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Hydrogen corridors in Europe: strategies and countries involved

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Abstract

The European Union and other countries worldwide have identified fossil-free hydrogen as a key resource for implementing the transition to a low-carbon economy. The European Commission, which had already emphasised the importance of the hydrogen economy within the Green Deal Industrial Plan, has recently quantified the import target for 2030, 2024, and 2050. Unlike oil and gas reserves, renewable energy and green hydrogen have numerous potential producing or supplying countries; therefore, identifying trading partners requires several research and policy initiatives and the adoption of both technoeconomic and political criteria.

The purpose of this study is to investigate the prospect for the development of future hydrogen energy corridors and how European states are organising their political and transport strategies. These strategies design international transport and logistics chains that include the entire hydrogen value chain (production, export, storage and consumption). A new transport and logistics structure is expected for the energy distribution of this vector. Networks and transport nodes will be substantially involved in anticipation of an increase in demand for this type of energy carrier, both in the vicinity of ports, due to industrial demand, and within ports, for the transport and storage of this resource, assuming the increasingly central role of energy hubs and making their role more and more complex, going beyond the classic connotation of intermodal nodes.

Keywords: Hydrogen, Energy corridors, Transport, Hydrogen Valley, Climate change

1. Introduction

Due to recent events related to the climate and energy crisis, the war in Ukraine on Europe's doorstep, and the more recent conflict between Israel and Palestine, the search for alternative, green, and as diverse as possible energy sources has brought the use of hydrogen to the forefront and attention. The long-term climate and energy targets of the Green Deal in Europe aim to achieve the production and diffusion of carbon-free energy, increased energy efficiency, and a deep decarbonisation of industry, transport and buildings. In recent years European Union have identified fossil-free hydrogen as a key resource for implementing the transition to a low-carbon economy and had already emphasised the importance of the hydrogen economy within the Green Deal Industrial

Plan (European Commission, 2023a), with reference to green hydrogen, which could play, in gradual steps, a central role in maintaining industries, reducing dependence on fossil fuels (Nunez & Quitzow, 2023). Furthermore, in order to analyse what the scenario of future green hydrogen corridors might be, we should understand, from the outset, where hydrogen production will be geographically located and how the supply of hydrogen will be managed, to the weights that will need it. European countries alone will not be able to produce the required amount of hydrogen internally, which is why in the European Commission's REPowerEU plan (European Commission 2022a), it is estimated that it will be necessary to import 10 million tonnes of hydrogen per year by 2030. Unlike in the case of oil and gas reserves, in the case of renewable energy and hydrogen the potential producing or supplying countries are numerous (Van de Graaf et al., 2020); identifying trading partners therefore requires several research and policy initiatives and the adoption of both technoeconomic and political criteria. Exporting energy and importing green hydrogen is not trivial, and those players who already have experience in this area, even if not in clean hydrogen, can benefit from production. For all other players who have no experience in this area, it will take about 15 years to build up (large-scale) clean hydrogen exports (Mense, 2023). The possibilities to fuel the supply of hydrogen are linked to infrastructural and scientific-technical advances (such as cost cutting or increased capacity of electrolysers). Similarly, export capacity appears to be influenced by access to financing, resources and accumulated experience in the energy sector. Import prices are mainly determined by production and transport costs, especially if we consider that ships capable of transporting this type of commodity have yet to be built, but they are still a more sustainable option than the construction of new pipelines, which require more time and more complex arrangements. This is why it would be preferable to identify countries closer to the European Union and with the capacity to produce green hydrogen on a large scale. Since the hydrogen production industry has a low learning curve the goal of significantly accelerating imports in a few years appears plausible and of paramount importance. Another vital goal is the affordability of clean hydrogen. Production conditions in exporting countries as well as their proximity to the EU are factors that impact european import strategies. Water scarcity is not seen as a significant obstacle to production based on current knowledge; therefore, it should not be a discriminating factor in the choice of business partners. In the context of the EU, trade agreements made with other countries are expected to be consistent with fundamental EU principles. In the case of hydrogen transition there is the problem of reconciling the requirements of the global sustainable development agenda with the application of the main foreign policy principles. However, it should be noted how in other areas this issue has been only occasionally addressed partly because of the multifaceted nature of the EU's values and overall consensus. In addition, it should also be considered that hydrogen production can bring some important benefits in terms of sustainable development to exporting countries; therefore, future trade agreements defining hydrogen production and import will have a significant impact on the very possibilities of global sustainable development. Since energy importation raises issues of strategic interdependence between countries, the ideal hydrogen exporter should not have geopolitical confrontation with the EU and its member states. In addition, it should also be considered that hydrogen production can bring some important benefits in terms of sustainable development to exporting countries; therefore, future trade agreements defining hydrogen production and

import will have a significant impact on the very possibilities of global sustainable development.

