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Is Hydrogen the Future of the Automotive Sector? A Critical Overview

Alessandro Blasi[1,*], Antonella Dimotta[2]

Abstract

The transition towards sustainable energy sources in the automotive sector has become imperative in light of escalating environmental challenges and the depletion of fossil fuels. Among alternative energy solutions, hydrogen has emerged as a promising candidate due to its high energy density, zero-emission potential, and technological advancements in fuel cell systems. This review critically examines the viability of hydrogen as a dominant energy source for future automotive applications. The paper assesses hydrogen production methods, storage solutions, infrastructure development, and the economic feasibility of large-scale adoption. Additionally, the review juxtaposes hydrogen fuel cell vehicles against battery electric vehicles, highlighting key technological, environmental, and logistical considerations. Despite substantial progress, several challenges remain, including high production costs, limited refueling infrastructure, and energy inefficiencies in hydrogen synthesis and distribution. This review concludes that while hydrogen holds significant potential, its role in the automotive sector will likely be complementary rather than predominant, depending on technological breakthroughs, policy support, and market dynamics.

Keywords: Hydrogen, automotive, zero emissions, renewable energy

INTRODUCTION

The automotive sector is undergoing a profound transformation driven by the urgent need to mitigate climate change, reduce greenhouse gas emissions, and transition towards sustainable energy sources [1–3]. With transportation being a major contributor to global CO_2 emissions, finding alternatives to fossil fuel-based internal combustion engines (ICEs) has become a critical priority [4–6]. Among the various alternatives, hydrogen has emerged as a compelling candidate for decarbonizing the automotive industry due to its high energy density, abundance, and ability to generate power without producing tailpipe emissions [7, 8]. Hydrogen fuel cell vehicles (HFCVs), which convert hydrogen into electricity using fuel cells, offer the promise of extended driving ranges, short refueling times, and a cleaner environmental footprint compared to conventional vehicles and even some electric vehicles (EVs) [9–11].

However, despite its potential, the widespread adoption of hydrogen in the automotive sector faces significant challenges. Issues such as the high cost of hydrogen production, energy inefficiencies in its supply chain, limited refueling infrastructure, and competition from battery electric vehicles (BEVs)

***Author for Correspondence**
Alessandro Blasi
E-mail: alessandro.blasi@enea.it

[1]Research Scholar, Department of Energy and Sustainable Economic, ENEA Italian National Agency for New Technologies, Energy and the Environment Energy Technologies and Renewable Sources Department C.R. Trisaia – S.S. 106 Jonica, km 419,575026 Rotondella (MT-Italy)
[2]Research Scholar, Department of Energy and Sustainable Economic, 2 Earth and Eco-System Expertise for Environmental Modeling and Restoration Company, EESEEMR, Synergy Centre ITT Dublin, Ireland.

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raise critical questions about the feasibility of hydrogen as a dominant energy source for future mobility [9, 12, 13]. Moreover, the environmental benefits of hydrogen are highly dependent on the method of production, with most current hydrogen supply relying on carbon-intensive processes such as steam methane reforming. The deployment of green hydrogen, produced via renewable energy-powered electrolysis, remains limited and costly [14–18].

This review aims to provide a comprehensive and critical assessment of hydrogen's potential role in the future automotive landscape. The analysis covers the current state of hydrogen production technologies, storage and distribution logistics, vehicle integration, and the economic and regulatory factors influencing market adoption. Additionally, the review compares HFCVs with BEVs, evaluating the strengths and weaknesses of each technology in terms of efficiency, environmental impact, scalability, and consumer acceptance. By synthesizing recent advancements, technological hurdles, and market dynamics, this review seeks to answer whether hydrogen can realistically serve as a cornerstone of the automotive industry's future, or if it will play a more complementary role alongside other low-carbon solutions.

