Engineering 7 (2021) 715–718

Contents lists available at ScienceDirect

Engineering

journal homepage: www.elsevier.com/locate/eng

Views & Comments

The Vision of France, Germany, and the European Union on Future Hydrogen Energy Research and Innovation

Fermin Cuevas, Junxian Zhang, Michel Latroche

University of Paris Est Creteil, CNRS, ICMPE, UMR 7182, Thiais 94320, France

Hydrogen (H_2) is an essential vector for freeing our societies from fossil fuels and effectively initiating the energy transition. Offering high energy density, hydrogen can be used for mobile, stationary, or industrial applications of all sizes. This perspective on the crucial role of hydrogen is shared by a growing number of countries worldwide (e.g., China, Germany, Japan, Republic of Korea, Australia, and United States), which are publishing ambitious roadmaps for the development of hydrogen and fuel cell technologies, supported by substantial financial efforts.

Hydrogen energy in France

France is part of this dynamic. Since the promulgation in August 2015 of the *Energy Transition Law for Green Growth* and the hosting of 21st Conference of Parties (COP21) in December 2015 in Paris, France has shown strong ambition to reduce greenhouse gas emissions. These initiatives notably led to the *National Hydrogen Plan* (NHP) in June 2018, which has three main objectives: the production of decarbonated hydrogen for industrial uses, hydrogen mobility and flexibility of the electricity grid, and the decarbonation of gas networks. As of 2019, the NHP had already invested 100 million EUR to develop at least 26 H_2 fueling stations and 380 fuel cell electric vehicles (FCEVs). Objectives have also been integrated into the *French Multi-Year Energy Plan* and the Energy–Climate Law, aiming at 400 fueling stations, 20 000 FCEVs, 800 heavy duty vehicles, and 20% decarbonated industrial H_2 by 2028.

In line with the European Union (EU)'s ambitions, France possesses major assets to promote hydrogen systems with a low carbon footprint. It benefits from the massive production of decarbonized electricity and a large hydrogen production industry. By 2050, France's low-carbon-footprint hydrogen could meet 20% of its final energy demand and could reduce its annual carbon dioxide (CO_2) emissions by around 55 Mt—equivalent to a third of the additional CO_2 reductions needed to close the gap between the target of the *French Climate Plan* (2017) and the current reference scenario (the EU regulatory technical standards (RTS) scenario) [1].

At the national level, research funding around hydrogen systems was mainly concentrated between 2005 and 2012 within the National Action Plan (PAH) of National Research Agency (ANR) [2], then the HPAC[†] programs for low technology readiness levels (TRLs), and the Ecologic Transition Agency (ADEME) and FUI[††] programs for demonstrations. The consequent funding allocated to these programs (123 million EUR from ANR over seven years) has strongly benefited the National Center for Scientific Research (CNRS) and the Commissariat of Atomic and Alternative Energies (CEA), and has resulted in a significant increase in French scientific production and in the number of patents filed. This targeted funding has sown the seeds of the industrial sectors that are now emerging in the fields of hydrogen production, storage, and conversion. Today, France benefits from this expertise and from key research players, mainly grouped within the Research Federation for Hydrogen (CNRS FRH2) and the CEA laboratories. In addition, the interface between public research and industry is at the heart of the research program contract "French Hydrogen Initiative (IFHy)" that is currently being set up. The objective of the IFHy is to develop and coordinate public–private partnerships to ensure a continuum between scientific research and commercial products, in order to participate in the structuring and development of an industrial hydrogen sector in France and thus contribute to the growth of the French industrial sector.

In September 2020, the French Government announced the launch of a national strategy for the development of decarbonized hydrogen in France. This strategy (which will occur during 2021–2030) will involve investing seven billion EUR and targeting three priorities: ① decarbonizing the industry by developing a French electrolysis sector; ② developing heavy mobility using decarbonated hydrogen; and ③ supporting research, innovation, and skills development to promote future uses (Fig. 1). Various objectives are foreseen for the last of these three priorities, including the development of hydrogen in energy networks, the identification of new usage in industry to reduce CO_2 emissions, the development of hydrogen-powered heavy mobility (aircraft and ships), and the conception of tomorrow's H_2 infrastructures. To accelerate this priority research plan, the strategy will support research and development (R&D) efforts in the hydrogen field and remains at the international forefront, as France has a leading research base in this field.

