21st International Conference Man and Working Environment
SEMSIE
Safety Engineering & Management - Science, Industry, Education

ORIGINAL SCIENTIFIC PAPER

DOI: 10.46793/SEMSIE25.289M

POTENTIAL AND IMPACT OF GREEN HYDROGEN ON GLOBAL ENERGY SECTOR

MILENA MANČIĆ[1]
MIOMIR RAOS[2]
MARKO MANČIĆ[3]
MILENA MEDENICA[4]
MARJAN POPOVIĆ[5]
MIRJANA LAKOVIĆ[6]

[1,2,4]University of Niš, Faculty of Occupational Safety, Serbia
[2,6]University of Niš, Faculty of Mechanical Engineering, Serbia
[5] Institute Miphem d.o.o, Serbia

[1]*milena.mancic@znrfak.ni.ac.rs*
[2] *miomir.raos@znrfak.ni.ac.rs*
[3] *markomancic@masfak.ni.ac.rs*
[4] *milena.medenica@znrfak.ni.ac.rs*
[5]*marjan@miphem.rs*
[6]*mirjanalakovic@masfak.ni.ac.rs*

Abstract: *The use of green hydrogen represents the most likely direction for the transformation of the energy sector of modern society, on the path of transition towards the use of sustainable energy in the future. Only green hydrogen, produced by using renewable energy sources, can significantly contribute to achieving the goals of the sustainable energy strategy, with a particular contribution to reducing carbon dioxide and global greenhouse gas emissions. This paper analyzes the current state and potential of the use of green hydrogen in different sectors, with a special emphasis on Europe, as a leader in the implementation of hydrogen-based technologies. A comparative analysis of cases shows how different approaches can contribute to accelerating the adoption of green hydrogen on a global scale. Through this paper, the aim is to provide a comprehensive overview of the current state, challenges and opportunities for the wider application of green hydrogen, and to point out its potential to become a key link in sustainable energy transformation and reduction of dependence on fossil fuels.*

Keywords: renewable energy sources, green hydrogen, energy demands

ORCID iDs:		
	Milena Mančić	https://orcid.org/0000-0002-6181-2286
	Miomir Raos	https://orcid.org/0000-0001-5586-0276
	Marko Mančić	https://orcid.org/0000-0001-7078-9658
	Milena Medenica	https://orcid.org/0000-0001-6561-5696
	Marjan Popović	N/A
	Mirjana Laković	https://orcid.org/0000-0001-6289-5151

INTRODUCTION

Green hydrogen, produced through renewable energy-powered electrolysis, is emerging as a pivotal element in the global transition towards sustainable energy systems. This fuel can be used in heavy industries and transportation, leading to a growing demand, especially in Europe, where it is seen as a way to reduce reliance on fossil fuels (Le et al., 2023). Green hydrogen's adaptability positions it as a cornerstone in the energy matrix of the future, with a critical role in industrial processes because of its unique characteristics and the pressing need for cleaner energy alternatives (Segovia-Hernandez et al., 2024). Hydrogen possesses a high energy content per unit mass and produces only water when burned or used in a fuel cell, making it an attractive substitute for conventional fuels (Segovia-Hernandez et al., 2024). Hydrogen can also store renewable energy, avoiding curtailment during periods of high production and low demand (Silva et al., 2024). Ambitious hydrogen strategies, such as those outlined in the European Green Deal, aim to produce millions of tons of green hydrogen annually (Franco, 2025). However, the success of these strategies hinges on careful planning and infrastructure development to ensure efficient storage, transfer, and utilization of green hydrogen (Franco, 2025). Its versatility extends to various sectors, including power generation, industrial feedstock, and transportation, offering a pathway to decarbonize hard-to-abate sectors (Papadaki et al., 2025). Green hydrogen is capable of promoting sustainable energy development and is gaining attention in the current global energy transition framework (Guarieiro et al., 2022). A significant investment is needed to increase green hydrogen production and build the required infrastructure (Nayebossadri et al., 2025). Major challenges include the high costs of production and the lack of infrastructure for distribution (Chiroșcă et al., 2024). The production of green hydrogen through electrolysis is energy-intensive and costly, but it has the potential to considerably lower emissions when using renewable electricity (Franco, 2025). However, the potential of green hydrogen to replace fossil fuels in various sectors, including energy production, transportation and industry, makes it a worthwhile pursuit (Chiroșcă et al., 2024). The European Commission's REPowerEU plan targets the production and import of 20 million tons of green hydrogen by 2030, emphasizing the role of green hydrogen in decarbonizing sectors that are difficult to electrify (Zeyen et al., 2023). Since the Paris Climate Agreement in 2015, the adoption of green hydrogen has become a key strategy for governments and businesses striving to meet global temperature targets and reduce greenhouse gas emissions (Guarieiro et al., 2022). This involves incorporating renewable energy sources like solar, wind, and hydroelectric power to produce hydrogen (Nayebossadri et al., 2025). Despite its potential, green hydrogen faces hurdles, including high production costs and the need for infrastructure development to facilitate its use (Franco, 2025). These issues are particularly relevant in isolated locations, where green hydrogen can offer a sustainable alternative to traditional fossil fuels (Zhao et al., 2025) (Superchi et al., 2025). Islands can especially benefit from green hydrogen technologies, substantially contributing to mitigating issues related to energy isolation and potentially minimizing emissions (Superchi et al., 2025). Integrating green hydrogen addresses long-term and short-term energy storage issues while also providing the possibility of complete decarbonization (Superchi et al., 2025). For instance, some studies have explored using hydrogen production systems to replace diesel generators with wind and photovoltaic systems, demonstrating that a fully renewable layout is feasible, but the hydrogen storage cycle would need three times the annual peak capacity of RES (Superchi et al., 2025). Green hydrogen is currently more expensive but will benefit from declining renewable electricity costs and government incentives (Curcio, 2025). However, uncertainty remains regarding the amount of green hydrogen Europe will need to produce in the coming decades, depending on demand, competition, and the success of carbon capture and storage (Greevenbroek et al., 2024). The deployment of hybrid renewable energy systems on islands demonstrates the importance of public-private partnerships, community involvement, and adaptive technologies in overcoming energy transition challenges (Papadaki et al., 2025). Islands are also uniquely positioned to adopt green hydrogen technologies early because of their decentralized energy systems, which allow for efficient integration of renewable energy sources (Papadaki et al., 2025). They can serve as testing grounds for hydrogen technologies, paving the way for broader adoption (Papadaki et al., 2025). This transition is driven by the need to decrease energy costs and increase energy independence by using local renewable resources (Papadaki et al., 2025). Several pilot projects and practical experiments are currently underway worldwide to develop and test these technologies (Marouani et al., 2023). These initiatives aim to refine the production processes, storage solutions, and infrastructure needed for a hydrogen economy (Hidouri et al., 2025) (Chiroșcă et al., 2024). These projects offer essential insights into the scalability and economic viability of green hydrogen production (Criollo et al., 2024). These projects also facilitate identifying the best hydrogen storage options, a vital aspect for the future of sustainable energy systems (Preuster et al., 2017).

