Hydrogen-Powered Vehicles:
A Clean Energy Alternative for a Greener Future



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Introduction

After the world entered the "global boiling era",various sectors worldwide have been implementing accelerated measures to reduce pollution emissions. Road transportation, in particular, is a major contributor to greenhouse gas emissions, accounting for over 12.2% of total emissions.[1/] Therefore, accelerating the transition to clean-energy vehicles not only supports the business sector and helps countries achieve long-term sustainability goals, but also serves as a driving force to create a better world for the future.

When discussing eco-friendly vehicles that produce zero greenhouse gas emissions during operation (Zero Emission Vehicles: ZEVs), most people primarily think of Battery Electric Vehicles (BEVs). However,**there is another clean-energy alternative for transportation and logistics: hydrogen-powered vehicles.** With key advantages such as refueling times as fast as conventional gasoline cars and emissions consisting only of water vapor, hydrogen vehicles are well-suited for both personal and commercial use. Nevertheless, the widespread adoption of hydrogen vehicles still faces several key challenges, particularly the limited availability of refueling infrastructure and the currently high cost of hydrogen fuel.



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1/ https://www.wri.org/insights/4-charts-explain-greenhouse-gas-emissions-countries-and-sectors

Understanding Hydrogen-Powered Vehicles

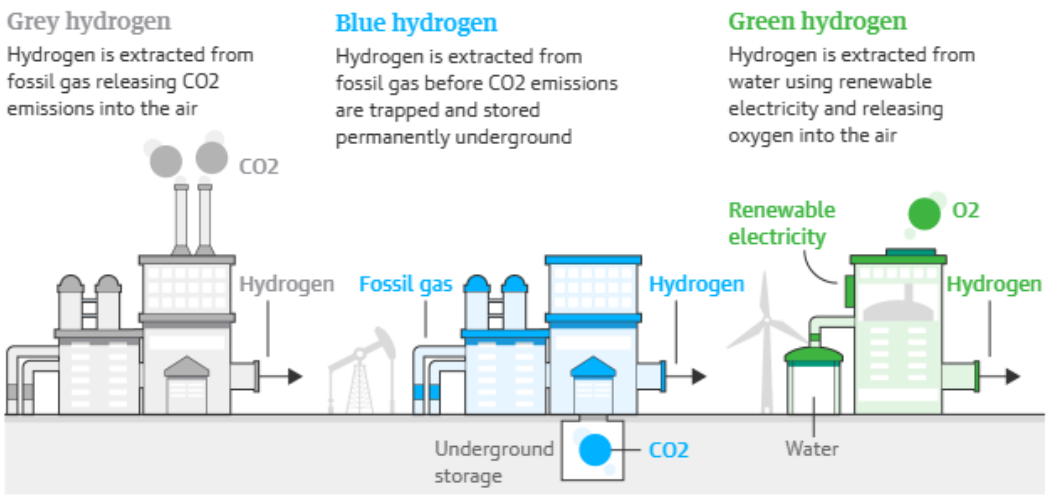
Hydrogen: An Alternative Energy for Environmental Sustainability

Hydrogen (H) is the most abundant element in the universe. In nature, it is found as part of compounds with other elements, appearing in solid, liquid, and gaseous states. Consequently, hydrogen is a component of nearly everything around us. For instance, when hydrogen chemically reacts with oxygen (O_2), it forms water (H_2O), and when combined with carbon, it produces hydrocarbon compounds, which are present in natural gas, coal, petroleum, and other fossil fuels.

The production of hydrogen for energy production is commonly classified by a color-coding system that indicates both environmental sustainability and production costs. For instance, Grey Hydrogen is produced from fossil fuels and has a low production cost, but it releases a high volume of greenhouse gases. Blue Hydrogen is also derived from fossil fuels, but it incorporates Carbon Capture and Storage (CCS) technology to trap and store carbon dioxide, resulting in lower emissions. Meanwhile, Green Hydrogen is produced through electrolysis of water using renewable energy sources such as solar and wind power. It is the most environmentally friendly form of hydrogen, though it currently has the highest production cost.

Figure 1

Hydrogen Production Methods by Source and Environmental Impact



Source: World Economic Forum

Hydrogen is therefore an important energy source for economic activities due to its diverse production pathways and versatile applications. Traditional industries utilize hydrogen in petroleum refining, steel production, and fertilizer manufacturing. In modern technologies, hydrogen is increasingly being used as a fuel in fuel cells to generate electricity for data centers, in energy storage systems, and as a power source for vehicles. This article will focus specifically on hydrogen's application as a clean energy source for vehicles.

How Hydrogen Is Converted into Power for Vehicles

Although Battery Electric Vehicles (BEVs) have continued to gain popularity, BEV users still harbor several concerns, including charging times, limited driving range per charge, and the carbon footprint[2/] across the entire BEV supply chain.[3/] These issues remain subjects of ongoing debate. As a result, **hydrogen-powered vehicles have emerged as an alternative form of eco-friendly propulsion.** Automakers have developed hydrogen vehicle technology in two principal variants, each exhibiting distinct advantages and operating mechanisms, as follows:

- **Fuel Cell Electric Vehicle: FCEV**

Fuel Cell Electric Vehicles (FCEVs) utilize electric motors for propulsion, similar to BEVs. However, a key difference lies in the **FCEV's ability to generate electricity onboard using hydrogen fuel, eliminating the need to rely on external electric charging sources** like BEVs or Plug-in Hybrid Electric Vehicles (PHEVs). At **the heart of an FCEVs is the hydrogen fuel cell, which functions like a compact power plant**. Hydrogen, stored in high-pressure gaseous form,[4/] is fed into the fuel cell where it undergoes a chemical reaction with oxygen from the air to produce electricity for the drivetrain and to recharge the battery. The process emits zero harmful pollutants, with only water vapor released through the exhaust. However, the overall environmental impact of FCEVs depends significantly on the source and production method of the hydrogen used as fuel. If the hydrogen is derived from renewable energy, FCEVs can be truly regarded as clean vehicles that contribute meaningfully to reducing the carbon footprint.

