

Hydrogen fuel cells for automobiles: Challenges and opportunities in achieving zero-emission transportation

Shreeshail Nuchhi ^{1,*} and Somashekarappa M ²

¹ Department of Automobile Engineering, Government Polytechnic, Basavanabagewadi, Takkalaki-586216, Karnataka, India.

² Department of Automobile Engineering, D A C G (Government) Polytechnic, Chikkamagaluru-577101, Karnataka, India.

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Abstract

Hydrogen fuel cell technology presents a promising solution for zero-emission transportation, offering high energy efficiency, rapid refueling, and a sustainable alternative to conventional internal combustion engines and battery electric vehicles. Unlike fossil fuel-powered vehicles, hydrogen fuel cells produce only water as a byproduct, significantly reducing greenhouse gas emissions and air pollutants. Additionally, fuel cells offer longer driving ranges and shorter refueling times compared to battery electric vehicles, making them an attractive option for various transportation sectors, including passenger cars, commercial trucks, and public transit systems. Despite these advantages, several challenges hinder widespread adoption. Key barriers include the high production cost of fuel cell systems, the limited availability of hydrogen refueling infrastructure, and the complexities of hydrogen storage and distribution. Moreover, the environmental impact and energy requirements of hydrogen production methods, such as steam methane reforming and electrolysis, remain critical factors in determining the overall sustainability of hydrogen as an energy carrier. This paper explores the current state of hydrogen fuel cell technology for automobiles, analyzing recent advancements, technical challenges, and market dynamics. It also examines policy frameworks, investment trends, and emerging solutions aimed at improving the efficiency, affordability, and accessibility of hydrogen-powered transportation. Through this analysis, the study aims to provide insights into the feasibility of large-scale hydrogen adoption and the potential pathways to a cleaner, more sustainable transportation future.

Keywords: Hydrogen Fuel Cells; Fuel Cell Vehicles (fcvs); Zero-Emission Transportation; Hydrogen Production; Green Hydrogen

1. Introduction

The global transition towards clean energy has intensified interest in hydrogen fuel cells as a viable and sustainable alternative to fossil fuel-powered vehicles. With growing concerns about climate change, air pollution, and depleting fossil fuel reserves, governments and industries worldwide are seeking efficient and eco-friendly mobility solutions. Hydrogen fuel cell electric vehicles (FCEVs) offer a compelling option by combining the benefits of high energy density, zero tailpipe emissions, and rapid refuelling, addressing some of the limitations associated with battery electric vehicles (BEVs) and internal combustion engine (ICE) vehicles.

Hydrogen fuel cells generate electricity through an electrochemical reaction between hydrogen and oxygen, producing only water and heat as byproducts. This process eliminates carbon dioxide (CO₂) emissions at the vehicle level, making FCEVs a crucial component of decarbonizing the transportation sector. Compared to BEVs, hydrogen fuel cells provide longer driving ranges and significantly shorter refueling times, making them particularly suitable for heavy-duty

* Corresponding author: Shreeshail Nuchhi.

transportation, public transit, and long-haul logistics. The versatility of hydrogen also extends beyond road transport, with potential applications in aviation, maritime shipping, and rail systems.

Despite these promising advantages, hydrogen fuel cell technology faces several challenges that hinder widespread adoption. One of the primary obstacles is the high cost of fuel cell systems, largely driven by expensive materials such as platinum used in catalysts, as well as the complex manufacturing processes involved. Additionally, hydrogen production remains energy-intensive, with the majority of hydrogen today being derived from fossil fuels through steam methane reforming (SMR), which emits CO₂. Although green hydrogen—produced via renewable-powered electrolysis—presents a sustainable alternative, its scalability and cost-effectiveness remain key concerns.