THE PATH TOWARDS A SUSTAINABLE AUTOMOTIVE SECTOR

The transition to a sustainable energy system is being driven by a new political landscape, shaped primarily by ambitious European climate goals. These objectives include reducing greenhouse gas emissions by at least 55% by 2030 (relative to 1990 levels) and achieving carbon neutrality by 2050 [19–21]. Attaining these targets will require significant improvements in energy efficiency, as well as a comprehensive shift toward renewable energy sources across various sectors, with transportation being a key focus. In the transport sector, the strategy is centered on replacing conventional fossil fuels with alternative, cleaner energy sources, such as electricity, hydrogen, and biofuels [22–26].

In the context of Italy, the Integrated National Energy and Climate Plan (PNIEC), which is aligned with the guidelines of the Renewable Energy Directive (RED II), sets ambitious objectives for renewable energy adoption in the transport sector. By 2030, Italy aims to ensure that 14% of the energy used in transportation comes from renewable sources. Notably, the plan allocates a modest but significant role to hydrogen, which is expected to contribute approximately 1% of this target. This hydrogen can either be used directly in vehicles—such as hydrogen-powered cars, buses, and trains—or be injected into the methane network for transport purposes [21, 27, 28].

The wider adoption of hydrogen as a fuel within the mobility sector is closely linked to the technological development and efficiency of vehicles capable of using it. There are two principal methods by which hydrogen can power vehicles:

- Direct combustion in internal combustion engines (ICEs);
- Conversion in fuel cells to generate electricity for electric motors.

While direct combustion of hydrogen in ICEs might appear to be a simpler solution, its practical application is limited due to its relatively low thermal efficiency, which is approximately 30%. In contrast, fuel cell technology offers a far more efficient alternative, with an energy efficiency of about 60%, roughly double that of hydrogen combustion. Furthermore, internal combustion engines running on hydrogen still produce nitrogen oxide emissions as a byproduct of the combustion process, whereas fuel cells produce only water as their emission, making them a much cleaner option in terms of environmental impact [27–31].

For these reasons, the automotive industry's focus is increasingly shifting toward fuel cell technology, which is widely regarded as the more efficient and sustainable path forward. Vehicles powered by fuel cells are essentially EVs that utilize hydrogen stored in high-pressure tanks—typically at 350 or 700 bar—and generate electricity onboard through the fuel cells. This approach not only maximizes efficiency but also significantly reduces the environmental footprint of transportation, aligning with the broader goals of the energy transition [29, 30]. By investing in and advancing these technologies, the transportation sector is poised to play a crucial role in reducing greenhouse gas emissions and achieving long-term sustainability.

THE FUTURE OF MOBILITY: HYDROGEN VERSUS ELECTRIC VEHICLES

In the evolving landscape of sustainable transportation, one of the most pertinent comparisons for understanding the future of mobility is between HFCVs and BEVs. Both technologies offer the potential for significant emissions reductions, particularly in a scenario where all electricity generation is derived from renewable energy sources. However, each has distinct advantages and challenges that must be considered, especially with regard to environmental impact, efficiency, and practicality [32, 33].

EVs are lauded for their ability to drastically reduce emissions, as they rely on electricity stored in batteries to power the motor. In an ideal long-term scenario, where renewable sources supply all electricity, EVs would effectively eliminate direct emissions from transportation. However, a major concern associated with EVs is the environmental and logistical complexity surrounding battery production and disposal. Batteries, particularly lithium-ion batteries, raise several issues: they are expensive to produce, contribute to limited driving range, require long charging times, and add significant weight to the vehicle. These drawbacks pose challenges for the widespread adoption of EVs, particularly for consumers seeking convenience and performance comparable to traditional ICE vehicles [34, 35].

Hydrogen fuel cell technology, on the other hand, offers a potential solution to some of these issues. By using hydrogen to generate electricity onboard the vehicle, FCVs can provide a longer driving range and shorter refueling times, addressing two of the key limitations of EVs. Hydrogen vehicles also tend to be lighter than battery-powered ones, contributing to better vehicle dynamics. However, hydrogen technology comes with its own set of challenges, most notably in terms of efficiency and cost [35, 36].