These partnerships and decentralized production potentials are crucial for securing a cheap and reliable future hydrogen supply, which is a prerequisite for affordable energy in systems with high hydrogen proportions (Niepelt et al., 2023). The integration of renewable energy sources with storage systems and conventional sources facilitates overall cost reductions and promotes integrated energy systems (Superchi et al., 2025).

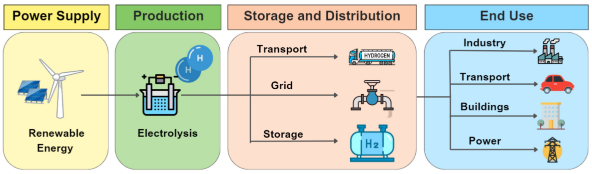

Fig 1. Green hydrogen value chain schematic representation (Gomez and Castro, 2024)

The interconnection and interdependence of hydrogen production, storage, safety, and utilization are critical for achieving a fully renewable and sustainable hydrogen economy (Dawood et al., 2020). Energy storage systems, including green hydrogen, are crucial for supporting fully autonomous electrical grids, especially in remote areas, due to their modularity and ease of installation (Superchi et al., 2025). These systems must be designed to balance energy generation and demand, especially in isolated locations (Icaza et al., 2025). This balance ensures reliability and resilience in the face of fluctuating renewable energy sources (Cheng et al., 2025). These systems require robust monitoring and control to optimize performance and adapt to changing conditions (Useche-Arteaga et al., 2024) (Superchi et al., 2025). System Integration Theory can be applied to renewable energy on islands, addressing the complexity of integrating various renewable energy source technologies with existing grid infrastructure to account for the fluctuation of renewable energy sources and improve overall system performance through coordinated operation and control (Papadaki et al., 2025). It is essential to develop effective distribution networks and infrastructure to ensure the continuous supply of green hydrogen and further reduce production and delivery costs (Gómez & Castro, 2024). Such integration is important to guarantee that renewable energy sources are used efficiently and that hydrogen technologies can be effectively used to store energy (Zhang et al., 2016). What is often overlooked is identifying coherent, scalable strategies that connect technological development with practical implementation in specific sectors (Franco, 2025).

SIGNIFICANCE OF GREEN HYDROGEN IN THE ENERGY TRANSITION

The adaptability of power-to-hydrogen (P2H) facilities is essential for integrating fluctuating renewable energy sources and delivering supplementary regulatory functions (Qiu et al., 2023). Utilizing hydrogen as an energy storage medium allows for the retention of surplus energy generated by renewable sources rather than curtailment. Sensitivity analysis reveals that the capital cost and discount rate substantially influence the levelized cost of hydrogen generation and storage (Urs et al., 2023). Hydrogen is a promising energy carrier, capable of storing and transmitting substantial energy quantities, with prospective applications in transportation, industrial manufacturing, and heating (Preuster et al., 2017). Moreover, hydrogen generation by electrolysis can be used with renewable energy sources to alleviate the effects of fluctuation on power quality and grid stability (Nguyen et al., 2021). Hydrogen possesses a high energy density and is essential for mitigating the constraints of intermittent renewable energy supply by turning surplus electricity into hydrogen for storage and transportation (Lee et al., 2025). Hydrogen storage is a critical element of a hydrogen system, particularly for large-scale production; yet, existing systems encounter issues related to weight, volume, and hydrogen embrittlement (Meda et al., 2023). Hydrogen contributes to diminishing the carbon footprint in transportation, as it may be generated by electrolysis using excess solar and wind energy (Segovia-Hernandez et al., 2024). In the chemical sector, green hydrogen is essential for the manufacturing of ammonia and fertilizers, as well as for oil refining, hence fostering sustainable industrial practices (Segovia-Hernandez et al., 2024). Hydrogen provides seasonal energy storage solutions, mitigating variations in energy supply and demand (Superchi et al., 2025). Green hydrogen, generated through electrolysis from renewable sources, has environmental advantages by producing no greenhouse gases or air pollutants during combustion, however nitrogen oxides may be created under certain conditions (Nayebossadri et al., 2025). Its adaptability enables utilization across multiple sectors, including transportation, chemical processing, and power generation (Nayebossadri et al., 2025).

CURRENT STATE OF HYDROGEN PRODUCTION TECHNOLOGIES

Consequently, there has been increasing interest in green hydrogen production using electrolysis for large-scale renewable energy applications in various sectors (Kumar and Lim, 2022). Electrolysis-based hydrogen production offers a sustainable method that aligns with global decarbonization efforts, especially when powered by renewable energy sources like solar and wind (Hamedani et al., 2024). Numerous projects are focusing on hydrogen and related domains, reflecting the growing scientific and technical interest in this field (Franco and Giovannini, 2023). The integration of green hydrogen addresses the limitations of intermittent renewable energy sources by providing a sustainable pathway for energy storage and utilization (Kumar & Lim, 2022). Renewable energy sources have minimal greenhouse gas emissions and are abundant and sustainable, ensuring a dependable energy supply and aiding energy security (Mahmoud et al., 2024). These sources can power the production of hydrogen for use directly as fuel, synthetic fuels, ammonia, fertilizers, and heavy oil upgrading (Dinçer, 2011). The flexibility of hydrogen as an energy carrier makes it suitable for various applications, enhancing the overall efficiency and sustainability of energy systems (Ramu & Choi, 2025) (Agyekum et al., 2022). However, there is a need for studies optimizing hydrogen production, especially concerning the integration of offshore ammonia refueling stations (Zhang et al., 2025). Europe is at the forefront of research into these integrated energy systems, exemplified by Belgium's construction of Princess Elizabeth Island, designed as a central hub for offshore power generation (Zhang et al., 2025). Such efforts highlight the geographical synergies and technological potentials in leveraging wind and wave energy for hydrogen production (Xylia et al., 2023). This necessitates the exploration of innovative capacity configurations and operational simulations to fully realize the potential of offshore energy islands (Zhang et al., 2025).