Box 1 How a Fuel Cell Works

A hydrogen fuel cell operates through an electrochemical process that converts hydrogen and oxygen into electricity, water, and heat. The process works as follows:

1) **A fuel cell consists** of two electrodes: a negative electrode (anode) and a positive electrode (cathode). Between them is an electrolyte, a substance that allows electrically charged atoms (ions) to pass through. This enables the movement of electric charge and the generation of electric current.
2) When hydrogen from the vehicle's storage tank is delivered to the **anode** of the fuel cell, a catalyst separates the hydrogen molecules into two components: protons (the positively charged hydrogen components) and electrons (the negatively charged hydrogen components).
3) The electrons flow through an external electrical circuit, **generating electric current to power the vehicle**. Excess electricity can charge the vehicle's battery to supplement the electric motor's power during acceleration.

2/ Carbon footprint refers to the total greenhouse gas emissions associated with business operations, products, or services. Read more at: https://www.krungsri.com/th/research/research-intelligence/Carbon-Footprint-2025

3/ While BEVs produce no direct emissions during driving, their overall environmental friendliness depends largely on the source of electricity generation. Currently, most of the world's electricity still comes from fossil fuels. As of 2024, renewable and nuclear energy together account for only 40.9% of global electricity production https://ember-energy.org/app/uploads/2025/04/Report-Global-Electricity-Review-2025.pdf

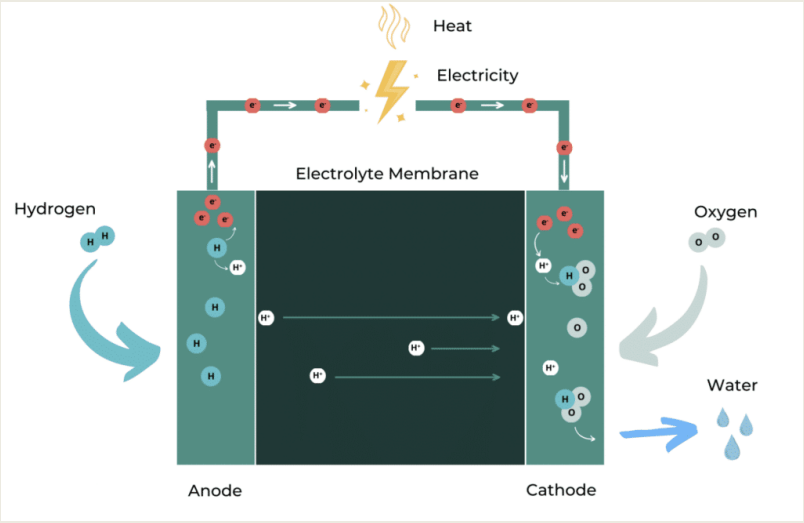
4/ Hydrogen fuel tanks must be made from strong and durable materials, such as Carbon Fiber Reinforced Polymer (CFRP).

Box 1 How a Fuel Cell Works (cont.)

4) As protons pass through the electrolyte and electrons travel through the external circuit, they eventually react with oxygen at the fuel cell's cathode, "forming water" as the only byproduct of this electrochemical process.

Figure 2

Electricity generation through chemical reactions in fuel cells



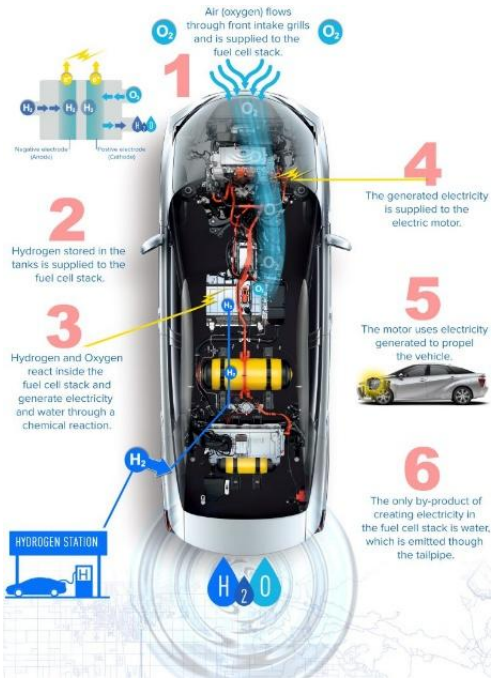
Source: Inocel

The electricity generated by the fuel cell is directly supplied to the electric motor to drive the vehicle, while a portion is used to charge the battery that serves as a backup energy storage system. This supports power demand during high-load conditions, such as acceleration or climbing steep inclines. This configuration allows FCEVs to reduce reliance on large battery packs for energy storage compared to BEVs, addressing the pain point of long charging times. Hydrogen refueling for FCEVs takes only 3–4 minutes. Moreover, FCEVs provide a driving experience comparable to BEVs, with strong acceleration, high torque across all speed ranges, and the absence of engine noise during acceleration.[5/]

5/ However, some drivers still prefer the auditory feedback of combustion engines, which enhances the driving experience and sense of vehicle control

Figure 3

Operation and Components of FCEVs



Source: Toyota UK

In summary, FCEVs utilize hydrogen as their energy source, with fuel cells generating electricity to power the electric motor and vehicle systems. This hydrogen fuel cell technology has attracted greater interest from automakers compared to other hydrogen-based propulsion methods.

- ### Hydrogen Internal Combustion Engine Vehicle: H2-ICE

In addition to electric motor–powered vehicles that help reduce greenhouse gas emissions, hydrogen internal combustion engine vehicles (Hydrogen Internal Combustion Engine: H2-ICE) offer another low-emission technology alternative**. H2-ICE engines operate similarly to conventional gasoline engines[6/] but combust hydrogen fuel to generate mechanical energy for vehicle propulsion.** The primary exhaust emission is water vapor, though minimal amounts of nitrogen oxides (NO_x) are produced, including nitric oxide (NO) and nitrogen dioxide (NO_2), albeit significantly less than fossil fuel vehicles.[7/] These gases are harmful air pollutants that pose serious environmental and health risks.