Infrastructure limitations further impede the growth of hydrogen-powered transportation. The establishment of hydrogen refueling stations requires substantial investment in production, storage, and distribution networks. Unlike the well-developed infrastructure for gasoline, diesel, and even electric charging stations, hydrogen refueling networks are still in their infancy, with limited availability in many regions. The lack of refueling stations discourages consumer adoption and limits the practicality of FCEVs for mainstream use. Addressing these infrastructure challenges is critical to accelerating the commercial viability of hydrogen-based mobility.

Another major concern is hydrogen storage and transportation. Hydrogen has a low volumetric energy density, requiring either high-pressure compression (typically at 350–700 bar) or liquefaction at extremely low temperatures (-253°C) for efficient storage and distribution. Both methods demand significant energy input and specialized containment systems, increasing the overall cost and complexity of hydrogen supply chains. Advances in material science and engineering, including the development of solid-state hydrogen storage solutions and innovative carrier technologies, are being explored to mitigate these challenges.

Beyond technological and infrastructural hurdles, economic factors play a crucial role in determining the feasibility of hydrogen fuel cells. The cost competitiveness of FCEVs relative to BEVs and traditional ICE vehicles depends on economies of scale, government policies, and market demand. Subsidies, tax incentives, and research funding have been instrumental in promoting hydrogen adoption, but long-term viability will require sustained cost reductions in fuel cell components, hydrogen production, and distribution infrastructure. Public-private partnerships and increased investment in renewable hydrogen production can help drive down costs and foster industry growth.

The role of policy and regulatory frameworks cannot be overlooked in shaping the future of hydrogen fuel cells. Governments worldwide have initiated hydrogen roadmaps, emissions regulations, and clean energy mandates to support the transition to hydrogen-powered transportation. Countries like Japan, Germany, and South Korea have made significant advancements in hydrogen infrastructure development, while initiatives such as the European Union's Hydrogen Strategy aim to accelerate hydrogen adoption across multiple sectors. However, coordinated global efforts are necessary to establish standardized regulations, safety guidelines, and international trade agreements to facilitate large-scale deployment.

This paper provides a comprehensive evaluation of hydrogen fuel cell technology in the automotive sector, analyzing its current status, challenges, and opportunities for future growth. By examining advancements in fuel cell efficiency, hydrogen production methods, and infrastructure expansion, the study aims to offer insights into the potential pathways for achieving a sustainable and economically viable hydrogen-powered transportation ecosystem. Through a multidisciplinary approach, this research highlights the technological innovations, policy measures, and strategic investments required to overcome existing barriers and unlock the full potential of hydrogen fuel cells in the global energy transition [1].

2. Current State of Hydrogen Fuel Cell Vehicles (fcvs)

Hydrogen fuel cell vehicles (FCVs) have gained significant attention as a promising alternative to conventional internal combustion engine (ICE) vehicles and battery electric vehicles (BEVs). Major automotive manufacturers, including Toyota, Hyundai, and Honda, have invested heavily in developing FCV technology, with models such as the Toyota Mirai, Hyundai Nexo, and Honda Clarity Fuel Cell demonstrating the viability of hydrogen-powered transportation. These vehicles utilize hydrogen fuel cells to generate electricity, offering benefits such as zero emissions, long driving ranges, and fast refueling times. Unlike BEVs, which require hours to recharge, FCVs can refuel in just a few minutes, making them a practical choice for high-mileage applications.

Despite these advancements, the adoption of FCVs remains relatively low compared to BEVs and hybrid electric vehicles. The primary barriers to widespread market penetration include high production costs, limited hydrogen

refueling infrastructure, and challenges in hydrogen production and storage. Currently, the cost of manufacturing an FCV is significantly higher than that of a BEV or ICE vehicle, mainly due to the expensive materials used in fuel cells, such as platinum-based catalysts. While research is ongoing to reduce material costs and improve manufacturing efficiency, the high upfront price of FCVs continues to deter potential buyers.