The scalability of water electrolysis, particularly when powered by renewable sources, is crucial for converting electricity into hydrogen fuel, thereby addressing both the global energy crisis and environmental concerns (Fang et al., 2018) (Squadrito et al., 2023). More specifically, water electrolysis offers a method to produce high-purity hydrogen, driven by renewable energy sources like solar and wind power (Tufa et al., 2018). However, to meet the required cost targets, advancements in materials and manufacturing are essential (Ayers, 2019). Such systems can utilize the characteristics of large-scale, low-cost, and long-term sub-surface compressed hydrogen storage (Zhang et al., 2025). This method is particularly effective for producing low-carbon hydrogen in autonomous systems, though the production of large system components may present environmental and investment challenges (Terlouw et al., 2022). The versatility of ammonia, with its higher energy density per unit volume compared to compressed and liquid hydrogen, makes it suitable for long-distance marine transportation, utilizing existing infrastructure designed for liquefied petroleum gas (Zhang et al., 2025). Offshore wind power presents a promising and readily available energy source for large-scale hydrogen production, making it a viable option (Singlitico et al., 2021).

POLICY AND REGULATORY FRAMEWORKS FOR GREEN HYDROGEN

Europe needs comprehensive policy frameworks that eliminate market barriers and promote investment in renewable energy infrastructure, as well as clear standards for green hydrogen production to ensure environmental integrity (Papadaki et al., 2025). These frameworks should encourage the adoption of carbon capture and storage techniques and the replacement of fossil fuels with alternative energy sources (Papadaki et al., 2025). Also, optimized sizing methods can balance the costs and decarbonization of the system (Superchi et al., 2025). Governments can further support green hydrogen deployment by funding R&D, increasing renewable electricity supply, and implementing carbon pricing policies (Cammeraat et al., 2022). Such policies should reduce the cost disparity between green hydrogen and conventional technologies, promote international standardization, and foster sound regulatory standards (Cammeraat et al., 2022). These strategies will facilitate the transition to a greener and more sustainable energy landscape (Marouani et al., 2023). Hydrogen can also provide sustainability and energetic independence to Europe if produced from renewable sources within its borders, with water electrolysis combined with wind or photovoltaic power being the most mature and affordable technologies (Silva et al., 2024). Case studies in regions like the Canary Islands and remote Australian islands demonstrate the feasibility of 100% renewable energy systems using wind, solar, and green hydrogen, highlighting the potential for minimizing emissions and achieving energy independence (Superchi et al., 2025). These systems often struggle to meet essential water demands, and seawater desalination effectively utilizes renewable energy and enhances the flexibility of system controls in these areas (Zhao et al., 2025). These case studies emphasize the importance of community participation, public-private partnerships, and adaptive technologies in overcoming energy transition challenges on islands (Papadaki et al., 2025). Streamlining regulatory frameworks by simplifying licensing procedures is essential to reducing regulatory challenges, which can advance sustainable energy solutions, contributing to broader climate goals and energy security (Papadaki et al., 2025). The European Union should adopt a more detailed strategic approach for low-carbon hydrogen, specifying its role in transitioning to renewable hydrogen, ensuring positive climate impacts, and regulating imports (Abánades et al., 2017). This necessitates careful evaluation of production sources and timelines to prevent inefficiencies (Franco, 2025). The EU aims to produce 10 million tonnes of renewable hydrogen and import another 10 million tonnes by 2030, which is crucial for decarbonizing sectors that are difficult to electrify (Zeyen et al., 2023). To tackle these challenges, independent testing and validation of hydrogen technologies are essential to better inform policymakers, the public, researchers, and investors, and to accelerate the development of new technologies and strategies (Nayebossadri et al., 2025) (Franco, 2025). As hydrogen gains traction as a clean energy alternative, it is crucial to foster global economic development by using it as an energy storage medium across various sectors, including transportation and industry (Criollo et al., 2024). Considering the integration of renewable energies is key to a sustainable energy system, many nations are setting ambitious goals to boost the production of solar, wind, geothermal, hydro, and biomass energy, particularly in Europe (Preuster et al., 2017). Green hydrogen, produced from renewable sources like solar and wind, offers a versatile solution for decarbonizing multiple sectors and achieving net-zero emissions (Nayebossadri et al., 2025). Islands, with their geographical isolation and abundant renewable resources, are ideal candidates for deploying hybrid renewable energy systems, reducing energy costs, and increasing energy independence (Icaza et al., 2025) (Papadaki et al., 2025) (Iliadis et al., 2020). Islands' decentralized energy systems enable them to effectively integrate renewable energy sources, thereby enhancing their capacity for autonomy and adaptability (Papadaki et al., 2025). Also, countries are forming strategic partnerships to secure cheap hydrogen supplies for the future, as access to affordable hydrogen is a prerequisite for energy affordability in systems with high hydrogen proportions (Niepelt et al., 2023). Such collaborations are essential, given that future hydrogen markets are expected to mirror natural gas markets, potentially leading to similar geopolitical dynamics ("The Geopolitics of Renewable Hydrogen in Low-Carbon Energy Markets," 2020). Tailored solutions and strong regulatory support are vital, emphasizing the suitability of islands for renewable energy projects due to their isolation and high energy import costs (Papadaki et al., 2025). Developing countries with robust renewable energy resources have the potential to produce green hydrogen locally, thereby creating economic opportunities and enhancing energy security ("Green Hydrogen in Developing Countries," 2020).

THE POTENTIAL OF GREEN HYDROGEN IN EUROPE

The European Union has positioned itself at the forefront of the green hydrogen revolution through policies like:

- European Green Deal
- Hydrogen Strategy for a Climate-Neutral Europe
- REPowerEU plan, which targets 20 million tonnes of renewable hydrogen consumption by 2030.

