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Hydrogen in the Strategies of the European Union Member States

Introduction

Energy and environmental challenges are two key issues related to the sustainable development of the Earth. Fossil fuels (oil, coal, and natural gas) still supply more than 85% of world energy consumption. Several nations around the globe are striving to provide access to clean and sustainable energy by 2030 (Hostettler et al. 2015).

When the Paris Agreement entered into force in 2016, many countries have recently announced serious commitments to significantly reduce their carbon dioxide emissions, promising to achieve "net zero" by 2050. The main goal is to limit global warming to well below 2 degrees Celsius, preferably to 1.5 degrees Celsius, compared to pre-industrial levels (IEA 2021). This requires a total transformation of the energy systems that underpin our economies. In the case of renewable energy technology deployment, hydrogen may provide a complementary solution, due to its flexibility as an energy carrier and storage medium.

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The European Union (EU), a signatory to the Paris Agreement demonstrated interest in hydrogen as an invaluable raw material in considerably reducing CO_2 emissions. Hydrogen in the EU energy mix is estimated to increase from the current level (less than 2%) to 13–14% in 2050 (EC 2018).

In 2019, the European Commission (EC) presented the European Green Deal, through which Europe is set to become the first climate-neutral continent by 2050 (EC 2019). It presents an ambitious package of measures, including as part of the related Hydrogen Strategy for a Climate Neutral Europe (EC 2020). Neutral hydrogen has been identified as a priority area for achieving carbon neutrality by 2050. In the short to medium term, hydrogen from fossil fuels with carbon capture and storage will play a notable role. The energy transformation will be implemented in the three-stage successive periods. In the first phase, the strategic objective is to install at least 6 GW of renewable hydrogen electrolyzers in the EU. Production up to 1 million tons of renewable hydrogen is intended to be used at refineries, steel mills, and chemical complexes (2020–2024). In the next phase, it will be 40 GW of renewable hydrogen electrolyzers and the production of up to 1 million tons of renewable hydrogen (2025–2030). In the final phase, hydrogen technologies should reach maturity and be deployed on a large scale in all sectors that are difficult to decarbonize (2030–2050) (EC 2019). It is recognized that there is a need to build a transparent range of profitable investment projects.

Hydrogen requires a comprehensive system of financial support that bridges the gap between three main dimensions: market requirements, sustainability, and climate requirements, and the development of hydrogen technology (Bleischwitz and Bader 2010). In the hydrogen strategy for a climate-neutral Europe (EC 2020) estimated investments in:

- electrolyzers (EUR 24–42 billion to 2030),
- required to scale up and directly connect 80–120 GW of solar and wind energy production capacity to the electrolyzers (EUR 220–340 billion to 2030),
- hydrogen transport, distribution and storage, and hydrogen refueling stations (EUR 65 billion to 2030),
- production capacities (EUR 180–470 billion to 2050).

The EU hydrogen strategy also presents indicative costs for different forms of hydrogen production. The current estimated cost of fossil-based hydrogen is around EUR 1.5/kg for the EU, dependent heavily on the price of natural gas and ignoring the cost of CO_2. The estimated costs of today's fossil fuel-derived hydrogen with carbon capture and storage are around EUR 2/kg, and renewable hydrogen is around EUR 2.5–5.5/kg (IEA 2019). Carbon prices in the range of EUR 55–90/tons of CO_2 would be needed for fossil fuel hydrogen with carbon capture to compete with fossil fuel hydrogen today.

In 2020, nine countries around the world announced hydrogen strategies or roadmaps (Australia, South Korea, the Netherlands, Germany, Portugal, Spain, Chile, Finland, Canada) and at least eleven more in 2021 (Austria, Colombia, Denmark, Italy, Morocco, Oman, Paraguay, the United Kingdom, Uruguay, Hungary, the Czech Republic) (IRENA 2021). It should be noted that Japan published the Basic Hydrogen Strategy in 2017, and France published the Hydrogen Strategy for the first time in 2018. However, these strategies are not indicative of either the beginning or the end of the hydrogen role in decarbonizing energy.

Strategies differ mainly in the scope, scale, and implementation period (IRENA 2021). The most ambitious green hydrogen strategies are in the EU. France, Germany, Italy, and Spain declared to install 21.1 GW of renewable hydrogen electrolyzers by 2030. These goals are respectively: 6.5, 5.0, 5.0 and 4.6 GW (FMGermany 2020; METFrance 2020; METDC 2020; MEDItaly 2021). Renewable hydrogen will play an important role in the energy transformation of global economies (Yue et al. 2021). However, relatively new hydrogen production technologies, including using renewable energy, are currently not as cost-competitive, although they are highly pollution-free (Baykara 2018).

In terms of technological progress towards hydrogen and fuel cells, Japan, South Korea, China, and the United States are the most advanced (FCH 2019). However, in the field of electrolysis technology, Europe is a world leader (IRENA 2020). In the last 10–15 years, it has filed about twice as many patents and publications as its closest competitors – the US, China, and Japan (FCHO 2021). On the other hand, Chile has ambitions to become a leader in the production of green hydrogen; similarly Costa Rica, Colombia, Brazil, Uruguay, Peru, and Argentina (ECPA 2021). The Chilean national government launched the Clean Hydrogen Strategy in 2020, which it sees as key to achieving carbon neutrality by 2050 (MEGChile 2020). Saudi Arabia has also started to explore the potential of hydrogen production by signed a Memorandum of Understanding (MoU) establishing cooperation on hydrogen with Germany. The first industrial-scale green hydrogen plant in the Middle East and North Africa is in the start-up phase at a solar park in the United Arab Emirates (Dubai) (Frangoul 2021).

To identify opportunities and challenges for the future of the hydrogen economy in the EU Member States, national strategies or roadmaps are reviewed. To a different extent, these policies correspond to the most important assumptions of the EU's hydrogen strategy. In particular, this applies to planned installed capacity, renewable electrolyzes, the budget of planned investments, and key sectors which will be affected by decarbonization. In particular, the steel, chemical, and transportation sectors will be the most challenging. The transition path from gray and blue hydrogen to green will also differ from country to country. Similarly, the amount of installed RES dedicated capacity for the production of green hydrogen through electrolysis will be varied.