Infrastructure development remains one of the most significant challenges for FCV adoption. Unlike gasoline stations or electric vehicle charging points, hydrogen refueling stations are sparse and concentrated in a few regions, primarily in Japan, South Korea, California (USA), and parts of Europe. The lack of a widespread refueling network limits the practicality of FCVs for daily commuting and long-distance travel, making them less appealing to consumers. Figure 1 illustrates the global adoption rate of FCVs over the past decade, highlighting the slow yet steady growth of the industry.

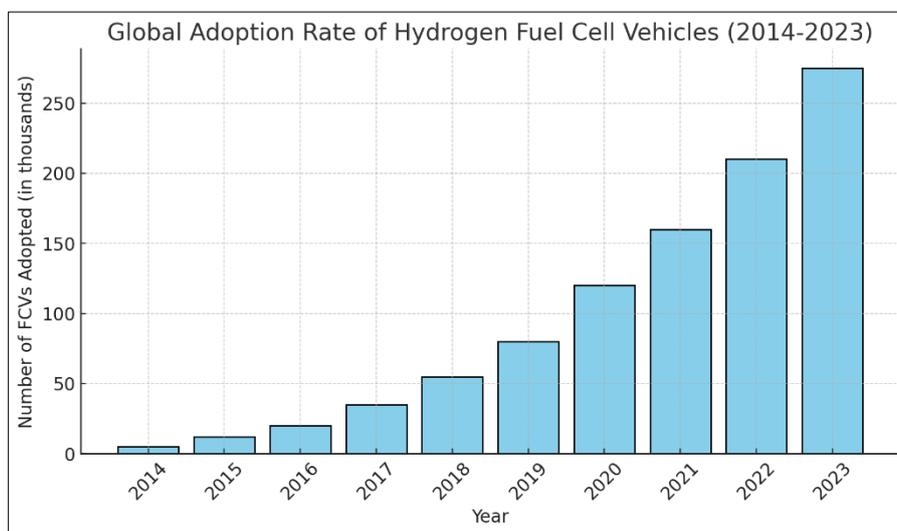


Figure 1 Global adoption rate of FCVs over the past decade

In response to these challenges, governments and private sectors are making efforts to expand hydrogen infrastructure. Countries such as Germany, Japan, China, and South Korea have launched national hydrogen strategies that include funding for refueling station deployment and incentives for FCV adoption. In the United States, California leads in hydrogen infrastructure development, with state incentives supporting both passenger and commercial hydrogen vehicles. Additionally, several automakers are collaborating with energy companies to build hydrogen refueling networks, aiming to enhance accessibility and convenience for FCV users [2].

Beyond passenger vehicles, hydrogen fuel cells are gaining traction in commercial and heavy-duty transportation sectors. Hydrogen-powered buses, trucks, and trains are being deployed in various countries as part of clean energy initiatives. Companies like Nikola, Daimler, and Volvo are developing hydrogen-powered trucks, while hydrogen-powered trains are already in operation in parts of Europe. These applications showcase the scalability of hydrogen fuel cells and their potential to reduce emissions in industries where battery-electric solutions face limitations, such as long-haul trucking and heavy industrial transport.

Despite the progress, the sustainability of hydrogen production remains a critical issue. Currently, most hydrogen is produced through steam methane reforming (SMR), which emits carbon dioxide and diminishes the environmental benefits of FCVs. Efforts are underway to scale up green hydrogen production, which involves using renewable energy sources such as solar and wind power for electrolysis. However, the high cost of green hydrogen production and the energy losses in the process pose challenges to achieving large-scale adoption.

Automotive manufacturers and research institutions continue to invest in fuel cell technology advancements, aiming to improve efficiency, reduce costs, and extend the lifespan of fuel cell systems. Innovations such as solid oxide fuel cells, improved hydrogen storage materials, and hybrid fuel cell-battery systems are being explored to enhance performance and affordability. Additionally, advancements in hydrogen distribution technologies, such as liquid organic hydrogen carriers (LOHCs) and on-site electrolysis, may help address current logistical challenges.

