Energy Science & Engineering

WILEY

IN THE FIELD OPEN ACCESS

Hydrogen Energy Research in Italy in the Bioeconomy Era

Mario Pagliaro

Istituto per lo Studio dei Materiali Nanostrutturati, CNR, Palermo, Italy

Correspondence: Mario Pagliaro (mario.pagliaro@cnr.it)

Received: 26 January 2026 | **Revised:** 14 April 2026 | **Accepted:** 4 May 2026

Funding: Ministero dell'Ambiente e dellla Sicurezza Energetica, Grant/Award Number: NextGenerationEU - M2C2 Investment 3.5

Keywords: fuel cell | green hydrogen | hydrogen energy | solar economy | solar hydrogen

ABSTRACT

In 2026, the nearly concomitant launch of the world's first H_2-powered ship in Ancona, the completion of the first green H_2 pipeline to refuel some 100 hydrogen electric buses in Venice, the start of large-scale green ammonia production in Saudi Arabia using electrolyzers designed and manufactured in Italy, and the start of Italy's first electrolyzer "gigafactory" near Milan show evidence of the practical relevance of H_2 energy technology developed or uptaken in Italy. This study investigates hydrogen energy research in Italy in the bioeconomy era in which energy is sourced from renewable energy sources, and functional substances manufactured by the chemical industry are obtained from biological resources. The conclusions offer several policy lessons that may be of relevance both to policy makers and researchers based in other countries working toward development and commercialization of hydrogen energy technology.

1 | Introduction

Solar (or "green") hydrogen obtained from water via electrolysis powered by electricity obtained from renewable energy sources, particularly photovoltaic, wind, and hydroelectric power, is a critically important clean energy storage technology [1]. Hydrogen thereby produced indeed can be readily recombined with air's oxygen in hydrogen–air fuel cells generating electricity and heat. Due to quick refueling rate and good volumetric energy density, H_2 compressed at 350 bar and safely stored in today's cylinders in composite material is well suited to power heavy-duty fuel cell electric vehicles such as trucks, buses, trains, and even airplanes [2]. The technology is uniquely versatile and H_2 can also be stored in reusable metal hydrides from which the fuel is reversibly released at lower pressure (30–35 bar) smoothly powering one or more commercial fuel cells.

After more than three decades (1980–2010) of unsuccessful attempts of commercializing fuel cell electric vehicles (FCEVs) and water electrolyzers for distributed H_2 production, the global uptake of photovoltaic and wind power in the first two decades of the 2000s led to the renaissance of fundamental and applied hydrogen energy research, with multiple achievements of practical relevance going from hydrogen storage to its production via enhanced water electrolyzers [3]. Similarly, several new FCEV manufacturers started commercialization of widely different vehicles, ranging from trucks and buses to cars and forklifts. As a result, for example, the number of hydrogen refueling stations (HRS) installed worldwide has gone from about 100 in 2014 to 1160 at the end of 2024 (chiefly situated in China, South Korea, Germany, and Japan) [4].

Research on green H_2 energy technology concerns both its production and utilization. In the field of production, research on green hydrogen obtained via water electrolysis is aimed at reducing production costs from today's \$5–6/kg to less than \$2/kg (\$1/kg by 2031) [5]. Requiring about 55 kWh of electricity per kg of H_2, today's green hydrogen at 30 bar pressure is chiefly sourced via alkaline water electrolysis (AWE) mediated by low cost and durable nickel-based electrodes in electrolysis cells operated at 80°C in 30% KOH [6]. The technology is employed to produce in situ less than 5% of the global hydrogen output

[7], with today's research aiming not only at reducing cost but also at improving low current density, enhance the slow dynamic response to load variation (typical of power from intermittent renewable energy sources), and reduce the size of electrolyzers [8].

Research on H_2 fuel cells, especially in the field of efficient proton-exchange membrane (PEM) fuel cells of high-power density and high durability, is aimed at reducing the amount and ultimately replace costly noble metal Pt as electrocatalyst with earth-abundant metals such as Fe or Co [9].

This study investigates hydrogen energy research in Italy in the early bioeconomy era, namely the unfolding age in which energy is sourced from renewable energy sources, and functional substances manufactured by the chemical industry are obtained from biological resources [10]. In 2026 (see below), the nearly concomitant launching of the world's first H_2-powered ship in Ancona, the completion of the first green H_2 pipeline to refuel some 100 hydrogen electric buses in Venice, the start of large-scale green ammonia production in Saudi Arabia using electrolyzers designed and manufactured in Italy, as well as the start of Italy's first electrolyzer "gigafactory" near Milan show evidence of the practical relevance of H_2 energy technology developed (or uptaken) in Italy.

The outcomes of the study offer research policy lessons of relevance both to policy makers and researchers based in other countries working toward development and uptake of hydrogen energy technology.

2 | Methodology

In the following, I first briefly outline the history of Italian research in the field of renewable energy sources and hydrogen energy. Hence, I analyze outcomes of Italian hydrogen energy research between 2007 and 2025 using data sourced from a proprietary research database (Scopus). Following a summary of recent selected industrial achievements, I discuss results of the analysis. The conclusions offer lessons that may be relevant to policy makers and researchers based in other countries working toward development and commercialization of hydrogen energy technology.

3 | Results

3.1 | Brief Historic Outlook

Though being a relatively small country, Italy is home to two of Europe's largest oil and natural gas (Eni) and electricity (Enel) energy companies. The country, furthermore, produces a significant yearly scientific output [11].

Interest in renewable energy sources in Italy goes back to the late 19th century when the country pioneered the use of hydroelectric energy. In 1937, Italy was already producing 20 billion kWh of hydroelectric power [12]. Interest in solar energy was similarly high, though technology far less developed. In 1964, the Italian section of the International Solar Energy Society (ISES Italia) was founded in Naples [13].

Research on hydrogen as energy carrier and fuel for H_2 fuel cells in Italy started with the work of Giordano, a research chemist formerly employed at Italy's largest chemical company (Montedison), where he had worked on hydrogen production via methane steam reforming. In the late 1970s, Giordano started work on phosphoric acid and molten carbonate H_2 fuel cells in Sicily where he had become professor of industrial chemistry in 1975 [14]. In 1980, with support from Italy's Research Council (CNR), he was appointed director of newly established CNR Institute of Researches on Methods and Chemical Processes for Transformation and Storage of Energy.

In the late 1980s, following a 1987 referendum on nuclear energy, the nuclear energy and alternative energies (ENEA) government research agency abandoned nuclear energy research focusing on renewable ("alternative") energy sources, including hydrogen energy. Early research in 1989 focused on PEM fuel cells, in collaboration with electrochemistry company De Nora [15]. The latter initiative led to creation of Nuvera Fuel Cells, a company sold in 2014 to a USA-based corporation during the "valley of the death" gap [16] for hydrogen energy technology that in Italy (see below) will last about two decades (2000–2020).

Research on hydrogen energy in Italy, however, did not stop and progressively expanded to university departments and other CNR research institutes beyond that founded by Giordano. The early 2000s saw the first commercialization efforts with the launch of the first water electrolyzers. Market demand, however, remained modest with little or no public incentives to stimulate demand. All changed starting in the early 2020s. Partly driven by the European Union's ambitious green hydrogen strategy outlined in 2020 [17], Italy adopted a national hydrogen energy strategy in 2024 [18]. The strategy includes both short (2024–2030), medium (2030–2040), and long (2040–2050) objectives. For example, Italy targets an objective of a demand for green hydrogen equal to 0.25 million tonnes and an installation of electrolytic capacity of 3 GW by 2030.

Unprecedented public funding to support the industrial uptake of hydrogen energy technology was made available by the government through the Italian National Recovery and Resilience Plan (PNRR) started in 2022 in application of NextGenerationEU European recovery plan [19].