Hydrogen can play a key role in synergies with renewable energy sources in the EU energy system. This, however, requires coordinated actions by all EU countries, and thus well-structured policies. Multiple factors influence the development of countries with zero-emission policies (Cader et al. 2021). The purpose of this article is to assess the strategies of EU members in the context of hydrogen and to compare the most important planned targets concerning the assumptions of the EU hydrogen strategy. The involvement of national clusters in the development of local production of hydrogen is also indicated. The planned initial investment budgets show where the most financial sources are needed. The results will be collected individually for each country and jointly in relation to the plans adopted by the European Commission.

The involvement of individual countries in creating a hydrogen economy in Europe is visible through the use of aggregate reports (e.g. Fuel Cells and Hydrogen Joint Undertaking (FCH JU) reports). Some of EU Member States can play the role of leaders, while others will be followers. These preliminary analyses show to what extent EU countries will implement the postulations adopted by the European Commission in the hydrogen strategy. Despite the initial phase and the presented estimates, it is already possible to show the progress of work on the development of hydrogen in the investigated EU countries. The presented analyses of strategies and roadmaps allow us to confirm the hypothesis: *The hydrogen strategies implemented by the EU Member States have a diversified impact on developing the hydrogen economy.* This was demonstrated by estimates of electrolyzer capacity, avoidance of CO_2 emissions, value added, increase in the share of renewable energy sources, and new jobs across the full value chain.

This study adds value to the extant literature in two ways. The first is the analysis of the possibilities for the development of the hydrogen-based economy in the European Union countries by indicating country-specific characteristics (e.g. production, export, import and demand for hydrogen, hydrogen projects and clusters, subsidies, CO_2 emissions, and energy consumption) and estimated values to achieve the policy targets. Secondly, the study improves the international debate on the steps taken so far in the EU to evolve the energy transition through the development of a hydrogen-based economy.

1. Methodology and basics of analysis

1.1. Methodology

The methodology combines the qualitative literature review with the leveraging of quantitative data. The strategic government documents showing the advancement of works on the development of hydrogen in the EU countries were analyzed. In the next step, the Fuel Cells and Hydrogen Joint Undertaking reports based on the strategies and roadmaps were investigated.

The analysis assesses the potential of EU countries to develop the hydrogen market, i.e. the possibilities of producing green hydrogen, the dominant hydrogen sectors, the importance of international cooperation, and R&D research. In the next stage, the socio-economic and environmental impacts were estimated, i.e. CO_2 emissions avoidance, new jobs, value added in the domestic economy.

1.2. Characteristics of the EU Member States

The pace of implementation of hydrogen technologies depends on the established climate, environmental and economic goals determined by the characteristics of the regions, visible in individual indicators. The development of the hydrogen economy is significantly influenced by environmental (e.g. reduction of greenhouse gas emissions) and energy (e.g. consumption of energy) factors.

Energy consumption is mainly in the EU countries in transport (30.9%), households (26.3%), and industry (25.6%). The highest total energy consumption is in Germany (200.6 million toe), France (139.4 million toe), Italy (113.1 million toe), Spain (81.5 million toe), Poland (69.1 million toe), and the Netherlands (44.7 million toe). In the case of energy consumption per capita, Luxembourg, Finland, Belgium, and Sweden are the leaders. The EU remains dependent on fossil fuels for energy production, but consumption of solid fossil fuels in the EU decreased to 20% over 2019 (Eurostat 2021a).

Achieving net-zero greenhouse gas emissions in 2050 is one of the main objectives of the European Green Deal (EC 2019). Reducing carbon dioxide emissions is of particular importance in this respect. The total carbon footprint in EU countries was 6.7 tons of CO_2 per person in 2019 (Eurostat 2021b). Among the countries with the highest CO_2 emissions, Germany stands out (741.1 million tons), whose emissions are more than twice as high as in France (344.9 million tons), Italy (352.2 million tons) and Poland (322.7 million tons). Taking into account CO_2 emissions by the source sector, emissions from the energy sector have the largest share.

The largest producers of hydrogen are Germany (2,398 million m^3), the Netherlands (2,015 million m^3), France (1,163 million m^3), and Spain (1,316 million m^3), which are also characterized by the highest consumption (IndexBox 2021) (Table 1). These countries, together with Italy, declare the commissioning of electrolyzers with the highest capacity in 2030. The largest hydrogen exporter is the Netherlands, while Belgium imports the largest amounts of hydrogen.

The European Union countries currently consume about 9.7 million tons of hydrogen per year (FCH 2019). Hydrogen demand varies across sectors of the economy. Hydrogen is considered a key element of the future energy system as an energy carrier for industry and transport. Currently, however, in the EU, the greatest total demand is visible in the refining sector (50.4%) and the production of ammonia (30.3%) (FCHO 2019). This trend continues in most countries (Figure 1). The greatest demand for hydrogen is in Germany (1.68 million tons), the Netherlands (1.28 million tons), Poland (0.77 million tons), Spain (0.60 million tons), and Italy (0.55 million tons).

The total public energy budget for energy research, development, and demonstration (RD&D) expenses for the EU in 2019 reached EUR 1.59 billion (2020 prices and exch. rates) (IEA 2020). The 6.3% of the budget, i.e. EUR 99.397 million is allocated to the category of Hydrogen and Fuel Cells technologies, including hydrogen production, storage, transport, infrastructures, systems, and end-uses (EUR 72.82 million), as well as Fuel Cells subcategory, including stationary and mobile applications (EUR 26.57 million). Among the IEA members and at the same time the Member States of the EU, the largest funds for the development of hydrogen technologies and fuel cells are allocated by Germany (EUR 45.98 million), France (EUR 38.74 million), Denmark (EUR 16.55 million), Spain (EUR 10.37 million), Austria (EUR 9.47 million), and Czech Republic (EUR 9.67 million).

Table 1. Production and consumption (million m^3) as well as export and import (thousand m^3) of hydrogen in EU countries in 2019

Tabela 1. Produkcja i konsumpcja [mln m^3] oraz eksport i import [tys. m^3] wodoru w krajach UE w 2019 r.