2. Literature review and theoretical background

As highlighted by theoretical and empirical studies, hydrogen is a crucial factor in decarbonizing society. Hydrogen can be produced from fossil fuels or renewable resources but nowadays hydrogen is still widely produced from fossil fuels (Bellocchi et al., 2023). Moreover hydrogen transport requires specialized equipment and infrastructure particularly over long-distance and hydrogen storage is energy and capital intensive process (Kannaiyan et al. 2023). Energy infrastructures have a strong impact on industrial production process, and several analyses reveal that a dedicated hydrogen network leads to a reduction of energy costs for the whole community (Neumann et al. 2023). Starting from this idea, the section is devoted to analyse the most relevant critical issues in the hydrogen distribution system. In this context, the main challenges of the development of green hydrogen economy are the requirements of adequate facilities for hydrogen transportation distribution and storage. Therefore the future of hydrogen, as energy carrier, depends on the realization of infrastructure that can delivery it to industrial, commercial and residential users (Danieli et al. 2022). At present, worldwide there are only 16,000 km of dedicate hydrogen pipeline, whereas natural gas pipeline extend beyond 2,90 million km (Kannaiyan et al. 2023). In recent years, several studies have suggested that natural gas grid infrastructure operational and management will undergo strong modifications in the future (Guandalini et al. 2017). Because of high initial capital costs of new pipeline construction, hydrogen distribution through existing natural gas system is under consideration. NaturalHY-Project (2010) studied the conditions and the maximum percentage under which hydrogen could be introduced in the natural gas pipeline. However as highlighted by Abe et al. (2019) existing infrastructure do not satisfy the future goals for the Hydrogen Energy System. As pointed by Bellocchi et al. (2023), scale economics play a crucial role in order to develop a dedicated and efficient hydrogen infrastructure with the aim of an extensive use of hydrogen, that is a hydrogen-oriented economy. Considering spatial agglomerations of economic activity, transactions between hydrogen suppliers and customers plays a crucial role in value-networks and value-chains. From a technical point of view, hydrogen can be distributed by compressed gaseous hydrogen trailers, liquefied hydrogen trucks, liquid organic hydrogen carriers, and pipelines. The economic feasibility of each technique depends on transport volumes and distance (Muhammad et al., 2021). Despite considerable fixed costs of hydrogen grid, this method is considered to be economical for large quantities. Therefore it is suitable for supplying of large industrial plants. To a lesser extent maritime transport allows an economical hydrogen transport in large amounts (Yang et al., 2023). Policy strategies to support hydrogen grid building or conversion natural gas pipeline are in process. In Germany 5,900 km of pipelines, that is 15% of the total national grid, will be converted to hydrogen. Globally a long-term policy for additional capital investments to meet hydrogen transport infrastructure is already underway (IRENA, 2021). Moreover, another relevant issue is the standardisation in terms of safety, hydrogen and pipeline features.

According to CEN – CENELEC (2018) European Union standardization process has already be started among member states. Moreover EU Member States should plan the implementation a roadmap moving towards an European hydrogen system by 2050. To address this issue, in 2020 European Commission launched the "Hydrogen strategy for a climate-neutral Europe" (Pellegrini et al., 2020). Furthermore by 2050 EU predicted the construction of dedicated hydrogen network from Eastern and Southern neighboring countries (Noussan et al. 2021). It is worth noting that hydrogen as well as natural gas grid work as a natural monopoly. Hence, as pointed by ENSTOG (2020) from an economic point of view, there are no room for parallel infrastructures, but it is crucial ensuring non-discriminatory access to hydrogen network. From an environmental point of view, current studies (Hren et al., 2023) show that hydrogen transport via pipeline produce a smaller quantity of GHG compared to transportation by road. From the latest ESPO report (2024), it is clear that ports have lost their classic role as multimodal hubs in the supply chain linking the sea to the hinterland, and are increasingly taking on the role of hubs and facilitators of sustainable energies in a complex and ever-changing goepolotic environment. New energy sources andrelated commodities are being handled in Europe's ports and this complexity requires major investments with potentially slow and risky returns on investment.

