of pan-European hydrogen and synthetic fuel infrastructure is expected , conversion of large sections of existing gas networks to hydrogen, storage systems, medium and large scale compression and liquefaction, as well as national interoperability with the European system.	The injection of relatively small amounts of hydrogen into the gas network is possible. Percentages of hydrogen up to 10% are considered to be safe to transport, with minimal modifications to the system, and to be used by existing end consumers. Higher percentages, up to 20%, require special adjustments (especially compression systems). The transmission system could in the future be used for the transport of pure hydrogen (repurposing) with investments ranging from 20% to 30% of the cost of construction of a new system.	Total investments in the hydrogen supply chain of about 3-4 billion EUR was estimated	NHS announced/ in preparation	https://www.tovima.gr/2022/06/07/inbox/greek-hydrogen-strategy-domestic-production-of--3500-gwh-in-2030/
Hungary	Production of 36 kt/y "green", other carbon-free and low-carbon hydrogen in 2030 - 20 kt/yof low-carbon hydrogen - 16 kt/y of "green" and other carbon--free hydrogen 240 MW electrolyser capacity		Total demand - Demand in transportation: 10 kt by 2030, 65 kt by 2040, 12 kt by 2050.	Industry, transport	Action plan: 1. Production of large volumes of low-carbon and decentralised carbon-free hydrogen 2. Industrial decarbonisation (24 kt/year "green", other carbon-free and low-carbon hydrogen to be used for industrial applications in 2030) - target petrochemical and chemical industries (primarily in ammonia production) by gradually replacing "grey" hydrogen 3. Green transportation (10 kt/year of "green" and other carbon-free hydrogen to be used for transportation in 2030; at least 20 hydrogen refuelling stations (with two refuelling points per refuelling station); use of 4.8 thousand hydrogen powered vehicles in total) 4. Electricity and natural gas support infrastructure (Building sector integration ability – primarily seasonal energy storage ability) 5. Taking advantage of industrial and economic development opportunities 6. Building of a supportive regulatory environment 7. Promoting international cooperation 8. RDI and education to promote the success of hydrogen during the transition	Building sector integration ability – primarily seasonal energy storage ability by utilising intersectoral synergy, establishing infrastructure that will enable the transition to carbon neutrality, and reconstructing existing infrastructure. - creating an average down-regulation capacity of at least 60 MW - enabling a volume blending ratio of 2% in the natural gas system on the short term, to be expanded on the medium term in accordance with tests carried out by that point	IPCEI State direct fundinng	NHS May 2021	https://cdn.kormany.hu/uploads/document/a/a2/a2b/a2b2b7ed5179b17694659b8f050ba-9648e75a0bf.pdf b2b7ed5179b17694659b8f050ba-9648e75a0bf.pdf
Italy	5 GW electrolyzers by 2030		Target NHS: 2% share of hydrogen in final energy demand by 2030 (around 0.7 Mton/year); 20% by 2050	For the next decade, the Government foresees the application of hydrogen in the transport sector, in particular heavy (for example longhaul trucks), in railways and in industry, with specific reference to those segments in which hydrogen is already used as a raw material (e.g., chemical industry and oil refining) In addition to this, the mixing of hydrogen in the gas network can be used to anticipate and stimulate the growth of the hydrogen market. By 2050 more applications: + ships, aviation + steel industry + storage & electricity generation +residential heating Although an official technical limit has yet to be defined in Italy, it is plausible to think that by 2030 an average of up to 2% of distributed natural gas could be replaced with hydrogen	Apart from targets and financial resources allocation ""it will probably be necessary to develop a national regulatory framework for the use of hydrogen along the entire value chain, with particular attention to safety and related responsibilities"". Also, collaboration with with other MSs to transport, distribute and store hydrogen Creation of a national R&D program should be undertaken to address priority areas such as the development of electrolysers and fuel cell technology. From a production point of view, it is expected that the Italian Government will support hydrogen both with incentive schemes and with the streamlining of the regulation of renewable capacity and the capacity of electrolysers, to allow the diffusion of hydrogen infrastructures and stimulate the demand at the same time (also through the possibility of creating Guarantee of Origin certificates). From the demand side, some type of support will have to be designed to accelerate the spread of hydrogen applications and the adoption of hydrogen-based mobility, i.e. long-haul trucks and trains or other new applications.	Intends to leverage the existence of a welldeveloped and interconnected gas network that also offers import and export opportunities.	To start hydrogen economy up to 10 billion EUR of investments between 2020 and 2030 will be needed Sources: EU (Next Genartion EU, Innovation fund, National Operational Plan (PON) 2021-2027, IPCEI) Italy (Sustainable Growth Fund (FRI), DL Agosto, and Mission Innovation, National Electricity System Research, CleanTech Fund, and Development and Cohesion Fund)	NHS announced/ in preparation	https://www.mise.gov.it/images/stories/documenti/Strategia_Nazionale_Idrogeno_Linee_guida_preliminari_nov20.pdf
Ireland								NHS announced/ in preparation	
Latvia								No NHS	
Lithuania								NHS announced/ in preparation	