Figure 1 outlines how this large budget for the development of hydrogen supply chain, amounting to €3531 million, has been allocated. Support was given to seven measures targeting the hard-to-abate sectors, transport (road and rail mobility), research and development, support for SMEs in installing electrolyzers, to the development of IPCEIs (Important Projects of Common European Interest) on hydrogen, and production of green hydrogen in dismissed areas ("Hydrogen valleys"). The latter measure, for example, is funded with 551 M€ to convert abandoned industrial sites and develop local hubs for the production and local use of hydrogen, with a direct impact on local enterprises and industrial districts.

3.2 | Italian Research on Hydrogen Energy (2007–2025)

Figure 2 shows the number of original research articles written in English dealing with green hydrogen published in scientific

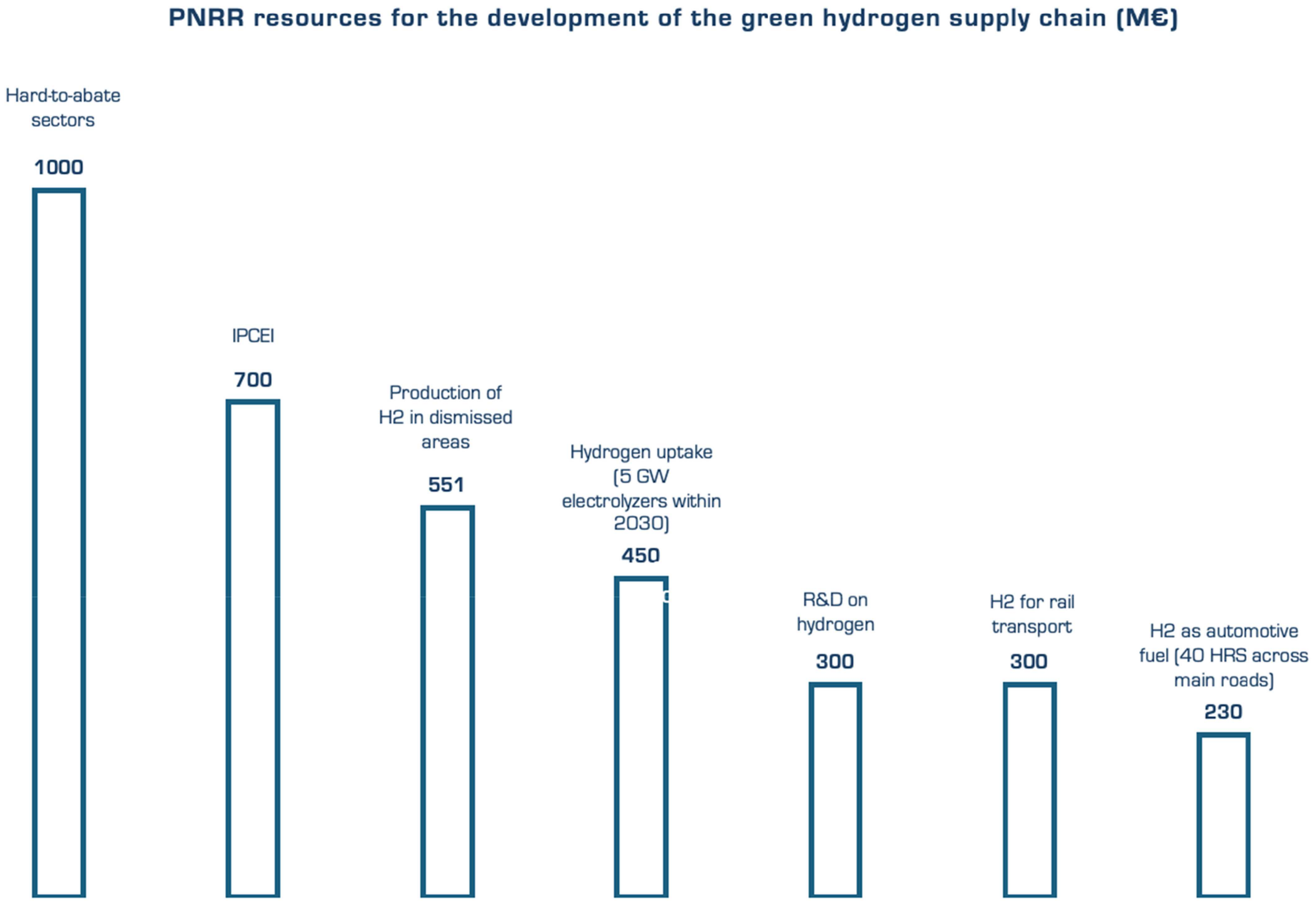

FIGURE 1 | PNRR financial resources (in M€) for the development of the green hydrogen supply chain. PNRR stands for Italian National Recovery and Resilience Plan. IPCEI stands for Important Project of Common European Interest [Source: Ref [19]].

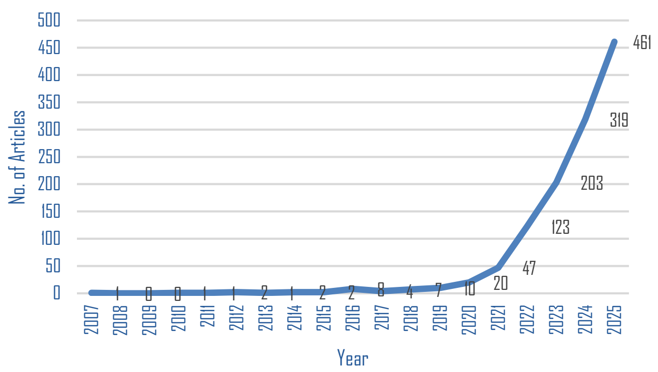

FIGURE 2 | Original research articles written in English by year dealing with green hydrogen published by Italian researchers between 2007 and 2025 in scientific journals indexed by Scopus. [Source: Scopus, 2026].

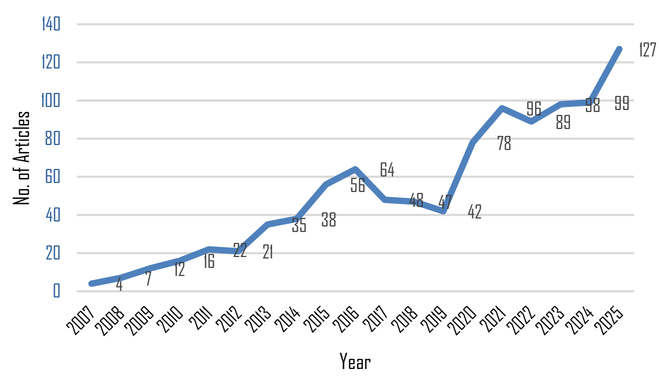

FIGURE 3 | Original research papers written in English by year dealing with solar hydrogen published by Italian researchers between 2007 and 2025 in scientific journals indexed by Scopus. [Source: Scopus, 2026].

journals indexed by a research database (Scopus) by researchers based in Italy between 2007 and 2025. Online search was conducted at scopus.com with the query "green hydrogen" amid "All fields" until 2025 limiting the search to "Article" published in English with author "Affiliation" limited to Italy [20].

Figure 3 shows the number of original research papers written in English dealing with solar hydrogen published in scientific journals indexed by a research database (Scopus) by researchers based in Italy between 2007 and 2025. Online search was conducted with the query "solar hydrogen" amid "All fields" until 2025 limiting the search to "Article" published in English with author "Affiliation" limited to Italy [21].

