*38th International Electric Vehicle Symposium and Exhibition (EVS38) Go¨teborg, Sweden, June 15-18, 2025*

# Challenges and opportunities of hydrogen electric vehicles for zero-emission mobility

Micari S., Costanzo L., Scardino A., Napoli G.
*National Research Council of Italy Institute of Advanced Technologies for Energy, Messina, 98126, Italy*
*salvatore.micari@cnr.it*

Executive Summary

Fuel Cell Electric Vehicles (FCEVs) are pivotal in the shift to zero-emission mobility, offering significant advantages over traditional combustion engines and complementing Battery Electric Vehicles (BEVs). However, different challenges must still be overcome for widespread technological implementation. Countries such as the USA, Europe and Japan are advancing energy transition processes where hydrogen plays a central role in achieving zero-emission mobility and climate neutrality. Nonetheless, several challenges remain in terms of costs, hydrogen production, storage systems, infrastructure networks and regulatory framework. System efficiency, supply chain sustainability, and infrastructure scalability emerge as key factors. This study explores the state of the art and the main experience currently underway, focusing on the challenges and opportunities for zero-emission vehicles that use hydrogen as an energy carrier for propulsion.

*Keywords: Fuel Cell electric Vehicles, Hybrid Electric Vehicles, Fuel Cell System, Environmental impact, Sustainable Energy*

## 1 Introduction

The transition toward zero-emission mobility represents one of the most critical global challenges in addressing environmental issues and combating climate change. In 2023, almost 14 million new electric cars were registered worldwide, increasing the total number of EVs on the road to 40 million [1] (Figure 1).

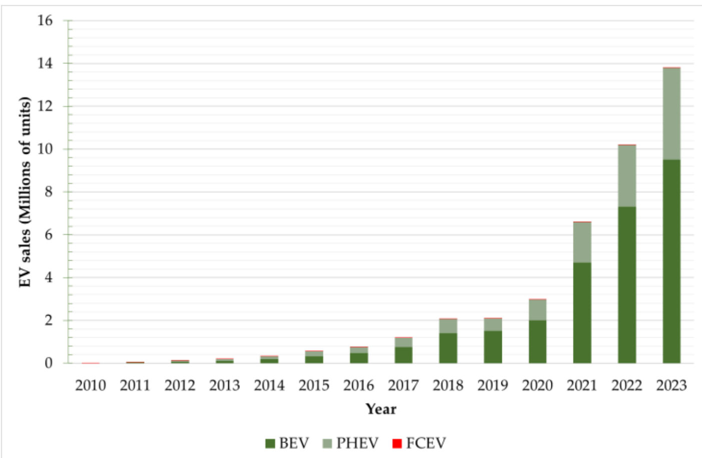


Figure 1:EV sales worldwide

Globally, the transport sector is responsible for approximately 25% of greenhouse gas emissions, remaining heavily reliant on fossil fuels [2], [3] (Figure 2).

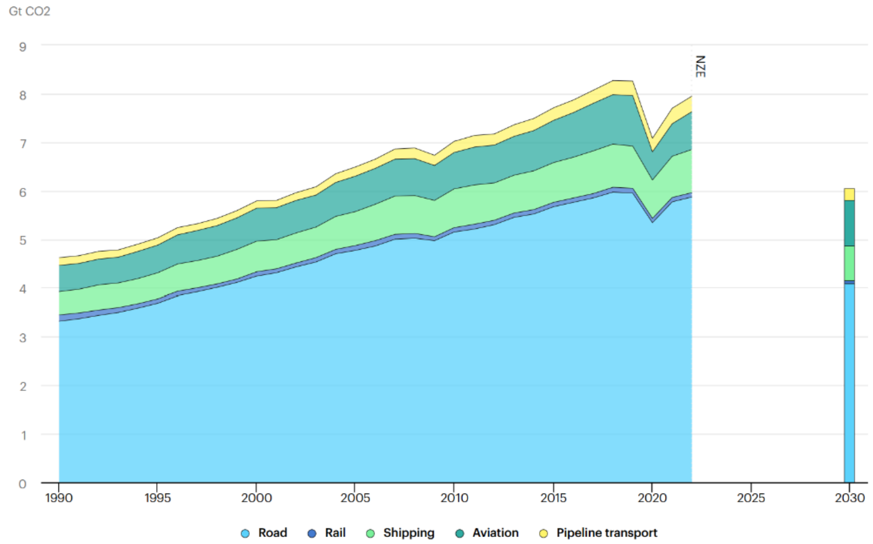


Figure 2: Global CO2 emissions from transport by sub-sector in the Net Zero Scenario, 2000-2030 *[3]*