Luxembourg			125-300 kt/year by 2050	Priority sectors: (A), industry, (B) transport and a (C) future-proof integrated energy system	NHS proposed 7 key measures to promote production, import and use of renewable hydrogen: 1. Contribute to the definition of the legal and regulatory framework at EU level 2. Cooperate with EU Member States and third countries 3. Identify opportunities in Luxembourg - Research and innovation 4. Materialise flagship projects 5. Prioritise actions - Towards targeted decarbonisation by renewable hydrogen 6. Develop instruments to support a developing renewable hydrogen market 7. Implement and continuously improve - Taskforce hydrogen Luxembourg	Luxembourg will ensure that, during the transition to climate neutrality any (cross-border) network development dedicated to hydrogen through new construction or, more likely consisting partly of converted pipelines, does not lead to lock-in effects. Luxembourg will support the limitation of the conditions for granting the PCI label in the framework of the revision of the TEN-E Regulation only to infrastructure projects (new or reconverted) exclusively dedicated to hydrogen and its derivatives Proposal of introduction of obligation to ensure presence of H infrastructure (and/or fast electric charging stations) for fuel cell electric vehicles (and/or battery electric vehicles), including heavy goods vehicles in concession contracts on motorway areas.	"EU, LU subsidies to ensure hydrogen supply (Investment aid or reduction of operational cost reduction (FiT or or Carbon CFDs) or tendering Money from Innovation Fun"	NHS (Sep 2021)	https://gouvernement.lu/dam-assets/documents/actualites/2021/09-septembre/27-turmes-hydrogene/Strategie-hydrogene-LU-fr.pdf
Malta								No NHS	

Country	Targets & Timeline		Expected hydrogen demand	Specific application areas	Particular steps proposed	Infrastructure development	Funds available	Policy Initiatives	Source
	Domestic production (electrolyzer capacity), GW	Hydrogen Imports/ Exports							
Netherlands	500 MW of installed capacity by 2025; 3-4 GW of installed capacity by 2030	Countries with cheap solar energy will focus on the export of hydrogen and the Netherlands will be able to continue to act as an energy hub in the future due to its favourable location, its ports and its extensive gas grid and storage capacity.	By 2050, gaseous energy carriers are expected to provide at least 30% of final energy consumption (IRENA). Berenschot study yielded a bandwidth of 337 to 775 PJ of gaseous energy carriers by 2050. This corresponds to approximately 30% to 50% of final energy consumption.	heavy-duty transport, industry (very hih tempreture processes), some heating applications (peak load of heat grids and hybrid heat pumps), grid alancing (energy storage)	Policy agenda with four pillars 1 Legislation and regulation a) Use of existing gas grid b) Market regulation and temporary tasks for network operators c) Guarantees of origin and certification d) Safety e) Main Energy Infrastructure Programme (electricity & gas grid coordination) 2 Cost reduction and scaling up green hydrogen a Support schemes for research, scaling up and rolling out b) Linking hydrogen to offshore wind energy c) Blending obligation 3 Sustainability of final consumption a) Ports and industry clusters b) hydrogen (incl. synthetic fuels) and zero emissions policies for transport c) Built environment d) Electricity sector e) Agrocultural sector 4 Supporting and flanking policy a International strategy b) Regional startegy c) Resrach & innovation	Part of the existing gas grid is expected to be used for the transport of hydrogen. The development of infrastructure will take into account the development of the North-western European hydrogen market, which is relevant with a view to the potential hub function played by the Netherlands for provision to neighbouring countries. The connections with and in Germany are of particular interest. Identifying the potential demand, supply and storage capacity required will be part of this review. In this context, the Port of Rotterdam will be identifying the potential import supply (from overseas territories).	To facilitate hydrogen scale-up, the government will be allocating approximately € 35 million per year by rearranging part of the existing funds for hydrogen pilot projects within the DEI+. Furthermore, projects will be able to rely on existing subsidy schemes (HER, SDE++). The relevant possibilities within the state aid framework are being considered - possible extension of IPCEI may be an option.	NHS (Apr 2020)	https://www.government.nl/binaries/government/documenten/publications/2020/04/06/government-strategy-on-hydrogen/Hydrogen-Strategy-TheNetherlands.pdf
Poland	technology-neutral approach (any type of low-emission processes and technologies for obtaining hydrogen) Tartget: 2 GW production capacity by 2030 (low- and zero-emission sources and processes)			3 priority areas of hydrogen use: energy, transport and industry	NHS Objectives: 1. Implementation of hydrogen technologies in power & heat 2. Use of hydrogen as an alternative fuel for transport 3. Supporting the decarbonisation of industryhydrogen production in new installations 4. hydrogen production & instalations 5. Efficient & safe hydrogen transmission, distribution & storage 6. Creating stable regulatory environment In pursuit of the goals set forth in the PHS, the Government of Poland plans to undertake a number of activities, such as: • Concluding a Hydrogen Economy Sector Deal, • Creating a Hydrogen Valley Ecosystem, • Establishing of a Hydrogen Technology Centre, • Building competencies for the hydrogen economy, • Educational activities and public campaigns, • European and international cooperation.	In the initial years of market development, hydrogen will be primarily transported by road and rail (tankers, tank trucks). Over time, as customer demand for hydrogen increases, existing gas infrastruc- ture or dedicated hydrogen pipelines will be used for transportation. Amongst the potential big scale hydrogen storage facilities, salt caverns were considered to be the most optimal solution. Hydrogen storage in large aboveground tanks may become necessary if hydrogen technologies start to be implemented on a mass scale.		NHS addopted in Nov 2021	https://www.gov.pl/attachment/06213bb3-64d3-4ca-8-afbe-2e50dadfa2dc