Country	Production	Consumption	Export	Import
Austria	17.9	27.5	126.4	9,791.6
Belgium	100.4	336.2	21,721.2	257,566.7
Croatia	–	0.2	2.6	221.2
Cyprus	–	0.0	–	0.02
Czech Republic	22.2	23.7	1,987.4	3,410.2
Denmark	1.3	2.1	535.6	1,300.8
Estonia	5.1	5.1	0.6	9.2
Finland	411.2	411.2	40.1	38.0
France	1,163.5	1,182.1	6,569.9	25,234.5
Germany	2,398.2	2,398.9	14,194.6	14,978.2
Greece	0.2	0.3	2.6	79.1
Hungary	333.8	331.8	1,996.5	14.1
Ireland	17.6	18.8	161.8	1,402.1
Italy	261.7	262.1	660.0	1,137.8
Lithuania	15.6	15.6	6.4	11.1
Luxembourg	–	15.5	9.9	15,539.5
Malta	–	0.03	–	25.7
Netherlands	2,015.0	1,761.9	263,700.4	10,605.5
Poland	17.8	18.1	1,565.7	1,935.3
Portugal	98.6	98.7	534.2	612.5
Romania	2.0	3.4	76.4	1,383.0
Slovakia	9.9	7.5	3,631.3	1,267.1
Slovenia	9.0	9.0	72.7	71.6
Spain	1,316.1	1,316.6	395.0	836.8
Sweden	3.1	2.9	356.4	123.1

Source: IndexBox database (IndexBox 2021).

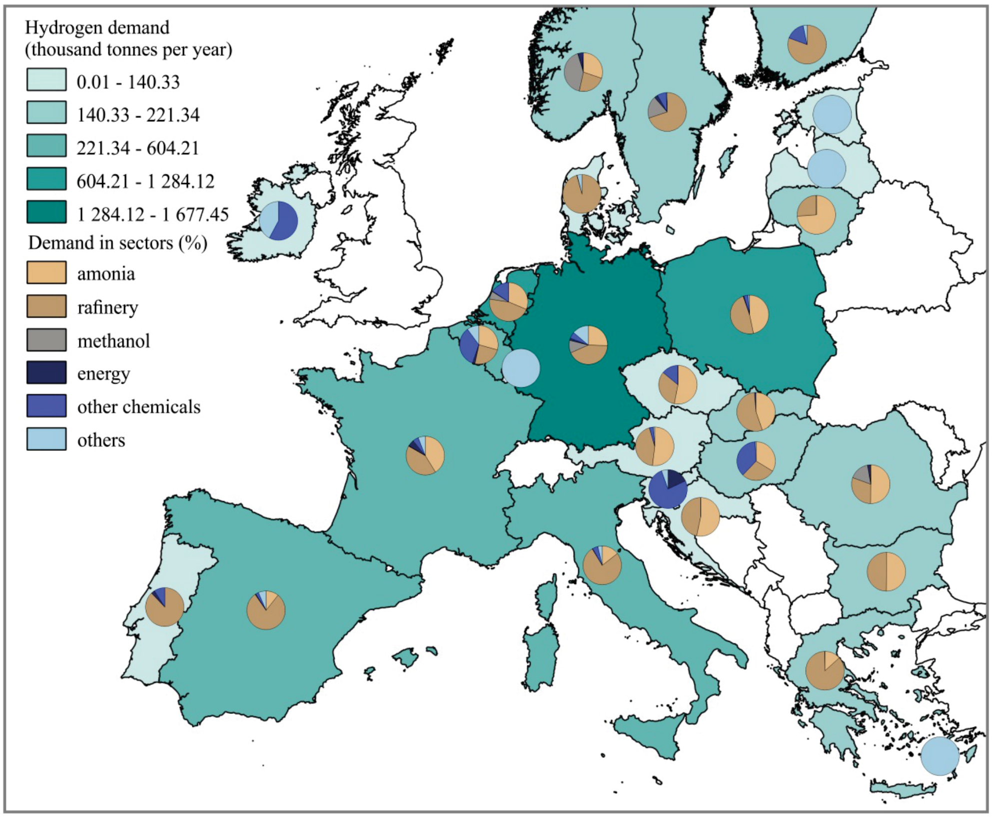


Fig. 1. Hydrogen demand by sector in tons per year (data as of the end of 2019).
"Others" category covers the demand from small to medium scale hydrogen users, including the food industry, glass manufacturing, automotive, and transport
Source: The Fuel Cells & Hydrogen Observatory (FCHO 2019)

Rys. 1. Zapotrzebowanie na wodór według sektorów w tonach na rok (dane na koniec 2019 r.).
Kategoria „Inne" obejmuje zapotrzebowanie małych i średnich użytkowników wodoru, w tym przemysłu spożywczego, szklarskiego, motoryzacyjnego i transportowego

One of the results of subsidies in the area of hydrogen technologies is patents. Among the EU Member States, Germany, Spain, France, Denmark, Poland, and Austria stand out especially in terms of the number of patents in this area in the period from 2015 to 2020 (FCHO 2021). Out of the total of 2,372 patents in the 5 years, 37% of the patents concerned the Fuel Cells area, while 63% were related to the Hydrogen Production category. About 36% of the patents concerned the electrolysis process.

1.3. The hydrogen strategies of the EU countries

In recent years, hydrogen production and fuel cell technologies have attracted the attention of governments in many countries. Hydrogen strategies have been published by six countries (Czech Republic, France, the Netherlands, Germany, Portugal, Hungary), and two of them have roadmaps (Finland, Spain). The remaining ones declare that they will publish strategies by the end of 2021, many of which are at the stage of public consultations, e.g. Poland, Italy.

The hydrogen strategies of the EU countries define the goals and actions for building a low-emission hydrogen economy, relating to energy, transport and the chemical, metallurgical, and refineries industries, as well as to its production, distribution, and R&D. Each country has also planned a budget for the transformation towards renewable hydrogen (France – EUR 7 billion, Spain – EUR 10 billion, Germany – EUR 12.36 billion, Portugal – EUR 8.5 billion).

The priorities of hydrogen strategies include the decarbonization of the chemical, metallurgical, and refineries industries. The steel industry (mainly steel production) is of great importance for Germany (FMGermany 2020), but also Portugal, Spain, and the Czech Republic (METDC 2020; MECA 2020; MITCzechia 2021). The Czech Republic, France, Spain, and Poland focus on the chemical industry (mainly ammonia production) (FCH JU 2020a). Refineries are well developed e.g. in Portugal and France. Only the Netherlands additionally mentions the reduction of CO_2 emissions in agriculture (MEACP 2020). Portugal distinguished the glass, ceramics, and cement industries in the chemical sector.