In the European Union, this share rises to around 29% of total greenhouse gas emissions, underlining the urgent need for decarbonization strategies within the sector [4]. In this context, the European Commission has established ambitious targets to drastically reduce transport-related emissions, aligning with the broader objective of achieving climate neutrality by 2050. Key among these initiatives in Europe are the EU Hydrogen Strategy [5] and the REPowerEU plan [6], which provide a comprehensive framework to accelerate the deployment of renewable and low-carbon hydrogen across multiple sectors, with a particular focus on transport decarbonization. The European Green Deal [7] and the Sustainable and Smart Mobility Strategy [8], foresee a significant shift toward zero-emission vehicles and the decarbonization of transport infrastructure. This roadmap promotes the adoption of alternative fuels, identifying hydrogen as a cornerstone for decarbonizing sectors that are difficult to electrify, such as heavy-duty road transport, rail, aviation, and maritime shipping. The EU Hydrogen Strategy reinforces this vision by setting specific objectives: scaling up renewable hydrogen production to 10 million tonnes per year by 2030, establishing cross-border infrastructure, and fostering industrial applications. The strategy emphasizes hydrogen's pivotal role in sector coupling, enabling surplus renewable electricity to be stored, transported, and flexibly utilized across various end-uses, enhancing the resilience of the energy system. Supporting this vision, the Clean Hydrogen Partnership [9] plays a central role in advancing hydrogen and fuel cell technologies. Together, these strategies and initiatives constitute a comprehensive effort by the European Union to position hydrogen and fuel cell technologies at the core of the energy transition, particularly within the transport sector, where they are critical for achieving the decarbonization targets outlined in the European Green Deal. Beyond Europe, several major economies are also advancing hydrogen strategies and decarbonization initiatives to transform their transport sectors and achieve climate targets. Japan, for instance, has established itself as a global leader in hydrogen deployment, with a strong focus on building an extensive refueling infrastructure and promoting hydrogen applications across mobility, industry, and power generation. Japan's Basic Hydrogen Strategy [10], first adopted in 2017, aims to position hydrogen as a key pillar of its long-term energy policy, with concrete targets such as reducing the cost of hydrogen and expanding the number of hydrogens refueling stations. Similarly, the United States is intensifying its focus on clean hydrogen through U.S. National Hydrogen Strategy and Roadmap [11]. Its provides a comprehensive framework to scale up hydrogen production, transport, storage, and utilization across multiple sectors. It establishes clear targets, market-driven metrics, and fosters collaboration among federal agencies, industry, academia, and communities to accelerate hydrogen deployment and support national decarbonization and energy transition objectives [12]. China is also accelerating investments in hydrogen technologies as part of its broader decarbonization strategy [13]. The Chinese government has set targets for deploying FCEVs and supporting the build-out of hydrogen infrastructure [14]. Hydrogen-powered mobility, particularly through FCEVs, emerge as a key element in the transition toward zero-emission transport. While BEVs are well-suited for urban and medium-range applications, FCEVs prove advantageous in long-range freight and heavy-duty sectors, where greater autonomy and shorter refueling times are essential. Despite growing interest in hydrogen as a solution for decarbonizing mobility, several structural challenges continue to limit its large-scale adoption. One of the most significant issues is the high production cost of hydrogen, and in particular for green hydrogen, which, although considered the most sustainable option due to its generation via electrolysis powered by renewable energy, remains economically uncompetitive compared to fossil-based alternatives such as grey or blue hydrogen [15], [16]. This cost disparity is primarily driven by the expensive electrolyzers [17], [18] and the reliance on stable renewable electricity supplies [19]. Another critical barrier relates to the overall energy efficiency of FCEVs compared to BEVs. The hydrogen value chain, from production to end-use in vehicles, requires multiple energy conversion stages (production, compression or liquefaction, transportation, and reconversion into electricity), each of which introduces energy losses. Consequently, FCEVs exhibit lower well-to-wheel efficiency than BEVs, which use electricity more directly with minimal intermediate transformations [20]. Additionally, the storage and transportation of hydrogen present major hurdles for hydrogen mobility. Due to hydrogen's low volumetric energy density, it must be either compressed at high pressures (350-700 bar) or liquefied at cryogenic temperatures (-253°C), both of which involve significant infrastructure investments and increase overall system costs. While solid-state storage technologies, such as metal hydrides and adsorbent materials, offer promising pathways to improve storage efficiency, they are still in early development stages and not yet commercially viable at scale [21]. The limited refueling infrastructure [22] also poses a significant constraint. One of the most persistent obstacles to scaling up hydrogen mobility lies in the limited availability and high costs of refueling infrastructure, which remains significantly underdeveloped when compared to electric charging networks. The hydrogen supply chain, encompassing production facilities, distribution networks, and refueling stations, faces substantial logistical and economic challenges [23]. The paper is structured as follows: after an overview of the climate context and policy strategies supporting zero-emission transport, the paper is structured as follows: Section 2 analyzes the role of hydrogen in mobility by comparing fuel cell and battery electric vehicles, highlighting their respective advantages across different transport segments. Section 3 focuses on hydrogen production, storage technologies, and distribution infrastructure for mobility, including pipeline networks, refueling stations, and the emergence of Hydrogen Valleys. Section 4 discusses the main challenges and future opportunities related to hydrogen mobility, such as efficiency gaps, infrastructure limitations, and material innovations. Finally, Section 5 presents the conclusions, summarizing key findings and outlining the conditions required for large-scale deployment of hydrogen-powered transport systems.