6/ For instance, the engine ignites hydrogen using spark plugs, similar to conventional gasoline internal combustion engines. Its components are also largely comparable to those found in gasoline-fueled engines. For further details, see: https://www.autodeft.com/deftanswer/how-gasoline-and-diesel-engine-work

7/ NOx is a harmful pollutant with significant impacts on both the environment and human health. In the case of H_2-ICE vehicles, NOx emissions result from the combustion of hydrogen in ambient air as well as from engine oil https://www.idtechex.com/en/research-article/idtechex-explores-whether-hydrogen-engines-are-truly-emissions-free/31914?utm

However, H2-ICE has attracted less attention than FCEVs due to several key reasons.

1) **H2-ICE demonstrate lower energy conversion efficiency,** achieving only 40-45% tank-to-wheel efficiency compared to 50-60%[8/] for FCEVs. As a result, H2-ICE vehicles require more hydrogen to travel the same distance.

2) **H2-ICE vehicles still emit certain pollutants,** although at lower levels compared to fossil fuels. This has raised concerns over whether H2-ICE can truly be considered zero-emission vehicles (ZEVs).

3) **The high cost of H2-ICE vehicles is primarily due to engine components** that must be designed to withstand high temperatures, resulting in costs up to 1.5 times higher than conventional gasoline engines.[9/] In comparison, although the fuel cell stack in FCEVs is expensive, FCEVs offer higher fuel efficiency and zero emissions, making them a more sustainable long-term option**. For these reasons, commercial production and sales of H2-ICE vehicles have yet to materialize.**

Figure 4

Engine Compartment of the Toyota Corolla Cross H2 Concept's H2-ICE System



Source: Toyota

In summary, H2-ICE technology uses hydrogen as a direct combustion fuel in an engine similar to fossil fuels but emits lower pollutants compared to conventional internal combustion engines. However, H2-ICE vehicles still face limitations in terms of efficiency and emissions when compared to FCEVs.

In addition to the two hydrogen vehicle technologies discussed above, plug-in fuel cell electric vehicles (Plug-in FCEVs) have recently been developed and commercially launched. The Honda CR-V e:FCEV is recognized as the first model to adopt this technology. These vehicles combine a hydrogen fuel cell system with a larger-capacity battery than conventional FCEVs, which can be charged from external power sources. This enables the vehicle to operate either by refueling with hydrogen or by electric charging, making it a "hybrid" between a plug-in hybrid electric vehicle (PHEV) and an FCEV. As a result, Plug-in FCEVs offer greater flexibility, especially in regions where hydrogen refueling stations remain limited.

It is evident that hydrogen vehicles demonstrate clear advantages in reducing fossil fuel dependence and enhancing environmental sustainability, especially in the case of FCEVs which emit only water vapor as exhaust. Additionally, FCEVs offer short refueling times comparable to battery electric vehicle charging and driving ranges per refuel that are similar to conventional internal combustion engine vehicles. It is unsurprising that major automakers, particularly Japanese manufacturers, are intensifying FCEV research and development to spearhead the transition toward eco-friendly mobility solutions.

8/ https://escholarship.org/content/qt4bn4r7td/qt4bn4r7td_noSplash_f07dc0630f520b562c408c96681fb0d1.pdf?t=si3nju

9/ the fuel injector of a hydrogen engine may cost as much as 1,000 US dollars. https://www.fleetequipmentmag.com/hydrogen-ice-fuel-cost-infrastructure-challenges/

Developments in Hydrogen-Powered Vehicles

Capitalizing on the aforementioned advantages of FCEVs, leading automakers have been actively investing in research and development of FCEVs as an environmentally friendly alternative. Over the years, major global car manufacturers have consistently introduced plans and launched hydrogen vehicle models. Examples include:

- **Toyota**

Toyota recognizes hydrogen as a key enabler in achieving carbon neutrality by 2050. As part of its multi-pathway approach, the company has been actively developing fuel cell electric vehicles (FCEVs) alongside hybrid electric vehicles (HEVs), plug-in hybrid electric vehicles (PHEVs), and battery electric vehicles (BEVs). This strategy reflects Toyota's commitment to providing a wide range of sustainable mobility solutions that align with global environmental goals.

Toyota began developing fuel cell electric vehicles (FCEVs) as early as 1992. In 2014, the company launched the "Mirai," the world's first commercially available FCEV passenger car, which offered a driving range of approximately 483 kilometers per hydrogen refill. In 2021, Toyota introduced the second-generation Mirai, featuring a lighter and more efficient fuel cell system that extended the driving range to 650 kilometers. In February 2025, Toyota introduced its third-generation fuel cell system, demonstrating 1.2 times greater energy efficiency and twice the durability of previous models. This next-generation system is designed for versatile applications across both passenger vehicles and heavy-duty trucks.[10/] Concurrently, Toyota continues to advance its H2-ICE prototype development as part of its multi-pathway approach to clean mobility.

Figure 5

First-Generation and Second-Generation Toyota Mirai



Source: Automobile Prope

10/ Toyota states that its third-generation fuel cell system offers durability comparable to that of a diesel engine. https://global.toyota/en/newsroom/corporate/42218558.html & https://www.autoinfo.co.th/online/567107

Honda

Honda has announced its strategic shift toward clean energy vehicles, committing to an exclusive global sales portfolio of battery electric vehicles (BEVs) and fuel cell electric vehicles (FCEVs) by 2040.[11/]

Honda began developing fuel cell electric passenger vehicles (FCEVs) around 1995, progressively refining fuel cell systems for compact packaging. In 2016, the company launched the Clarity Fuel Cell, the world's first FCEV capable of seating five passengers.[12/] A subsequent breakthrough emerged in 2024 with the CR-V e:FCEV, Honda's innovative plug-in fuel cell electric vehicle (Plug-in FCEV) combining hydrogen fuel cell and external charging capabilities, now commercially available in the U.S. and Japanese markets.[13/]

Figure 6

Honda FCX Clarity & Honda CR-V e:FCEV



Source: Autospinn, Honda

Hyundai

Hyundai commenced fuel cell technology research in 1998. In 2013, the company launched the ix35 Fuel Cell, the world's first mass-produced hydrogen fuel cell vehicle.[14/] The company further advanced its FCEV capabilities with the 2025 launch of the All-New NEXO, engineered on a dedicated fuel cell platform. This model delivers class-leading performance with a driving range of over 700 kilometers range per hydrogen refueling,[15/] making it one of the longest-range fuel cell vehicles available.