Around 2018, the term "green hydrogen" superseded "solar hydrogen" so as to encompass H_2 produced also by other renewable energy sources such as wind, hydroelectric, and biomass energy. Accordingly, the former term was adopted in

TABLE 1 | Main research organizations in green hydrogen research in Italy in terms of original research papers published in journals in English between 2007 and 2025. [Source: Scopus, 2026].

Organization	Original research articles
Consiglio Nazionale delle Ricerche (CNR)	130
Politecnico di Milano	107
Politecnico di Torino	105
Sapienza Università di Roma	99
Università degli Studi di Napoli Federico II	70
Università degli Studi di Genova	62
Università degli Studi di Pisa	55
Ente per le Nuove Tecnologie, l'Energia e l'Ambiente (ENEA)	50
Università della Calabria	50
Università degli Studi di Palermo	47

the aforementioned EU hydrogen strategy published in 2020 [17]. Reflecting said strategy adoption and nearly concomitant plentiful research funding made available to academic and industrial research teams (see below), the number of research papers on green hydrogen from Italian researchers experienced a sudden growth in 2021, continuing to grow at fast rate afterward until reaching 461 in 2025. In the same year, the number of original research articles dealing with solar hydrogen crossed the 120 threshold.

Results in Table 1 show evidence that the Italian Research Council (CNR) is the largest contributor to Italian innovation in the science and technology of green hydrogen, with 130 original research articles co-authored by its researchers between 2007 and 2025 out of 1212 identified by the research database.

Italian research in the field is highly collaborative, with the number of papers co-authored by researchers based at different research institutes, in Italy and abroad, rapidly increasing following 2017–2018.

A survey of said original research papers shows that Italian researchers work at the development of new electrocatalysts, new photocatalysts, new membranes for new generation electrolyzers and fuel cells of lower cost, longer durability, smaller size, enhanced productivity, and broad applicability in stationary and mobile applications. Furthermore, they conduct plentiful modeling work that goes from modeling the energy and economic costs of "hydrogen valleys" to liquified hydrogen for refueling hydrogen ships.

Nearly all research articles were co-authored by academic researchers. Yet, industry's researchers lately started to publish outcomes and perspectives on green hydrogen, for example reporting the outcomes of industrial research to advance AWE electrolyzers [22]. Research in the field of water electrolysis focuses on both new electrocatalysts and on new ion-selective membranes of enhanced conductivity, chemical stability, and mechanical robustness so as to improve electrolyzer durability, lower capital and operational costs. Research efforts are aimed at addressing the main limitations of AWE technology (low current density, slow dynamic response to load variation typical of power produced from sun and wind energy sources, limited flexibility, and large overall footprint); as well as to replace costly (and rare) iridium from PEM electrolyzers.

In the field of FCs, Italian research goes from testing commercial solid oxide electrolysis cells under different operating conditions to evaluate electrochemical performance, to platinum group metal-free electrocatalysts for anion exchange membrane (AEM) fuel cells.

Consistent with previous studies finding that higher growth rates of scientific production are in new research fields rather than old ones [23], substantial acceleration in the number of publications in applied and fundamental green hydrogen energy research in Italy could be clearly identified.

Italian enterprises (see below) started to commercialize new catalytic membranes for electrolyzers and new electrolyzers, as well as new hydrogen FCEVs for specialized uses. It is therefore relevant to look at selected industrial and commercial achievements, as well as to learn from the insight of industry's managers guiding companies in the emerging bioeconomy in which H_2 sourced from water will play an important role in the energy and transport sectors (markets).

3.3 | Selected Industrial Achievements

In mid 2025, a Fincantieri subsidiary specialized in advanced fuel cell technologies, inaugurated a new production line in Bari dedicated to the development and testing of hydrogen PEM fuel cells, with applications in both the civil (ship) and defense (submarine) sectors. Among the first applications is a PEM fuel cell module that will be installed on board the Viking Libra, the world's first cruise ship to be powered by onboard-stored hydrogen (used both for propulsion and electricity generation) under construction in Italy by Fincantieri.

Completed in Ancona on March 2026 after assembling a part built in Castellammare di Stabia at another facility of the ship building company [24], the 239 m long cruise ship Viking Libra (Figure 4) employs liquid H_2 (stored at −253°C) in two reservoirs onboard as fuel of the stacks of two PEM fuel cells each generating approximately 3.15 MW of power, for a total maximum power output of 6.3 MW [25].

The power generation system is supported by a 4.7 MWh Li-ion battery energy storage system to manage load fluctuations via "peak shaving," namely by reducing peak power demand from the FCs during peak periods to enhance the fuel cell stability and durability.

In the same year, a new company begun producing catalytic membrane electrode assembly (MEA) for green hydrogen production via PEM water electrolysis using hydroelectric energy at a 6000 m² plant staffed by a team of 30 professionals [26].

FIGURE 4 | The hydrogen-powered Viking Libra prior to its launch on March 2026 [image courtesy of Fincantieri].

Alongside 10 other partners from 7 EU member states, the same company a few weeks later received approval for IPCEI funding of approximately €22 million from the European Commission for the applied research project “Hy2Move” to accelerate industrialization of hydrogen technologies applied to mobility. Funding will support the creation of new 96 jobs at Italy's company, including funding for PhD and MSci theses. According to the company's chief executive officer commenting why the company opted for the PEM technology “in the field of alkaline water electrolysis, competition has been won by Chinese companies, who produce at one-third of the European cost” [27].

In early 2025, an Italian railway company received from Germany the first hydrogen-powered train at the new maintenance and hydrogen refueling facility in Rovato. Designed and built for the maintenance and refueling of hydrogen trains by an established industrial gas supplier, the facility is Italy's first hydrogen train depot [28].

A few months later, another Italian company presented the first hydrogen fuel cell-powered shunting locomotive. Dubbed, “Fenhyce,” the locomotive employs a hydrogen storage system [29] based on metal hydrides developed by Italy's MetHydor (a company established in Genova in 2021) whose metal hydride-based storage systems have a volumetric density comparable to hydrogen storage at 400 bar but operate at low pressure (30/35 bar), reducing costs and energy consumption during refueling. Its state of the art storage system (Rack Hydor S240) can store 7.6 kg of hydrogen, with a standard module comprising 16 stainless steel tubes, can be installed as a single module or multiple modules achieving a total storage capacity of up to 260 kg H_2) [30].

Hydrogen-powered bus and trains are being increasingly adopted on scale, which inevitably leads to create the required H_2 supply infrastructure, including green hydrogen production. For example, a joint venture (Green Hydrogen Venezia) is currently completing in Porto Marghera an 8 MW water electrolysis plant, connected to a hydrogen pipeline and an H_2 refueling station with a 1.700 kg H_2/day capacity, enough to refuel 90 H_2-powered electric buses lately purchased (75 buses long 12 m, and 15 long 18 m), and the four already running [31]. The first four hydrogen-powered buses regularly operate since late 2023, refueling at the first HRS open to the public in Italy in mid 2022. The station dispenses H_2 pressurized at 350 or 700 bar, so far to the aforementioned four buses and to three hydrogen-powered FC electric cars donated to the city of Venice [32].

Italy hosts an increasing number of water electrolyzer manufacturers. Chiefly based in northern Italy, said companies commercialize either small [33] (a few kW) or large [34, 35] (500 kW, 1 MW, and up to 5 MW) electrolyzers, using either alkaline or PEM water electrolysis technology. In mid 2024, benefiting also from €32million of financial support from recovery plan part of the IPCEI program, Italy's and world's largest supplier of activated electrodes (supplying chemical companies in chlorine and caustic soda production, components for electronics, and non-ferrous metal refining), commenced works for the “Gigafactory” with capacity up to 2 GW electrolyzers based on AWE technology [36].