3. Background

The research methodology is of a qualitative and analytical nature and aims to verify, from the analysis of studies and data, what the state of the art is with respect to the topic in question, in order to establish certain points and give indications with respect to future research on a very current and challenging topic.

The match between economic development of hydrogen-exporting countries and the pursuit of global sustainability goals (Sustainable Development Goals), will depend heavily on local policies as the risk is that the economic advantages and rents from a country's resource availability could even exacerbate social and economic inequalities, well explained as the 'resource curse' (Ploeg, 2011), the phenomenon of which could largely be applied to hydrogen (Leonard et al., 2022). A balance should be sought between favouring imports from developing countries and respecting local autonomy, avoiding that the management of imports, which require infrastructure, skilled profiles and high technology, should be managed by the importing entities themselves, implementing imperialist policies and dependence on these countries. (Ansari, D., 2022b, Latulippe & Klenk, 2020, Mahony & Hulme, 2018). The relationship between importing and exporting hydrogen and the rewards for importing and exporting countries in terms of sustainable development is neither clear nor trivial. It is easier to verify this relationship for countries importing hydrogen in terms of spillovers for SDGs 7 and 13, while it is less clear for hydrogen exporting weights, for the reasons stated above (Bianco, 2021). The levels of dependence on exporting countries can be real and not only for energy imports but for all those elements in the value chain (raw materials, electrolysers, solar panels) that can jeopardise the stability of importing countries (Grinschgl et al., 2021, Rabe et al., 2017, Pepe, 2022a; 2022b). Agrees that, in order to define what the European hydrogen corridors will be, the relationship between import-export of this resource and geopolitics

is crucial, partly explored in IRENA, 2022. (International Renewable Energy Agency). By this we mean what Michael Bradshaw (2009) defines as the impact on power dynamics between states that exchange energy resources and their entire value chain. But the future of hydrogen and its relative geopolitics has many areas of uncertainty, volatility, complexity and ambiguity, and consequently, even forecasts of development and agreements between states, offer many margins for caution.

Hydrogen also has the potential to act as a link connecting the gas and electricity sectors, including their respective infrastructures, uniting traditional energy sectors with more innovative ones. It is a clean, versatile and flexible energy carrier and can therefore be used as a raw material in many sectors, ranging from industry to households for heating buildings and as a zero-emission fuel for transport (land, sea and air). Based on Hydrogen Roadmap Europe (2019) by 2050, we expect 2,250 TWh of hydrogen in Europe, which represents roughly a quarter of the EU's total energy demand in 2050 that could come from different sources. What we do know is that it will be necessary for European countries to import renewable energy from solar and wind sources from other states in order to achieve its decarbonisation goal. But the good news is that hydrogen carriers (synthetic methane, ammonia, liquid organic hydrogen carriers (LOHC)) can be used to efficiently transport and distribute renewable energy over large distances, without having to handle large quantities of hydrogen. This will mean that Europe will not be completely independent of foreign energy supplies, but for hydrogen, rather than eliminating its dependencies, it will be able to partly limit them, also thanks to the role of supply chains (Pepe et al., 2023). Geopolitical dynamics as well as the global distribution of raw materials and allocation of energy production areas will influence hydrogen policy and decision-making along the entire value chain, with actors often prioritising socio-economic, geopolitical and techno-political considerations. In this sense, European policy should pursue proactive hydrogen policies, seeking to capture the needs of key players and form pragmatic partnerships with industry, building a strategic role on a global level without losing sight of climate objectives. To avoid sectoral dependencies, it will be necessary to work in advance and diversify in the choice of supply areas and types of energy sources. Defining clear governance at the institutional level will be necessary in this regard. For European countries, the use of hydrogen can undoubtedly have many advantages, ranging from social and ecological spin-offs to the creation of new jobs and a leading position for Europe in terms of technological advancement. Europe could

maintain its position as a technological leader if it focuses on the strengths and capabilities of its industries.