Mobility is also of great importance in national energy and climate plans (Hydrogen Europe 2020). European regions are in the lead, including through the European Hydrogen Valley Partnership (the European Hydrogen Valleys Partnership, launched in May 2019, is part of the Smart Specialisation Platform for Industrial Modernisation of the European Commission and involves 35+ European regional authorities). The 25 Member States explicitly mention hydrogen mobility applications with varying levels of detail. For example, in France, more than 700 thousand light vehicles, 2.4 thousand buses, 91.9 thousand trucks, 181 trains, and 1.1 thousand hydrogen refueling stations are expected by 2030 (FCH JU 2020b). Another example is the Italian strategy according to which half of the international railways will be powered by hydrogen by 2030. The strategies also pay attention to shipping and air transport (MEDItaly 2021) (Table 2).

A priority for hydrogen strategies is also the construction sector (industrial and commercial buildings difficult to decarbonize). The gradual introduction of hydrogen solutions may also lead to the diversion or re-use of parts of the existing natural gas infrastructure, keeping the economic viability and legitimacy of gas grid investments. All countries indicate in their strategic documents that they will want to use the existing transport infrastructure.

Currently, in Europe, there is a well-developed natural gas network of around 2.2 million km of pipelines. With relatively small investments, most of this gas network can be retrofitted and allocated to 100% hydrogen. As the amount of hydrogen grows, dedicated

Table 2. Hydrogen in transport in 2030

Tabela 2. Wodór w transporcie w 2030 r.

Country	Buses	Trains	Trucks	Cars	Refueling stations
Austria	210	43	6,120	110,400	210
Belgium	320	120	11,520	129,900	249
Bulgaria	160	3	5,750	40,200	84
Croatia	60	6	1,070	16,800	34
Cyprus	10		300	3,000	6
Czech Republic	980	21	7,040	59,200	123
Denmark	310	91	5,680	59,900	128
Estonia	40	4	230	3,800	8
Finland	90	8	1,740	34,800	68
France	2,410	181	91,940	703,400	1,113
Germany	1,510	340	64,770	954,000	1,342
Greece	230	12	9,660	63,500	133
Hungary	1,000	11	6,300	82,200	160
Ireland	60	7	1,350	14,100	30
Italy	1,040	9	50,040	811,600	1,160
Latvia	40	10	480	8,200	17
Lithuania	40	18	280	7,300	16
Lithuania	40	18	280	7,300	16
Luxembourg	20	1	230	5,600	11
Malta	10	0	113	1,400	3
Poland	1,260	40	24,280	140,500	291
Portugal	350	5	830	109,400	196
Romania	280	30	3,680	37,200	78
Slovakia	60		1,000	15,900	31
Slovenia	30	4	810	12,600	25
Spain	1,330	30	63,290	540,300	890
Sweden	340	2	7,200	103,700	200

Source: the Fuel Cells and Hydrogen Joint Undertaking (FCH JU 2020a).

hydrogen pipelines will be created, initially linking industrial clusters and then extending to regional and national hydrogen infrastructures. Europe currently has around 1.6 thousand km of hydrogen pipelines (Steen 2016). A European hydrogen backbone of 6.8 thousand km of new pipeline networks by 2030 is planned for building and by 2040 this

Table 3. Hydrogen clusters affiliated to the European Clean Hydrogen Alliance

Tabela 3. Klastry wodorowe zrzeszone w European Clean Hydrogen Alliance

Cluster	Region
CARA	France: Auvergne-Rhône-Alpes
Chemical Cluster Delfzijl	Netherlands: Groningen
Cleantech and energy Innovation Cluster	Italy: Piedmont
Clust-ER Greentech – Emilia Romagna	Italy: Emilia-Romagna
Cluster Energy Technology Berlin-Brandenburg	Germany: Brandenburg
Cluster Green Transport	Bulgaria: South-West (Bulgaria)
Commercial Vehicle Cluster – Nutzfahrzeug GmbH	Germany: Rhineland-Palatinate
Ecoplus. The Business Agency of Lower Austria, Food Cluster	Austria: Lower Austria
ITECAM, Metal-Mechanical Cluster of Castilla-La Mancha	Spain: Castile-La Mancha
Logistics-Initiative Hamburg Management GmbH	Germany: Hamburg
Málaga TeckPark	Spain: Andalusia
Metaindustry4. Cluster of Advanced Manufacturing of Metal Industry in Asturias	Spain: Asturias
Metall/Kunststoff DIALOG	Germany: Baden-Württemberg
NAE (Normandie AeroEspace – Defense)	France: Normandy
National Energy Technology Cluster	Italy: Lazio
North South Logistics & Transport Cluster	Poland: Pomorskie
Pôle Véhicule du Futur	France: Burgundy-Franche-Comté
Polish Cluster of Composite Technologies	Poland: Małopolskie
Slovak National Hydrogen Association – Claster	Slovakia: Bratislava
Southwest Hungarian Engineering Cluster	Hungary: South Transdanubia
Testmj – co	Belgium: Brussels Region
TWEED	Belgium: Walloon Region

Source: The European Clean Hydrogen Alliance members (EC 2021a).

backbone could reach 23 thousand km. Moreover, the EU has approximately 1.2 thousand TWh of underground storage (Guidehouse 2020).

The decarbonization of the industrial use of hydrogen is also supported by the creation of hydrogen valleys and hydrogen clusters that act as a demonstration of the entire hydrogen ecosystem in the region as a portfolio of related projects. Active regions in the field of H_2 are those characterized by the location of innovation clusters (Madsen and Andersen 2010). 22 hydrogen clusters are part of the European Clean Hydrogen Alliance(Table 3).

Energy policy will have to support the implementation of hydrogen in energy systems, while research and development work will reduce costs and improve its competitiveness (McPherson et al. 2018).

R&D programs related to hydrogen are valid for every EU country. The thematic scope of R&D projects is included in the strategy of Germany and France. These topics include pioneering hydrogen technologies and other PtX technologies in the chemical and steel industries (FCH JU 2020c). Transport (especially low-emission planes and ships), but also energy networks and gas sector infrastructure (liquid H2, reuse in the gas network) are considered as important areas (FCH JU 2020b). On the other hand, in the strategy Portugal proposed the creation of a hydrogen laboratory as a national and international center for research and development activities related to the relevant elements of the hydrogen value chain (FCH JU 2020d).