Portugal	2-2.5 GW electrolyzer capacity by 2030 5 GW by 2050	Hydrogen seen as a way to strenghten renewable energy export potential	Target NHS: 1.5 to 2 % of green hydrogen in final energy consumption by 2030 + targets for individual sectors	NHS established targets: 2% to 5% of green hydrogen in the energy consumption of the industry sector; 1 % to 5 % of green hydrogen in the energy consumption of road transport; 3-5% of green hydrogen in the energy consumption of domestic sea transport;	1. Implementing transperent & competitive mechnisam for green hydrogen production 2. Creating necessary regulatory framework for hydrogen 3. Setting hydrogen incorporation targets 4. Supporting investments in hydrogen projects 5. Formalising aplication to IPCEI for hydrogen projects 6. Implementing nationall alliance for hydrogen	NHS established targets: 10 % to 15 % of green hydrogen injection in natural gas networks; reation of 50 to 100 hydrogen filling stations	EUR 7-9 bilion investment in hydrogen production projects EUR 900-100 milion supports to investment and production	NHS (Aug 2020)	https://www.dgeg.gov.pt/media/5eac1vcd/resolu%C3%A7%C3%A3o-do--conselho-de-ministros-n-%C2%-BA-632020.pdf
Romania								NHS announced/ in preparation	
Slovakia	The main goal stated in NHS is to cover as much of the hydrogen needs as possible from domestic sources only. The priority interest will be the effort to cover the hydrogen needs in industry by as many domestic sources as possible.	Imports expected	By 2030, Slovakia will consume 200 kt year, by 2050 - 400-600 kt/y. 90% of which will be covered by low-carbon sources. "	The biggest consumers of hydrogen in Slovakia will be the sectors of industry, transportation, and later, energy.	The Slovak government will participate in: - implementation of measures to use low-carbon hydrogen and its compounds in transportation; - implementation of policies of use of low-carbon hydrogen technologies in the relevant areas of national economy; - establishment of a common standard for low emissions of CO2 as part of the implementation chain of low-carbon hydrogen; - introduction of general terminology and criteria for certification of process quality based on use of low-carbon hydrogen over its full cycle – from production, through transportation and distribution, to its use; - introduction of legislative and regulatory measures and safety regulations to support the readiness of the gas infrastructure for transportation, distribution, and storage of hydrogen; and - support of research, development, and innovations related to hydrogen technologies. In order to secure sufficient volumes of hydrogen produced in Slovakia or purchased from other countries which can produce it cheaper and to use it on a large scale, the Slovak government needs to: - draw up policies to stimulate demand in sectors of end use of hydrogen, connecting goals in the area of decarbonisation; - implement supporting measures, making the establishment of innovative products, technologies and industrial solutions for hydrogen production and processing in Slovak industry and energy; - participate in preparing a common standard for low CO2 emissions during the production of hydrogen, as well as over its execution cycle, which is to be implemented in the respective regulation; - introduce common terminology and hydrogen certification criteria; - secure participation of Slovakia in setting-up a pilot programme to support production of low-carbon and recycled steel and basic chemicals; - take into account scenarios of hydrogen production in national strategic documents from the perspective of impacts on electricity consumption and development of energy infrastructure, as well as the electricity source; - as part of the legal framework of support of renewable energy sources, establish conditions for issuing guarantees of origin for hydrogen produced of renewable energy sources in form of self- consumption and create conditions for expanding the guarantees of origin for hydrogen from low- carbon production, as well; and - evaluate and suggest supporting measures to stimulate the readiness of gas infrastructure to transport, distribute, and store hydrogen.	The growth of hydrogen consumption for various intensity scenarios of its use should be taken into account when planning the expansion and modernisation of the energy infrastructure.	Recovery and Resilience Facility designed for investments and reforms focusing on green and digital economy; European Union funds for the programming period of 2021 – 2027; Fond for Fair Transformation, which has previously been connected with coal-mining regions, and covers regions with energy demanding industry (Košice), as well; Strategic Investments Instrument, which is to mobilize private investments with the support of European Investment Bank and national supporting banks; Connecting Europe Facility – grants for financing respective infrastructure, hydrogen filling stations or the adjustments to gas networks; ETS Innovation Fund linked to emission trading is to mobilise investments to innovative low-carbon technologies in the volume of around 10 billion euros (depending on the price of carbon) in 2020-2030 – the first call was announced on 3 July 2020; Modernisation Fund which is designed to fund investments to modernisation of energy systems and increase of energy effectiveness; at the same time, the European Commission will promote international projects covering the full value chain by allowing state subsidies for important projects of common European interest (IPCEI); InvestEU Fund, which will provide 30% of its funds to support activities related to solutions for implementation of climate changes35; EU mechanism of funding common projects of use renewable source energy, which will allow support of blanket introduction of innovative technologies; the mechanism can be combined with other EU instruments	NHS June 2021	https://nvas.sk/NVS_EN.pdf