# 2 Role of hydrogen in mobility

The transition toward zero-emission mobility relies on two primary powertrain configurations: BEV and FCEVs. Both configurations aim to eliminate tailpipe emissions, but their energy storage and conversion systems differ significantly, influencing their efficiency, range, recharging/refueling times, and suitability for specific transport sectors. A BEV relies on a battery pack, typically lithium-ion, to store the energy required to power an electric motor that drives the wheels. The motor provides instant torque to the wheels, ensuring smooth and responsive acceleration. The battery capacity defines the vehicle's driving range, while power electronics regulate the flow of energy between the battery and the motor. When the driver accelerates, energy flows from the battery to the motor. During certain conditions, for example in braking phase or downhill roads, the regenerative braking system engages, converting kinetic energy from the wheels in recharging energy for the battery. On the other hand, FCEVs integrate a hydrogen fuel cell system that generates electricity on board by hydrogen from high-pressure tanks by means of a fuel cell system. This electricity powers an electric motor, supported by a small battery for energy buffering and regenerative braking [24]. This configuration enables longer driving ranges and fast refueling times, positioning FCEVs as a strategic option for heavy-duty, long-haul transport, public transit, and maritime sectors, where battery capacity limitations and charging times pose operational challenges. The powertrain configurations of both are depicted in Figure 3.

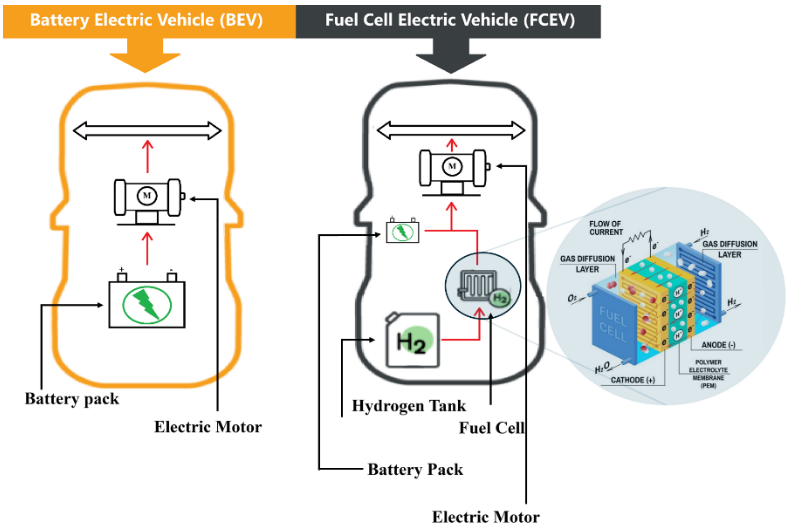


Figure 3: BEV and FCEV powertrain configurations

Although BEVs have proven to be highly effective for urban and short/medium distance mobility, their use becomes challenging in sectors where longer ranges, high load capacity and minimal downtime are essential. An example are the "hard-to-abate" sectors such as heavy-duty transport [25], long-haul freight [26], maritime transport and aviation [27], [28] that require solutions that go beyond the current technological capacity of batteries. Hydrogen, with a gravimetric energy density of approximately 120 MJ/kg, contains more energy per unit of weight compared to batteries [29], enabling vehicles to travel longer distances without significantly increasing their weight. This characteristic is particularly critical in applications such as freight transport and aviation, where vehicle mass directly impacts operational efficiency. Despite the strategic potential of FCEVs in decarbonizing hard-to-abate transport sectors, several technological challenges continue to hinder their widespread adoption. One of the most significant barriers is their lower well-to-wheel efficiency compared to BEVs. In [30], Krause et al. conduct a scenario-based analysis of carbon-neutral road transport in the EU27 by 2050, using a well-to-wheel approach to evaluate different vehicle technologies and fuel pathways. The study compares BEVs, FCHEVs, and e-fuel scenarios, showing that BEVs have the lowest overall energy demand, while hydrogen-based options offer meaningful reductions in final energy use. The complementary roles of batteries and hydrogen in the transition to low-carbon mobility are extensively discussed in the literature. In [31] Badawi et al. examine both technologies across stationary and transport applications, highlighting recent advances in battery design, such as solid-state batteries and the use of graphene-based materials, while also acknowledging unresolved challenges related to cost, safety, and degradation. Hydrogen, on the other hand, is portrayed as a flexible and scalable energy carrier, particularly effective in sectors requiring high energy density and operational flexibility. This analysis is complemented by Andújar et al., who provide a technical and commercial comparison between battery and hydrogen storage systems. They assess a range of battery chemistries such as lithium-ion, molten salt, redox flow, and metal-air batteries and compare them with multiple hydrogen storage options such as compressed gas, liquid hydrogen, metal and complex hydrides, and physisorption methods. The authors evaluate system efficiency and energy availability, emphasizing that hydrogen's high energy density makes it better suited for long-duration and large-scale applications, while batteries offer advantages in round-trip efficiency and decentralized integration. They conclude that the two technologies are best seen as complementary, especially in hybrid systems that combine the fast response of batteries with the long-term storage capacity of hydrogen [32]. An increasingly relevant application for hydrogen-powered vehicles lies in urban and suburban distribution networks, where high range autonomy and operational flexibility are essential. Commercial fleets operating in logistics, parcel delivery, retail distribution, and refrigerated transport often cover hundreds of kilometers daily, with limited windows for vehicle downtime. In these contexts, FCEVs offer a compelling alternative to BEVs, as they combine zero-emission operation with the ability to refuel in minutes, allowing fleets to maintain high availability and route coverage without compromising payload capacity. Gallo and Marinelli in [33] assess the potential impact of FCEVs on fuel consumption and $CO_2$ emissions in the Italian road freight sector, focusing on long-distance transport. Using a detailed simulation model of the national freight network, they evaluate the effects of introducing FCEVs according to the targets set by the Italian National Recovery and Resilience Plan (PNRR), which includes the deployment of 40 hydrogen refueling stations (HRS) and forecasts a 5–7% penetration of FCEVs in heavy-duty transport by 2030. The analysis explores three scenarios—pessimistic, linear, and optimistic—spanning from 2025 to 2040. The authors assume the exclusive use of green hydrogen and conclude that this transition represents a significant step toward achieving national decarbonization goals, especially in segments of road freight transport where battery electric solutions remain operationally limited. In [34], Napoli et al. examine the implementation of a sustainable urban freight distribution system through a real case study in Sicily, where a dedicated electric delivery van (EDV) operates within a renewable-powered urban distribution center (UDC). The system combines freight logistics and localized renewable energy generation in a single infrastructure, demonstrating how urban delivery services can be made entirely zero-emission. By optimizing delivery routes using a vehicle routing problem with time windows, the study minimizes energy consumption while respecting operational constraints such as delivery slots and battery autonomy. The authors show that, depending on route conditions and vehicle load, energy consumption for urban delivery vehicles can vary significantly, ranging between 115 and 300 Wh/km, highlighting the importance of route optimization and appropriate energy sizing. The case study confirms that electric urban freight vehicles, when supported by integrated infrastructure and energy planning, can meet the autonomy and operational demands of daily logistics missions, making them a viable and sustainable option for last-mile distribution. To fully unlock the decarbonization potential of transport systems, hydrogen mobility must be understood not as an alternative to battery electric solutions, but as a complementary pathway tailored to the specific needs of energy-intensive, long-range, and logistically demanding applications. Its high gravimetric energy density, rapid refueling capabilities, and adaptability to various transport modes, ranging from freight logistics to public transit and aviation, position hydrogen as a key enabler of zero-emission mobility beyond the limits of electrification alone. As deployment accelerates and supporting infrastructure expands, FCEVs are expected to play a progressively central role in building a diversified and resilient clean transport ecosystem.