Pilot H2-based steel production (Germany, Sweden) As Europe aims for its 2030 sustainability targets, decreasing the levelized cost of energy and optimizing trade flows will significantly influence its future energy landscape, turning to greener energy sources and decreasing the region's reliance on fossil fuels (Guarieiro et al., 2022). Focusing on hybrid renewable energy systems demonstrates the EU's dedication to decreasing greenhouse gas emissions, especially on islands with limited dimensions and geographical seclusion (Papadaki et al., 2025). Categorizing European islands based on their economic activities, such as tourism or industry, is crucial for understanding their specific energy needs and aligning energy strategies with their economic drivers (Papadaki et al., 2025). This categorization aids in deploying hybrid renewable energy systems tailored to the unique demands of each island (Papadaki et al., 2025). Such systems, combining various renewable energy sources and storage solutions, have shown promise in enhancing energy security and reducing carbon emissions (Papadaki et al., 2025). The production of 25 Mt/a of green hydrogen by 2040 would hedge against the risk of failing carbon capture and storage and green fuel imports, which requires subsidies but is unlikely to be overly expensive (Greevenbroek et al., 2024). Green hydrogen production is projected to constitute 95% of the world's hydrogen power production, positioning it as a crucial element in the global energy transition (Hidouri et al., 2025). Its versatility and emission reduction potential make it a cornerstone of future energy systems (Segovia-Hernandez et al., 2024). The EU anticipates that hydrogen will constitute 13–14% of its secondary energy consumption by 2050, with a significant portion derived from renewable sources (Brusiło et al., 2025). To achieve this, advancements in hydrogen storage, distribution, and transportation are essential, alongside supportive policies and infrastructure development (Guarieiro et al., 2022). Reports indicate that many hydrogen projects are being planned in Europe, highlighting the region's commitment to leveraging hydrogen for its energy transition (Agyekum et al., 2022). These initiatives will help in establishing a competitive hydrogen market and ensuring energy security (Niepelt et al., 2023). Given the EU's commitment to climate neutrality by 2050, offshore renewable energy sources, including wind, wave, and solar, are anticipated to play a vital role, especially when combined with energy storage solutions in floating offshore energy islands. These islands can convert electrical power into green hydrogen, which can then be stored and converted back to electricity, thus reaching total decarbonization of the energy system (Superchi et al., 2025). This integrated strategy considers the economic and environmental implications of hydrogen production, enabling the identification of optimal locations for large-scale production while accounting for cost and environmental constraints (Terlouw et al., 2024). The interconnection and interdependence of hydrogen production, storage, safety, and utilization must be considered to achieve a fully renewable and sustainable hydrogen economy (Dawood et al., 2020). By 2050, the demand for hydrogen energy is expected to increase tenfold compared to present levels, especially in regions like Japan, the United States, and Europe, where significant investments and innovations in hydrogen production, storage, and utilization are already underway (Jianghao, 2021). The high-energy content and clean by-products of green hydrogen position it as a viable alternative, in alignment with international agreements for a sustainable, low-emission future (Segovia-Hernandez et al., 2024).

Key projects include:

- The Hydrogen Backbone pipeline network
- The Princess Elisabeth Island offshore hub (Belgium)
- Pilot H2-based steel production (Germany, Sweden).

APPLICATIONS OF GREEN HYDROGEN IN EUROPEAN INDUSTRIES

Hydrogen can be effectively utilized in the mobility sector, industrial production, and heat market, which may significantly enhance its economic value (Preuster et al., 2017). In the marine transportation sector, for example, ammonia produced from hydrogen is expected to fuel approximately 45% of ships by 2050, which will help to achieve emission reduction targets (Zhang et al., 2025). To further reduce emissions, offshore energy islands can integrate offshore wind power, hydrogen energy, energy storage, and offshore refueling stations (Zhang et al., 2025). Hydrogen stands out as a promising energy carrier because of its high energy density, but conventional production methods that depend on fossil fuels result in carbon dioxide emissions (Wu et al., 2025). Therefore, green hydrogen production methods are essential to mitigate environmental damages caused by the combustion of fossil fuels (Dinçer, 2011). This can be achieved via electrolysis, which offers the advantage of converting surplus renewable energy into hydrogen (Zhao et al., 2025) (Nayebossadri et al., 2025).

INTERNATIONAL COLLABORATIONS IN GREEN HYDROGEN DEVELOPMENT

Comparative Case Studies of Global Hydrogen Strategies The development and deployment of green hydrogen technologies vary significantly across regions, shaped by national priorities, resource endowments, policy environments, and levels of technological readiness. A comparative analysis of key global players illustrates how different countries adopt tailored strategies to position themselves within the emerging hydrogen economy. 6.1 Japan and South Korea: Hydrogen Import and Fuel Cell Mobility Japan and South Korea have adopted hydrogen-centric strategies focused primarily on energy security and transport sector decarbonization. With limited domestic renewable energy potential, both countries have turned to the import of green hydrogen and its derivatives—notably ammonia—from resource-rich regions. Their national roadmaps emphasize the deployment of hydrogen fuel cell technologies in public transportation, passenger vehicles, and stationary power systems. Japan's "Basic Hydrogen Strategy" and South Korea's "Hydrogen Economy Roadmap" include clear targets for the number of fuel cell vehicles, refueling stations, and hydrogen power plants by 2030 and beyond. Both countries are also investing in international supply chain agreements with partners such as Australia, Saudi Arabia, and Chile. 6.2 Australia and Chile: Hydrogen Export Leadership Australia and Chile leverage their abundant renewable resources (solar and wind) to become major green hydrogen exporters. Both countries have developed hydrogen strategies centered on producing low-cost hydrogen for international markets, particularly targeting Northeast Asia and Europe. Australia's "National Hydrogen Strategy" supports large-scale hydrogen hubs, while Chile's strategy envisions the country as the world's lowest-cost producer of green hydrogen by 2030. These strategies are supported by government incentives, pilot projects, and foreign investment in electrolyzer capacity and port infrastructure. 6.3 Germany and the Netherlands: Industrial Decarbonization and Infrastructure Development Germany and the Netherlands are positioning themselves as industrial leaders in hydrogen deployment, particularly within the steel, chemicals, and refining sectors. Their strategies prioritize the integration of green hydrogen into hard-to-abate industrial processes and the construction of cross-border infrastructure, including pipelines, terminals, and storage facilities. Germany's "National Hydrogen Strategy" includes €9 billion in funding, with a strong emphasis on electrolyzer deployment, while the Netherlands focuses on developing the Hydrogen Backbone pipeline network, enabling cross-border trade and domestic distribution of green hydrogen. Both countries are also investing in hydrogen valleys, R&D, and certification systems to facilitate market development. 6.4 Island Nations: Autonomous Energy Systems with Hybrid RES-H_2 Solutions Island nations such as Iceland, Fiji, and several EU overseas territories face unique energy challenges due to isolation and dependence on imported fossil fuels. These regions are emerging as testing grounds for fully autonomous energy systems integrating renewable energy sources (RES) with green hydrogen production and storage. Projects often combine photovoltaic (PV) and wind power with water electrolysis and hydrogen fuel cells, enabling energy self-sufficiency and zero-emission electricity generation. These systems also serve as real-world laboratories for optimizing energy balancing, grid stability, and hybrid storage configurations under variable renewable inputs. 6.5 Lessons Learned These case studies underscore the importance of context-specific strategies. Countries with limited renewable resources emphasize import and fuel cell deployment, while resource-rich nations focus on export-oriented hydrogen production. Industrialized economies prioritize infrastructure and decarbonization of heavy industry, and remote island regions explore decentralized hydrogen systems for energy autonomy. The pace and scale of green hydrogen adoption depend heavily on: Policy and regulatory frameworks Access to low-cost renewable energy Infrastructure readiness Stakeholder coordination International cooperation Understanding these diverse approaches helps identify best practices and transferable models that can support global green hydrogen development.