Slovenia								No NHS	
Spain	4 GW elecrolyzers by 2030	Due to the high potential as hydrogen producer, the Roadmap forsees that Spain could become an exporter of renewable hydrogen to the rest of Europe		Industry that uses hydrogen as a raw material (oil refining, fertilizers and chemicals, among others), public transport, urban services or various uses in intermodal transport nodes such as ports, airports or logistics platforms; heat sector (industrial, residential); isolated energy systems	60 measures grouped into 4 areas of action (regulatory, sectoral, raising knowledge, R&D) Promotion and encouragement of hydrogen valleys	100-150 public fulling stations by 2030	Funds from EU Next Generation, Clean hydrogen Alliance	Hydrogen roadmap (Oct 2020)	https://ec.europa.eu/info/sites/default/files/energy_climate_change_environment/events/presentations/02.03.02_mf34_presentation-spain-hydrogen_roadmap-cabo.pdf https://img.fuelcellsworks.com/wp-content/uploads/2020/10/hydrogenexecutivesummary-Spain.pdf https://energia.gob.es/es-es/Novedades/Documents/hoja_de_ruta_del_hidrogeno.pdf

Country	Targets & Timeline		Expected hydrogen demand	Specific application areas	Particular steps proposed	Infrastructure development	Funds available	Policy Initiatives	Source
	Domestic production (electrolyzer capacity), GW	Hydrogen Imports/ Exports							
Sweden								NHS announced/ in preparation	
UK	5 GW production target by 2030 both green and blue; 1GW production capacity by 2025	Expects to be an active participant in international markets as they develop, maximising export opportunities and utilising import opportunities as appropriate.	250-460 TWh by 2050 (up 20-35% of UK final energy consumption)	2022-2024: Some transport (buses, early HGV, rail & aviation trials); industry demonstrations; neighbourhood heat trial 2025-2027: Industry applications; transport (HGV, rail & shipping trials) village heat trial; blending (tbc) 2028-2030: Wide use in industry; power generation & flexibility; transport (HGVs, shipping); heat pilot town (tbc) 2030-onwards: Full range of end users incl. steel; power system; greater shipping & aviation; potential gas grid conversion	Hydrogen production Launch the £240m Net Zero Hydrogen Fund in early 2022 for co-investment in early hydrogen production projects. Deliver the £60 million Low Carbon Hydrogen Supply 2 competition. Finalise design of UK standard for low carbon hydrogen by early 2022. Finalise Hydrogen Business Model in 2022, enabling first contracts to be allocated from Q1 2023. Provide further detail on our production strategy and twin track approach by early 2022. Hydrogen networks and storage Launch a call for evidence on the future of the gas system in 2021. Review systemic hydrogen network and storage requirements in the 2020s and beyond, including need for economic regulation and funding, and provide an update in early 2022. Deliver the £68 million Longer Duration Energy Storage Demonstration competition. Use of hydrogen Launch a call for evidence on 'hydrogen-ready' industrial equipment by the end of 2021. Launch a call for evidence on phase out of carbon intensive hydrogen production in industry within a year. Deliver Phase 2 of the £315m Industrial Energy Transformation Fund. Launch a £55 million Industrial Fuel Switching 2 competition in 2021. Prepare for hydrogen for heat trials – a hydrogen neighbourhood by 2023, hydrogen village by 2025 and potential pilot hydrogen town by 2030. Consult in 2021 on 'hydrogen-ready' boilers by 2026. Continue our multi-million pound support for transport decarbonisation, including for deployment, trials and demonstration of hydrogen buses, HGVs, shipping, aviation and multi-modal transport hubs. Creating a market Establish a Hydrogen Regulators Forum in 2021. Assess market frameworks to drive investment and deployment of hydrogen, and provide an update in early 2022. Assess regulatory barriers facing hydrogen projects, and provide an update in early 2022. Complete an indicative assessment of the value for money case for blending up to 20% hydrogen into the existing gas network by late 2022, and aim to make a final policy decision in late 2023.	Existing hydrogen production and use in the UK is currently on a small scale, and hydrogen tends to be produced and used in the same location. There is limited distribution through hydrogen pipelines, used to supply industrial users located in industrial clusters, as well as some transport of hydrogen by road into these hubs in either compressed gaseous or liquefied form. Alongside this, there is limited use of above ground metal storage tanks in industrial facilities. Significant development and scale up of hydrogen network and storage infrastructure for the development of a UK hydrogen economy is neeed.	£240m Net Zero Hydrogen Fund for co-investment in early hydrogen production projects £60 million Low Carbon Hydrogen Supply 2 competition £68 million Longer Duration Energy Storage Demonstration competition £55 million Industrial Fuel Switching 2 competition	NHS (Aug 2021)	https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1011283/UK-Hydrogen-Strategy_web.pdf
Australia								NHS November 2019	https://www.industry.gov.au/sites/default/files/2019-11/australias-national-hydrogen-strategy.pdf