The same company between 2023 and mid 2025 manufactured and supplied to Saudi Arabia's Neom 110 electrolyzers of 20 MW each, producing 33,000 electrochemical cells measuring 3 m^2 [37]. The electrolyzers currently being installed in Saudi Arabia by the end of 2026 will start producing up to 600 t/day of green H_2 that will be used to manufacture ammonia.

All electrical energy powering the electrolyzers will be sourced from a huge (2.2 GW) PV solar park using bi-facial photovoltaic technology equipped with robotic cleaners to clean the modules when required, and a large (1.6 GW) wind park, both connected through a dedicated grid to the hydrogen plant. Situated on the Red Sea coast about 14 km northwest of Duba City, the plant will use water and nitrogen as raw materials, respectively, sourced from the ocean in the form of desalinated seawater and from air [38].

It is also instructive to learn how these companies expanded their activity to manufacture large-scale electrolyzers for green hydrogen production. Some were active in technical gas manufacturing. Others in valves and control systems production for oil refineries. Another is Italy's largest electrochemical company. One, finally, is a pure hydrogen energy company that pioneered the anion exchange membrane AWE technology offering a range of electrolyzers ranging from 2.4 kW single module through 1.5 MW containerized electrolyzers [33]. Showing evidence of growing demand, in over 20 years since 2004, the latter company has delivered over 7500 electrolyzers in use by more than 360 customers in over 55 countries.

The history of the latter company is instructive. Founded in Italy in 2004, focusing on research in fuel cell and AEM electrolysis, the company supplied several electrolyzer prototypes to the German entrepreneur owner of a residence in Thailand using self-produced photovoltaic energy using green H_2 as fuel in which to store excess energy for use at night or in cloudy days. Thirteen years later, the same entrepreneur purchased the company. In 2022, the rebranded company opened a new electrolyzer production facility in Italy. Hydrogen produced with its electrolyzers is used for different end energy uses. For example, a producer of stainless steel and nickel alloys based in Aosta, Italy, in 2024 ordered a 1 MW AEM electrolyzer for its plant. The electrolyzer, for which the company received financial support from the 52 state-funded "Hydrogen valleys" program, includes a 300 kg H_2 storage unit and will save nearly 115,000 m^3 of natural gas per year [39].

4 | Discussion

Green hydrogen energy technology has two pillars: H_2 production via water electrolysis, and its conversion in electricity (and heat) in a fuel cell. Another highly promising avenue for green H_2 production in the "sunbelt" countries (those within a latitude between 20° and 40° North and South of the equator) is photocatalysis driven by solar light using a photocatalyst to split water [40].

From a practice-oriented viewpoint, however, both water electrolysis and hydrogen fuel cell technology are mature technologies finally experiencing large-scale commercialization. Hydrogen fuel cells are now a commercial reality whose versatility compares to that of internal combustion engines and power generators fueled by oil-derived combustibles. Indeed, fuel cell cars, trucks, trains, drones, and ships are now a commercial reality. Similarly, commercial H_2 fuel cells are increasingly used for "stationary" applications such as power (and heat) generation in buildings.

4.1 | Positive Developments

Following unprecedented research funding made available since 2022, Italian research in green hydrogen surged (Figure 2). Alone, in the context of the Recovery plan (PNRR) Mission 2, Component 2, Investment 3.5 line the Italian Ministry of Environment and Energy Security made available 160 M € in research funding in four key areas ("research objectives" in the terminology of the research policy documents used by the Italian policy makers) of today's hydrogen energy research:

- Production of clean and green hydrogen.
- Innovative technologies for hydrogen storage and transportation and its transformation into derivatives and electrofuels.
- Fuel cells for stationary and mobility applications.
- Intelligent integrated management systems to improve the resilience and reliability of smart hydrogen infrastructure.

In detail, 20 M€ were awarded to seven research projects (out of 39) received by academic institutions [41], and 30 M€ to 15 industrial research projects (out of 56 received).

Table 2 shows the fundamental research projects funded by the Ministry. The reviewers of the Ministry opted to support production of green H_2 from seawater (or from biomethane), with particular attention to H_2 storage in new adsorbent materials. Funding was also granted to one project in the field of PEM fuel cells and to another on enzymatic production of H_2. With the exception of one receiving less than €1 M for funding exhaustion, most fundamental research projects funded received about €3 M.

As mentioned above, industrial companies too received substantial funding with 30 M€ allocated to 15 research projects (Table 3) [42]. Inspection of said projects unveils to academic researchers that Italian hydrogen energy industry after the end of the "valley of the death" technology cycle is chiefly interested in advanced electrolyzers and fuel cells, fuel cell powertrain, including solutions for aviation, hydrogen storage, and e-fuels obtained from green hydrogen. Such a progress indicates willingness of Italy's government to support the highly needed intermediate research between discovery and innovation, aiming to drive commercialization of technically and economically viable H_2-based energy devices.

This attention for intermediate-stage research between discovery and commercialization in the innovation process is what is

TABLE 2 | Research projects and academic institutions funded by Italy's Ministry of the Ecologic Transition following a 2022 PNRR call for fundamental hydrogen energy research. [Source: Ref [41]].

Organization	R&D project	Funding (€M€)
Università di Messina	Green H_2 from biomethane cracking using an innovative technology based on non-thermal plasma and catalysis with nanocarbons	3.0
Università della Calabria	Novel materials for hydrogen storage	3.13
Università di Genova	Green H_2 production from seawater via an innovative electrolyzer operating at high temperatures with integration into the power-to-methanol process	3.50
Università di Parma	Artificial enzymes for photocatalytic hydrogen production in photosynthetic bacteria	2.14
Sapienza Università di Roma	Innovative technologies for production of clean H_2 without CO_2 emissions	0.87
Università del Piemonte Orientale	Eco-sustainable development of polymers and ultra-porous carbons for hydrogen storage and transport	3.96
Politecnico di Milano	Advanced materials and components for PEM fuel cells with innovative multi-scale structuring for improved durability and stability	3.40

TABLE 3 | Research projects and industrial companies funded by Italy's Ministry of the Ecologic Transition following a 2022 PNRR call for fundamental hydrogen energy research. [Source: Ref [42]].

Organization	R&D project	Funding (€M)
Enapter Srl	Optimization and industrialization of the dry cathode for AEM electrolyzers	0.98
SAPIO Produzione Idrogeno Ossigeno Srl	HyPER Mantova - Hydrogen High Pressure Efficient Renewing at Mantova Facility Innovation and efficiency improvement of the compressed hydrogen distribution chain	1.77
Gap Solutions Srl	MH2 - Material Handler – H_2 fuel cell powertrain	2.41
Techfem SpA	SMARTHYDRO GRID - SMART HYDROGEN MICROGRID for energy transition and deep decarbonization	2.51
Graded SpA	GRETHA - A novel Green Energy Technology based on fuel cells, Hydrogen And renewables	2.63
Distretto Tecnologico Aerospaziale Scarl	Development of Zero-Emission Propulsion Architectures for General Aviation - Serena	2.50
Eni SpA	Innovative Integrated Process for the Intensified Production of eGas from Green Hydrogen – IPEReGas	1.74
Archimede Srl Società di Ingegneria	Development of an innovative, eco-sustainable process for the treatment of olive wastewater and olive mill wastewater, with final valorization of the organic content into advanced biofuel.	2.20
Ecos Srl	Development and optimization of renewable energy systems for hydrogen production and its application in internal combustion engines for sustainable mobility.	2.34
Esea Automation Srl	Innovative Solutions for Hydrogen Tanks (SIDRO)	2.08
Hyter Srl	Developing an innovative, scalable, and more than 1 MW electrolyzer for the production of clean, green hydrogen - SIRIUS	2.13
GVS SpA	Innovative Materials for Electrolyzers - MAINE	1.33
Ansaldo Green Tech SpA	New Electrodes and Membranes for Industrial-Scale Electrolyzers: NEMESI	2.64
Turboden SpA	Study, development, and industrial validation of an innovative high-temperature, high-pressure (300°C – 50 bar) alkaline electrolyzer for hard-to-abate applications in combination with heat recovery. Acronym: AWE-HTP	0.899
aizoOn Consulting Srl	HEHS: High Efficency Hydrogen Storage	Partly funded

required to solve the frequent difficulty of obtaining funding for intermediate stages of the innovation process, that then creates the "valley of the death" in the innovation process [16].