A primary disadvantage of hydrogen-powered vehicles lies in the multiple energy conversion steps required to produce, transport, and use hydrogen as fuel. In contrast to EVs, where energy stored in the battery is used directly by the electric motor, hydrogen-powered vehicles experience energy losses at various stages. Hydrogen must first be produced through electrolysis, compressed, and transported to refueling stations, which typically results in around a 10% energy loss. Once in the vehicle, the hydrogen is converted back into electricity by the fuel cell, a process with a typical efficiency of about 60%. These multiple conversions lead to a cumulative energy loss that reduces the overall efficiency of hydrogen-powered vehicles [35, 36].

To illustrate the efficiency gap between the two technologies, consider the following example. Starting with 50 kWh of electricity, electrolysis can produce approximately 1 kg of hydrogen. When this hydrogen is used in a fuel cell vehicle, around 20 kWh of usable energy is delivered to the motor, which enables a driving range of roughly 100 km. By comparison, using the same 50 kWh directly to power an electric vehicle's motor allows for a range of approximately 240 km. This stark difference in efficiency highlights one of the key challenges for hydrogen technology as it competes with battery electric vehicles for dominance in the future mobility market (Figure 1) [35–38].

In summary, while both HFCVs and EVs offer promising paths toward decarbonizing transportation, they represent two distinct approaches, each with its own strengths and limitations. EVs currently hold an advantage in terms of energy efficiency and infrastructure, particularly as renewable energy sources become more prevalent. However, HFCVs, with their longer range and quicker refueling capabilities, offer an attractive alternative, particularly for applications such as heavy-duty transport, long-haul trucking, and public transportation, where battery limitations are more pronounced. Ultimately, the future of mobility may depend on a combination of these technologies, each tailored to meet the specific needs of different sectors of the transport industry.

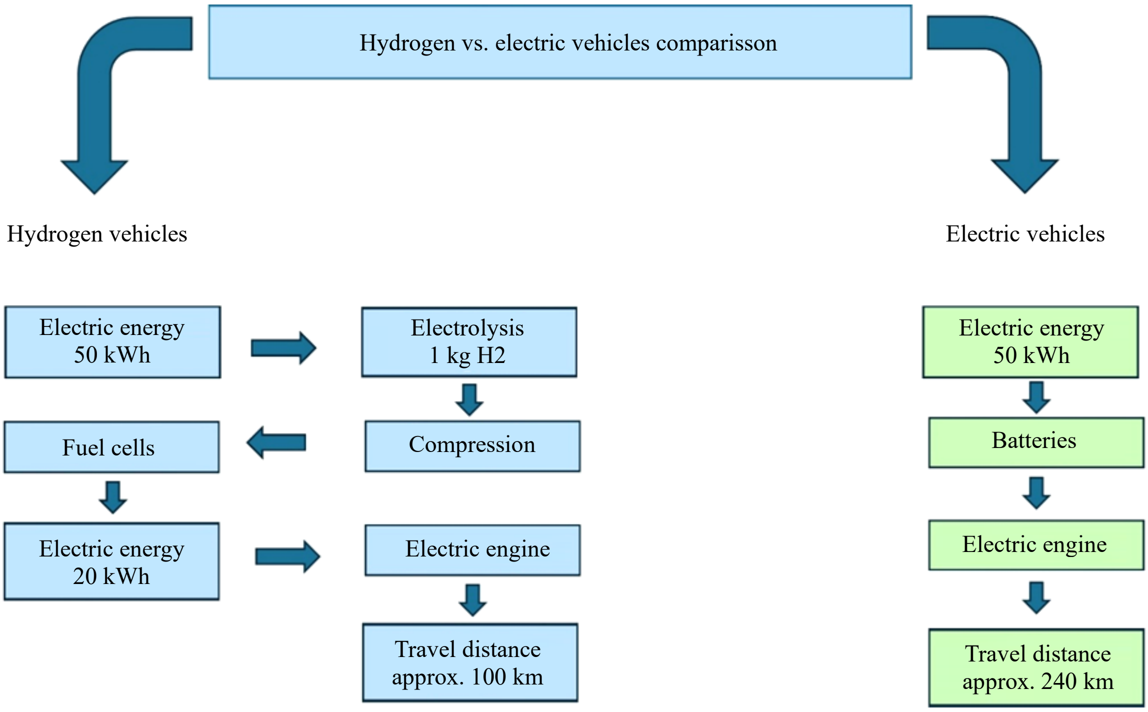

Figure 1. Hydrogen versus electric vehicles comparison [35–38].