China	100-200 Mt of renewable-produced hydrogen annually by 2025			Target of fleet of 50,000 hydrogen-fueled vehicles by 2025 By 2035, a hydrogen energy industry system will be formed, covering transportation, energy storage, industrial and other applications				In March 2022 the Chinese government released the country's first-ever long-term plan for hydrogen (2021-2035)	"https://www.ndrc.gov.cn/xxgk/zcfb/ghwb/202203/P020220323314396580505.pdf https://www.csis.org/analysis/china-unveils-its-first-long-term--hydrogen-plan"
Chile						Plans for developing adequate and coordinated port, electrical, and distribution infrastructure to foster the growth of hubs.		NHS November 2020	https://energia.gob.cl/sites/default/files/national_green_hydrogen_strategy_-_chile.pdf

Country	Targets & Timeline		Expected hydrogen demand	Specific application areas	Particular steps proposed	Infrastructure development	Funds available	Policy Initiatives	Source
	Domestic production (electrolyzer capacity), GW	Hydrogen Imports/ Exports							
Norway		Open to blue hydrogen export to Europe idea		Currently, the most relevant applications appear to be the maritime sector, heavy goods transport and industrial processes. There is still some uncertainty regarding this, since the technology for several of these applications is at an early stage. Several of the applications being considered in other countries are of little relevance to Norway. For instance, Norway has a robust hydropower supply and virtually emission-free heating, therefore, typical applications for hydrogen such as an energy storage unit for variable renewable energy are less relevant.	The necessary technological developments • The government will, through current policy instruments, continue to support the necessary technological developments. The authorities will monitor developments and adjust the policy instruments if needed. • The government will in conjunction with the Climate Plan for 2030 evaluate policy instruments to promote the development and use of hydrogen in Norway. • The government will continue to support research into, and the development and demonstration of hydrogen technologies through relevant schemes, with a focus on projects of a high scientific quality and potential for commercial development. Competitive production of clean hydrogen • The government will contribute to developing technology for the capture, transport and storage of CO2, and has ambitions to build cost-effective solutions for full-scale CCS plants in Norway, given that this will generate technology development in an international perspective. CCS is essential for the production of clean hydrogen from natural gas. Emission-free transport • The government will perform a survey of all ferry routes, high-speed ferry routes and other scheduled maritime traffic in order to establish which zero emission technologies could be suitable. This is in order to ensure that the authorities and private companies have a better overview of what could be of interest in terms of low and zero emission technologies in the maritime sector, including the use of hydrogen. Green public procurements • The government will prepare an action plan in order to increase the proportion of climate-friendly and environmentally-friendly public procurements and green innovation. Safety and standards • The government will continue the work of developing regulations and standards, nationally and internationally, for the use of hydrogen-based systems within new areas of application, and in line with technological and market developments. • The government will ensure that the Norwegian Maritime Authority and Norwegian Coastal Administration has the capacity and skills to handle new green shipping solutions, including the development of regulations for the use of hydrogen in maritime industries. National research • The government will increase its focus on research initiatives towards the transition to a low emission society, cf. its Long-term plan for research and higher education (2019–2028). The government will also prioritise the development of technology and solutions for the green transition. International collaboration and research • The government will continue facilitating participation in relevant international fora that contribute to promote and establish sustainable technologies and markets for hydrogen as a low emission solution.	Large scale, natural gas-based hydrogen export from Norway is not currently regarded as a realistic option. However, this may be possible in the longer term, if factors such as more stringent requirements regarding greenhouse gas emissions, combined with demand and the willingness to pay for blue hydrogen are present. Currently, the possibility that Norwegian natural gas could play an important role in a European hydrogen strategy is more realistic. The Norwegian authorities will work to ensure that natural gas reforming combined with CCS can compete on equal terms with hydrogen from water electrolysis in the European energy market.	Zero Emissions Fund, ENERGIX (research)	NHS (June 2020)	https://www.regjeringen.no/contentassets/8ffd54808d7e42e8bce81340b13b6b7d/hydrogenstrategien-engelsk.pdf
Japan								Basic NHS 2017 - first adopter of national hydrogen framework The national government has also issued several strategic documents covering technological and economic aspects, such as the Strategic Roadmap for Hydrogen and Fuel Cells (2014, 2016, 2019), and the green growth strategy.	https://www.env.go.jp/seisaku/list/ondanka_saisei/lowcarbon-hydrogen-sc/PDF/Summary_of_Japan's_Hydrogen_Strategy.pdf https://www.csis.org/analysis/japans-hydrogen-industrial-strategy