An even larger research budget of 110 M€ on hydrogen energy research was made available by the same Ministry to three public research organizations: ENEA (75 M€), CNR (20 M€), and RSE (15 M€) who partnered in the Operational Research Plan (POR) on Hydrogen, with ENEA having the main role as actuator of the plan [43].

Research was articulated in 131 activity lines (LA) organized in 16 "work packages" (WP). An outlook of the impressive amount of research (and educational) work undertaken can be drawn from surveying the WPs of plan (Table 4) [44]. Each research line had a researcher from ENEA, CNR, or RSE appointed as responsible (principal investigator, PI). In detail, out of 131 research lines, 73 had a PI from ENEA, 44 from CNR, and 14 from RSE. Often, one researcher was responsible for multiple research lines.

The new national approach of the H_2 POR Plan for academic research also provided substantial new benefits to Italian research in the field. Lack of synergy in research, particularly in materials science and in chemistry [45], and high fragmentation are two characteristic weaknesses of Italian research, in the latter case in common with several other European countries [46].

Showing evidence how the new NextGenerationEU approach adapted for the H_2 POR Plan solved these issues, for instance, following appointment PIs at CNR surveyed colleagues at different research institutes distributed across the country asking to collaborate. Researchers from different backgrounds (chemists, physicists, engineers, e.g.) who had not collaborated previously started to collaborate. This was the case, for example, of one of the research lines of the Plan (LA 1.1.6 "Development of materials and components free from critical materials for anionic electrolyzers (AEMs) operating even at high differential pressures"). Following start of the collaboration, new electrocatalyst NiGraf based on earth-abundant Ni and entrapped

TABLE 4 | Work packages of Italy's Operational Research Plan (POR) on Hydrogen (2022–2025). [Source: Ref [44]].

Work package	Title	No. of research activity lines (LA) and PI affiliation
Production of clean and green hydrogen		
WP 1.1	Research and development of advanced electrolyzers (low and high temperature), or other innovative technologies, for the production of green and low-emission hydrogen	37 (24 with PI from ENEA, 10 with PI from CNR, and 3 from RSE)
WP 1.2	Research, development, and modeling of next-generation technologies, components, and systems for specific applications: feedstock for industry, transport, heat, and energy	8 (3 with PI from ENEA, 4 with PI from CNR, and 1 with PI from RSE)
WP 1.3	Definition of standards, methodologies, and guidelines for the testing and validation of innovative technologies and processes for hydrogen production, Social Life Cycle Assessment, Life Cycle Assessment, and training of professional figures	6 (4 with PI from ENEA and 2 with PI from CNR)
Hydrogen storage and transportation and its transformation into derivatives and electrofuels		
WP2.1	Research and development of Power to Gas systems and processes and liquid e-fuels derived from organic hydrogen	12 (4 with PI from ENEA, 6 with PI from CNR, and 2 from RSE)
WP2.2	Research and development of solutions for the transport, distribution, and end-use of hydrogen in natural gas networks	8 (3 with PI from ENEA, 2 with PI from CNR, and 3 from RSE)
WP2.3	Research and development of innovative technologies for hydrogen storage: liquid, solid materials, hybrid solutions, and non-organic liquid carriers	8 (4 with PI from ENEA and 4 with PI from CNR)
WP2.4	Development and optimization of components and systems for hydrogen refueling stations to improve efficiency and reduce land use	2 (2 with PI from ENEA)
WP2.5	Definition of standards, methodologies, and guidelines for the testing and validation of innovative technologies and processes for P2G, e-fuel and hydrogen storage, technical-economic analyses, Social Life Cycle Assessment, Life Cycle Assessment, and training of professional figures	7 (5 with PI from ENEA and 2 with PI from CNR)
Fuel cells		
WP3.1	Research and development of stack technologies, components, and processes, to improve their performance and reduce costs	7 (5 with PI from ENEA and 2 with PI from CNR)
WP3.2	Research and development of advanced reversible cell solutions based on ionic and protonic conductors	3 (1 with PI from ENEA and 2 with PI from CNR)
WP3.3	Research and development of fuel cell components and systems for heavy transport (road, rail, and maritime) and aviation applications	7 (5 with PI from ENEA and 2 with PI from CNR)
WP3.4	Research and development of fuel cell components and systems powered by pure hydrogen, hydrogen–methane blends, and unconventional feedstocks, for stationary applications and local energy communities.	4 (1 with PI from ENEA, 1 with PI from CNR, and 2 from RSE)
WP3.5	Definition of standards, methodologies, and guidelines for the testing and validation of innovative fuel cell technologies and systems, technical-economic analyses, Social Life Cycle Assessment, Life Cycle Assessment, and training of professional figures	6 (4 with PI from ENEA and 2 with PI from CNR)
Hydrogen-based smart infrastructure		
WP4.1	Research, development, and implementation of smart management algorithms for hydrogen-based infrastructure, for the provision of ancillary services, and interoperability with other systems and networks. Testing and applications	4 (2 with PI from ENEA, 1 with PI from CNR, and 1 from RSE)

(Continues)

TABLE 4 | (Continued)

Work package	Title	No. of research activity lines (LA) and PI affiliation
WP4.2	Testing and validation of a hydrogen-based infrastructure at microgrid scale	4 (1 with PI from ENEA, 2 with PI from CNR, and 1 from RSE)
WP4.3	Definition of standards, methodologies, and guidelines for the testing and validation of emerging technologies, components, and management and control systems for hydrogen-based infrastructures and training of professional figures	8 (5 with PI from ENEA, 2 with PI from CNR, and 1 from RSE)

graphene oxide for low-cost AWE electrolyzers [47, 48], and highly stable new anion exchange membranes [49] for AEM alkaline electrolysis were readily developed.

The new scientific links created by the relationship borne out of the hydrogen research in the specific field of the aforementioned research line became permanent, and research on hydrogen expanded well beyond AWE to include new proton exchange membranes for PEM electrolyzers [50], and is currently expanding to other subfields of hydrogen energy fundamental and applied research.

On the other hand, incentives made available to energy users to drive demand of hydrogen energy technology and as direct subsidies to hydrogen technology manufacturers to accelerate the energy transition to renewable energy [17], led electrolyzer and electrode manufacturers who had conventionally supplied the chemical and metal refining industries with their products to re-discover water electrolysis, particularly durable and lower cost alkaline water electrolyzers employing Ni-based catalytic coatings. Today's alkaline electrolyzers, however, are produced in highly automized manufacturing lines [22] according to the principles of Industry 4.0, namely full production automation chiefly conducted by robots in which information technology connects engineering and operational technology [51].

Finally, one may notice that the electrolytic green H_2 production is part of a renaissance of electrochemistry for chemical productions driven by sustainability societal megatrend that is profoundly affecting the chemical industry. Said progress requires to reshape undergraduate education in electrochemistry to foster students' interest and learning in a cross-disciplinary and often overlooked field of chemical science [52]. It is instructive and noticeable, in this respect, the insertion of "training of professional figures" of all WPs comprising Italy's H_2 Research Plan [44], that eventually translated into the organization of four Hydrogen Schools held between 2022 and 2025 [53].