[†] Hydrogen and fuel cells

[††] Support for collaborative projects of competitiveness clusters

https://doi.org/10.1016/j.eng.2021.04.010

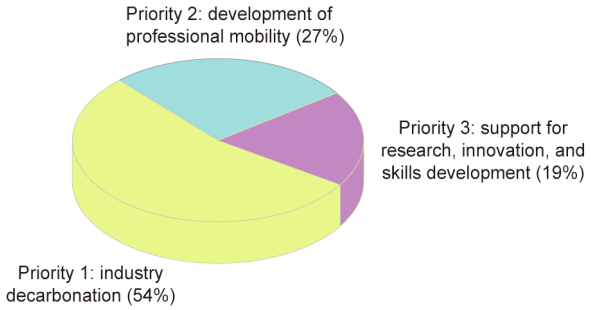

Fig. 1. Repartition of the budget (3.4 billion EUR in total) allocated in 2020–2023 for the national strategy for the development of decarbonated hydrogen in France.

Hydrogen energy in Germany

Germany is also an important game player in this field and aims for carbon neutrality by 2050, as adopted by the *2030 Climate Action Plan*. For Germany to become a greenhouse-gas-neutral country and meet the international commitments of the COP21 Paris Agreement, hydrogen has been established as a decarbonization option. The German Government considers only hydrogen produced from renewable energy (i.e., clean green hydrogen) to be sustainable.

In general, German research funding is open to all topics. However, as an exception, hydrogen technology has attracted attention from the federal government. Between 2006 and 2016, around 700 million EUR was approved under the National Innovation Program on Hydrogen and Fuel Cell Technology, and between 2016 and 2026, a total of 1.4 billion EUR will be provided. In addition, the federal government is using the financial resources provided under the Energy Research Program to build an excellence research landscape [3].

Since the start of the coronavirus disease 2019 (COVID-19) pandemic, Germany has enhanced its support for both energy transition and the green hydrogen projects. In June 2020, the German Federal Government adopted the National Hydrogen Strategy and established the National Hydrogen Council to advise and support the State Secretary Committee through project proposals and recommendations for action in implementing the hydrogen strategy [4]. The planned ambitions are: establishing hydrogen as an alternative energy source, making hydrogen a sustainably based material for the industrial sector, developing the domestic market and establishing international markets, strengthening German industry and, finally, making hydrogen economically viable [5].

In this plan, the transport, industry, and building sectors are specially supported. For transport, in order to trigger the market, 3.6 billion EUR in grants is available for purchases of electric or climate-friendly vehicles. To encourage investment, 4.5 billion EUR will be provided for the installation of electricity-based fuels and for refueling infrastructure buildings. For the aviation and maritime sectors, 50 million EUR has been earmarked for developing hybrid electric- and hydrogen-powered planes and ships. For industry, various tools for the switchover from conventional fossil fuels to hydrogen have been foreseen. Finally, for the building sector, the Energy Efficiency Incentive Program has been in place since 2016, and funding will continue with 700 million EUR for the period 2020–2024.

Research is a strategic element underpinning the energy policy. Between 2020 and 2023, 310 million EUR will be provided under the Energy and Climate Fund for practice-oriented basic research on green hydrogen, and there are plans to provide another 200 million EUR over this period to strengthen practice-oriented energy research on hydrogen technology. In addition, 600 million EUR will be provided between 2020 and 2023 to foster the regulatory sandboxes for the energy transition initiative, which helps to speed up the transfer of technology and innovations from the laboratory to the market. As part of Germany's decarbonization program, more than one billion EUR is provided for investment in technologies and largescale industrial facilities, which will use hydrogen to decarbonize their manufacturing processes between 2020 and 2023. There are also programs that promote the use of hydrogen in manufacturing and the elimination of carbon emissions in the material industry. The aim of these programs is to encourage industry to invest in hydrogen solutions. On 3 June 2020, the Coalition Committee adopted a "package for the future" that makes available another seven billion EUR for speeding up the market rollout of hydrogen technology in Germany and another two billion EUR for fostering international partnerships.