In addition to passenger vehicles, Hyundai has also placed strong emphasis on commercial FCEVs. In 2020, the company launched the XCIENT Fuel Cell, the world's first commercially available hydrogen fuel cell heavy-duty truck.

11/ https://global.honda/content/dam/site/global-en/newsroom-new/cq_img/news/2025/05/c250520eng/c250520eng_01.pdf

12/ The first-generation Toyota Mirai, launched in 2014, was the world's first commercially available FCEV sold to individual customers. However, design constraints and the packaging of the hydrogen fuel cell system limited this model to seating only four passengers.

13/ https://www.headlightmag.com/2024-06-07-world-news-honda-starts-production-of-cr-v-efcev/ The price was approximately 1.6 million baht, but interested customers could only acquire the vehicle through long-term leasing, which included hydrogen fuel credit Honda Announces Lease Prices for Fuel-Cell 2025 CR-V e:FCEV | Cars.com

14/ However, the Hyundai ix35 FCEV was not commercially available to retail customers, instead being marketed exclusively through long-term leasing programs.

15/ https://www.headlightmag.com/2025-hyundai-nexo-fcev/

Figure 7

All-New Hyundai NEXO & XCIENT Fuel Cell



Source: Headlightmag, Hyundai

- **SAIC (Shanghai Automotive Industry Corporation)**

SAIC is the first Chinese automaker to develop hydrogen fuel cell technology alongside new energy vehicles (NEVs), including BEVs and PHEVs. The company initiated its FCEV development program in 2001[16/] and has since focused on creating dedicated vehicle architectures and structural designs optimized specifically for hydrogen fuel cell powertrains in passenger cars.

In 2021, SAIC launched its domestically developed hydrogen fuel cell system, achieving full localization of core components.[17/] The following year, the company introduced the MAXUS MIFA Hydrogen, the world's first premium hydrogen-powered multi-purpose vehicle (MPV). SAIC deployed 80 units[18/] of this model through its ride-hailing platform, Xiangdao Chuxing, in Shanghai, demonstrating the company's leadership in hydrogen fuel cell technology among Chinese automakers.

Figure 8

MAXUS MIFA Hydrogen



Source: Fuel Cell Work

16/ https://www.saicmotor.com/english/latest_news/saic_motor/56199.shtml

17/ The fuel cell system, named "PROME M4H," is claimed by SAIC to offer performance and quality on par with that of Toyota.

18/ Xiangdao Chuxing is a ride-hailing and mobility solutions platform developed by SAIC to expand its business into the digital mobility services market. https://fuelcellsworks.com/news/saic-motor-puts-first-batch-of-80-hydrogen-fuel-cell-vans-into-service-in-china

- **BMW**

While currently placing greater emphasis on BEVs, BMW considers hydrogen technology a critical component of its zero-emission mobility strategy. The automaker has collaborated with Toyota since 2013 to exchange hydrogen technology expertise. In 2023, BMW unveiled the iX5 Hydrogen Fuel Cell prototype, produced in a limited run of just 100 units for testing ahead of potential future commercialization. BMW believes that hydrogen-powered vehicles can offer convenience comparable to internal combustion engine (ICE) vehicles, particularly due to their fast-refueling times.

Figure 9

BMW iX5 Hydrogen Fuel Cell



Source: Autospinn

Box 2 Automakers Expanding Hydrogen Technology into Other Sectors

In addition to developing hydrogen-powered vehicle innovations, automakers have also expanded the use of hydrogen as an energy source in other sectors, such as:

- **Toyota**[19/] plans to apply fuel cell technology to trucks, trains, and even maritime transport. Additionally, the company has developed a prototype smart city called Woven City, which features cutting-edge technologies such as autonomous transportation systems and robotic pets for elderly care. Hydrogen serves as the city's primary energy source, supporting a sustainable and environmentally friendly energy ecosystem.
- **Honda** is advancing hydrogen fuel cell technology across multiple dimensions to build a clean energy ecosystem, which includes: (1) the development of fuel cell-powered vehicles for general consumers; (2) commercial vehicles; (3) fuel cell-based power generation systems; and (4) the use of hydrogen fuel cells in construction equipment.
- **Hyundai**[20/] has unveiled its Hydrogen Vision 2040, aiming to establish hydrogen as a versatile energy source that extends far beyond the transportation sector. The company envisions FCEVs playing a key role in driving major industries such as energy, steel, and chemicals.

19/ Woven City is located near Mount Fuji in Japan, covering an area of approximately 708,000 square meters. The development of this futuristic city has a budget exceeding 350 billion baht

20/ Electrification - Innovation | Company - Hyundai Worldwide

Figure 10

Hydrogen Vehicle Development by Automakers

	Toyota	Honda	Hyundai	BMW	SAIC
H2 Fuel Vehicle Line-up	★★★★	★★★	★★★★	★★★	★★★★
H2 Passenger Vehicles — Planned for Future	★★★★	★★★★	★★★★	★★★★	★★★★
Investments in H2 Fuel	★★★★★	★★★★	★★★★	★★★★	★★★
Strategic Roadmap for H2 Fuels	★★★★	★★★★	★★★★★	★★★	★★★★

Source: Frost & Sullivan, Krungsri Research

Examples of Government Policies Supporting Hydrogen Vehicles

- **Japan**

Japan is a global leader in hydrogen technology development, encompassing production, utilization, and infrastructure. It was the first country to commercially launch FCEVs. In 2017, the Japanese government introduced its “Basic Hydrogen Strategy”, outlining a long-term roadmap to promote systematic hydrogen use.[21/] Both the public and private sectors have committed to jointly investing over JPY 15 trillion by 2038 to accelerate hydrogen adoption and related technological advancements. Additionally, Japan aims to expand its hydrogen refueling infrastructure, targeting 1,000 hydrogen stations by 2030 to support the anticipated growth of FCEVs.