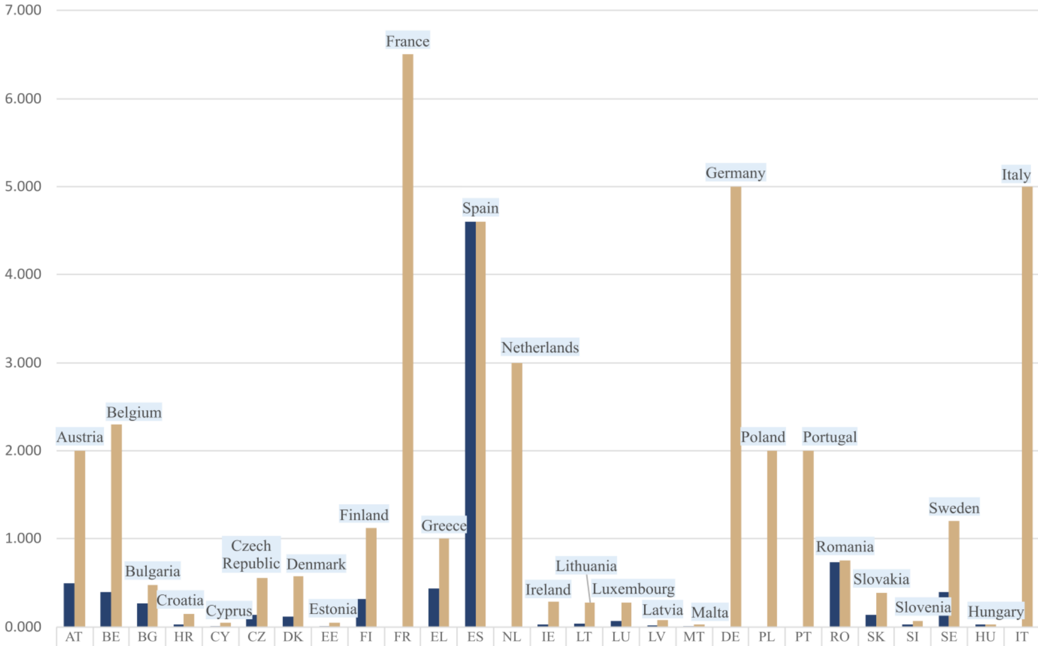
International cooperation will also be very helpful in the development of the hydrogen market, e.g. Germany will cooperate with Morocco, Ukraine, and Russia; Greece with Macedonia; Portugal with Japan and Canada. The European Commission is also proposing a partnership of European countries that will be based on the work of the Fuel Cells and Hydrogen Joint Undertaking to accelerate the development and implementation of the European value chain in the field of clean hydrogen technologies (EC 2021b).

2. Results – strategy targets

Among the various hydrogen production processes, electrolysis was found to be the most promising. The production market for hydrogen decarbonized by electrolysis should evolve towards larger projects and greater capacity. In 2030, the highest capacities of electrolyzers are planned to be achieved by France (6.5 GW), Germany (5 GW), Italy (5 GW), Spain (4.6 GW), and the Netherlands (3 GW) (Figure 2) (FCH JU 2020a). Switching to renewable hydrogen will require appropriate installation sizes of dedicated RES capacity for the production of green hydrogen through electrolysis (Figure 3).

In the longer term, countries involved in developing low-carbon or zero-carbon hydrogen technologies will contribute to CO_2 emissions avoidance, new jobs, and value added in the domestic economy.

Limitations on CO_2 emission targets such as 100% decarbonization by 2050 and 55% reducing emissions by 2030 compared to 1990 is a key requirement for the European Com-



	AT	BE	BG	HR	CY	CZ	DK	EE	FI	FR	EL	ES	NL	IE	LT	LU	LV	MT	DE	PL	PT	RO	SK	SI	SE	HU	IT
min	0.500	0.400	0.270	0.026	0.007	0.140	0.120	0.005	0.320		0.440	4.600		0.031	0.040	0.070	0.017	0.003				0.740	0.140	0.023	0.400	0.024	
max	2.000	2.300	0.480	0.150	0.051	0.560	0.580	0.046	1.120	6.500	1.000	4.600	3.000	0.290	0.280	0.280	0.076	0.027	5.000	2.000	2.000	0.760	0.390	0.065	1.200	0.024	5.000

■ min ■ max

Fig. 2. Scenarios of electrolyzer capacity in EU countries in 2030 (GW)
Source: The Fuel Cells and Hydrogen Joint Undertaking studies (FCH JU 2020a)

Rys. 2. Scenariusze mocy elektrolizerów w krajach UE w 2030 r. (GW)

mission to become the world's first climate-neutral continent by 2050. Some countries would like to make faster changes. Finland aims to reach that goal by 2035, Austria and Iceland by 2040, and Sweden by 2045 (IEA 2021).

Malta, Cyprus, and Latvia make the smallest contribution to CO_2 emissions, and also have a small share in the consumption of fossil fuels, in contrast to, for example, Germany or Poland. The GHG emissions in Germany should be reduced by 290 Mt CO_2 in 2030, compared to 2015. In the scenarios considered, the deployment of hydrogen could contribute 5.8–18.7 Mt CO_2 to this goal, which is equivalent to 2–6.5% of the required emission reduction (FCH JU 2020c). While GHG emissions in Poland should be reduced by 99 Mt CO_2 in 2030, compared to 2015. In the scenarios considered, the deployment of hydrogen could contribute 0.7–1.8 Mt CO_2 to this goal, which is equivalent to 0.7–1.8% of the required emission reduction (FCH JU 2020e). The estimated emissions avoided by other countries are presented in Figure 4.

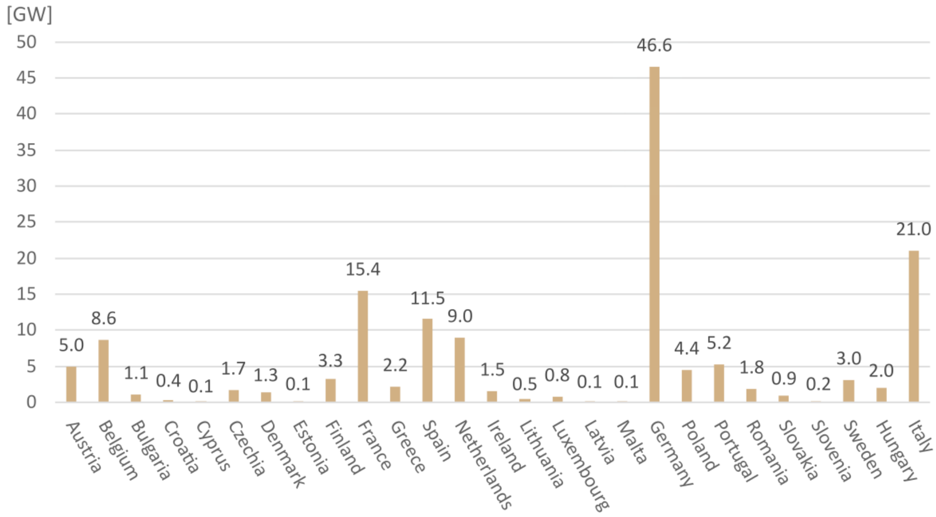


Fig. 3. Installed RES capacity dedicated to green hydrogen production through electrolysis in 2030 (GW)
Source: The Fuel Cells and Hydrogen Joint Undertaking studies (FCH JU 2020a)