CONCLUSION

Green hydrogen has progressed from a conceptual decarbonisation vector to a cornerstone of net-zero roadmaps across industry, transport, power and agriculture. Its advantages—zero-carbon production (when powered by renewables), high gravimetric energy density, and versatility as both fuel and feedstock—make it uniquely capable of displacing fossil-derived energy carriers in hard-to-abate sectors while simultaneously providing long-duration energy storage. Europe's policy leadership, the rapid fall in renewable-electricity costs, and a surge of pilot projects on islands and industrial hubs collectively demonstrate that large-scale green-hydrogen systems are technically feasible and increasingly bankable.

Yet the analysis also reveals a set of persistent constraints—chiefly high electrolyser CAPEX and electricity costs, immature value-chain infrastructure, limited water availability in arid and offshore settings, and an absence of harmonised certification and trade standards. Overcoming these barriers will require coordinated advances in technology, finance, regulation and social acceptance. Future research should prioritize lowering electrolyzer capital costs via earth-abundant catalysts and scalable manufacturing, advancing large-scale hydrogen storage and grid-integrated infrastructure, and establishing harmonized safety and life-cycle standards for renewable hydrogen systems.

ACKNOWLEDGEMENTS

This paper is supported by the Ministry of Science, Technological Development and Innovation of the Republic of Serbia pursuant to agreement № 451-03-66/2024-03/ 200148 with the University of Niš, Faculty of Occupational Safety.

REFERENCES

Abánades, J. C., Rubin, E. S., Mazzotti, M., & Herzog, H. J. (2017). On the climate change mitigation potential of CO2 conversion to fuels. Energy & Environmental Science, 10(12), 2491. https://doi.org/10.1039/c7ee02819a

Agyekum, E. B., Nutakor, C., Agwa, A. M., & Kamel, S. (2022). A Critical Review of Renewable Hydrogen Production Methods: Factors Affecting Their Scale-Up and Its Role in Future Energy Generation [Review of A Critical Review of Renewable Hydrogen Production Methods: Factors Affecting Their Scale-Up and Its Role in Future Energy Generation]. Membranes, 12(2), 173. Multidisciplinary Digital Publishing Institute. https://doi.org/10.3390/membranes12020173

Ayers, K. E. (2019). The potential of proton exchange membrane–based electrolysis technology. Current Opinion in Electrochemistry, 18, 9. https://doi.org/10.1016/j.coelec.2019.08.008

Baral, S., & Šebo, J. (2024). Techno-economic assessment of green hydrogen production integrated with hybrid and organic Rankine cycle (ORC) systems. Heliyon, 10(4). https://doi.org/10.1016/j.heliyon.2024.e25742

Bauer, C., Treyer, K., Antonini, C., Bergerson, J., Gazzani, M., Gençer, E., Gibbins, J., Mazzotti, M., McCoy, S., McKenna, R., Pietzker, R., Ravikumar, A., Romano, M. C., Ueckerdt, F., Vente, J. F., & Spek, M. van der. (2021). On the climate impacts of blue hydrogen production. https://doi.org/10.33774/chemrxiv-2021-hz0qp

Brusiło, P., Węgrzyn, A., Graczyk, A., & Graczyk, A. M. (2025). Hydrogen SWOT Analysis of Poland's Energy Transition. Energies, 18(7), 1789. https://doi.org/10.3390/en18071789

Cammeraat, E., Dechezleprêtre, A., & Lalanne, G. (2022). Innovation and industrial policies for green hydrogen. In OECD science, technology and industry policy papers. https://doi.org/10.1787/f0bb5d8c-en

Cheng, J., Meng, J., Bao, G., & Hu, X. (2025). Control of DC Bus Voltage in a 10 kV Off-Grid Wind–Solar–Hydrogen Energy Storage System. Energies, 18(9), 2328. https://doi.org/10.3390/en18092328

Chiroșcă, A.-M., Rusu, E., & Mînzu, V. (2024). Green Hydrogen—Production and Storage Methods: Current Status and Future Directions. Energies, 17(23), 5820. https://doi.org/10.3390/en17235820

Criollo, A., Minchala, L. I., Benavides, D., Ochoa-Correa, D., Tostado-Véliz, M., Meteab, W. K., & Jurado, F. (2024). Green Hydrogen Production—Fidelity in Simulation Models for Technical–Economic Analysis. Applied Sciences, 14(22), 10720. https://doi.org/10.3390/app142210720

Curcio, E. (2025). Techno-Economic Analysis of Hydrogen Production: Costs, Policies, and Scalability in the Transition to Net-Zero. arXiv (Cornell University). https://doi.org/10.48550/arxiv.2502.12211

Dawood, F., Anda, M., & Shafiullah, G. (2020). Hydrogen production for energy: An overview. International Journal of Hydrogen Energy, 45(7), 3847. https://doi.org/10.1016/j.ijhydene.2019.12.059