4.2 | Delays and Risk Factors

Besides positive developments discussed above, Italy's structural weaknesses in the field of hydrogen energy research and uptake should also be noted. The number of hydrogen refueling stations in Italy remains low, especially when compared to the gross domestic product (GDP) of Italy and its achievements in solar and wind energy uptake. To date (April 2026), only four HRS operate in Italy, located in Bolzano, Mestre, Brunico, and Carugate (near Milan). The first along a highway, the latter, opened in mid 2025, includes three dispensers of compressed H_2 pressurized at 350 and 700 bar, with a dispensing capacity of about 1 ton per day [54]. Also located along a highway and dispensing only green hydrogen sourced from hydroelectric power, the one in Brunico opened in January 2026 also dispenses H_2 pressurized at 350 and 700 bar, with a dispensing capacity of about 800 kg per day [55]. Expansion projects are underway, with northern Italy expected to rely on five HRS by the end of 2026 [54]. For comparison, however, by mid 2025 Switzerland hosted 18 HRS [56].

Reputed analysts ascribe Italy's delays in the uptake of green H_2 (manufactured via water electrolysis) to its high production cost, driven by the high cost of electricity in Italy (€110/MWh average price in 2024–2025 vs. €77/MWh a Germany, and €44/MWh in Scandinavian countries) that would amount to €13/kg, significantly higher than €5–9/kg bids submitted to the European Hydrogen Bank [57]. Another important limitation to the widespread uptake of H_2 energy in Italy is the restrictive safety regulation. Italy's Association for Hydrogen and Fuel Cells (H2IT) is working along with different Ministries to harmonize safety regulations and guidelines in order to expedite the deployment of hydrogen energy projects [58].

In brief, it is now clear that the main barrier to the uptake of green H_2 as energy source is its high cost. Hence, based on the successful case of the feed-in-tariff to photovoltaic solar energy replacing the old incentives to purchase of PV arrays that led to the collapse of the production cost of PV modules and thus to a global solar boom since 2005–2007 [59], on March 2026 the European Commission approved Italy's €6 billion incentives scheme aimed to support the development of significant hydrogen production capacity in Italy, providing incentives up to 200,000 tons of green H_2 per year until the end of 2029 [60].

Based on two-way contracts for difference, assigned through competitive auctions, the scheme will pay a financial incentive to the producers of green H_2 primarily sold for industrial and transportation sectors. The price for hydrogen will be determined through tenders, based on the offers submitted by producers. If the price of the reference alternative fuel falls below the strike price, the State pays the difference to hydrogen producers. Conversely, if the market price exceeds the strike price, beneficiaries will return the excess. The mechanism therefore ensures revenue stabilization for producers while simultaneously limiting excess profits [60].

5 | Conclusions

The study of hydrogen energy research in Italy in the bioeconomy era started in the early 2000s offers six research policy lessons of relevance both to research policy makers and researchers based in other countries working toward development and commercialization of hydrogen energy technology. Today indeed well beyond research chemists and chemical engineers, many other professionals, including naval and mechanical engineers, materials scientists, physicists, data science, and artificial intelligence researchers, collaborate in cross-disciplinary teams working at different companies and research organizations for the development and commercialization of H_2 hydrogen energy in widely different mobile and stationary applications.

First, prolonged "valley of the death" period in the innovation process lasting for two decades between 2000 and 2020 points to the relevance of providing intermediate-stage funding in the innovation process.

Second, the new research policy approach adopted in 2022 with the launch of a national H_2 Research Plan funded as part of the Italian (PNRR) and European (NextGenerationEU) recovery plans, successfully solved the lack of synergy and pronounced fragmentation of Italian research in the field of hydrogen research.

Third, substantial public funding made available to manufacturing companies to support production and commercialization of electrolyzers, catalytic membranes, and fuel cells with which to produce and use green hydrogen has been instrumental in the rise of a vibrant Italian hydrogen industry.

Fourth, selected Italy's achievements, including ongoing construction of the world's first hydrogen-powered ship and Europe's first electrolyzer GigaFactory, demonstrate that hydrogen energy technology can be smoothly integrated in existing manufacturing sectors more than one century old.

Fifth, showing further evidence of the relevance of fundamental and applied research in new fields, achievements of Italian companies in the field of hydrogen energy were made possible by applying knowledge of a small *élite* of research chemists and engineers who pioneered hydrogen energy research in Italy during the first two decades of the 2000s, including research chemists and chemical engineers based at Italy's largest (and oldest) electrolyzer company who rediscovered alkaline water electrolysis and rapidly advanced the technology.

Sixth, the rapid concomitant growth of a flourishing green hydrogen energy industrial sector, demonstrates that skepticism in the field of renewable energy technologies is not helpful neither in conducting research nor in research and energy policy-making. In 2025, over 600 GW of photovoltaic (PV) power was installed across the world, with high-efficiency PV modules selling around \$0.13/W in Asia and \$0.25/W in the USA due to tariffs. For decades numerous scholars warned that the cost of PV solar cells was limited by the inherent cost of solar-grade crystalline silicon and that the latter could not diminish below \$3–4/W.

Looking to future work complementing this analysis, a comparative investigation of the citation impact analysis of Italy's research on hydrogen energy beyond publication counts per year, would unveil also the scientific impact of Italian research in the field in comparison to peer EU countries.

Author Contributions

Mario Pagliaro: conceptualization, methodology, formal analysis, data curation, writing – original draft, writing – review and editing, investigation.

Acknowledgments

Thanks to Ministero dell'Ambiente e dellla Sicurezza Energetica under Piano Operativo della Ricerca "Ricerca e sviluppo sull'idrogeno" financially supported by the European Union - NextGenerationEU - M2C2 Investment 3.5, in the framework of the project PNRR Ricerca e Sviluppo sull'Idrogeno 2022–2025 - Accordo di Programma "Idrogeno" (PRR.AP015.017.002), "Obiettivo 1 - Produzione di idrogeno verde e pulito," LA 1.1.6 and 1.1.7. Open access publishing facilitated by Consiglio Nazionale delle Ricerche, as part of the Wiley - CRUI-CARE agreement.

Conflicts of Interest

The author declares no conflicts of interest.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

References

1. M. Pagliaro and A. G. Konstandopoulos, *Solar Hydrogen* (RSC Publishing, 2012).

2. N. Dadashzadeh, S. Dadashzadeh, and A. Qadir, "Hydrogen-Based Trains, Trucks, and Buses: Techno-Socio-Economic Challenges and Perspective." in *Hydrogen and e-Mobility*, eds. J. J. Liu, M. R. Salehizadeh, and M. Inci (Elsevier, 2026), 241–256, https://doi.org/10.1016/B978-0-443-34013-0.00011-6.

3. A. Lakhouit, "Investigating the Hydrogen Renaissance in the Global Energy Transition With AI Integration," *Energy Conversion and Management: X* 26 (2025): 101010, https://doi.org/10.1016/j.ecmx.2025.101010.

4. Ludwig-Bölkow-Systemtechnik, "Milestone Reached: Over 1,000 Hydrogen Refuelling Stations in Operation Worldwide in 2024," Munich, 2025, https://www.h2stations.org/press-release-2025-milestone-reached-over-1000-hydrogen-refuelling-stations-in-operation-worldwide-in-2024/.

5. U.S. Department of Energy, Hydrogen and Fuel Cell Technologies Office, *Multi-Year Program Plan*, Washington, DC: 2024, https://www.energy.gov/sites/default/files/2024-05/hfto-mypp-2024.pdf.

6. N. Guillet and P. Millet, "Alkaline Water Electrolysis." In: *Hydrogen Production*, eds. A. Godula-Jopek (Wiley-VCH, 2015), 117–166, https://doi.org/10.1002/9783527676507.ch4.