Below is an outline of the investments up to 2030 could be along the entire hydrogen value chain (65 billion)

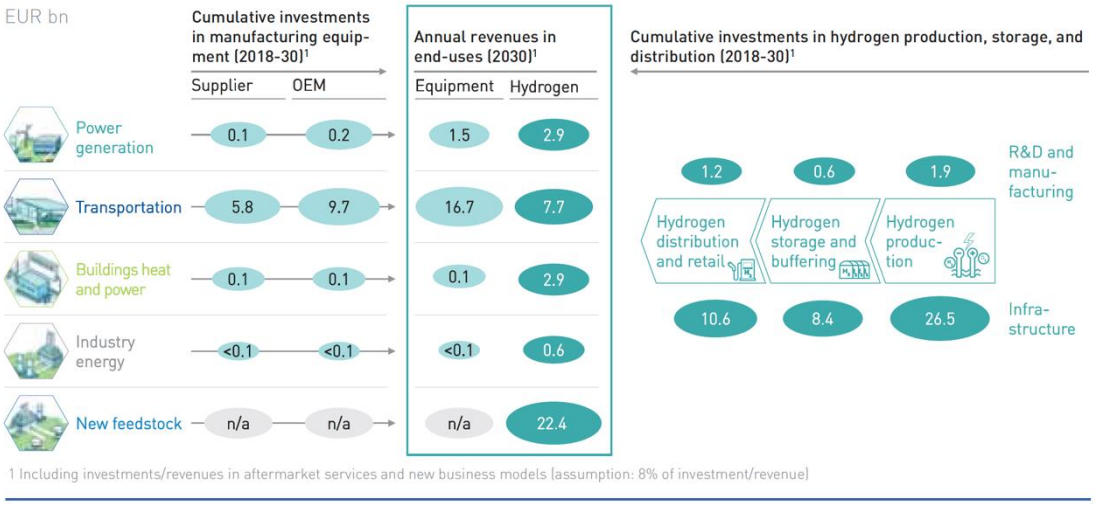

Fig.1: Investments of Eur 65 billion required until 2030 Along The Value Chain. Source: Hydrogen roadmap Europe

One question to ask, in order to understand what the future development of the European corridors will be, is: what will be the European sources of hydrogen supply? The Study on hydrogen in ports and industrial coastal areas (Report 1), commissioned by the Clean Hydrogen Partnership to Deloitte (2023) shows that looking ahead to 2030, 2040 and 2050, part of the green hydrogen production will come from local European coastal and offshore wind farms, solar photovoltaic plants, imported green and blue hydrogen (also from Norway and the UK), part of grey to blue hydrogen conversion towards a gradual transition to green hydrogen. Two possible supply scenarios are envisaged; one for a baseline hydrogen supply scenario that corresponds to the hydrogen demand projected in the three demand scenarios, respectively; the other for an increased import supply scenario that corresponds only to the hydrogen demand projected in the ambitious demand scenario and incorporates a 5% deployment rate of European renewable energy sources for hydrogen until 2050.

For the baseline scenario with respect to local hydrogen production and import, respectively:

- It is predicted that by 2050 around, 75% of the local green hydrogen demand in Europe could be met thanks to solar photovoltaics, whose production is highly

diversified across Europe (highest in Spain, Denmark, Greece and Italy) and identified as the most economically competitive renewable energy source.

- Local hydrogen production in Europe should be supplemented by 25% by 2050 by green and blue hydrogen imports from North Africa and the Middle East

Regarding the increased import supply scenario, with respect to local hydrogen production and import, respectively:

- Should the need arise to impose constraints to facilitate the local deployment of energy from renewable sources, then it will be necessary to provide for the import of green hydrogen, as local production at the European level will only be able to cover this need by 30% in 2050.

- In this scenario, more significantly than in the previous one, Europe will have to draw on more foreign sources, i.e., increased imports from North Africa and the Middle East, but also from potentially more distant countries.

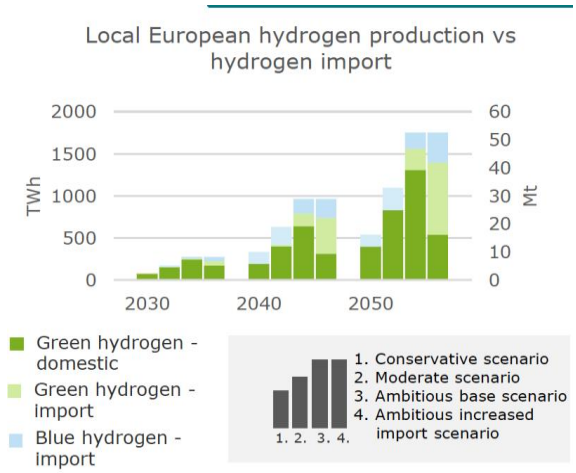

Fig.2: Hydrogen production scenarios over time (2030, 2040, 2050). Source: Study on hydrogen in ports and industrial coastal areas