# 3 Production, Storage and distribution infrastructure for mobility

A critical aspect of enabling hydrogen-powered mobility lies in the development of a robust infrastructure for hydrogen production, storage, and distribution. Hydrogen is a versatile energy carrier that can be produced through several methods, classified by color codes that reflect their carbon intensity and energy origin. Qureshi et al. [35] provide an extensive overview of these hydrogen production pathway by color codes. Their study details the characteristics of grey, blue, green, turquoise, pink, yellow, and white hydrogen, discussing not only production processes but also the associated environmental trade-offs and technological readiness levels. Gray hydrogen is obtained from fossil fuels, especially natural gas, via steam methane reforming, and is associated with high $CO_2$ emissions. Blue hydrogen improves upon this by incorporating carbon capture and storage (CCS) technologies, reducing its environmental footprint. Water electrolysis stands out as the most promising route for decarbonization. This process uses electricity from renewable sources to split water into hydrogen and oxygen, without producing direct greenhouse gas emissions. Several electrolysis technologies exist, including Alkaline Electrolysis (AEC), Anion Exchange Membrane (AEM), Proton Exchange Membrane (PEM), and Solid Oxide Electrolysis Cells (SOEC), each with different operational characteristics, efficiencies, and levels of technological maturity. Green hydrogen, produced through electrolysis powered by renewable electricity, currently represents the cleanest form of hydrogen and plays a central role in both European and national decarbonization strategies [36], [37]. However, the widespread adoption of green hydrogen is currently limited by high production costs, mainly due to the expense of electrolyzers that depend on a continuous supply of electricity from renewable sources. [38], [39]. According to the European Hydrogen Observatory, the cost of green hydrogen using grid electricity in Europe ranges between 4,06 and 17,36 €/kg [40]. The International Council on Clean Transportation (ICCT) projects future costs of 3.70 $/kg in the U.S. and 5.60 $/kg in the EU by 2030 [41]. Meanwhile, the Hydrogen Council, in its latest report, estimates the current levelized cost of renewable hydrogen production between 4.5 and 6.5 $/kg with projections indicating a decrement cost to 2.5–4.0 $/kg by 2030 driven by technological advancements and economies of scale [42] (Table 1).

Table 1: Green Hydrogen Cost Estimates

| | Region | Cost Range | References |
|---|---|---|---|
| **European Hydrogen Observatory** | EU | 4,06–17,36 €/kg | [40] |
| **ICCT (2030 Projection)** | US/EU | 3,70 \$/kg (US)<br>5.60 \$/kg (EU) | [41] |
| **Hydrogen Council (Current)** | Global | 4.5–6.5 \$/kg | [42] |
| **Hydrogen Council (2030 Projection)** | Global | 2.5–4.0 \$/kg | [42] |