7. IRENA, *Hydrogen – Overview*. Dubai: 2025, https://www.irena.org/Energy-Transition/Technology/Hydrogen.

8. Q. Zhang, Y. Hao, H. Chen, et al., "Toward Energy-Efficient Alkaline Water Electrolysis: Advances in Mass Transport Optimization and Electrolyzer Design," *Advanced Energy Materials* 16 (2026): e04039, https://doi.org/10.1002/aenm.202504039.

9. Y. Cheng and S. Wang, "The Advancement of Catalysts for Proton-Exchange Membrane Fuel Cells." In: *Water Photo- and Electro-Catalysis*, eds. S. Shen and S. Wang (Wiley-VCH, 2024), 321–361, https://doi.org/10.1002/9783527831005.ch9.

10. M. Pagliaro and M. Pagliaro, "The Central Role of Chemistry in the Transition to Solar Economy: Outcomes of Two Lectures at the Russian Academy of Sciences," *General Chemistry* 6 (2020): 200007-0, https://doi.org/10.21127/yaoyigc20.

11. R. Ciriminna, C. Della Pina, and M. Pagliaro, "Italy's Excellence in Research," *Heliyon* 11 (2025): e41335, https://doi.org/10.1016/j.heliyon.2024.e41335.

12. F. Tajani, "La Produzione Idroelettrica in Italia: Una Strana Proposta," *Giornale degli Economisti e Annali di Economia* 11, no. 12 (1940): 754–763, https://www.jstor.org/stable/23234265.

13. C. Silvi, "Can the History of Energy Technology and Use Educate Us for a Solar Energy Future? The Italian Case." *Proceedings ISES Solar World Congress*, Göteborg, 2003, https://altronovecento.fondazionemicheletti.eu/wp-content/uploads/2021/09/9714_2010.4.22_ISES_Italia.pdf.

14. A. S. Aricò, "CNR Contribution to National Development of Sustainable Hydrogen Technologies," *Energia, Ambiente e Innovazione* 1 (2021): 40–43.

15. G. Graditi, "ENEA and Hydrogen: A 30-Year History," *Energia, Ambiente e Innovazione* 1 (2021): 10–13.

16. T. R. Beard, G. S. Ford, T. M. Koutsky, and L. J. Spiwak, "A Valley of Death in the Innovation Sequence: An Economic Investigation," *Research Evaluation* 18 (2009): 343–356, https://doi.org/10.3152/095820209X481057.

17. European Commission, *Hydrogen Strategy for a Climate-Neutral Europe*, Brussels: 2020, https://eur-lex.europa.eu/legal-content/EN/ALL/?uri=COM:2020:301:FIN.

18. Ministero dell'Ambiente e della Sicurezza Energetica, Strategia Nazionale Idrogeno, 2024, https://www.mase.gov.it/portale/documents/d/guest/strategia-nazionale-idrogeno-pdf.

19. Details (in Italian) at: Governo Italiano, Piano Nazionale di Ripresa e Resilienza, Missione: Rivoluzione Verde e Transizione Ecologica, Componente: Energia Rinnovabile, Idrogeno, Rete e Mobilità Sostenibile, Rome, 2026, https://www.italiadomani.gov.it/it/Interventi/investimenti/ricerca-e-sviluppo-sull-idrogeno.html.

20. Online Search Conducted at scopus.com on January 25, 2026 With the Query "green hydrogen" Amid "All Fields" Until 2025 Limiting the Search to "Article" Published in English With Author "Affiliation" Limited to Italy.

21. Online Search Conducted at scopus.com on January 25, 2026 With the Query "solar hydrogen" Amid "All Fields" Until 2025 Limiting the Search to "Article" Published in English With Author "Affiliation" Limited to Italy.

22. M. Perego and P. Scilabra, "Shaping the Future of Green Hydrogen: De Nora's Electrochemical Technologies for Fueling the Energy Transition," *Pure and Applied Chemistry* 96 (2024): 487–491, https://doi.org/10.1515/pac-2023-0810.

23. M. Coccia, "The Evolution of Scientific Disciplines in Applied Sciences: Dynamics and Empirical Properties of Experimental Physics," *Scientometrics* 124 (2020): 451–487, https://doi.org/10.1007/s11192-020-03464-y.

24. Fincantieri, Varata at Ancona. "Viking Libra", Prima Nave da Crociera al Mondo Alimentata a Idrogeno, March 19, 2026, https://www.fincantieri.com/it/newsroom/news-e-comunicati-stampa/2026/fincantieri-varata-ad-ancona-viking-libra-prima-nave-da-crociera-al-mondo-alimentata-a-idrogeno (Accessed April 14, 2026).

25. Fincantieri: Road to Net Zero, Riviera, May 16, 2025, https://www.rivieramm.com/expert-views/expert-views/fincantieri-road-to-net-zero.

26. UFI Hydrogen, "UFI Hydrogen Launches at Its New Trentino Plant the Production of Membranes for Green Hydrogen: Italy's First in Four Key Technologies," May 1, 2025, https://www.ufihydrogen.com/news/ufi-hydrogen-launches-at-its-new-trentino-plant-the-production-of-membranes-for-green-hydrogen-italys-first-in-four-key-technologies/.

27. M. Lazzaroni, cit. In: F. Piazza, Ufi Filter fa Partire l'idrogeno: Al Via la Produzione in Trentino, *Corriere Economia*, April 17, 2025, https://www.ilnordest.it/economia/imprese/ufi-filter-fa-partire-lidrogeno-al-via-la-produzione-in-trentino-ckgk0ubq.

28. N. Martello, "H2iseO: A Rovato Test di Rifornimento per Treni a Idrogeno," *Rinnovabili & Risparmio*, February 2, 2025, https://www.rinnovabilierisparmio.it/2025/02/19/h2iseo-a-rovato-test-di-rifornimento-per-treni-a-idrogeno/.

29. Fenhyce – Trainare il Futuro. Hydrogen-News.it, October 24, 2025, https://hydrogen-news.it/fenhyce-trainare-il-futuro/.

30. M. Crucianelli, "Materiali Avanzati per l'Immagazzinamento dell'Idrogeno," *Chimie et Industrie* 11, no. 5 (2024): 10–13, https://www.soc.chim.it/sites/default/files/chimind/pdf/2024_5_5792_on.pdf.

31. M. A. Marchi, "Venezia, 90 Autobus ad Idrogeno e Sfida al Nord Europa. "È il Primo Impianto di Queste Dimensioni in Italia." Il Riformista, (December 27, 2025). https://www.ilriformista.it/venezia-90-autobus-ad-idrogeno-e-sfida-al-nord-europa-e-il-primo-impianto-di-queste-dimensioni-in-italia-494101/.

32. S. Zuccato, "Mestre, ecco com'è il Primo Distributore di Idrogeno in Italia." *Venezia Today*, June 10, 2025, https://www.veneziatoday.it/cronaca/stazione-rifornimento-idrogeno-mestre.html.

33. Enapter, "AEM Enapter Electrolyzers. The Best of Two Worlds," Pisa, 2026, https://enapter.com/en/enapter-products-aem/.

34. ErreDue Gas, "Generatori di Idrogeno ad Alta Purezza Serie H-MW," Livorno, 2026, https://www.erreduegas.it/wp-content/uploads/Brochure_Hmega_rev1.pdf.

35. IMI Remosa, "Hydrogen Production," Cagliari, 2026, https://processautomation.imiplc.com/about-us/brands/imi-vivo.

36. Industrie De Nora, "De Nora: Al Via i Lavori per la Costruzione della Gigafactory," Milano, June 11, 2024, https://www.denora.com/it/media/press-release/2024/De-Nora-breaks-ground-on-the-Italian-Gigafactory.html.