The hydrogen value chain involves the construction and/or adaptation of different types of infrastructure ranging from production, transport, import, storage and consumption. Depending on the scenarios, it will only be possible to partially cover the production of green hydrogen at the domestic (European) level and it will be necessary to provide geographical import areas via dedicated corridors. Mostly, import will take place by ship with ammonia transport. As far as storage is concerned, it is possible to envisage the use of existing underground gas storage sites, which would, however, only be able to cover 60% of requirements, with new plants and/or the reconversion of other sites than those already mapped having to be envisaged. As far as consumption is concerned,

infrastructure and facilities are all to be planned, both in terms of filling stations and bunkering.

As the full-scale use of hydrogen envisages long-term scenarios, investments in all areas (from infrastructure to regulation and governance) should be planned and envisaged in the short to medium term. In the short term (2030), import corridors are envisaged from Spain to France, from Italy, Croatia and Greece (inland import infrastructure will be needed for these countries), to Central Eastern Europe and from Greece to Bulgaria and South-Central Romania.

Fig.3: Hydrogen import corridors. The colours from lightest to darkest represent time scenarios, short, medium and long term respectively (2030, 2040, 2050). Source: Study on hydrogen in ports and industrial coastal areas

In 2040, the import corridors will involve northern Germany, the Baltic States, Belgium, the Netherlands, and Scandinavian countries through the import of energy from the Corridor from North Africa and the western Mediterranean coast. In 2050 the Corridor will involve almost all central European countries.

On 8 July 2020, the European Commission adopted communications entitled 'Energy for a climate-neutral economy: an EU strategy for energy system integration' and 'A hydrogen strategy for a climate-neutral Europe'. A European Hydrogen Strategy, developed in 20 points. The hydrogen strategy envisages a gradual trajectory to accelerate the development of clean hydrogen over three strategic phases between 2020 and 2050. The first phase, until 2024, will focus on initial deployment near demand centres. The next phase, until 2030, will focus on cost reduction and infrastructure development. After 2030, renewable hydrogen technologies will reach maturity with large-scale deployment and demand. The regulatory and legislative definition of the sector is still to be designed in a harmonious and uniform manner at a European level, but having outlined the terms of a European strategy and the approaching definition of an Italian national strategy, help to draw the overall picture on which to design guidelines and details. Italy's national

hydrogen strategy is aligned with the European Strategy's macro objectives and implementation timeline, enabling Italy to realise supply chain benefits in new industrial and technological sectors (in particular, electrolysers, fuel cells and components), leading to important positive effects on economic growth, with positive impacts also on employment in the various phases of plant design, construction and operation.

4. Results

The goals of sustainable development based on hydrogen import may conflict with each other. For example, the need for affordability and speed would lead to identifying countries that already have infrastructure and resources as potential trading partners; but this would undermine the chances of sustainable development in low-income countries. Similarly, rapid development of the hydrogen economy would enable the EU to be at the forefront of industrial challenges; but it would only be possible by diversifying the suppliers, thus establishing viable economic relationships with countries far from European democratic standards. However, rapid growth in hydrogen imports, even at the expense of affordability, should be considered a priority: a delay would in fact be incompatible with Europe's ambitious climate targets, potentially ending up undermining the entire transition. The issue then of the EU's strategic autonomy and the need to contain the geopolitical risks associated with the transition appear as the necessary condition for hydrogen imports; countries that are in open conflict with the EU should not be considered as import partners. Further attempts to establish criteria for choosing partners by combining techno-economic and socio-political aspects often appear flawed by Eurocentrism and some ambiguities of approach. Finally, sustainable development criteria should rather be assessed for each project instead of being adopted for selecting trading partners. Based on Ansari and Pepe, (2023), and in light of the criteria just outlined, **Canada and Norway** appear as ideal prospective hydrogen exporters for the European countrues. However, hydrogen production in these countries could be adversely affected by low solar irradiation, although other characteristics would be favourable, particularly for obtaining green hydrogen. The **United States** is another potential hydrogen exporter to Europe, given its strong political-commercial integration and advanced techonological infrastructure. In this case, the main obstacles would be represented by the volatility of the price of 'American' hydrogen, possible divergence on the definition of 'green hydrogen,' as well as opportunities for trade competition. The states of the **Gulf Cooperation Council** -particularly **Oman**, Saudi Arabia, and the **United Arab Emirates**- have the potential to become major hydrogen exporters, but the trade corridor with Europe is characterized by high geopolitical tensions; moreover, a partnership with these countries could hardly be compatible with EU principles, with the exception of Oman alone. **Egypt** is another relvant candidate, but its political instability and limited investment capacity would negatively affect its hydrogen production and export. The **Maghreb countries** (Morocco, Algeria and Tunisia) are viable prospective exporters of hydrogen. However, beside the issue posed by local political tensions and persistent problems of accessing credit, the entire infrastructure used for natural gas would have to be adapted, making it impossible to develop exports rapidly. The possibility of identifying trading partners in **Eastern Europe (Ukraine)** and **Central Asia (Kazakhstan)** appears to be seriously undermined by the conflict in Ukraine as well