US	DOE aims to increase clean hydrogen production from nearly zero today to 10 MT per year by 2030, 20 MT per year by 2040, and 50 MT per year by 2050.	Counts with U.S. leadership role in supporting the global transition from fossil fuels, enabling energy security and resiliency by exporting clean hydrogen Plans to develop market structures and regulatory guidance to enable clean hydrogen exports by 2030-2035	Deployments of clean hydrogen to decarbonize industry, transportation, and the power grid can enable 10 Mt/year of demand by 2030, 20 Mt/year of demand by 2040, and 50 Mt in 2050 Demand projections depend on hydrogen price	While hydrogen's versatility enables it to be used in numerous applications, DOE's focus will be on clean hydrogen for decarbonizing segments such as in industry and heavyduty transportation that are difficult to electrify. Within these segments, processes that use fossil fuels as a chemical feedstock or in the generation of high-temperature heat or long-duration, dispatchable power will require clean fuels, such as hydrogen, to decarbonize.	Extensive list of Actions and Milestones for the Near, Mid, and Long-term • Actions to support clean, affordable, and sustainable hydrogen production • Actions to support safe, efficient, and reliable clean hydrogen delivery and storage infrastructure • Actions to support clean hydrogen use and broader market adoption • Actions to enable a safe, affordable, and sustainable clean hydrogen economy and ensure energy justice	Third, DOE's strategic approach to scale will focus on regional networks by ramping up hydrogen production and end-use in close proximity to drive down transport and infrastructure costs and create holistic ecosystems that provide local benefits. By leveraging the hydrogen hub program as established in the BIL, DOE will focus on matching supplies with off-takers, avoiding stranded assets and unlocking private capital.	In November 2021, Congress passed, and President Joseph R. Biden, Jr. signed the Infrastructure Investment and Jobs Act (Public Law 117-58), also known as the Bipartisan Infrastructure Law (BIL). This historic, once-in-a-generation legislation authorizes and appropriates $62 billion for the U.S. Department of Energy (DOE), including $9.5 billion for clean hydrogen. Furthermore, in August 2022, the President signed the Inflation Reduction Act (IRA) into law (Public Law 117-169), which provides additional policies and incentives for hydrogen including a production tax credit which will further boost a U.S. market for clean hydrogen.	NHS draft September 2022	https://www.hydrogen.energy.gov/pdfs/clean-hydrogen-strategy-roadmap.pdf

Country	Targets & Timeline		Expected hydrogen demand	Specific application areas	Particular steps proposed	Infrastructure development	Funds available	Policy Initiatives	Source
	Domestic production (electrolyzer capacity), GW	Hydrogen Imports/ Exports							
Slovakia	The main goal stated in NHS is to cover as much of the hydrogen needs as possible from domestic sources only. The priority interest will be the effort to cover the hydrogen needs in industry by as many domestic sources as possible.	Imports expected	By 2030, Slovakia will consume 200 kt year, by 2050 - 400-600 kt/y. 90% of which will be covered by low-carbon sources.	The biggest consumers of hydrogen in Slovakia will be the sectors of industry, transportation, and later, energy.	The Slovak government will participate in: - implementation of measures to use low-carbon hydrogen and its compounds in transportation; - implementation of policies of use of low-carbon hydrogen technologies in the relevant areas of national economy; - establishment of a common standard for low emissions of CO2 as part of the implementation chain of low-carbon hydrogen; - introduction of general terminology and criteria for certification of process quality based on use of low-carbon hydrogen over its full cycle – from production, through transportation and distribution, to its use; - introduction of legislative and regulatory measures and safety regulations to support the readiness of the gas infrastructure for transportation, distribution, and storage of hydrogen; and - support of research, development, and innovations related to hydrogen technologies. In order to secure sufficient volumes of hydrogen produced in Slovakia or purchased from other countries which can produce it cheaper and to use it on a large scale, the Slovak government needs to: - draw up policies to stimulate demand in sectors of end use of hydrogen, connecting goals in the area of decarbonisation; - implement supporting measures, making the establishment of innovative products, technologies and industrial solutions for hydrogen production and processing in Slovak industry and energy; - participate in preparing a common standard for low CO2 emissions during the production of hydrogen, as well as over its execution cycle, which is to be implemented in the respective regulation; - introduce common terminology and hydrogen certification criteria; - secure participation of Slovakia in setting-up a pilot programme to support production of low-carbon and recycled steel and basic chemicals; - take into account scenarios of hydrogen production in national strategic documents from the perspective of impacts on electricity consumption and development of energy infrastructure, as well as the electricity source; - as part of the legal framework of support of renewable energy sources, establish conditions for issuing guarantees of origin for hydrogen produced of renewable energy sources in form of self- consumption and create conditions for expanding the guarantees of origin for hydrogen from low- carbon production, as well; and - evaluate and suggest supporting measures to stimulate the readiness of gas infrastructure to transport, distribute, and store hydrogen.		