- **United States**

In 2021, the U.S. Department of Energy (DOE) launched the "Hydrogen Shot" initiative, aiming to reduce the cost of clean hydrogen production to USD 1 per kilogram within a decade. This ambitious goal is intended to accelerate hydrogen adoption across various industrial sectors. The Hydrogen and Fuel Cell Technologies Office (HFTO) leads the initiative and plays a key role in driving research and development of hydrogen and fuel cell technologies.[22/]

At the state level, California has made significant progress in promoting hydrogen vehicle use through clear policies, including subsidies and tax incentives. For example, the EnergIIZE program provides grants for purchasing and installing infrastructure for zero-emission vehicles, including hydrogen refueling stations for FCEVs.[23/]

21/ Most recently, in 2024, the government issued a revised version of the strategy, incorporating policies to enhance competitiveness and promote the safe use of hydrogen. For more details, please refer to: https://www.meti.go.jp/shingikai/enecho/shoene_shinene/suiso_seisaku/pdf/20230606_5.pdf

22/ https://www.energy.gov/sites/default/files/2021-08/factsheet-hydrogen-shot-introduction-august2021.pdf

23/ 2024-EnergIIZE-Hydrogen-Fact-Sheet.pdf

- **China**

China has released its Medium- and Long-Term Hydrogen Industry Development Plan (2021–2035), [24/] aiming to become a leader in commercial hydrogen vehicle deployment. Over the past three years, the country has allocated more than RMB 5.1 billion (approximately THB 230 billion)[25/] to support FCEV production, expand hydrogen refueling stations, and promote hydrogen use in the transportation sector.In a significant milestone, China launched a 1,150-kilometer interregional hydrogen truck route in April 2025, featuring four hydrogen refueling stations along the way. The country aims to have more than 1,500 FCEV trucks operating on this route by 2027, which is expected to reduce carbon dioxide emissions by over 200,000 metric tons annually.[26/]

- **Thailand**

The Thai government recognizes hydrogen as a key energy source to reduce fossil fuel dependency and has incorporated hydrogen industry development into the National Energy Plan (2024-2037), with implementation beginning in 2025.[27/] Additionally, the Energy Policy and Planning Office (EPPO) has adopted this framework to promote hydrogen use in Thailand. The medium-term plan (2031–2040) focuses on advancing commercial hydrogen development and FCEV adoption, while the long-term plan (2041–2050) aims to establish regulations related to FCEV standards and hydrogen refueling stations.[28/]

24/ Entered into force in March 2022 https://www.ndrc.gov.cn/xxgk/zcfb/ghwb/202203/t20220323_1320038.html?code=&state=123

25/ https://fuelcellsworks.com/2025/04/23/green-investment/china-allocates-321-million-to-boost-regional-hydrogen-fuel-cell-vehicle-deployment

26/ https://english.news.cn/20250414/9cd05035256848689508ecb065880026/c.html

27/ https://www.thansettakij.com/climatecenter/net-zero/616823?utm

28/ ไฮโดรเจน พลังงานทางเลือกใหม่ ขับเคลื่อนไทยสู่เป้าหมาย Carbon Neutrality

Limitations of Hydrogen Vehicles Despite Their Environmental Benefits

While hydrogen is a promising sustainable energy alternative, hydrogen-powered vehicles still face several key limitations that hinder widespread consumer adoption:

- **High Cost of Hydrogen Fuel**

The current cost of hydrogen fuel ranges from approximately USD 13 to USD 16 (THB 424– THB521) per kilogram. This cost is composed of three main components: (1) hydrogen production accounts for only about 15% of the total fuel cost; (2) refueling station expenses, including compressors, dispensers,[29/] and on-site hydrogen storage, make up roughly 50%; and (3) transportation and distribution costs contribute around 35%.[30/] Due to these high fuel costs, FCEVs incur fuel expenses of about THB 6 per kilometer, which is higher than both BEVs and ICE vehicles, limiting consumer incentives to adopt hydrogen-powered vehicles at present.[31/]

- **Limited Hydrogen Refueling Infrastructure**

As of October 2024, there are only 1,168 hydrogen refueling stations worldwide,[32/] which remains significantly limited compared to the charging infrastructure for BEVs and PHEVs, as well as conventional gasoline stations for ICE vehicles. This limitation creates a classic "chicken-and-egg" dilemma: the relatively small number of hydrogen vehicles on the road results in low demand for hydrogen refueling, which in turn discourages investment in expanding the refueling infrastructure. Conversely, the insufficient and geographically limited refueling infrastructure undermines consumer confidence in purchasing hydrogen vehicles due to concerns about refueling convenience. This cyclical challenge poses a significant barrier to the growth of the hydrogen vehicle market.

Figure 11

Number of Hydrogen Refueling Stations



Source: H2station.org

29/ The cost of a single hydrogen dispenser is approximately 50 million baht, compared to an initial investment of 1.2 million baht for a 150-kilowatt DC fast charger for BEVs Source: https://www.thairath.co.th/news/auto/news/2504646 https://www.thansettakij.com/pr-news/social-biz/579614

30/ https://www.weforum.org/stories/2024/05/hydrogen-hidden-costs-energy-transition/

31/ Calculated by the author, based on data from How efficient are hydrogen cars? What mpg can I expect, and more - Driving Hydrogen
The units have been converted to Thai baht per kilometer.