37. L. Magna, "Dentro il Progetto Neom con il ceo Paolo Dellachà," *Industria Italiana*, December 11, 2025. https://www.industriaitaliana.it/de-nora-dellacha-idrogeno-elettrochimica-neom-energia/.

38. NEOM Green Hydrogen, 2026, https://nghc.com.

39. V. Morreale, "Progetti di Innovazione in Valle D'Aosta per la Transizione Energetica – Cogne Acciai Speciali," *Il Piano Energetico Ambientale Regionale al 2030: Un Percorso Concreto*. Aosta, April 30, 2025, https://www.regione.vda.it/allegato.aspx?pk=118269.

40. Y. Li, L. Li, H. Yuan, et al., "Scaling Solar Photocatalytic Hydrogen Production in China: Integrated Geospatial-Meteorological Analysis," *Applied Energy* 381 (2025): 125179, https://doi.org/10.1016/j.apenergy.2024.125179.

41. Ministero della Transizione Ecologica., Avviso Pubblico del 23.03.2022 per la selezione di proposte progettuali inerenti attività di ricerca fondamentale nell'ambito del Piano Nazionale di Ripresa e Resilienza (PNRR), Missione 2 "Rivoluzione Verde e Transizione Ecologica", Componente 2 "Energia rinnovabile, idrogeno, rete e mobilità sostenibile", Investimento 3.5 "Ricerca e sviluppo sull'idrogeno", finanziato dall'Unione Europea – Next Generation EU a valere sul Decreto del Ministro della Transizione Ecologica del 23.12.2021, n. 545 Articolo 1, Comma 5, Lettera A. Approvazione della graduatoria. Rome, 2022, https://www.mase.gov.it/portale/documents/d/guest/avviso_r_s_h2_tipo_a_dd_126_27_06_2022-pdf.

42. Ministero dell'Ambiente e della Sicurezza Energetica., Avviso pubblico del 23.02.2022 per la selezione di proposte progettuali inerenti

attività di ricerca fondamentale nell'ambito del Piano Nazionale di Ripresa e Resilienza (PNRR), Missione 2 "Rivoluzione Verde e Transizione Ecologica", Componente 2 "Energia rinnovabile, idrogeno, rete e mobilità sostenibile", Investimento 3.5 "Ricerca e sviluppo sull'idrogeno", finanziato dal'Unione Europea – Next Generation EU a valere sul Decreto del Ministro della Transizione Ecologica del 23.12.2021, n. 545 Articolo 1, Comma 5, Lettera B. Approvazione della graduatoria. Rome, 2022, https://www.mase.gov.it/portale/documents/d/guest/avviso_r_s_h2_tipo_b_dd_127_27_06_2022-pdf.

43. V. Cigolotti, Ricerca e Sviluppo di Tecnologie per la Filiera dell'Idrogeno. *POR H2 - Organismi di Ricerca e Università insieme per lo sviluppo della filiera nazionale dell'idrogeno*, Rome, July 16–17, 2024, https://www.eventi.enea.it/images/presentazioni2024/2024_07_16_conferenza_por_h2/POR_H2_INTRO.pdf.

44. ENEA, Piano Operativo di Ricerca (POR) Idrogeno, Rome, 2022. https://www.pnrr-ricercah2.it/produzione-di-idrogeno/.

45. R. Sessoli, "Italian Research at a Turning Point: An Opportunity That Cannot Be Missed," *Angewandte Chemie International Edition* 54 (2015): 1374–1375, https://doi.org/10.1002/anie.201410490.

46. P.-A. Balland, V. Di Girolamo, F. Benoit, et al., *Divided We Fall Behind – Why a Fragmented EU Cannot Compete in Complex Technologies*, (Publications Office of the European Union, 2025), https://data.europa.eu/doi/10.2777/8548441.

47. M. Pagliaro, M. V. Pagliaro, R. Caliandro, C. Giannini, R. Ciriminna, and A. Lavacchi, "NiGraf: A New Nickel-Based Molecularly Doped Metal for Enhanced Water Electrolysis," *Materials Advances* 5 (2024): 2759–2766, https://doi.org/10.1039/d3ma00700f.

48. R. Caliandro, E. Berretti, M. V. Pagliaro, et al., "Structural Dynamics of a Nickel Electrocatalyst During Water Splitting Observed Via Operando Pair Distribution Function," *Cell Reports Physical Science* 5 (2024): 102341, https://doi.org/10.1016/j.xcrp.2024.102341.

49. E. Fontananova, R. Ciriminna, D. Talarico, et al., "CytroCell@PIL: A New Citrus Nanocellulose-Polymeric Ionic Liquid Composite for Enhanced Anion Exchange Membranes," *Nano Select* 6 (2025): e70001, https://doi.org/10.1002/nano.70001.

50. D. Talarico, E. Fontananova, T. Sibillano, et al., "CytroCell@Nafion: Enhanced Proton Exchange Membranes," *Global Challenges* 9 (2025): e00338, https://doi.org/10.1002/gch2.202500338.

51. N. Ilanković, A. Zelić, M. Gubán, and L. Szabó, "Smart Factories – The Product of Indrusty 4.0," *Prosperitas* 7 (2020): 19–31, https://doi.org/10.31570/Prosp_2020_01_2.

52. R. Ciriminna, M. Ghahremani, F. Varmaghani, et al., "Improving Education in Electrochemistry Via a Modeling Approach and Focusing on Green Chemistry Applications," *Sustainable Chemistry and Pharmacy* 31 (2023): 100931, https://doi.org/10.1016/j.scp.2022.100931.

53. ENEA, "Hydrogen Summer School," 2025. https://h2summerschool.enea.it/en/.

54. "Northern Italy to Rely on Five Hydrogen Refueling Stations by the End of 2026," *Sustainable Truck & Van*, July 1, 2025, https://www.sustainabletruckvan.com/northern-italy-hydrogen-refueling-stations/.

55. Alperia, Inaugurata la Prima "stazione di rifornimento green" in Italia, January 29, 2026, https://www.alperiagroup.eu/it/alperia-inaugurata-la-prima-stazione-di-rifornimento-green-italia.

56. "Only 18 Refuelling Stations for Hydrogen Vehicles in Switzerland," *swissinfo.ch*, April 12, 2025, https://www.swissinfo.ch/eng/science/hydrogen-refuelling-energy-transition-switzerland/89152512.

57. AGICI, *Policy e Strategie per il Presente e il Futuro dell'Idrogeno: È ora di Agire!*, Milan, November 21, 2025, https://www.linkedin.com/pulse/policy-e-strategie-per-il-presente-futuro-dellidrogeno-è-ora-di-ga0zf/.

58. C. Maggi, "Il Contesto Normativo e le Linee Guida della Strategia Nazionale Idrogeno," *Webinar 1 - Idrogeno: Aggiornamento per le Imprese su Strategie Nazionali e Prospettive in Sardegna*, Sardegna Ricerche, Ottobre 13, 2025, https://www.youtube.com/watch?v=WihtXM1xO4Y.

59. F. Meneguzzo, R. Ciriminna, L. Albanese, and M. Pagliaro, "The Great Solar Boom: A Global Perspective Into the Far Reaching Impact of an Unexpected Energy Revolution," *Energy Science & Engineering* 3 (2015): 499–509, https://doi.org/10.1002/ese3.98.

60. "Nuovi Incentivi per l'Idrogeno Rinnovabile, c'è il Via Libera Ue," *QualEnergia.it*, March 30, 2026, https://www.qualenergia.it/articoli/via-libera-ue-nuovi-incentivi-idrogeno-rinnovabile/.