In parallel with hydrogen production, the challenge of efficient hydrogen storage is central to enabling its use in mobility applications. Recent advances in high-pressure, membrane-less electrolysers using metal hydride electrodes, such as $LaNi_5Hx$, have demonstrated the potential to integrate hydrogen generation, compression, and storage in a single step, enhancing system efficiency by up to 10% and enabling energy densities suitable for mobility applications [43]. Hydrogen has a very low volumetric energy density, approximately 0.0899 kg/m$^3$, requiring advanced storage solutions to make its use feasible in transportation systems. This poses a challenge for transport applications, where space and weight are critical constraints. As a result, developing reliable, high-performance storage solutions is essential to achieving the energy density and compactness needed for onboard hydrogen storage in FCEVs. For transport applications, hydrogen is most commonly stored in the form of compressed gas at high pressures, typically between 350 and 700 bar, within advanced reinforced composite tanks [44]. High-pressure storage enables vehicles to achieve sufficient range without compromising cargo space or drastically increasing system weight, making it particularly advantageous for heavy-duty and long-distance transport applications. However, the infrastructure required to compress, store, and distribute hydrogen at such high pressures involves complex safety requirements and high capital investment [45]. Hydrogen distribution infrastructure is also a key enabling factor. Pipelines offer the most efficient means for large-scale transport over long distances, but their development is constrained by high costs, regulatory challenges, and compatibility with existing gas infrastructure. Alternative distribution methods include high-pressure tube trailers [46], [47], [48] and liquefied hydrogen transport, each with trade-offs in terms of energy consumption, logistics, and scalability [49]. Ahn et al. provide a comprehensive review of the liquefied hydrogen ($LH_2$) supply chain, identifying its potential for intercontinental trade due to its higher volumetric energy density compared to gaseous hydrogen. Their study highlights the challenges of energy-intensive liquefaction, boil-off losses, and the need for advanced cryogenic insulation, but also emphasizes technological advances in liquefaction cycles and shipping that can enhance the viability of large-scale $LH_2$ distribution in support of hydrogen mobility [50]. To support vehicle refueling, the deployment of HRS is expanding globally [51]. In Europe, the Alternative Fuels Infrastructure Regulation (AFIR) [52] mandates that HRS be available along the Trans-European Transport Network (TEN-T) [53] core corridors at intervals no greater than 200 km. Germany and Japan lead in HRS deployment, while the United States continues to invest in station development through Department of Energy programs. To complement fixed stations, mobile hydrogen refueling units are being tested to serve remote areas and emerging hydrogen vehicle markets. A more integrated approach to infrastructure development is exemplified by the rise of Hydrogen Valleys, geographically localized ecosystems that locate hydrogen production, storage, and end-use across transport, industry, and energy sectors [54]. Hydrogen Valleys enhance supply chain synergies, reduce transport costs, and foster local innovation, acting as critical accelerators for the hydrogen transition.

# 4 Challenges and opportunities

Despite the increasing momentum of hydrogen mobility, several technical, economic, and systemic barriers continue to constrain its full-scale deployment. One of the most critical challenges is the overall energy efficiency of hydrogen pathways, particularly in transport applications. While FCEVs offer faster refueling times and longer ranges compared to BEVs, their well-to-wheel efficiency remains substantially lower due to the multiple conversion steps involved, from electricity to hydrogen (via electrolysis), to compression or liquefaction, and finally to electricity within the vehicle’s fuel cell. Another pressing issue is the cost of green hydrogen. Although electrolyzer costs are gradually declining and renewable electricity is becoming more accessible, the overall cost of producing green hydrogen remains significantly higher than fossil-based alternatives. Achieving cost parity will require advances in electrolyzer technology, economies of scale, and further integration with low-cost renewable power. The development of refueling infrastructure also presents a bottleneck. While some countries have made progress many regions still lack the minimum infrastructure needed to support widespread FCEV adoption. This challenge is exacerbated by the classic “chicken-and-egg” dilemma, where limited vehicle uptake slows investment in infrastructure, and vice versa. Coordinated efforts among industry, governments, and investors are essential to resolve these problems. Standardization and regulatory harmonization are further areas that demand attention. Ensuring the safe storage, transport, and handling of hydrogen, especially under high-pressure or cryogenic conditions, demands strict compliance with advanced technical standards. Establishing unified international standards for hydrogen quality, safety, and refueling operations is essential to facilitate widespread deployment and interoperability of hydrogen mobility systems. Despite these hurdles, opportunities are emerging. Advances in materials science could lead to the development of efficient hydrogen storage solutions, including solid-state systems with better energy density. At the same time, integrated projects such as hydrogen hubs and valleys provide practical examples of how hydrogen production, storage, and consumption can be brought together to optimize efficiency and scalability. Moreover, policy support, including tax incentives, subsidies, and infrastructure, remains a powerful driver of adoption. In summary, overcoming these challenges will require an approach that combines technological innovation, infrastructure development, international collaboration, and strong policy alignment. If addressed effectively, hydrogen mobility could become a cornerstone of the global energy transition, particularly in sectors beyond the reach of conventional electrification.

# 5 Conclusions

Hydrogen-based mobility represents a key pillar in the transition to zero-emission transport, particularly for hard-to-abate sectors. This paper has explored the strategic role of FCEVs, assessing their operational benefits, system architecture, and integration with renewable hydrogen production. It has also examined the infrastructure needed to support large-scale deployment, including production pathways, storage technologies, distribution systems, and policy frameworks. While FCEVs offer clear advantages in terms of range, refueling speed, and suitability for high-load applications, they face important challenges. These include lower well-to-wheel efficiency compared to BEVs, the high cost of green hydrogen, and limited refueling infrastructure. However, promising developments in materials science, solid-state storage, and electrolyzer technologies, combined with policy initiatives like Hydrogen Valleys, indicate a path forward. To unlock the full potential of hydrogen mobility, coordinated action is needed to align innovation, investment, and regulation. If these efforts succeed, hydrogen can become a cornerstone of a resilient, flexible, and low-carbon transport ecosystem.