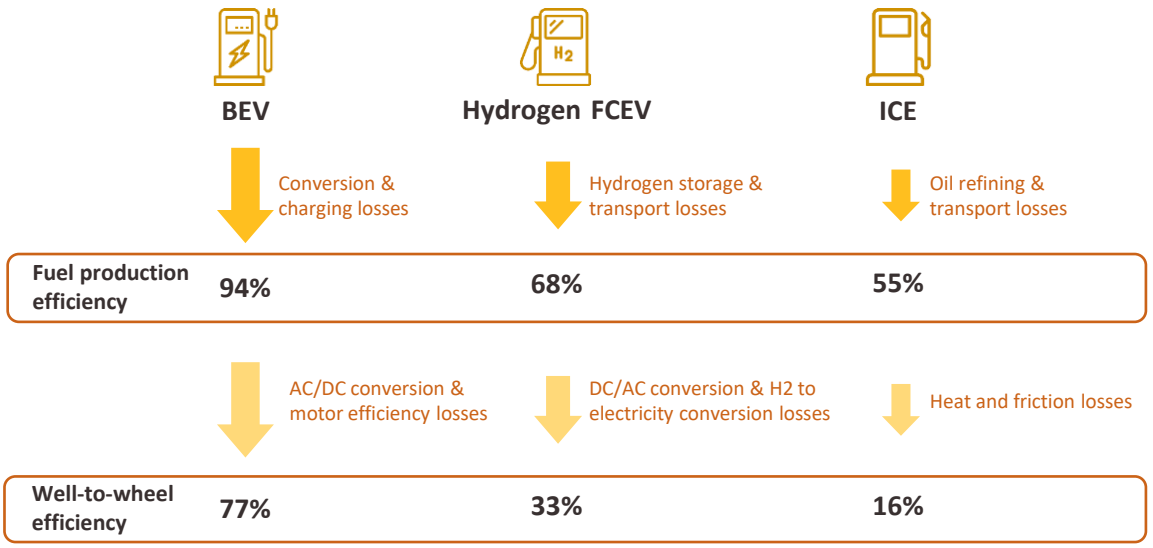
32/ https://hydrogencouncil.com/wp-content/uploads/2024/09/Hydrogen-Insights-2024.pdf

- **Unclear Energy Efficiency**

Hydrogen undergoes multiple processes that incur energy losses at each stage before it can be used as propulsion energy, including production, compression for storage, transportation, and conversion into electricity within the fuel cell. Well-to-wheel efficiency comparisons reveal that FCEV vehicles achieve only 33% efficiency, which is significantly lower than BEVs at 77%, though still higher than internal combustion engine vehicles at 16%.[33/] This raises questions about the overall energy efficiency and cost-effectiveness of using FCEVs.

Figure 12

Energy Efficiency of BEV, FCEV, and ICE Powertrains



Source: The Guardian, Transportenviorment.org, Krungsri Research

33/ https://insideevs.com/news/332584/efficiency-compared-battery-electric-73-hydrogen-22-ice-13/

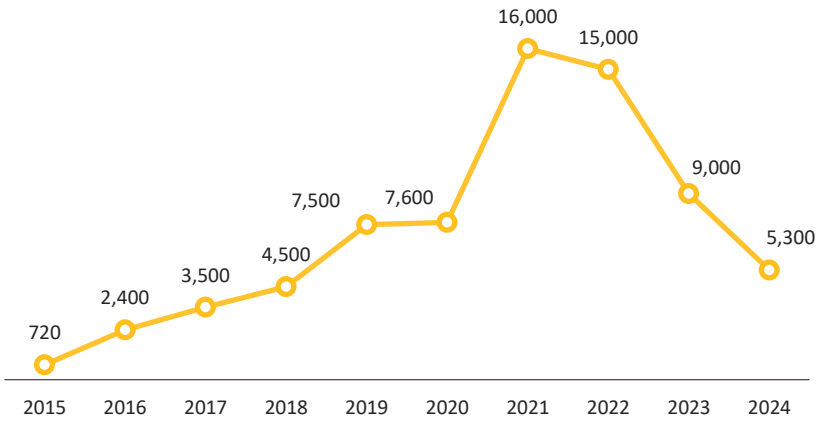
The Future Direction of Hydrogen Vehicles

Currently, FCEVs remain in the early adoption phase, as reflected in sales figures that, despite continuous growth from merely 720 units in 2015 to a peak of 16,000 units in 2021, subsequently declined to 5,300 units in 2024 (Figure 13).

An interesting case study is the Toyota Mirai, which saw sales decline to just 499 units in 2024 from 2,737 units in 2023.[34/] As a result, in January 2025, Toyota launched a promotional price reduction for the Mirai in California, cutting the price from USD 51,285 (approximately THB 1.7 million) to USD 17,005 (around THB 560,000), representing a 70% discount. This pricing made the Mirai comparable to the Nissan Versa, which was among the cheapest vehicles in the US market at the time.[35/] The key factor affecting sales was the limited hydrogen refueling infrastructure, which undermined consumer confidence. **This highlights that developing the entire supply chain — from hydrogen production to refueling stations and after-sales service[36/] — is crucial for driving consumer adoption of hydrogen vehicles, particularly in the passenger car segment.**

Figure 13

Global FCEV Sales between 2015 and 2024 (Units)



Source: IEA, Krungsri Research

Nevertheless, the FCEV market is expected to continue expanding in the future. According to Allied Market Research, the global FCEV market is projected to grow from USD 609 million (approximately THB 19.8 billion) in 2025 to USD 12.6 billion (approximately THB 410.3 billion) by 2033, representing a strong compound annual growth rate (CAGR) of 46%. This growth will be primarily driven by **stringent government environmental regulations and supportive policies promoting eco-friendly vehicles,** encouraging all sectors to transition to environmentally friendly transportation. Additionally, **advances in hydrogen production technology will reduce production costs and hydrogen fuel prices.**

34/ https://www.forbes.com/sites/peterlyon/2025/01/28/at-17000-toyotas-fuel-cell-mirai-is-now-americas-cheapest-car/

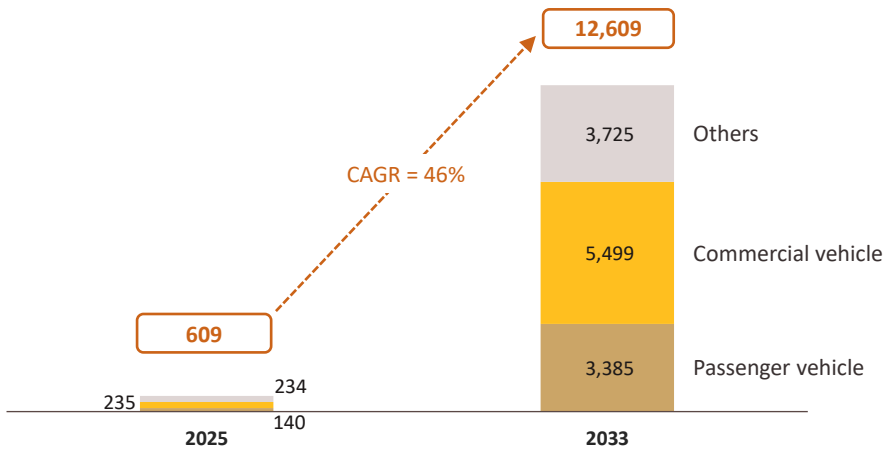
35/ The retail price of the Nissan Versa in the United States starts at a Manufacturer's Suggested Retail Price (MSRP) of USD 17,190 (approximately THB 560,000). For more details, see: 2025 Nissan Versa Specs, Trims, Dimensions & Prices