as by some logistical-infrastructural considerations. **Australia,** on the other hand, is a promising exporter of hydrogen for the EU, although the distance from Europe and the competitiveness of hydrogen demand (from both the domestic market and Asian countries) pose significant challenges. **Latin America** poses a comparable problem in terms of long-distance transport; moreover countries such as **Chile** have some infrastructural problems that are difficult to overcome in the short term. The best candidate in the region is **Brazil**, which has considerable experience in the field of energy exports, as well as the closest ports to Europe. In recent years, however, the country has shown a volatile political leadership, a factor that could affect industrial policy and foreign policy choices.

Due to its limited development, which prevents the construction of a price index, the hydrogen market is likely to remain based on bilateral trade in the short term. The introduction of fixed green premium subsidies, made accessible to members of the Hydrogen Alliance, would lead to a gradual multilateralization of trade; gradually, this system could give way to auction schemes that can determine supply and demand. This mechanism, if properly institutionalized through international agreements, would bring some considerable benefits in terms of production and cost reduction. Based on Ansari and Pepe, (2023), International governance should include the internationalisation of the Hydrogen Bank and the establishment of an innovation fund capable of allowing exporting countries privileged access to the EU common market, otherwise, a regulatory framework unilaterally set by EU would discourage membership of the Hydrogen Alliance.

5. Conclusions

In the transport related literature, little attention has been devoted to the entire hydrogen value chain. To contribute to bridging the gap, the purpose of this paper is to discuss some objectives and priorities of the hydrogen transition process. In this context, we investigate the development of European hydrogen energy corridors and political and transport strategies. The discussion reveals the following conclusions of importance.

First, the path to a hydrogen-powered future is complex and problematic, and as discussed above, some difficult choices of various kinds will need to be made. Second, widespread hydrogen deployment will require a strong effort and will on the part of all key players and along the entire value chain, from politicians, investors and industrial and research players. A further consideration concerns the Eurocentric perspective adopted by the analysis; Europe, it should be remembered, is not the only target market for most exporters and in the future sellers' market scenario, exporters' preferences will become increasingly relevant. This will impose on European countries the need to find compromises when it comes to regulation and to renew forms of collaboration within the EU itself.

Some degree of institutionalization would certainly foster the Global Hydrogen Transition. If the chances of forming a supranational body capable of governing the process are clearly low, an intergovernmental agreement that actively involves the member countries of the 'Hydrogen Alliance' (the way is currently dubbed) would be

higly desirable. Compared to today's bilateral agreements, the multilateral character of the Alliance has far more important geopolitical implications. A plausible scenario is represented by a two-tiered Alliance: the first tier would include exporters such as Brazil, Canada, Norway and Oman, capable of rising to fast producers and with whom rapid political and economic integration would be possible; the second tier would include countries that are unable to deliver hydrogen before 2030 due to infrastructure deficiencies, political instability, and lack of experience. Bilateral cooperation with these countries would remain in force and, with the adoption of appropriate support schemes, their participation in hydrogen value chains could be encouraged; the green hydrogen transport infrastructure would be furtherly developed through multinational banks. From the point of view of the reference framework of European and national guidelines, the definition of a 2020 European Strategy and the outlining of an Italian National Hydrogen Strategy, which is aligned with the timeline and objectives of the European one, help to have a clearer regulatory and legislative framework in perspective. The results highlight that the main challenges of the development of green hydrogen economy are the realisation of dedicated facilities for hydrogen transportation distribution and storage. Our prospective research will concentrate on testing the findings generated in this study by undertaking cross-country comparative studies on countries planning the transition to a low-carbon economy based on fossil-free hydrogen.

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Conflict of Interest

The authors confirm that there is no conflict of interest to declare for this publication.

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