Early in 2015, the Ministry for Economic Affairs and Energy inaugurated the Energy Transition Research and Innovation platform. In the frame of this platform, the Kopernikus project is one of the largest German research initiatives in the field of the energy transition [6]. The project comprises four pillars, each with its own objective: EUSURE to develop the power grid of the future; P2X to investigate the conversion of CO_2, water, and electricity from renewable sources into gases, fuels, chemicals, and plastics; SynErgie to study how energy-intensive industrial processes can be more flexible in order to adapt them to the availability of renewable energy sources; and, finally, Ariadne [7] as a joint learning process between science and society to analyze how policy measures work, from individual sectors to the big picture.

Hydrogen energy in the European Union

At the continental level, the policy of the EU strongly supports the implementation of a hydrogen-based energy system as one of the key tools to achieve the European Green Deal [8] and Europe's clean energy transition. This execution complies with the COP21 Paris Agreement and contributes to the EU target of reaching carbon neutrality by 2050 [9]. Moreover, it aims to limit European dependence on hydrocarbons and contribute to the EU's economic growth. In combination with the EU's leadership in renewable technologies, the emergence of a hydrogen value chain serving a multitude of industrial sectors and other end uses could employ up to one million people.

Early in the 21st century, the European Commission (EC) had already identified the need to build up an effective strategy for developing a hydrogen-oriented energy economy toward 2050, with a snapshot targeted for 2020 [10]. Under the umbrella of the 6th Framework Program (FP6; 2002–2006), 300 million EUR was allocated to hydrogen-energy research projects. Furthermore, in January 2004, the EC initiated the so-called European Hydrogen and Fuel Cell Platform. Through this public platform, the EC aimed to promote commercially viable hydrogen and fuel cell applications, and to initiate an appropriate hydrogen infrastructure. This instrument served as a springboard for the 2008 creation of the Fuel Cells and Hydrogen Joint Undertaking (FCH-JU) partnership [11].

Today, the FCH-JU is the most important European instrument to support research and technology development (RTD) in hydrogen energy. It is a public–private partnership formed by three members: the EC, Hydrogen Europe Research, and Hydrogen Europe [12], which respectively comprise public authorities, the research communities, and industrial partners (Fig. 2). Aligning the efforts of public and private stakeholders was identified as a necessary condition for the deployment of a hydrogen economy in the EU. In 2008, the first FCH-JU RTD program was launched

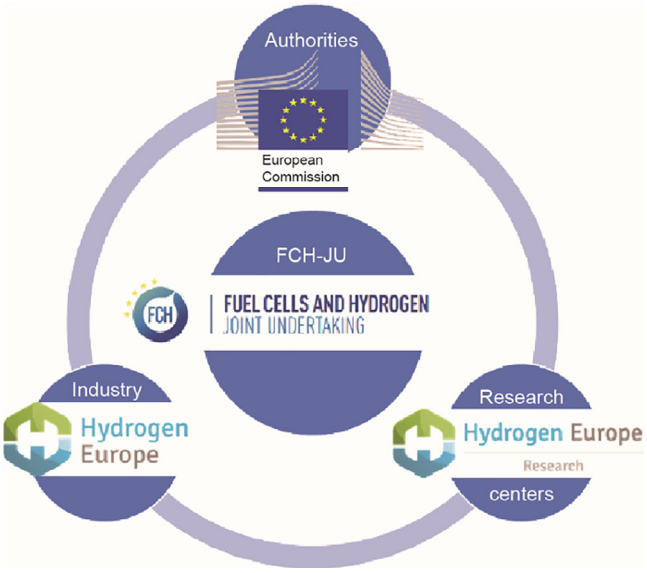

Fig. 2. The Fuel Cells and Hydrogen Joint Undertaking (FCH-JU) public–private partnership.

with a total budget of 947 million EUR for the period 2007–2013, which included support for RTD projects that continued running until 2017. The European community contributed half of this budget through the research program FP7, while the rest was covered by in-kind contributions from industrial legal entities [13]. Next, the second FCH-2-JU RTD program, which ran under the umbrella of the EU program Horizon 2020 (2014–2020), increased the budget to 1.33 billion EUR, half of which was again covered by private members [14]. The core objectives of the FCH-2-JU program are displayed in Fig. 3 [15].