36/ FCEVs require hydrogen tank safety inspections every six months, fuel cell system checks annually, and replacement of consumable parts —such as the fuel cell air filter and ion exchanger element—every three years. These services must be performed exclusively at authorized FCEV service centers. For more details, please refer to T-MMS-24Mirai.pdf

Furthermore, given the advantages of FCEVs—including longer driving range and shorter refueling time compared to BEVs, combined with supportive government policies in multiple countries—FCEVs are particularly well-suited for commercial applications, especially in trucking and long-haul transportation. By 2036, commercial FCEVs are expected to capture approximately 44% of the market share, while passenger cars will account for around 27% (Figure 14).

Figure 14

Global FCEV Market Value Forecast (million USD)



Note: Commercial vehicles include light commercial vehicles and trucks. Others include buses and off-road vehicles.
Source:Allied Market Research , Krungsri Research

Although hydrogen fuel cell vehicles, particularly FCEV technology, continue to attract significant attention as an environmentally friendly transportation technology, SWOT and PESTEL framework analysis reveals that they still face multiple limitations in terms of technology, costs, and infrastructure readiness, as detailed in Table 1.

Table 1

Analysis of Hydrogen Vehicles Based on SWOT and PESTEL Frameworks

		Positive Factors	Negative Factors
		S - Strengths	W - Weaknesses
Internal Factors	For manufacturers and operators	• FCEV aligns with Zero Emission Vehicle (ZEV) development strategies, as it produces only water vapor as exhaust emission • Many automakers have shown interest and continuously collaborate on research and development of FCEVs, covering both passenger cars and commercial vehicles	• FCEV components such as fuel cells and hydrogen storage tanks remain expensive • Hydrogen storage and transportation involve high costs
	For users (including the banking sector)	• FCEV enables rapid refueling, making it suitable for commercial vehicles or long-distance travel • Businesses, including the banking sector, can utilize FCEV to reduce direct emissions or Scope 1 emissions.	• Hydrogen refueling stations remain limited in number, with additional concerns regarding maintenance and secondary market issues • The high purchase and operating costs of FCEVs compared to alternative options remain significant barriers to consumer acceptance

Table 1 (Cont.)

Analysis of Hydrogen Vehicles Based on SWOT and PESTEL Frameworks

		Positive Factors	Negative Factors
External Factors		O -Opportunities	T-Threats
	P – Political	• Governments worldwide are increasingly aware of the global boiling crisis and are seeking solutions to mitigate the situation, such as the Paris Agreement, which sets clear targets for greenhouse gas reduction. • Many countries have implemented policies supporting clean energy vehicles, including hydrogen-powered vehicles, to achieve sustainability goals. • Thailand has policies promoting clean energy vehicles, such as targeting zero-emission vehicles (ZEVs) to account for at least 30% of total vehicle production by 2030)	• Policy uncertainty in some countries may result in inconsistent support for the hydrogen industry, including promotional measures for hydrogen-powered vehicles.
	E - Economic factors	• The hydrogen industry is gaining increased attention, which will help reduce hydrogen fuel costs in the future and make hydrogen vehicle usage more cost-effective	• Investment in hydrogen supply chain infrastructure, such as refueling stations, has yet to achieve economies of scale or investment viability.
	S - Social factors	• FCEV represents a viable option for environmentally conscious consumers and businesses, helping to enhance corporate ESG initiative. • Performance-oriented consumers may be interested in FCEV due to its superior driving experience, offering excellent acceleration and consistent torque across all speed ranges	• Consumers still lack knowledge about hydrogen vehicles and confidence in hydrogen refueling infrastructure. • Safety concerns persist regarding the use of hydrogen, as it is a highly flammable gas.
	T - Technological factors	• Automakers have developed hydrogen fuel cell systems that manage energy more efficiently, with improved performance and greater durability. • Green hydrogen production technology continues to advance, resulting in lower production costs and higher future production volumes, supporting increased acceptance of hydrogen usage across various sectors, including transportation.	• FCEV technology still exhibits lower energy efficiency compared to BEVs. • Competing technologies like BEVs—such as batteries and energy management systems—are rapidly advancing, reducing barriers to adoption. • Synthetic fuels (E-Fuels) and biofuels, which represent new fuel production techniques for the transportation sector, are being continuously developed.
	E – Environmental factors	• The goal of reducing greenhouse gas emissions to achieve Net Zero is driving the transportation sector to increasingly adopt clean energy vehicles • Environmental issues, including PM2.5 pollution, are driving increased interest in clean energy vehicles.	• If hydrogen production continues to rely on fossil fuels, the use of FCEVs cannot be considered truly environmentally friendly energy
	L - Legal factors	• Carbon footprint reporting regulations are becoming increasingly stringent; for example, listed companies on the Stock Exchange of Thailand are now required to disclose their greenhouse gas emissions.	• Regulations regarding hydrogen production and transportation remain unclear in many countries, causing private sector hesitation in investment. • Thailand still lacks regulatory readiness to promote and support hydrogen usage, production, transportation, and sales.

Source: Krungsri Research

Opportunities and Adaptation for Banks

Banks have previously played a crucial role in sustainability adaptation through the development of financial instruments and products that respond to ESG objectives. Banks can expand this role by supporting operators in the supply chain and consumers interested in hydrogen vehicles through financial instruments such as:

- **Green bonds**

Currently, many countries worldwide are increasingly interested in investing in the hydrogen industry. According to Hydrogen Insight (2024), global investment needs in the hydrogen sector are estimated at over USD 335 billion (approximately THB 1.1 trillion) by 2030.[37/] Banks can play a vital role by issuing Green Bonds, allocating funds to businesses within the hydrogen supply chain. This approach helps meet substantial financing demands, bridges funding gaps, and supports both infrastructure development and widespread adoption of hydrogen vehicles.