Rys. 3. Wielkość zainstalowanej mocy OZE przeznaczonej do produkcji zielonego wodoru poprzez elektrolizę w 2030 r. (GW)

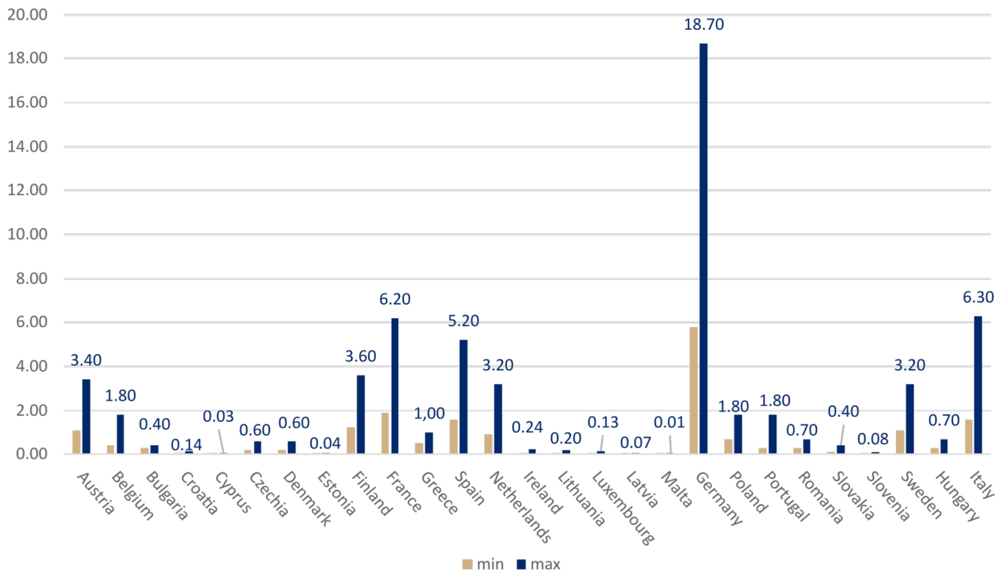


Fig. 4. CO_2 emissions avoided (Mt CO_2 per year) as one of the main effects of the hydrogen vision development by 2030 in the EU countries
Source: The Fuel Cells and Hydrogen Joint Undertaking studies (FCH JU 2020a)

Rys. 4. Uniknięta emisja CO_2 (Mt CO_2 rocznie) jako jeden z głównych efektów rozwoju wizji gospodarki wodorowej do 2030 r. w krajach UE

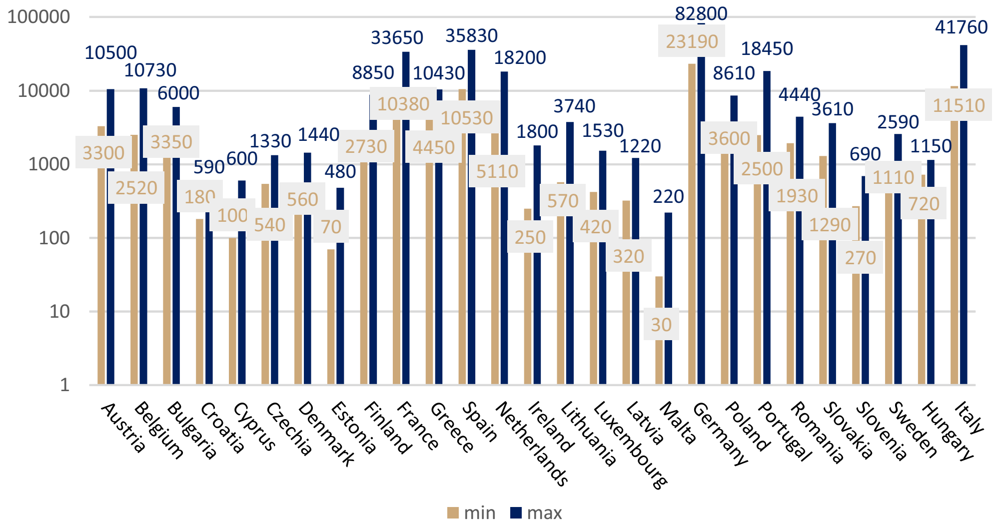


Fig. 5. New jobs as one of the main effects of the hydrogen vision development by 2030 in the EU countries
Source: The Fuel Cells and Hydrogen Joint Undertaking studies (FCH JU 2020a)

Rys. 5. Nowe miejsca pracy jako jeden z głównych efektów rozwoju
wizji gospodarki wodorowej do 2030 r. w krajach UE