Dinçer, İ. (2011). Green methods for hydrogen production. International Journal of Hydrogen Energy, 37(2), 1954. https://doi.org/10.1016/j.ijhydene.2011.03.173

Fang, Y., Zhou, H., Huang, Y., Sun, J., Qin, F., Bao, J., Goddard, W. A., Chen, S., & Ren, Z. (2018). High-performance bifunctional porous non-noble metal phosphide catalyst for overall water splitting. Nature Communications, 9(1). https://doi.org/10.1038/s41467-018-04746-z

Franco, A. (2025). Green Hydrogen and the Energy Transition: Hopes, Challenges, and Realistic Opportunities. Hydrogen, 6(2), 28. https://doi.org/10.3390/hydrogen6020028

Franco, A., & Giovannini, C. (2023). Recent and Future Advances in Water Electrolysis for Green Hydrogen Generation: Critical Analysis and Perspectives. Sustainability, 15(24), 16917. https://doi.org/10.3390/su152416917

Franzmann, D., Heinrichs, H., Lippkau, F., Addanki, T., Winkler, C., Buchenberg, P., Hamacher, T., Blesl, M., Linßen, J., & Stolten, D. (2023). Green hydrogen cost-potentials for global trade. International Journal of Hydrogen Energy, 48(85), 33062. https://doi.org/10.1016/j.ijhydene.2023.05.012

Gómez, J. L., & Castro, R. (2024). Green Hydrogen Energy Systems: A Review on Their Contribution to a Renewable Energy System [Review of Green Hydrogen Energy Systems: A Review on Their Contribution to a Renewable Energy System]. Energies, 17(13), 3110. Multidisciplinary Digital Publishing Institute. https://doi.org/10.3390/en17133110

Graaf, T. V. de, Øverland, I., Scholten, D., & Westphal, K. (2020). The new oil? The geopolitics and international governance of hydrogen. Energy Research & Social Science, 70, 101667. https://doi.org/10.1016/j.erss.2020.101667

Green Hydrogen in Developing Countries. (2020). In World Bank, Washington, DC eBooks. https://doi.org/10.1596/34398

Greevenbroek, K. van, Schmidt, J., Zeyringer, M., & Horsch, A. (2024). Little to lose: the case for a robust European green hydrogen strategy. arXiv (Cornell University). https://doi.org/10.48550/arxiv.2412.07464

Guarieiro, L. L. N., Anjos, J. P. dos, Silva, L. da, Santos, A. Á. B., Calixto, E. E. da S., Pessoa, F. L. P., Almeida, J. de, Filho, M. A., Marinho, F. de S., Rocha, G. O. da, & Andrade, J. B. de. (2022). Technological Perspectives and Economic Aspects of Green Hydrogen in the Energetic Transition: Challenges for Chemistry. Journal of the Brazilian Chemical Society. https://doi.org/10.21577/0103-5053.20220052

Hamedani, E. A., Alenabi, S. A., & Talebi, S. (2024). Hydrogen as an energy source: A review of production technologies and challenges of fuel cell vehicles [Review of Hydrogen as an energy source: A review of production technologies and challenges of fuel cell vehicles]. Energy Reports, 12, 3778. Elsevier BV. https://doi.org/10.1016/j.egyr.2024.09.030

Han, Z., Yuan, S., Dong, Y., Ma, S., Bian, Y., & Mao, X. (2022). Research on the Flexibility Margin of an Electric–Hydrogen Coupling Energy Block Based on Model Predictive Control. Frontiers in Energy Research, 10. https://doi.org/10.3389/fenrg.2022.879244

Hartley, P. G., & Au, V. (2020). Towards a Large-Scale Hydrogen Industry for Australia. Engineering, 6(12), 1346. https://doi.org/10.1016/j.eng.2020.05.024

Hidouri, D., Omrane, I. B., Khalil, K., & Chérif, A. (2025). Energy Management of a 1 MW Photovoltaic Power-to-Electricity and Power-to-Gas for Green Hydrogen Storage Station. World Electric Vehicle Journal, 16(4), 227. https://doi.org/10.3390/wevj16040227

Icaza, D., Jurado, F., Østergaard, P. A., Tostado-Véliz, M., & Flores-Vázquez, C. (2025). Cornerstones for greater participation of smart renewable energy on clustered islands: The case of Guayas in Ecuador towards 2050. Energy Reports, 13, 1350. https://doi.org/10.1016/j.egyr.2025.01.006

Iliadis, P., Ntomalis, S., Atsonios, K., Nesiadis, A., Nikolopoulos, N., & Grammelis, P. (2020). Energy management and techno-economic assessment of a predictive battery storage system applying a load levelling operational strategy in island systems. International Journal of Energy Research, 45(2), 2709. https://doi.org/10.1002/er.5963

James, N., & Menzies, M. (2022). Spatio-temporal trends in the propagation and capacity of low-carbon hydrogen projects. International Journal of Hydrogen Energy, 47(38), 16775. https://doi.org/10.1016/j.ijhydene.2022.03.198

Jianghao, N. (2021). Research on the Hydrogen Production Technology. IOP Conference Series Earth and Environmental Science, 813(1), 12004. https://doi.org/10.1088/1755-1315/813/1/012004

Kumar, S. S., & Lim, H. (2022). An overview of water electrolysis technologies for green hydrogen production. Energy Reports, 8, 13793. https://doi.org/10.1016/j.egyr.2022.10.127

Lapi, T., Chatzimpiros, P., Raineau, L., & Prinzhofer, A. (2022). System approach to natural versus manufactured hydrogen: An interdisciplinary perspective on a new primary energy source. International Journal of Hydrogen Energy, 47(51), 21701. https://doi.org/10.1016/j.ijhydene.2022.05.039

Le, P.-A., Trung, V. D., Nguyen, P. L., Phung, T. V. B., Natsuki, J., & Natsuki, T. (2023). The current status of hydrogen energy: an overview [Review of The current status of hydrogen energy: an overview]. RSC Advances, 13(40), 28262. Royal Society of Chemistry. https://doi.org/10.1039/d3ra05158g

Lee, J., Lee, S. A., Lee, T. H., & Jang, H. W. (2025). Unlocking the potential of chemical-assisted water electrolysis for green hydrogen production. Industrial Chemistry and Materials. https://doi.org/10.1039/d4im00163j