In summary, while FCVs present a viable solution for zero-emission transportation, their widespread adoption depends on overcoming challenges related to cost, infrastructure, and hydrogen production methods. The ongoing efforts in

technological innovation, government policies, and infrastructure expansion indicate a growing commitment to hydrogen mobility. If these challenges are successfully addressed, FCVs could play a crucial role in the future of sustainable transportation, complementing battery-electric vehicles and contributing to global decarbonization efforts.

3. Challenges in Hydrogen Fuel Cell Adoption

Despite the potential of hydrogen fuel cell vehicles (FCVs) to provide a zero-emission transportation solution, several challenges hinder their widespread adoption. These challenges span the production and supply chain, infrastructure availability, storage and transportation, and overall economic feasibility. Addressing these barriers is essential for the large-scale deployment of hydrogen fuel cell technology [3].

3.1. Hydrogen Production and Supply Chain

One of the primary obstacles to hydrogen adoption is the method of production and associated environmental impact. Currently, the majority of hydrogen is produced via steam methane reforming (SMR), a process that extracts hydrogen from natural gas but generates significant carbon dioxide (CO₂) emissions. This reliance on fossil fuels undermines the environmental benefits of hydrogen fuel cells. Although carbon capture and storage (CCS) can mitigate emissions from SMR, this approach increases costs and requires further technological advancements.

A more sustainable alternative is green hydrogen production, which utilizes electrolysis to split water into hydrogen and oxygen using electricity from renewable sources. While green hydrogen eliminates direct carbon emissions, it remains costly and energy-intensive. The efficiency of electrolyzers is currently limited, and scaling up production requires substantial investments in renewable energy infrastructure. Table 1 compares different hydrogen production methods, highlighting the trade-offs in cost, efficiency, and environmental impact.

Table 1 Comparison of different hydrogen production methods

Production Method	Energy Source	CO ₂ Emissions	Efficiency	Cost
Steam Methane Reforming (SMR)	Natural Gas	High	~65-75%	Low
Electrolysis (Green Hydrogen)	Renewable Energy (Wind, Solar)	None	~60-70%	High
Coal Gasification	Coal	Very High	~45-55%	Medium
Biomass Gasification	Organic Biomass	Low	~50-65%	Medium

3.2. Infrastructure Limitations

The lack of hydrogen refueling infrastructure is one of the most critical challenges to FCV adoption. Unlike gasoline or diesel stations, hydrogen refueling stations are limited in number and are concentrated in select regions such as Japan, South Korea, Germany, California, and China. The expansion of refueling networks is essential for increasing consumer confidence and making hydrogen vehicles practical for everyday use.

Developing hydrogen infrastructure requires significant investment, as stations must be equipped with high-pressure storage, safety mechanisms, and specialized refueling technology. The cost of building a single hydrogen station can range between \$1 million and \$2 million, making widespread deployment financially challenging. Figure 2 illustrates the distribution of hydrogen refueling stations across key regions, highlighting the disparity in infrastructure availability.

3.3. Storage and Transportation Issues

Hydrogen presents unique storage and transportation challenges due to its low volumetric energy density. Unlike conventional fuels, hydrogen must be stored under high pressure (typically 350–700 bar) or at extremely low temperatures (-253°C) in liquid form. Both methods require specialized containment systems, increasing the cost and complexity of hydrogen supply chains.

Additionally, transporting hydrogen over long distances remains a logistical hurdle. The current options include:

- Compressed hydrogen transportation: Requires high-pressure tanks, which add to infrastructure costs.
- Liquefied hydrogen transportation: Involves cryogenic storage, demanding large amounts of energy for cooling.

- Hydrogen carriers (e.g., ammonia, liquid organic hydrogen carriers - LOHCs): Offer promising alternatives but require conversion processes that reduce overall efficiency.