To foster scientific initiatives in Europe until 2027, a novel EU research and innovation program called Horizon Europe will enter into force in 2021 with a budget of 100 billion EUR. The full range of instruments available under this program will support activities in transport, including batteries, clean hydrogen, low-carbon steel making, circular bio-based sectors, and the built environment. In regard to hydrogen energy, a new partnership called "clean hydrogen for Europe" [16] is under construction as a continuation of the FCH-2-JU program. This partnership will be a key player in implementing the recent European roadmap communicated by the EC in July 2020. This roadmap, entitled "A hydrogen strategy for a climate-neutral Europe" [8], is based on a previous report published in 2019 [17]. The roadmap is anchored in the entire hydrogen industrial value chain from production via transmission to mobility, industry, energy, and heating applications, while considering related skills and cross-cutting issues (i.e., regulations, safety, education and training, socio-economic research, etc.).

The European hydrogen roadmap establishes as its final target the development of clean hydrogen produced from renewable sources using mainly wind and solar energy. However, clean hydrogen costs are currently considered to be too expensive (at 2.5–5.5 EUR·kg^{-1}), as compared with the hydrogen currently produced from fossil fuels (at 1.5 EUR·kg^{-1}), and intermediate solutions (e.g., fossil-based hydrogen with carbon capture and storage, with an estimated cost of around 2 EUR·kg^{-1}) must be considered during the early days of the energy transition. In this context, three phases are defined in the European roadmap: ① 2020–2024, in which the implementation will occur of 6 GW of renewable hydrogen electrolyzers targeting onsite hydrogen production for the chemical sector and heavy-duty transport (buses and trucks); ② 2025–2030, in which the electrolyzer installations will be increased to 40 GW, focusing on hydrogen production for novel markets (i.e., steel making and rail and maritime applications), hydrogen refueling stations, daily or seasonal energy storage, grid balance, local hydrogen networks, and the provision

Fig. 3. The core objectives of the FCH-2-JU program [15].

of heat for residential and commercial buildings; and ③ 2030–2050, in which there will be largescale development of electricity production, with a quarter of renewable electricity being used for clean hydrogen production.

Exceptional investments are needed to finance this roadmap. For example, electrolytic hydrogen production—as well as its transport, distribution, and storage—and hydrogen refueling stations will be supported with about 100 billion EUR from 2020 to 2030. This will be accompanied by a tremendous effort (of about 300 billion EUR) dedicated to the production of clean electricity using solar and wind energy. These investments will be supported by the European Clean Hydrogen Alliance [18], which brings together industry, national and local public authorities, civil society, and other stakeholders.

The European roadmap also establishes the necessity of international collaborations at two levels: first, with neighboring countries (i.e., in West Europe and North Africa), as an opportunity to promote cooperation on clean hydrogen, contribute to their clean energy transition, and foster sustainable growth and development; and second, with global actors for the development of international standards and the setting up of common definitions and methodologies. The latter will be conducted through international institutions such as International Partnership for Hydrogen and Fuel Cells in the Economy (IPHE) [19], the International Energy Agency (IEA), and the International Renewable Energy Agency (IRENA), along with Group of Twenty (G20) cooperation.

In conclusion, considerable efforts are being made at the national level in France and Germany, with the support of the EU, to develop research and innovation in the field of a hydrogen-based energy transition. These roadmaps and ambitious programs aim at cutting-edge technologies that will pave the way for a carbon-free world that will benefit humankind for centuries to come.

References

[1] EU reference scenario 2016 [Internet]. Luxembourg: Directorate-General for Energy, European Commission; c2016 [cited 2020 Nov 24]. Available from: https://ec.europa.eu/energy/data-analysis/energy-modelling/eu-reference-scenario-2016_en.

[2] PAN-H national action plan for hydrogen [Internet]. Paris: Agence Nationale de la Recherche; [cited 2020 Nov 24]. Available from: https://anr.fr/en/call-for-proposals-details/call/plan-daction-national-sur-lhydrogene-et-les-piles-a-combustible-pan-h/. French.