COMPARISON BETWEEN LIGHT AND HEAVY VEHICLES: EFFICIENCY AND TECHNOLOGICAL FEASIBILITY

The previous analysis underscores that EVs offer superior efficiency, particularly for light vehicles, as they utilize renewable energy without the need for additional conversions. This direct application of energy is a key advantage of EV technology. However, ongoing research and development efforts are crucial to further enhance battery performance, particularly in terms of reducing costs, improving energy density, and shortening charging times. Equally important is the advancement of technologies aimed at recycling and recovering the materials used in batteries, such as lithium and cobalt, to mitigate the environmental impact of battery production and disposal [39–41].

While EV technology is well-suited for light vehicles, the situation changes significantly when considering heavier modes of transportation. In sectors such as heavy-duty transport, including buses, trucks, freight vehicles, and trains, the limitations of current battery technology—particularly with respect to range and charging time—make it impractical and inefficient. These vehicles require higher energy capacities and faster refueling times to meet the demands of long-distance travel and heavy loads, challenges that battery technology is currently unable to address effectively [42, 43].

The heavy-duty sector is particularly relevant in terms of energy consumption and emissions. For instance, in the EU-25, freight transport accounts for over 40% of all liquid fuel consumption in the road transport sector. This highlights the need for alternative technologies that can deliver the same level of performance as traditional ICEs while significantly reducing greenhouse gas emissions [40, 42].

HFCVs offer a viable solution for heavy-duty applications. In vehicles such as trucks and freight carriers, hydrogen fuel cells provide a range that is comparable to that of diesel-powered vehicles. By equipping these vehicles with hydrogen tanks capable of storing between 30 and 100 kg of hydrogen, they can achieve driving ranges on par with diesel counterparts. This makes hydrogen an attractive alternative for long-haul freight and heavy commercial vehicles, where battery-powered electric vehicles would struggle to meet operational demands due to their limited range and long recharging times [40, 42].

The potential of hydrogen technology is not limited to road transport. In the rail sector, hydrogen-powered trains are emerging as a sustainable replacement for diesel trains, particularly in countries like Italy, where a significant portion of the rail network remains non-electrified. As of today, 4717 km of Italian railway tracks (28.1% of the total) are still non-electrified, meaning diesel locomotives are necessary. Hydrogen trains already demonstrate performance characteristics similar to those of diesel trains, offering comparable range, acceleration, and operational reliability. Current hydrogen trains can cover distances of 600 to 800 km on a single tank and reach speeds of up to 140 km/h, making them an environmentally friendly and efficient alternative for non-electrified railways [43].

In conclusion, while EVs are poised to dominate the light vehicle market due to their superior efficiency and potential for integration with renewable energy sources, hydrogen fuel cell technology holds significant promise for heavier modes of transport. For sectors such as freight, commercial transport, and rail, hydrogen offers the range and refueling convenience required to meet the operational demands, positioning it as a crucial component of the future sustainable transport landscape. Each technology—battery electric and hydrogen fuel cells—will likely play a complementary role in reducing emissions across different sectors of transportation, tailored to the specific needs of light and heavy vehicles.

THE BOTTLENECK OF HYDROGEN PRODUCTION

One of the most significant challenges facing the widespread adoption of hydrogen as a clean energy source lies in the production process. While hydrogen generated via electrolysis holds the promise of being the most sustainable option, particularly when powered entirely by renewable energy, achieving this ideal state remains a distant goal. The global energy transition is still underway, and for the foreseeable future, alternative methods of hydrogen production will be needed to ensure that hydrogen can be produced more sustainably than through conventional methods, such as methane steam reforming (MSR), which generates gray hydrogen [44–46].

A more sustainable option is the production of blue hydrogen, which is still derived from natural gas through MSR but is paired with carbon capture and storage (CCS) technologies. This process captures the CO_2 emissions produced during hydrogen generation and stores them underground, thus reducing the environmental impact compared to conventional methods. A further advancement in this field is electric steam reforming, which relies on electrical energy rather than heat generated by burning fossil fuels. This method not only produces less CO_2 directly but also facilitates more efficient carbon capture, making it a more environmentally friendly solution during this transitional period [47, 48].