Recovery and Resilience Facility designed for investments and reforms focusing on green and digital economy; European Union funds for the programming period of 2021 – 2027; Fond for Fair Transformation, which has previously been connected with coal-mining regions, and covers regions with energy demanding industry (Košice), as well; Strategic Investments Instrument, which is to mobilize private investments with the support of European Investment Bank and national supporting banks; Connecting Europe Facility – grants for financing respective infrastructure, hydrogen filling stations or the adjustments to gas networks; ETS Innovation Fund linked to emission trading is to mobilise investments to innovative low-carbon technologies in the volume of around 10 billion euros (depending on the price of carbon) in 2020-2030 – the first call was announced on 3 July 2020; Modernisation Fund which is designed to fund investments to modernisation of energy systems and increase of energy effectiveness; at the same time, the European Commission will promote international projects covering the full value chain by allowing state subsidies for important projects of common European interest (IPCEI); InvestEU Fund, which will provide 30% of its funds to support activities related to solutions for implementation of climate changes35; EU mechanism of funding common projects of use renewable source energy, which will allow support of blanket introduction of innovative technologies; the mechanism can be combined with other EU instruments	NHS June 2021	https://nvas.sk/NVS_EN.pdf
Slovenia						The growth of hydrogen consumption for various intensity scenarios of its use should be taken into account when planning the expansion and modernisation of the energy infrastructure.		No NHS	
Spain	4 GW elecrolyzers by 2030	Due to the high potential as hydrogen producer, the Roadmap forsees that Spain could become an exporter of renewable hydrogen to the rest of Europe		Industry that uses hydrogen as a raw material (oil refining, fertilizers and chemicals, among others), public transport, urban services or various uses in intermodal transport nodes such as ports, airports or logistics platforms; heat sector (industrial, residential); isolated energy systems	60 measures grouped into 4 areas of action (regulatory, sectoral, raising knowledge, R&D) Promotion and encouragement of hydrogen valleys		Funds from EU Next Generation, Clean hydrogen Alliance	Hydrogen roadmap (Oct 2020)	https://ec.europa.eu/info/sites/default/files/energy_climate_change_environment/events/presentations/02.03.02_mf34_presentation-spain-hydrogen_roadmap-cabo.pdf https://img.fuelcellsworks.com/wp-content/uploads/2020/10/hydrogenexecutivesummary-Spain.pdf https://energia.gob.es/es-es/Novedades/Documents/hoja_de_ruta_del_hidrogeno.pdf
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Australia						Existing hydrogen production and use in the UK is currently on a small scale, and hydrogen tends to be produced and used in the same location. There is limited distribution through hydrogen pipelines, used to supply industrial users located in industrial clusters, as well as some transport of hydrogen by road into these hubs in either compressed gaseous or liquefied form. Alongside this, there is limited use of above ground metal storage tanks in industrial facilities. Significant development and scale up of hydrogen network and storage infrastructure for the development of a UK hydrogen economy is neeed.		NHS November 2019	https://www.industry.gov.au/sites/default/files/2019-11/australias-national-hydrogen-strategy.pdf
China	100-200 Mt of renewable-produced hydrogen annually by 2025			Target of fleet of 50,000 hydrogen-fueled vehicles by 2025 By 2035, a hydrogen energy industry system will be formed, covering transportation, energy storage, industrial and other applications				In March 2022 the Chinese government released the country's first-ever long-term plan for hydrogen (2021-2035)	"https://www.ndrc.gov.cn/xxgk/zcfb/ghwb/202203/P020220323314396580505.pdf https://www.csis.org/analysis/china-unveils-its-first-long-term--hydrogen-plan"
Chile								NHS November 2020	https://energia.gob.cl/sites/default/files/national_green_hydrogen_strategy_-_chile.pdf

Country	Targets & Timeline		Expected hydrogen demand	Specific application areas	Particular steps proposed	Infrastructure development	Funds available	Policy Initiatives	Source
	Domestic production (electrolyzer capacity), GW	Hydrogen Imports/ Exports							
Norway		Open to blue hydrogen export to Europe idea		Currently, the most relevant applications appear to be the maritime sector, heavy goods transport and industrial processes. There is still some uncertainty regarding this, since the technology for several of these applications is at an early stage. Several of the applications being considered in other countries are of little relevance to Norway. For instance, Norway has a robust hydropower supply and virtually emission-free heating, therefore, typical applications for hydrogen such as an energy storage unit for variable renewable energy are less relevant.	The necessary technological developments • The government will, through current policy instruments, continue to support the necessary technological developments. The authorities will monitor developments and adjust the policy instruments if needed. • The government will in conjunction with the Climate Plan for 2030 evaluate policy instruments to promote the development and use of hydrogen in Norway. • The government will continue to support research into, and the development and demonstration of hydrogen technologies through relevant schemes, with a focus on projects of a high scientific quality and potential for commercial development. Competitive production of clean hydrogen • The government will contribute to developing technology for the capture, transport and storage of CO2, and has ambitions to build cost-effective solutions for full-scale CCS plants in Norway, given that this will generate technology development in an international perspective. CCS is essential for the production of clean hydrogen from natural gas. Emission-free transport • The government will perform a survey of all ferry routes, high-speed ferry routes and other