Mahmoud, M., Semeraro, C., Abdelkareem, M. A., & Olabi, A. G. (2024). Designing and Prototyping the Architecture of a Digital Twin for Wind Turbine. International Journal of Thermofluids, 22, 100622. https://doi.org/10.1016/j.ijft.2024.100622

Marocco, P., Novo, R., Lanzini, A., Mattiazzo, G., & Santarelli, M. (2022). Towards 100% renewable energy systems: The role of hydrogen and batteries. Journal of Energy Storage, 57, 106306. https://doi.org/10.1016/j.est.2022.106306

Marouani, I., Guesmi, T., Alshammari, B. M., Alqunun, K., Alzamil, A., Alturki, M., & Abdallah, H. H. (2023). Integration of Renewable-Energy-Based Green Hydrogen into the Energy Future. Processes, 11(9), 2685. https://doi.org/10.3390/pr11092685

McQueen, S., Stanford, J., Satyapal, S., Miller, E. L., Stetson, N., Papageorgopoulos, D., Rustagi, N., Arjona, V., Adams, J., Randolph, K., Peterson, D., Hill, L., Koleva, M., Reinhardt, T., Frye, E., Schrecengost, R., Kokkinos, A., Litynski, J., Conrad, R., … Costa, R. T. da. (2020). Department of Energy Hydrogen Program Plan. https://doi.org/10.2172/1721803

Meda, U. S., Bhat, N., Pandey, A., Subramanya, K. N., & Raj, M. A. L. A. (2023). Challenges associated with hydrogen storage systems due to the hydrogen embrittlement of high strength steels. International Journal of Hydrogen Energy, 48(47), 17894. https://doi.org/10.1016/j.ijhydene.2023.01.292

Mekonnin, A. S., Wacławiak, K., Humayun, M., Zhang, S., & Ullah, H. (2025). Hydrogen Storage Technology, and Its Challenges: A Review [Review of Hydrogen Storage Technology, and Its Challenges: A Review]. Catalysts, 15(3), 260. Multidisciplinary Digital Publishing Institute. https://doi.org/10.3390/catal15030260

Nayebossadri, S., Walsh, M., & Smailes, M. (2025). An Overview of the Green Hydrogen Value Chain Technologies and Their Challenges for a Net-Zero Future. https://doi.org/10.20944/preprints202503.1114.v1

Nguyen, B. L.-H., Panwar, M., Hovsapian, R., Nagasawa, K., & Vu, T. (2021). Power Converter Topologies for Electrolyzer Applications to Enable Electric Grid Services. IECON 2020 The 46th Annual Conference of the IEEE Industrial Electronics Society, 1. https://doi.org/10.1109/iecon48115.2021.9589044

Niepelt, R., Schlemminger, M., Bredemeier, D., Peterssen, F., Lohr, C., Bensmann, A., Hanke-Rauschenbach, R., & Brendel, R. (2023). The Influence of Falling Costs for Electrolyzers on the Location Factors for Green Hydrogen Production. Solar RRL, 7(17). https://doi.org/10.1002/solr.202300317

Noussan, M., Raimondi, P. P., Scita, R., & Häfner, M. (2020). The Role of Green and Blue Hydrogen in the Energy Transition—A Technological and Geopolitical Perspective. Sustainability, 13(1), 298. https://doi.org/10.3390/su13010298

Offshore renewable energies: A review towards Floating Modular Energy Islands—Monitoring, Loads, Modelling and Control. (2024). https://ezproxy.nb.rs:2055/science/article/pii/S0029801824025897

Papadaki, A., Savvakis, N., Sifakis, N., & Arampatzis, G. (2025). Analysis of Hybrid Renewable Energy Systems for European Islands: Market Dynamics, Opportunities and Challenges. Sustainable Futures, 100601. https://doi.org/10.1016/j.sftr.2025.100601

Preuster, P., Alekseev, A. S., & Wasserscheid, P. (2017). Hydrogen Storage Technologies for Future Energy Systems [Review of Hydrogen Storage Technologies for Future Energy Systems]. Annual Review of Chemical and Biomolecular Engineering, 8(1), 445. Annual Reviews. https://doi.org/10.1146/annurev-chembioeng-060816-101334

Qiu, Y., Zhou, B., Zang, T., Zhou, Y., Chen, S., Qi, R., Li, J., & Lin, J. (2023). Extended load flexibility of utility-scale P2H plants: Optimal production scheduling considering dynamic thermal and HTO impurity effects. Renewable Energy, 217, 119198. https://doi.org/10.1016/j.renene.2023.119198

Ramu, A. G., & Choi, D. (2025). Interfacial water engineering for enhanced pure water electrolysis. Scientific Reports, 15(1). https://doi.org/10.1038/s41598-025-98853-9

Reyes-Barquet, L. M., Rico-Contreras, J. O., Azzaro-Pantel, C., Moras-Sánchez, C. G., González-Huerta, M. Á., Vásquez, D. V., & Aguilar-Lasserre, A. A. (2022). Multi-Objective Optimal Design of a Hydrogen Supply Chain Powered with Agro-Industrial Wastes from the Sugarcane Industry: A Mexican Case Study. Mathematics, 10(3), 437. https://doi.org/10.3390/math10030437

Segovia-Hernandez, J. G., Hernández, S., Cossío-Vargas, E., Juárez-García, M., & Sánchez-Ramírez, E. (2024). Green Hydrogen Production for Sustainable Development: A Critical Examination of Barriers and Strategic Opportunities. RSC Sustainability. https://doi.org/10.1039/d4su00630e

Silva, H., Merrouni, A. A., Touili, S., & Neto, J. A. (2024). Determination of photovoltaic hydrogen production potential in Portugal: a techno-economic analysis. Frontiers in Energy Research, 12. https://doi.org/10.3389/fenrg.2024.1380543

Singlitico, A., Østergaard, J., & Chatzivasileiadis, S. (2021). Onshore, offshore or in-turbine electrolysis? Techno-economic overview of alternative integration designs for green hydrogen production into Offshore Wind Power Hubs. Renewable and Sustainable Energy Transition, 1, 100005. https://doi.org/10.1016/j.rset.2021.100005

Squadrito, G., Maggio, G., & Nicita, A. (2023). The green hydrogen revolution. Renewable Energy, 216, 119041. https://doi.org/10.1016/j.renene.2023.119041