# Acknowledgments

This research was funded by the European Union – NextGeneration EU from the Italian Ministry of Environment and Energy Security POR H2 AdP MMES/ENEA with involvement of CNR and RSE, PNRR - Mission 2, Component 2, Investment 3.5 “Ricerca e sviluppo sull’idrogeno”, CUP: B93C22000630006

# References

[1] «Global EV Data Explorer – Data Tools», IEA. Consultato: 30 settembre 2024. [Online]. Disponibile su: https://www.iea.org/data-and-statistics/data-tools/global-ev-data-explorer
[2] «Transport - Energy System», IEA. Consultato: 25 febbraio 2025. [Online]. Disponibile su: https://www.iea.org/energy-system/transport
[3] «Global CO2 emissions from transport by subsector, 2000-2030 – Charts – Data & Statistics», IEA.

Consultato: 16 aprile 2025. [Online]. Disponibile su: https://www.iea.org/data-and-statistics/charts/global-co2-emissions-from-transport-by-subsector-2000-2030
[4] «Greenhouse gas emissions from transport in Europe». Consultato: 25 febbraio 2025. [Online]. Disponibile su: https://www.eea.europa.eu/en/analysis/indicators/greenhouse-gas-emissions-from-transport
[5] «Key actions of the EU Hydrogen Strategy». Consultato: 25 aprile 2025. [Online]. Disponibile su: https://energy.ec.europa.eu/topics/eus-energy-system/hydrogen/key-actions-eu-hydrogen-strategy_en
[6] «REPowerEU». Consultato: 25 marzo 2025. [Online]. Disponibile su: https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal/repowereu-affordable-secure-and-sustainable-energy-europe_en
[7] «The European Green Deal - European Commission». Consultato: 10 marzo 2025. [Online]. Disponibile su: https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal_en
[8] «Mobility Strategy - European Commission». Consultato: 25 aprile 2025. [Online]. Disponibile su: https://transport.ec.europa.eu/transport-themes/mobility-strategy_en
[9] «Homepage - Clean Hydrogen Partnership». Consultato: 25 aprile 2025. [Online]. Disponibile su: https://www.clean-hydrogen.europa.eu/index_en
[10] «Hydrogen is developing fast in Japan, closer to societal use», World Economic Forum. Consultato: 25 aprile 2025. [Online]. Disponibile su: https://www.weforum.org/stories/2024/04/hydrogen-japan/
[11] «U.S. National Hydrogen Strategy and Roadmap | Hydrogen Program». Consultato: 25 aprile 2025. [Online]. Disponibile su: https://www.hydrogen.energy.gov/library/roadmaps-vision/clean-hydrogen-strategy-roadmap?utm_source=chatgpt.com
[12] Y. Zhu, G. A. Keoleian, e D. R. Cooper, «The role of hydrogen in decarbonizing U.S. industry: A review», *Renew. Sustain. Energy Rev.*, vol. 214, p. 115392, mag. 2025, doi: 10.1016/j.rser.2025.115392.
[13] L. Du *et al.*, «Spatial feasibility prediction of green hydrogen scale-up in China under decarbonization policies: Based on improved diffusion model», *Int. J. Hydrog. Energy*, vol. 93, pp. 770–787, dic. 2024, doi: 10.1016/j.ijhydene.2024.10.406.
[14] X. Wang, L.-W. Fan, H. Zhang, e P. Zhou, «Hydrogen fuel cell technology development in China: Technology evolution, city-cluster network and industry chain distribution», *Energy*, vol. 322, p. 135606, mag. 2025, doi: 10.1016/j.energy.2025.135606.
[15] M. Rezaei, A. Akimov, e E. MacA. Gray, «Cost-competitiveness of green hydrogen and its sensitivity to major financial and technical variables», *Int. J. Hydrog. Energy*, vol. 90, pp. 1365–1377, nov. 2024, doi: 10.1016/j.ijhydene.2024.10.068.
[16] «Cost of hydrogen production | European Hydrogen Observatory». Consultato: 27 aprile 2025. [Online]. Disponibile su: https://observatory.clean-hydrogen.europa.eu/hydrogen-landscape/production-trade-and-cost/cost-hydrogen-production
[17] S. G. Nnabuife, A. K. Hamzat, J. Whidborne, B. Kuang, e K. W. Jenkins, «Integration of renewable energy sources in tandem with electrolysis: A technology review for green hydrogen production», *Int. J. Hydrog. Energy*, vol. 107, pp. 218–240, mar. 2025, doi: 10.1016/j.ijhydene.2024.06.342.
[18] B. Yang, R. Zhang, Z. Shao, e C. Zhang, «The economic analysis for hydrogen production cost towards electrolyzer technologies: Current and future competitiveness», *Int. J. Hydrog. Energy*, vol. 48, fasc. 37, pp. 13767–13779, apr. 2023, doi: 10.1016/j.ijhydene.2022.12.204.
[19] «(PDF) Challenges, stability and reliability of the energy network after the continuous integration of renewable energy sources», ResearchGate. Consultato: 27 aprile 2025. [Online]. Disponibile su: https://www.researchgate.net/publication/376682055_Challenges_stability_and_reliability_of_the_energy_network_after_the_continuous_integration_of_renewable_energy_sources
[20] H. Togun *et al.*, «Development and comparative analysis between battery electric vehicles (BEV) and fuel cell electric vehicles (FCEV)», *Appl. Energy*, vol. 388, p. 125726, giu. 2025, doi: 10.1016/j.apenergy.2025.125726.
[21] L. Mulky *et al.*, «An overview of hydrogen storage technologies – Key challenges and opportunities», *Mater. Chem. Phys.*, vol. 325, p. 129710, ott. 2024, doi: 10.1016/j.matchemphys.2024.129710.
[22] «Hydrogen Refuelling Infrastructure | Hydrogen Mobility Europe», Hydrogen Mobility Europe |. Consultato: 27 aprile 2025. [Online]. Disponibile su: https://h2me.eu/about/hydrogen-refuelling-infrastructure/