- **Green loans**

Commercial banks are increasingly offering preferential interest rates for environmentally friendly activities or projects.[38/] For hydrogen vehicles, banks can extend such support to operators within the hydrogen industry ecosystem, including hydrogen refueling stations, fuel cell manufacturers and related components, transportation operators, and consumers seeking transition to hydrogen vehicles. Expanding credit to these segments represents an opportunity to create lending channels while supporting sustainable growth for both banks and their customers.

In addition to their role in capital allocation to customers, banks can demonstrate their commitment to reducing direct greenhouse gas emissions (Scope 1) by incorporating FCEVs into their business operations or customer services, which will further enhance the bank's environmental-conscious image.

However, expanding business into the FCEV ecosystem involves certain considerations. Since FCEVs are still relatively new technology for consumers and automakers are continuously improving fuel cell system efficiency, the resale value of older FCEV models has significantly declined. For example, in the U.S. market, a 7-year-old first-generation Toyota Mirai has a used car starting price of only USD 7,640 (around 250,000 THB),[39/] which is a sharp drop from the new car price of USD 58,365 (approximately 1.9 million THB)[40/] —representing just 13% of the original price. **Therefore, providing financing for FCEV leases faces challenges due to the difficulty in accurately assessing collateral value, as the resale value of FCEVs tends to depreciate rapidly.**

37/ https://hydrogencouncil.com/wp-content/uploads/2024/09/Hydrogen-Insights-2024.pdf

38/ Krungsri offers sustainability business loans that cover clean energy businesses, electric vehicle charging stations, and electric vehicle parts manufacturing. For more details, please visit: https://www.krungsri.com/th/business/loans/krungsri-sme-sustainability-loan-for-all/krungsri-sustainability-businesses

39/ https://www.edmunds.com/toyota/mirai/2018/review/

40/ https://www.cars.com/research/toyota-mirai-2018/

Additionally, with the limited number of FCEV vehicles in actual use, the insurance industry lacks data for assessing damage values in case of accidents. Furthermore, critical FCEV components such as fuel cell stacks and hydrogen storage tanks remain expensive. The insurance industry must therefore carefully determine premium rates, and banks should consider insurance costs when evaluating customers' debt servicing capacity

It is evident that if banks can seize the opportunities arising from the transition to clean energy, such as hydrogen-powered vehicles, they can generate revenue while supporting the green economy and contributing to long-term environmental sustainability to protect our planet. However, given that FCEV technology is still in its early stages, leading to a sharp decline in resale value and high insurance premiums, these remain key challenges that must be carefully considered to design suitable financial products and manage risks comprehensively.

Box 3 Examples of Banks Supporting Hydrogen Vehicles

- In 2020, **BNP Paribas**[41/] acted as a lead arranger for a 10-year Green Bond worth €1 billion issued by Daimler, a subsidiary of Mercedes-Benz. The bond aimed to support the transition to a low-carbon business operation, including the development of FCEV technology and related infrastructure.

- In 2021, **MUFG**[42/] signed a hydrogen-linked loan agreement valued at USD 50 million with First Element Fuel, the largest developer and operator of hydrogen fueling stations in California. Additionally, in 2024, MUFG invested in the Japan Hydrogen Fund, which targets investments across the hydrogen industry value chain—from production, storage, and transportation to end-use applications in various sectors.

41/ https://cib.bnpparibas/bnp-paribas-joint-bookrunner-for-daimlers-first-green-bond/ & https://group.mercedes-benz.com/investors/refinancing/green-finance/green-bond.html?

42/ Japan's MUFG Bank Supports California's Largest Hydrogen Fuel Stations Business With Debt Financing & https://www.bk.mufg.jp/global/newsroom/news2024/pdf/newse0913.pdf

Krungsri Research View

Although the global hydrogen vehicle market is not particularly vibrant at present, several countries have begun implementing policies for commercial hydrogen fuel usage in trucks and public transportation systems. However, looking ahead, the hydrogen vehicle market remains highly uncertain. While many automotive manufacturers continue to show interest in developing this technology, some remain opposed, such as Elon Musk, co-founder and CEO of Tesla, who has expressed clearly negative attitudes and disagreement with hydrogen fuel cell technology[43/]

Nevertheless, we should closely monitor developments in the hydrogen vehicle sector. If hydrogen fuel costs decrease, infrastructure becomes more developed, government policies provide strong support, and financial sectors offer backing, these factors will serve as key drivers for hydrogen vehicles to become major players in the clean energy vehicle market. In the future, we may see hydrogen vehicles widely on the roads, comparable to BEVs.

Hydrogen vehicles are not only an eco-friendly transportation option for consumers but also present opportunities for banks in developing financial products and services, as well as playing a role in promoting environmental sustainability. **Therefore, banks should prepare to develop financial products and services that support businesses within the hydrogen vehicle industry's supply chain. This requires studying and understanding the market and building internal expertise to assess feasibility before developing financial products tailored to these businesses**.

In the initial phase, banks may face challenges in assessing risks associated with hydrogen vehicle-linked financial products, such as the uncertain secondary hydrogen vehicle market, depreciation assessments, maintenance costs, and developing financial models for credit approval considerations. Therefore, careful planning is required in developing financial products for hydrogen vehicles.

Additionally, banks can establish partnerships with industry sectors to exchange knowledge about hydrogen-powered vehicles, such as hydrogen fuel producers to understand costs and price trends, refueling station operators to assess investment opportunities, automotive manufacturers to stay informed about industry developments, and transportation operators to understand business sector demand or readiness for transitioning to clean energy vehicles. Such knowledge exchange opportunities will help lead to the development of appropriate financial instruments that align with the environmental sustainability goals of both banks and their customers.

Ultimately, whether we choose to adopt BEVs or hydrogen vehicles, environmental friendliness should not be overlooked throughout the entire life cycle, from production and transportation to usage and end-of-life management. A comprehensive life cycle assessment is essential to accurately evaluate the environmental impact and ensure that the transportation sector truly contributes to sustainability goals.

43/ https://www.cnbc.com/2019/02/21/musk-calls-hydrogen-fuel-cells-stupid-but-tech-may-threaten-tesla.html

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