Advancements in solid-state hydrogen storage materials and chemical carriers could help overcome these limitations, but large-scale commercialization is still in progress.

3.4. Cost and Economic Feasibility

The economic viability of hydrogen fuel cells is another major challenge. The cost of manufacturing an FCV is significantly higher than that of a battery electric vehicle (BEV) or an internal combustion engine vehicle. The primary cost drivers include:

- Fuel cell stack production, particularly the use of platinum-based catalysts
- Hydrogen storage systems, which require high-pressure or cryogenic tanks
- Hydrogen refueling station development, which has high infrastructure costs

A comparison between hydrogen FCVs and BEVs in terms of cost structure is illustrated in Bar Chart 1, which highlights key cost components such as fuel cell stack materials, battery packs, and infrastructure needs. As seen, FCVs have a higher fuel cell system cost, while BEVs are dominated by battery costs.

While costs are expected to decline as fuel cell technology advances and production scales up, government incentives and subsidies remain crucial in the short term. Countries leading in hydrogen adoption have implemented subsidies for FCV purchases, tax credits for hydrogen station development, and research funding to lower production costs and accelerate deployment.

The widespread adoption of hydrogen fuel cell vehicles depends on overcoming technological, economic, and infrastructural challenges. Continued advancements in hydrogen production, storage, and distribution will be essential to reducing costs and increasing efficiency. Additionally, investments in refueling infrastructure and global policy support will play a critical role in making FCVs a viable alternative to traditional and battery-electric vehicles. If these barriers are addressed, hydrogen mobility could become a key player in the future of sustainable transportation [4].

4. Opportunities for Hydrogen Fuel Cells

Despite the challenges associated with hydrogen fuel cells, ongoing technological advancements, policy support, and integration with renewable energy present significant opportunities for their widespread adoption. Addressing cost barriers and improving efficiency will be key to making hydrogen fuel cell vehicles (FCVs) a mainstream transportation solution.

4.1. Advancements in Hydrogen Production

The cost and environmental impact of hydrogen production remain critical factors influencing the adoption of FCVs. However, innovations in electrolysis and renewable energy integration are driving progress in sustainable hydrogen generation.

- **Electrolysis Improvements:** Traditional proton exchange membrane (PEM) electrolyzers are becoming more efficient, with new materials such as solid oxide electrolysis cells (SOECs) and anion exchange membranes (AEMs) showing promise for cost-effective hydrogen production.
- **Renewable Energy Integration:** The use of surplus wind and solar energy for hydrogen production is gaining traction. Power-to-gas (P2G) systems convert excess renewable electricity into hydrogen, which can be stored and used as needed.
- **Scale-up of Green Hydrogen Projects:** Countries such as Germany, Australia, and the U.S. are investing in large-scale green hydrogen production plants, significantly reducing production costs through economies of scale.

If these advancements continue, green hydrogen could achieve cost parity with fossil fuel-derived hydrogen (gray hydrogen) within the next decade, making FCVs more economically viable.

4.2. Policy and Investment Initiatives

Government support plays a pivotal role in accelerating hydrogen adoption. Many nations have implemented strategic policies, subsidies, and infrastructure investment programs to boost hydrogen production and refueling networks. Table 2 summarizes key hydrogen policies worldwide.

Table 2 Key hydrogen policies worldwide

Country/Region	Key Hydrogen Policies & Investments
European Union	€10 billion investment in hydrogen projects under the Green Deal, Hydrogen Strategy for Climate Neutrality
United States	\$8 billion for regional hydrogen hubs under the Bipartisan Infrastructure Law
Japan	Hydrogen Society Roadmap, FCV subsidies, investment in refueling stations
China	Hydrogen vehicle subsidies, national targets for hydrogen infrastructure expansion
South Korea	Hydrogen Economy Roadmap, plans for 6.2 million FCVs by 2040
Australia	National Hydrogen Strategy, funding for electrolyzer development and green hydrogen exports

These initiatives reduce the financial burden on manufacturers and consumers, helping accelerate the transition to hydrogen-powered transportation.