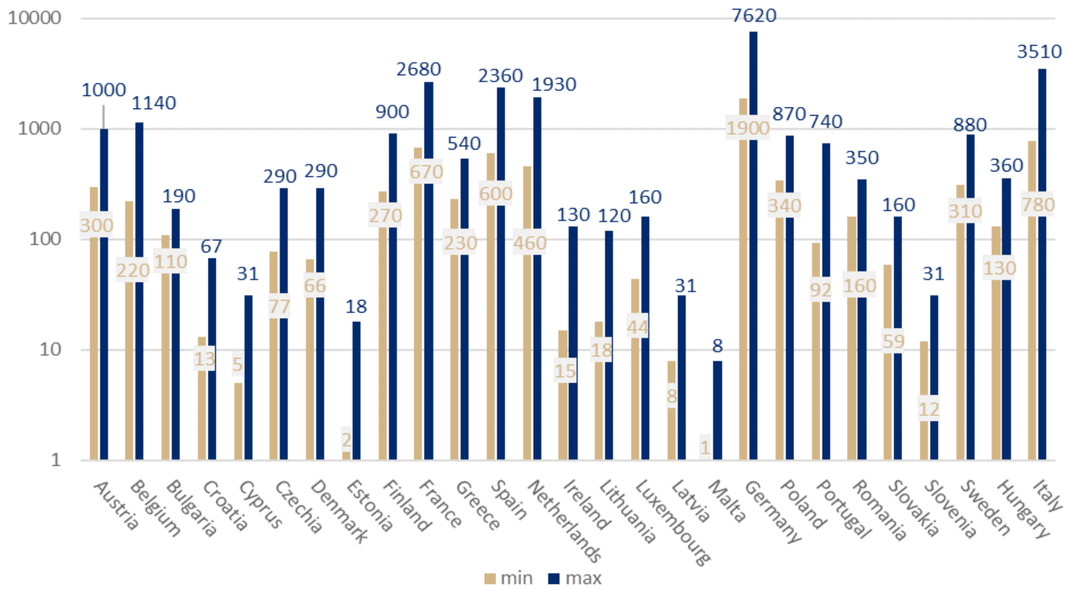


Fig. 6. Value Added in the domestic economy (million Euros per year)
as one of the main effects of the hydrogen vision development by 2030 in the EU countries
Source: The Fuel Cells and Hydrogen Joint Undertaking studies (FCH JU 2020a)

Rys. 6. Wartość dodana w krajowej gospodarce [mln Euro rocznie]
jako jeden z głównych efektów rozwoju wizji wodoru do 2030 r. w krajach UE

In addition, it is estimated that hydrogen-related expenditure in 2020–2030 will generate a total of over 311 thousand direct jobs (in production, operation, and maintenance) in all analyzed countries and contribute to the creation of further indirectly related jobs. Most of these jobs are expected to be generated in the renewable electricity generation sector by building and maintaining the efficiency of electrolyzers and in the industrial sector. Most jobs will be created in Germany (82.8 thousand), Italy (41.76 thousand), Spain (35.83 thousand), and France (33.65 thousand) (Figure 5).

The implementation of hydrogen strategies will be also reflected in value added in the domestic economy. Estimates show that in the years 2020–2030 over EUR 6.9 billion a year (low scenario) may be retained in the economies of EU countries as an added value and over EUR 26.4 billion in high scenario (value added is defined here as the sum of wages for employees, margins for companies and taxes). Most of this value added is expected to be created by building and operating dedicated renewable electricity sources and electrolyzers for hydrogen production, and in the automotive and steelmaking industry (Figure 6).

3. Discussion

The national hydrogen strategies and roadmaps aim to facilitate and accelerate energy transmission in different sectors. They define the present and future role of hydrogen in the energy sector. Priorities for action in the strategies are determined by the country's energy policy, including the diversification of the energy mix of countries, the impact, and needs of individual sectors of the economy, but also the obligation to build a sustainable and decarbonized energy system. Moreover, strategic plans include a set of measures and goals for the gradual introduction of hydrogen as part of the economy in light of the European Union's hydrogen strategy. A comprehensive strategic action plan has been developed to help different industries make changes, gain investor confidence, and secure investment financing.

The results of the planned actions in the strategies will influence the generation of value added in the domestic economy, including by creating jobs in the production, construction, and exploitation of hydrogen technology, and will contribute to the reduction of greenhouse gas emissions.

1. In order to compare these values, it cannot be unequivocally stated that the forecast size of the EU countries corresponds to the assumptions adopted by the European Commission in the hydrogen strategy, i.e.:
2. Installing the capacity of electrolyzers powered by energy from renewable sources by 2030 reaches a difference of over 8 GW.
3. It is not easy to compare the amount of CO_2 reduction, which results from the adopted period and units of measurement. The EU plans to reduce greenhouse gas emissions by 2030 by at least 50–55%, and its members at a maximum level of 60.5 Mt CO_2/a.
4. It is difficult to compare the number of jobs. EU members indicate the creation of a maximum of almost 270 thousand direct new jobs in production and opera-

tions & maintenance and indirectly related jobs will be created in the production of electricity from renewable sources by building and maintaining electrolyzer efficiency and in industrial applications. In contrast, the EU will have 1 million jobs directly and indirectly linked to hydrogen in the value chain for many industrial sectors, RES production, and other end-uses.

5. The sum of the budgets of estimated investments in hydrogen by EU members will be possible after the publication of the final versions of national hydrogen strategies. Currently, taking into account France, Spain, Germany, and Portugal, there is almost EUR 38 billion in investments, including in hydrogen necessary for production, distribution structures, hydrogen consumption, research and development, investments in infrastructure, e.g. gas networks. This value constitutes 4% of the budget forecast by the European Commission.
6. Value added in the domestic economy is mentioned only in national strategies. The maximum for all members is over EUR 26.406 billion per year.

Each country has a chance to improve its economic situation thanks to thoughtful investments. To maximize the potential and achieve further economic growth, each region identified industries that enable decarbonization. Additionally, they have been adapted to the specifics of their economies in order to gain a competitive advantage over other countries. Domestic expenditure on the necessary replacement of infrastructure and construction in the areas of energy, buildings, transport, industry, and agriculture will contribute to obtaining value added in the national economy.

Decarbonization should improve the trade balance of countries that are leaders in obtaining energy from renewable energy sources, as well as those that currently import hard coal. Significant economic benefits could be obtained by the development of low-emission sectors of the economy, e.g. the production of electric vehicle components, as well as research and development activities and technology implementation.

The innovative solutions for more efficient and cheaper electrolyzers and fuel cells will bring substantial financial gains. International cooperation with other regions will also be helpful, in the form of conducting international R&D projects, establishing partnerships (e.g. The International Partnership for Hydrogen and Fuel Cells in the Economy, Fuel Cells and Hydrogen Joint), and creating hydrogen valleys (The Hydrogen Valley Platform). Investing in low-carbon infrastructure and technologies can also create many new jobs and accelerate the recovery of the economy. In each of the analyzed countries, new jobs will be created to a greater or lesser extent. Some of the current jobs in mining could be replaced by jobs related to renewable energy sources. It should be remembered that investments in low- and zero-carbon solutions should be considered not only in terms of their net financial impact but also other factors, including who will be making the inputs and who will benefit from them.

It is necessary to minimize the factors that may complicate taking action for the climate. These are diverse value chains (e.g. infrastructure, technology, supply), legal regulations, and the possible conflicts between existing market participants and representatives of new industries.

However, the fact that in the near future, climate action may seem less important than the need to combat the economic effects of the coronavirus pandemic should be taken into account. This approach may affect planned investments or commitments already made.