[3] dfg.de [Internet]. Bonn: Deutsche Forschungsgemeinschaft; c2010–2021 [cited 2020 Nov 24]. Available from: https://www.dfg.de.

[4] Mertens A. Securing a global leadership role on hydrogen technologies [Internet]. Berlin: Federal Ministry for Economic Affairs and Energy; 2020 Oct 6 [cited 2020 Nov 24]. Available from: https://www.bmwi.de/Redaktion/EN/Pressemitteilungen/2020/20200610-securing-a-global-leadership-role-on-hydrogen-technologies.html.

[5] The national hydrogen strategy [Internet]. Berlin: Federal Ministry for Economic Affairs and Energy; 2020 Oct 6 [cited 2020 Nov 24]. Available from: https://www.bmwi.de/Redaktion/EN/Publikationen/Energie/the-national-hydrogen-strategy.html.

[6] Kopernikus project home [Internet]. Bonn: Federal Ministry for Education and Research; [cited 2020 Nov 24]. Available from: https://www.kopernikus-projekte.de/en/home.

[7] Messina S. How the Copernicus Project Ariadne intends to act as a guide through the energy turnaround [Internet]. Bonn: Federal Ministry for Education and Research; [cited 2020 Nov 24]. Available from: https://www.kopernikus-projekte.de/en/projects/ariadne.

[8] The European Green Deal. Communication from the commission to the European parliament, the European council, the council, the European economic and social committee and the committee of the regions [Internet]. Brussels: European Commission; 2019 Dec 11 [cited 2020 Nov 24]. Available from: https://ec.europa.eu/info/sites/info/files/european-green-deal-communication_en.pdf.

[9] 2050 long-term strategy [Internet]. Brussels: European Commission; [cited 2020 Nov 24]. Available from: https://ec.europa.eu/clima/policies/strategies/2050_en.

[10] European hydrogen and fuel cell technology platform. Deployment strategy [Internet]. Brussels: Advisory Council of the European Hydrogen and Fuel Cell Technology Platform; 2005 Aug [cited 2020 Nov 24]. Available from: https://www.fch.europa.eu/sites/default/files/documents/hfp_ds_report_aug2005.pdf.

[11] Fuel cells and hydrogen joint undertaking (FCH-JU) [Internet]. Brussels: European Commission; [cited 2020 Nov 24]. Available from: https://www.fch.europa.eu/.

[12] Hydrogen Europe [Internet]. Brussels: European Commission; [cited 2020 Nov 24]. Available from: https://hydrogeneurope.eu/.

[13] Fuel cells and hydrogen joint undertaking, annual activity report 2010 [Internet]. Brussels: European Commission; 2010 Nov [cited 2020 Nov 24]. Available from: https://www.fch.europa.eu/sites/default/files/FCH%20JU%20Annual%20Activity%20Report%202010_0.pdf.

[14] Fuel cells and hydrogen joint undertaking, annual activity report 2014 [Internet]. Brussels: European Commission; 2015 Feb [cited 2020 Nov 24]. Available from: https://www.fch.europa.eu/sites/default/files/FCH-annualreport2014-D-15May2015-WEB.PDF.

[15] Program review report 2017 [Internet]. Brussels: European Commission; c2018 [cited 2020 Nov 24]. Available from: https://www.fch.europa.eu/publications/program-review-report-2017.

[16] Clean hydrogen for Europe [Internet]. Brussels: European Commission; [cited 2020 Nov 24]. Available from: https://hydrogeneurope.eu/clean-hydrogen-europe.

[17] Hydrogen roadmap Europe [Internet]. Luxembourg: Publications Office of the European Union; 2019 Jan [cited 2020 Nov 24]. Available from: https://www.fch.europa.eu/sites/default/files/Hydrogen%20Roadmap%20Europe_Report.pdf.

[18] Internal market, industry, entrepreneurship and SMEs [Internet]. Brussels: European Commission; 2020 [cited 2020 Nov 24]. Available from: https://ec.europa.eu/growth/industry/policy/european-clean-hydrogen-alliance_en.

[19] iphe.net [Internet]. International Partnership for Hydrogen and Fuel Cells in the Economy; c2020 [cited 2020 Nov 24]. Available from: https://www.iphe.net/.