[23] D. L. Greene, J. M. Ogden, e Z. Lin, «Challenges in the designing, planning and deployment of hydrogen refueling infrastructure for fuel cell electric vehicles», *eTransportation*, vol. 6, p. 100086, nov. 2020, doi: 10.1016/j.etran.2020.100086.
[24] G. Napoli, S. Micari, G. Dispenza, S. Di Novo, V. Antonucci, e L. Andaloro, «Development of a fuel cell hybrid electric powertrain: A real case study on a Minibus application», *Int. J. Hydrog. Energy*, vol. 42, fasc. 46, pp. 28034–28047, 2017, doi: 10.1016/j.ijhydene.2017.07.239.
[25] D. Daminelli, L. Masotti, e S. Corigliano, «Renewable hydrogen systems for a sustainable heavy-duty mobility: The Italian case», *Renew. Energy Focus*, vol. 52, p. 100656, mar. 2025, doi: 10.1016/j.ref.2024.100656.
[26] H. Liu, J. D. Ampah, S. Afrane, H. Adun, C. Jin, e M. Yao, «Deployment of hydrogen in hard-to-abate transport sectors under limited carbon dioxide removal (CDR): Implications on global energy-land-water system», *Renew. Sustain. Energy Rev.*, vol. 184, p. 113578, set. 2023, doi: 10.1016/j.rser.2023.113578.
[27] F. Urban, A. Nurdiawati, F. Harahap, e K. Morozovska, «Decarbonizing maritime shipping and aviation: Disruption, regime resistance and breaking through carbon lock-in and path dependency in hard-to-abate transport sectors», *Environ. Innov. Soc. Transit.*, vol. 52, p. 100854, set. 2024, doi: 10.1016/j.eist.2024.100854.
[28] W. Suwaileh *et al.*, «Exploring hydrogen fuel as a sustainable solution for zero-emission aviation: Production, storage, and engine adaptation challenges», *Int. J. Hydrog. Energy*, vol. 121, pp. 304–325, apr. 2025, doi: 10.1016/j.ijhydene.2025.03.348.
[29] «Developments and challenges in batteries, and hydrogen as a future fuel, and storage and carrier devices», *Int. J. Hydrog. Energy*, vol. 105, pp. 1242–1260, mar. 2025, doi: 10.1016/j.ijhydene.2024.10.367.
[30] J. Krause *et al.*, «Well-to-wheels scenarios for 2050 carbon-neutral road transport in the EU», *J. Clean. Prod.*, vol. 443, p. 141084, mar. 2024, doi: 10.1016/j.jclepro.2024.141084.
[31] N. Badawi M *et al.*, «Developments and challenges in batteries, and hydrogen as a future fuel, and storage and carrier devices», *Int. J. Hydrog. Energy*, vol. 105, pp. 1242–1260, mar. 2025, doi: 10.1016/j.ijhydene.2024.10.367.
[32] «Batteries and Hydrogen Storage: Technical Analysis and Commercial Revision to Select the Best Option». Consultato: 2 maggio 2025. [Online]. Disponibile su: https://www.mdpi.com/1996-1073/15/17/6196
[33] M. Gallo e M. Marinelli, «The Impact of Fuel Cell Electric Freight Vehicles on Fuel Consumption and CO2 Emissions: The Case of Italy», *Sustainability*, vol. 14, fasc. 20, Art. fasc. 20, gen. 2022, doi: 10.3390/su142013455.
[34] G. Napoli, S. Micari, G. Dispenza, L. Andaloro, V. Antonucci, e A. Polimeni, «Freight distribution with electric vehicles: A case study in Sicily. RES, infrastructures and vehicle routing», *Transp. Eng.*, vol. 3, p. 100047, mar. 2021, doi: 10.1016/j.treng.2021.100047.
[35] F. Qureshi *et al.*, «Contemporary avenues of the Hydrogen industry: Opportunities and challenges in the eco-friendly approach», *Environ. Res.*, vol. 229, p. 115963, lug. 2023, doi: 10.1016/j.envres.2023.115963.
[36] I. Perissi e A. Jones, «Investigating European Union Decarbonization Strategies: Evaluating the Pathway to Carbon Neutrality by 2050», *Sustainability*, vol. 14, fasc. 8, Art. fasc. 8, gen. 2022, doi: 10.3390/su14084728.
[37] G. S. Seck *et al.*, «Hydrogen and the decarbonization of the energy system in europe in 2050: A detailed model-based analysis», *Renew. Sustain. Energy Rev.*, vol. 167, p. 112779, ott. 2022, doi: 10.1016/j.rser.2022.112779.
[38] «Global Hydrogen Review 2023 – Analysis», IEA. Consultato: 6 dicembre 2024. [Online]. Disponibile su: https://www.iea.org/reports/global-hydrogen-review-2023
[39] J. M. M. Arcos e D. M. F. Santos, «The Hydrogen Color Spectrum: Techno-Economic Analysis of the Available Technologies for Hydrogen Production», *Gases*, vol. 3, fasc. 1, Art. fasc. 1, mar. 2023, doi: 10.3390/gases3010002.
[40] «Cost of hydrogen production | European Hydrogen Observatory». Consultato: 4 maggio 2025. [Online]. Disponibile su: https://observatory.clean-hydrogen.europa.eu/hydrogen-landscape/production-trade-and-cost/cost-hydrogen-production
[41] D. Scott, «The price of green hydrogen: How and why we estimate future production costs»,