scheduled maritime traffic in order to establish which zero emission technologies could be suitable. This is in order to ensure that the authorities and private companies have a better overview of what could be of interest in terms of low and zero emission technologies in the maritime sector, including the use of hydrogen. Green public procurements • The government will prepare an action plan in order to increase the proportion of climate-friendly and environmentally-friendly public procurements and green innovation. Safety and standards • The government will continue the work of developing regulations and standards, nationally and internationally, for the use of hydrogen-based systems within new areas of application, and in line with technological and market developments. • The government will ensure that the Norwegian Maritime Authority and Norwegian Coastal Administration has the capacity and skills to handle new green shipping solutions, including the development of regulations for the use of hydrogen in maritime industries. National research • The government will increase its focus on research initiatives towards the transition to a low emission society, cf. its Long-term plan for research and higher education (2019–2028). The government will also prioritise the development of technology and solutions for the green transition. International collaboration and research • The government will continue facilitating participation in relevant international fora that contribute to promote and establish sustainable technologies and markets for hydrogen as a low emission solution.	Plans for developing adequate and coordinated port, electrical, and distribution infrastructure to foster the growth of hubs.	Zero Emissions Fund, ENERGIX (research)	NHS (June 2020)	https://www.regjeringen.no/contentassets/8ffd54808d7e42e8bce81340b13b6b7d/hydrogenstrategien-engelsk.pdf
Japan						Large scale, natural gas-based hydrogen export from Norway is not currently regarded as a realistic option. However, this may be possible in the longer term, if factors such as more stringent requirements regarding greenhouse gas emissions, combined with demand and the willingness to pay for blue hydrogen are present. Currently, the possibility that Norwegian natural gas could play an important role in a European hydrogen strategy is more realistic. The Norwegian authorities will work to ensure that natural gas reforming combined with CCS can compete on equal terms with hydrogen from water electrolysis in the European energy market.		Basic NHS 2017 - first adopter of national hydrogen framework The national government has also issued several strategic documents covering technological and economic aspects, such as the Strategic Roadmap for Hydrogen and Fuel Cells (2014, 2016, 2019), and the green growth strategy.	https://www.env.go.jp/seisaku/list/ondanka_saisei/lowcarbon-hydrogen-sc/PDF/Summary_of_Japan's_Hydrogen_Strategy.pdf https://www.csis.org/analysis/japans-hydrogen-industrial-strategy
US	DOE aims to increase clean hydrogen production from nearly zero today to 10 MT per year by 2030, 20 MT per year by 2040, and 50 MT per year by 2050.	Counts with U.S. leadership role in supporting the global transition from fossil fuels, enabling energy security and resiliency by exporting clean hydrogen Plans to develop market structures and regulatory guidance to enable clean hydrogen exports by 2030-2035	Deployments of clean hydrogen to decarbonize industry, transportation, and the power grid can enable 10 Mt/year of demand by 2030, 20 Mt/year of demand by 2040, and 50 Mt in 2050 Demand projections depend on hydrogen price	While hydrogen's versatility enables it to be used in numerous applications, DOE's focus will be on clean hydrogen for decarbonizing segments such as in industry and heavyduty transportation that are difficult to electrify. Within these segments, processes that use fossil fuels as a chemical feedstock or in the generation of high-temperature heat or long-duration, dispatchable power will require clean fuels, such as hydrogen, to decarbonize.	Extensive list of Actions and Milestones for the Near, Mid, and Long-term • Actions to support clean, affordable, and sustainable hydrogen production • Actions to support safe, efficient, and reliable clean hydrogen delivery and storage infrastructure • Actions to support clean hydrogen use and broader market adoption • Actions to enable a safe, affordable, and sustainable clean hydrogen economy and ensure energy justice	Third, DOE's strategic approach to scale will focus on regional networks by ramping up hydrogen production and end-use in close proximity to drive down transport and infrastructure costs and create holistic ecosystems that provide local benefits. By leveraging the hydrogen hub program as established in the BIL, DOE will focus on matching supplies with off-takers, avoiding stranded assets and unlocking private capital.	In November 2021, Congress passed, and President Joseph R. Biden, Jr. signed the Infrastructure Investment and Jobs Act (Public Law 117-58), also known as the Bipartisan Infrastructure Law (BIL). This historic, once-in-a-generation legislation authorizes and appropriates $62 billion for the U.S. Department of Energy (DOE), including $9.5 billion for clean hydrogen. Furthermore, in August 2022, the President signed the Inflation Reduction Act (IRA) into law (Public Law 117-169), which provides additional policies and incentives for hydrogen including a production tax credit which will further boost a U.S. market for clean hydrogen.	NHS draft September 2022	https://www.hydrogen.energy.gov/pdfs/clean-hydrogen-strategy--roadmap.pdf

Connecting the dots: Sector coupling and hydrogen policies in Europe

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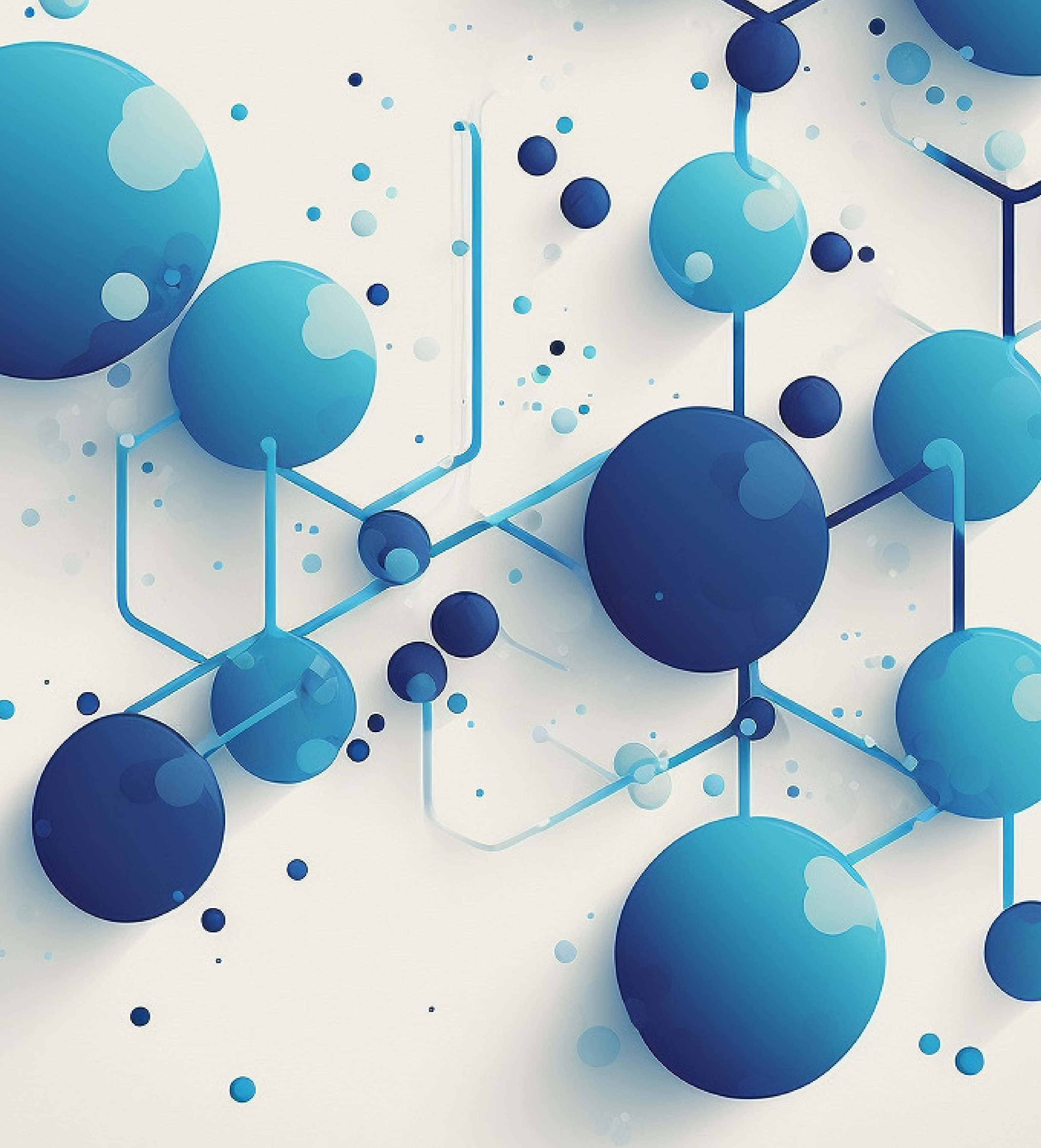

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