Superchi, F., Bianchini, A., Moustakis, A., & Pechlivanoglou, G. (2025). Towards Sustainable Energy Independence: A Case Study of Green Hydrogen as Seasonal Storage Integration in a Small Island. Renewable Energy, 122813. https://doi.org/10.1016/j.renene.2025.122813

Tang, W., Tan, Q., & Cai, R. (2022). Current situation analysis of electrohydrogen production under the background of "Carbon Neutralization." IOP Conference Series Earth and Environmental Science, 983(1), 12035. https://doi.org/10.1088/1755-1315/983/1/012035

Tebibel, H. (2021). Methodology for multi-objective optimization of wind turbine/battery/electrolyzer system for decentralized clean hydrogen production using an adapted power management strategy for low wind speed conditions. Energy Conversion and Management, 238, 114125. https://doi.org/10.1016/j.enconman.2021.114125

Terlouw, T., Bauer, C., McKenna, R., & Mazzotti, M. (2022). Large-scale hydrogen production via water electrolysis: a techno-economic and environmental assessment. Energy & Environmental Science, 15(9), 3583. https://doi.org/10.1039/d2ee01023b

Terlouw, T., Rosa, L., Bauer, C., & McKenna, R. (2024). Future hydrogen economies imply environmental trade-offs and a supply-demand mismatch. Nature Communications, 15(1). https://doi.org/10.1038/s41467-024-51251-7

The Geopolitics of Renewable Hydrogen in Low-Carbon Energy Markets. (2020). Geopolitics History and International Relations, 12(1), 7. https://doi.org/10.22381/ghir12120201

Tufa, R. A., Hnát, J., Němeček, M., Kodým, R., Curcio, E., & Bouzek, K. (2018). Hydrogen production from industrial wastewaters: An integrated reverse electrodialysis - Water electrolysis energy system. Journal of Cleaner Production, 203, 418. https://doi.org/10.1016/j.jclepro.2018.08.269

Urs, R. R., Chadly, A., Al-Sumaiti, A. S., & Mayyas, A. (2023). Techno-economic analysis of green hydrogen as an energy-storage medium for commercial buildings. Clean Energy, 7(1), 84. https://doi.org/10.1093/ce/zkac083

Useche-Arteaga, M., Gomis-Bellmunt, O., Cheah-Mañé, M., Lacerda, V. A., & Gebraad, P. (2024). AC energy islands for the optimal integration of offshore wind energy resources: Operation strategies using multi-objective nonlinear programming. Sustainable Energy Grids and Networks, 101576. https://doi.org/10.1016/j.segan.2024.101576

Vedrtnam, A., Kalauni, K., & Pahwa, R. (2025). Water Electrolysis Technologies and Their Modeling Approaches: A Comprehensive Review [Review of Water Electrolysis Technologies and Their Modeling Approaches: A Comprehensive Review]. Eng—Advances in Engineering, 6(4), 81. Multidisciplinary Digital Publishing Institute. https://doi.org/10.3390/eng6040081

Veras, T. da S., Mozer, T. S., Santos, D. da C. R. M. dos, & César, A. da S. (2016). Hydrogen: Trends, production and characterization of the main process worldwide. International Journal of Hydrogen Energy, 42(4), 2018. https://doi.org/10.1016/j.ijhydene.2016.08.219

Verhelst, S., & Wallner, T. (2009). Hydrogen-fueled internal combustion engines. Progress in Energy and Combustion Science, 35(6), 490. https://doi.org/10.1016/j.pecs.2009.08.001

Wu, L., Xu, Y., Wang, Q., Zou, X., Pan, Z., Leung, M. K. H., & An, L. (2025). Direct seawater electrolysis for green hydrogen production: electrode designs, cell configurations, and system integrations. Energy & Environmental Science. https://doi.org/10.1039/d5ee01093d

Wu, Q., Long, P., Han, G., Shu, J., Yuan, M., & Wang, B. (2025). Deep-Learning-Based Scheduling Optimization of Wind-Hydrogen-Energy Storage System on Energy Islands. Energy, 135107. https://doi.org/10.1016/j.energy.2025.135107

Xie, Z., Jin, Q., Su, G., & Lu, W. (2024). A Review of Hydrogen Storage and Transportation: Progresses and Challenges [Review of A Review of Hydrogen Storage and Transportation: Progresses and Challenges]. Energies, 17(16), 4070. Multidisciplinary Digital Publishing Institute. https://doi.org/10.3390/en17164070

Xylia, M., Passos, M. V., Piseddu, T., & Barquet, K. (2023). Exploring multi-use platforms: A literature review of marine, multifunctional, modular, and mobile applications (M4s) [Review of Exploring multi-use platforms: A literature review of marine, multifunctional, modular, and mobile applications (M4s)]. Heliyon, 9(6). Elsevier BV. https://doi.org/10.1016/j.heliyon.2023.e16372

Zeyen, E., Victoria, M., & Brown, T. (2023). Endogenous learning for green hydrogen in a sector-coupled energy model for Europe. Nature Communications, 14(1). https://doi.org/10.1038/s41467-023-39397-2

Zhang, F., Zhao, P., Niu, M., & Maddy, J. (2016). The survey of key technologies in hydrogen energy storage. International Journal of Hydrogen Energy, 41(33), 14535. https://doi.org/10.1016/j.ijhydene.2016.05.293

Zhang, W., Li, Q., Yuan, J., & Xu, C. (2025). Configuration optimization of offshore energy islands coupled with ammonia refueling station and submarine salt cavern hydrogen storage. International Journal of Hydrogen Energy, 113, 669. https://doi.org/10.1016/j.ijhydene.2025.02.481

Zhao, W., Wang, B., Pan, T., Chen, Y., Tao, H., Guo, B., Varbanov, P. S., & Lu, J. (2025). Optimisation of island integrated energy system based on marine renewable energy.

Zhao, Y., Yuan, H., Liu, X., Zhang, J., Song, J., & Wang, H. (2025). Zero-carbon energy system for offshore Islands: Integrating freeze desalination, hydrogen storage, and fuel cells. Applied Thermal Engineering, 126702. https://doi.org/10.1016/j.applthermaleng.2025.126702

Zhu, D., Yang, B., Liu, Q., Ma, K., Zhu, S., Ma, C., & Guan, X. (2020). Energy trading in microgrids for synergies among electricity, hydrogen and heat networks. Applied Energy, 272, 115225. https://doi.org/10.1016/j.apenergy.2020.115225