International Council on Clean Transportation. Consultato: 4 maggio 2025. [Online]. Disponibile su: https://theicct.org/the-price-of-green-hydrogen-estimate-future-production-costs-may24/
[42] J. Sampson, «Hydrogen Insights 2023 December Update», Hydrogen Council. Consultato: 4 maggio 2025. [Online]. Disponibile su: https://hydrogencouncil.com/en/hydrogen-insights-2023-december-update/
[43] V. V. Solovey, A. V. Rusanov, M. M. Zipunnikov, I. O. Vorobjova, e A. L. Kotenko, «Increasing of efficiency of hydrogen energy storage system by the use of high-pressure electrolyser with metal hydride electrode», *J. Energy Storage*, vol. 99, p. 113316, ott. 2024, doi: 10.1016/j.est.2024.113316.
[44] A. Magliano, C. Perez Carrera, C. M. Pappalardo, D. Guida, e V. P. Berardi, «A Comprehensive Literature Review on Hydrogen Tanks: Storage, Safety, and Structural Integrity», *Appl. Sci.*, vol. 14, fasc. 20, Art. fasc. 20, gen. 2024, doi: 10.3390/app14209348.
[45] A. M. Sadeq *et al.*, «Hydrogen energy systems: Technologies, trends, and future prospects», *Sci. Total Environ.*, vol. 939, p. 173622, ago. 2024, doi: 10.1016/j.scitotenv.2024.173622.
[46] oneh2023, «OneH2 Launches 931 Bar High-Pressure Tube Trailers for Hydrogen Delivery», OneH2. Consultato: 3 maggio 2025. [Online]. Disponibile su: https://oneh2.com/oneh2-launches-931-bar-high-pressure-tube-trailers-for-hydrogen-delivery/
[47] «Hydrogen Trailer». Consultato: 3 maggio 2025. [Online]. Disponibile su: https://hyfindr.com/en/hydrogen-knowledge/hydrogen-trailer
[48] K. Reddi, A. Elgowainy, N. Rustagi, e E. Gupta, «Techno-economic analysis of conventional and advanced high-pressure tube trailer configurations for compressed hydrogen gas transportation and refueling», *Int. J. Hydrog. Energy*, vol. 43, fasc. 9, pp. 4428–4438, mar. 2018, doi: 10.1016/j.ijhydene.2018.01.049.
[49] Z. Xie, Q. Jin, G. Su, e W. Lu, «A Review of Hydrogen Storage and Transportation: Progresses and Challenges», *Energies*, vol. 17, fasc. 16, Art. fasc. 16, gen. 2024, doi: 10.3390/en17164070.
[50] T. Zhang, J. Uratani, Y. Huang, L. Xu, S. Griffiths, e Y. Ding, «Hydrogen liquefaction and storage: Recent progress and perspectives», *Renew. Sustain. Energy Rev.*, vol. 176, p. 113204, apr. 2023, doi: 10.1016/j.rser.2023.113204.
[51] «Highway hydrogen refueling station siting considering hydrogen sources, transportation and station type», *Renew. Energy*, vol. 247, p. 123025, lug. 2025, doi: 10.1016/j.renene.2025.123025.
[52] «Alternative Fuels Infrastructure - European Commission». Consultato: 3 maggio 2025. [Online]. Disponibile su: https://transport.ec.europa.eu/transport-themes/clean-transport/alternative-fuels-sustainable-mobility-europe/alternative-fuels-infrastructure_en
[53] «Trans-European Transport Network (TEN-T) - European Commission». Consultato: 3 maggio 2025. [Online]. Disponibile su: https://transport.ec.europa.eu/transport-themes/infrastructure-and-investment/trans-european-transport-network-ten-t_en
[54] M. Bampaou e K. D. Panopoulos, «An overview of hydrogen valleys: Current status, challenges and their role in increased renewable energy penetration», *Renew. Sustain. Energy Rev.*, vol. 207, p. 114923, gen. 2025, doi: 10.1016/j.rser.2024.114923.

## Presenter Biography

Salvatore Micari earned his Ph.D. in "Materials and Construction Engineering and Chemistry" from the University of Messina in September 2022. He is currently a researcher at the National Research Council (CNR) – Institute for Advanced Energy Technologies (ITAE) in Messina. His research activities focus on the design and development of prototypes for fuel cell and battery-based electric and hybrid vehicles, as well as on integrating technologies for energy efficiency and sustainable mobility. He has participated in numerous research projects within ERC sectors PE7, PE8, and SH7, holding roles involving scientific responsibility and coordination.