Another innovative and promising approach to hydrogen production is the concept of circular hydrogen, which is derived from waste materials. This process, known as waste-to-hydrogen or waste gasification, utilizes non-recyclable waste as a feedstock to produce hydrogen. In doing so, it addresses two environmental challenges simultaneously: it reduces the volume of waste requiring disposal and cuts down on overall emissions. Hydrogen production from waste is rapidly gaining traction in the market, thanks to its dual environmental benefits and its competitive production costs, which are currently estimated at around 2 to 3 euros per kilogram of hydrogen. These costs are comparable to those of traditional gray hydrogen production technologies, making waste-derived hydrogen a viable alternative in the near term [49–51].

While electrolyzers are widely considered the key to a carbon-free hydrogen economy, their potential to eliminate CO_2 emissions depends heavily on the source of the electricity used in the process. At present, much of the electricity for electrolysis still comes from non-renewable sources, which results in hydrogen production associated with significant carbon emissions—approximately 10 kg of CO_2 per kilogram of hydrogen produced. This emission level is similar to that of hydrogen produced via conventional steam reforming. By contrast, hydrogen produced through waste gasification results in significantly lower emissions, around 1.5 kg of CO_2 per kilogram of hydrogen, making it a more sustainable option during the transition to a fully renewable energy system [52–55].

In summary, while electrolytic hydrogen production powered by renewable energy remains the ultimate goal for a truly sustainable hydrogen economy, the current transition phase necessitates the exploration and deployment of alternative technologies. Blue hydrogen with CCS, electric steam reforming, and circular hydrogen derived from waste represent important interim solutions that can reduce emissions and ensure that hydrogen production remains economically viable and environmentally responsible. These technologies, particularly waste-to-hydrogen processes, offer competitive costs and lower CO_2 footprints, positioning them as critical components of the evolving hydrogen landscape.

CONCLUSIONS

The role of hydrogen as a potential cornerstone in the future of the automotive sector remains a topic of significant debate and analysis. Hydrogen-powered vehicles, particularly fuel cell electric vehicles (FCEVs), present a viable pathway for reducing emissions, especially in the context of decarbonizing heavy-duty transport and other sectors where BEVs face limitations due to range, weight, and refueling constraints. However, the widespread adoption of hydrogen technology in the automotive industry hinges on several critical factors: technological advancements, cost reductions, infrastructure development, and, crucially, the sustainability of hydrogen production itself.

While fuel cell technology offers distinct advantages in terms of efficiency and environmental impact, particularly when compared to internal combustion engines, its broader application is currently hindered by the relatively low energy efficiency of hydrogen production, storage, and distribution. The future viability of hydrogen-powered vehicles is largely dependent on the advancement of green hydrogen production—derived from renewable energy sources through electrolysis—as this is the only pathway that can fully decouple hydrogen from its current reliance on fossil fuels. Until renewable energy becomes the predominant source for hydrogen production, alternative methods such as blue hydrogen, electric steam reforming, and waste-derived hydrogen must be explored and optimized to mitigate carbon emissions during the transition period.

For light vehicles, BEVs currently hold a competitive edge due to their higher energy efficiency and expanding infrastructure. However, in sectors such as freight transport, rail, and other heavy-duty applications, where the limitations of battery technology are more pronounced, hydrogen fuel cells present a promising solution. The complementary roles of both hydrogen and battery technologies will likely shape a diverse and multifaceted automotive future, where each technology is suited to specific applications and transportation needs.

In conclusion, while hydrogen holds significant promise for the future of mobility, particularly in heavy-duty and long-range applications, its role in the automotive sector will depend on overcoming key challenges related to production efficiency, cost, and infrastructure. A continued focus on research, development, and policy support will be critical to unlocking the full potential of hydrogen and ensuring that it can contribute meaningfully to the broader goals of reducing greenhouse gas emissions and achieving sustainable mobility.

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