Conclusions

Green hydrogen could prove to be a turning point on the way to decarbonize the energy system and achieve net-zero CO_2 by 2050 in the EU. However, this requires the coordination of activities of all EU countries, a well-organized policy, and the organization of legal regulations that will facilitate the undertaking of investment projects, both at the national and international levels.

Most of the EU Member States show a great interest in hydrogen. These countries have developed or are in the process of publishing their hydrogen strategies. Dedicated national policies set long-term goals until 2030 and described the projected effects of the implemented activities. Despite the prognostic approach, a large part of the strategy information allows for the initial recognition of factors related to the involvement in creating a hydrogen-based economy, i.e. the number of public funds, key sectors, the subject of hydrogen research, and finally the role of clusters in the development of local hydrogen production around industrial centers and international cooperation.

Nevertheless, it turns out that it is difficult to compare the assumptions adopted by the EC in the EU's hydrogen strategy with the strategies of its members. On the one hand, this is due to the lack of all national strategies. On the other hand, there are differences in the methodology of measuring long-term effects, e.g. new jobs, CO_2 reduction, as well as failure to specify the indicator in the EU strategy concerning the national documents, or vice versa, e.g. value added in the domestic economy. Also, the information described in national strategies often does not correspond with each other, e.g. no indication of the size of the budget but only the sources of financing (Czech Republic).

Hydrogen strategies implemented by the EU Member States have a varied impact on creating a hydrogen economy. Four countries dominate that have published strategies (Germany, France), roadmaps (Spain), or are at the level of strategic document approval (Italy). Their goals by 2030 are ambitious and exceed the others in terms of job creation, CO_2 reduction, value added in the domestic economy, and installed RES capacity dedicated to green hydrogen production through electrolysis. On the other hand, they are characterized by the highest negative environmental impact in terms of greenhouse gas emissions in the EU (Germany, France, Italy). Additionally, they have the highest total energy consumption (France, Italy, Spain) and hydrogen demand (Germany, Spain, Italy). The smallest countries in terms of area (Cyprus, Malta, Estonia, Lithuania, Latvia) in all the analyzed long-term results should be considered a negligible share in the creation of the hydrogen economy.

The results obtained are essential for the development of policies conducive to the energy transition in the EU. This is also particularly important with regard to the role of green hydrogen and the national consequences of expanding renewable electricity generation capacity. In the future, further analyzes are necessary for conjunction with the monitoring of the gradual implementation of the strategies. This will make it possible to control the effectiveness of the inculcation of the assumptions of the national strategies in relation to the goals adopted by the European Commission in the European Green Deal and the EU hydrogen strategy.

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HYDROGEN IN THE STRATEGIES OF THE EUROPEAN UNION MEMBER STATES

Keywords

hydrogen, renewable energy sources, energy transition, climate neutrality, hydrogen strategy

Abstract

Strategies and roadmaps are essential in areas that require long-term planning, such as the energy transition. Strategic plans can play an important role in developing visions for reducing CO_2 emissions, developing renewable energy sources (RES) and hydrogen technologies. Hydrogen can be included in value chains in various sectors of the economy as raw material, emission-free fuel, or as an energy carrier and storage. The analysis of the future of hydrogen energy, which is an essential component of transforming the economy into an environmentally neutral one, is an integral part of the strategies of the European Union (EU) Member States.

This article reviews the strategic documents of the EU countries in the field of a hydrogen economy. Currently, six EU Member States have approved the hydrogen strategy (Germany, France, the

Netherlands, Portugal, Hungary, Czech Republic), and two of them have roadmaps (Spain, Finland). The others are working on their completion in 2021. EU countries have the possibility of energy transformation based on a hydrogen policy, including green hydrogen, within the framework of the European Green Deal, i.e. aiming for climate neutrality and creating a modern and environmentally friendly economy.

By 2030, some of the countries plan to become a leader not only in the field of hydrogen production or RES development aimed at this process but also in the areas of research and development (R&D), sales of new technologies, and international cooperation. Member countries are focused on the production of clean hydrogen using electrolysis, creating incentives to stimulate demand, developing a hydrogen market, and implementing hydrogen infrastructure.

WODÓR W STRATEGIACH PAŃSTW CZŁONKOWSKICH UNII EUROPEJSKIEJ

Słowa kluczowe

odnawialne źródła energii, wodór, transformacja energetyczna, strategia wodorowa, neutralność klimatyczna

Streszczenie

Strategie i mapy drogowe są niezbędne w obszarach wymagających długoterminowego planowania, takich jak transformacja energetyczna. Plany strategiczne mogą odgrywać ważną rolę w tworzeniu wspólnych wizji w zakresie obniżania emisji CO_2, rozwoju odnawialnych źródeł energii (OZE) i technologii wodorowych. Wodór może być włączany do łańcuchów wartości w zróżnicowanych sektorach gospodarki jako surowiec, bezemisyjne paliwo, lub jako nośnik i magazyn energii. Analiza przyszłości energetyki wodorowej, która jest niezbędnym komponentem przekształcenia gospodarki na neutralną dla środowiska, stanowi nieodłączny element strategii państw członkowskich Unii Europejskiej (UE).

W niniejszym artykule dokonano przeglądu dokumentów strategicznych krajów UE w zakresie gospodarki wodorowej. Obecnie sześć państw członkowskich UE zatwierdziło strategie wodorowe (Niemcy, Francja, Holandia, Portugalia, Węgry, Czechy), a dwa mapy drogowe (Hiszpania, Finlandia). Pozostałe pracują nad ich zakończeniem w 2021 r. Państwa UE mają możliwość transformacji energetycznej w oparciu o politykę wodorową, w tym zielony wodór, w ramach założeń Europejskiego Zielonego Ładu, tzn. dążenia do neutralności klimatycznej oraz tworzenia nowoczesnej i przyjaznej środowisku gospodarki.

W horyzoncie do 2030 r. niektóre z państw planują osiągnąć pozycję lidera nie tylko w zakresie produkcji wodoru lub rozwoju OZE ukierunkowanego na ten proces, ale również w obszarach działalności badawczo-rozwojowej (B+R), sprzedaży nowych technologii oraz współpracy na arenie międzynarodowej. Kraje członkowskie skupione są na produkcji czystego wodoru z wykorzystaniem elektrolizy, tworzeniu zachęt do pobudzania popytu, rozwoju rynku wodorowego oraz wdrażaniu infrastruktury wodorowej.