4.3. Technological Innovations in Storage and Fuel Cell Efficiency

Innovations in hydrogen storage and fuel cell materials can enhance performance, reduce costs, and improve safety.

- **Solid-State Hydrogen Storage:** Researchers are exploring metal hydrides, carbon nanotubes, and boron-based compounds for hydrogen storage at lower pressures, offering safer and more compact storage solutions.
- **Alternative Catalysts:** Platinum-based catalysts are expensive, but new research focuses on non-precious metal catalysts, such as nickel, cobalt, and iron-based materials, to reduce costs.
- **Fuel Cell Durability Improvements:** Advanced membrane materials and hybrid fuel cell designs are increasing efficiency and extending the lifespan of fuel cells, making them more competitive with battery technology.

These innovations will enhance hydrogen vehicle range, performance, and affordability, making them a stronger competitor to battery electric vehicles (BEVs).

4.4. Integration with Renewable Energy and Grid Balancing

Hydrogen is not just a fuel for vehicles—it can act as an energy carrier, playing a vital role in grid stability and renewable energy storage.

- **Energy Storage Solution:** Hydrogen can store excess energy generated from renewable sources like solar and wind, balancing supply and demand fluctuations.
- **Fuel for Stationary Applications:** Hydrogen fuel cells are being used in backup power systems, microgrids, and industrial applications, improving overall energy resilience.
- **Sector Coupling:** Hydrogen can facilitate cross-sector decarbonization, powering industries such as steel production, aviation, and maritime transport.

As the world transitions to clean energy systems, hydrogen's versatility makes it a key component in long-term energy sustainability. The future of hydrogen fuel cells is promising, driven by advancements in production technology, policy support, breakthroughs in fuel cell efficiency, and integration with renewable energy systems. If these opportunities are fully realized, hydrogen can emerge as a major player in the global transition to zero-emission transportation and energy storage [5].

5. Conclusion

Hydrogen fuel cell vehicles (FCVs) hold great potential as a sustainable transportation solution, but widespread adoption depends on overcoming key challenges such as high production costs, infrastructure limitations, and hydrogen

storage complexities. Ongoing advancements in fuel cell efficiency, storage technologies, and hydrogen production methods are expected to enhance the feasibility of FCVs in the coming years. One of the most promising developments is the expansion of green hydrogen production through renewable-powered electrolysis. As solar and wind energy costs decline, hydrogen can be produced more affordably, reducing reliance on fossil-fuel-based methods like steam methane reforming. Additionally, advancements in fuel cell technology, such as the development of alternative catalysts and high-efficiency membranes, are helping lower costs and improve performance.

Infrastructure expansion is also critical for FCV adoption. Countries such as Japan, Germany, and the United States are investing in hydrogen refueling stations, ensuring greater accessibility for consumers and commercial fleets. On-site hydrogen generation and distribution networks will further improve refueling convenience, making FCVs more practical for everyday use. Beyond passenger vehicles, hydrogen fuel cells are gaining traction in heavy-duty transportation, maritime shipping, and aviation. Hydrogen-powered trucks, trains, and even aircraft are being developed to provide long-range, zero-emission mobility solutions. These applications could accelerate hydrogen adoption and drive economies of scale, ultimately making the technology more cost-competitive. Despite these advancements, the success of hydrogen fuel cell technology depends on continued policy support, private-sector investments, and industry collaboration. Government incentives, carbon pricing mechanisms, and strategic partnerships between automakers and energy providers will be essential in scaling up production and infrastructure. In conclusion, while hydrogen FCVs are not yet a mainstream solution, ongoing research and investments indicate a strong future for hydrogen-powered transportation. With the right technological and economic advancements, FCVs could complement battery electric vehicles in achieving a cleaner and more sustainable mobility ecosystem.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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