CLEAN ENERGY TECHNOLOGIES JOURNAL

Volume 3
Number 1
Year 2025

YTU PRESS

www.cetj.yildiz.edu.tr

CLEAN ENERGY TECHNOLOGIES JOURNAL

Volume 3 Number 1 Year 2025

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Journal Description: The journal is supported by Yildiz Technical University officially, and is a blind peer-reviewed free open-access journal, published two times a year.
Publisher: Yildiz Technical University - YTU Press
Language of Publication: English
Frequency: Two issues
Publication Type: Online e-version
Press Date: June 2025

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Volume 3 Number 1 Year 2025

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Clean Energy Technol J, Vol. 3, No. 1, pp. 1-19, June, 2025

Clean Energy Technologies Journal
Web page info: https://cetj.yildiz.edu.tr
DOI: 10.14744/cetj.2025.0001

CLEAN ENERGY TECHNOLOGIES JOURNAL

Review Article

The role of hydrogen in sustainable transportation: An international review of distribution and supply systems

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ARTICLE INFO

Article history
Received: 22 May 2025
Accepted: 11 June 2025

Key words:
Fuel Cell Vehicles; Hydrogen Refueling Stations; Hydrogen Strategies.

ABSTRACT

The goal of reducing the impact of road transportation on carbon emissions highlights the growing importance of hydrogen as an alternative fuel. Although hydrogen fuel cell vehicles (FCEVs) offer a zero-emission solution, their widespread adoption is limited by the scarcity of hydrogen refueling stations (HRSs). This review provides an overview of on-site (production at the station) and off-site (delivery-based supply) HRS types and examines recent studies related to HRS planning. Particular attention is given to optimization approaches, economic analyses, and the influence of hydrogen transportation costs on infrastructure decisions. Furthermore, the global distribution of HRSs and national hydrogen strategies are evaluated with a focus on Europe, Asia, and North America. The findings underscore the necessity of integrated planning approaches covering production, distribution, and consumption processes for a sustainable and scalable hydrogen mobility ecosystem. The study reveals that the effective use of hydrogen in transportation is achievable through holistic infrastructure planning and coherent policy frameworks.

Cite this article as: Mutlu G, Çiçek A, Erdinç O. The role of hydrogen in sustainable transportation: An international review of distribution and supply systems. Clean Energy Technol J 2025;3(1):1–19.

INTRODUCTION

Carbon dioxide emissions have been steadily increasing from past years to the present day [1]. In recent years, the global energy crisis and environmental concerns have led to the widespread use of fossil fuels being recognized as the primary source of carbon dioxide emissions that contribute to global warming and climate change [2]. In 2024, the transportation sector is responsible for 19.33% of global CO_2 emissions, with road transportation accounting for 73.98% of the transportation sector's total emissions [3]. Moreover, the future of petroleum-based fuels such as gasoline and diesel in the transportation and energy sectors remains uncertain. Political instability in regions with large oil reserves and a decline in crude oil supply, combined with stringent emissions regulations, have collectively increased the demand for alternative fuels [4].

Although electric vehicles (EVs) have gained popularity due to their zero-emission performance, low fuel costs, and reduced maintenance expenses, they also have disadvantages such as long charging times and limited driving range.

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Hydrogen-powered vehicles emerge as a promising alternative that can overcome these limitations with their shorter refueling times and longer-range capabilities [5]. However, the high cost of hydrogen fuel cells, the underdeveloped hydrogen production and distribution infrastructure, and the limited availability of HRSs are among the most critical factors affecting the widespread adoption of FCEVs. From an economic perspective, enhancing the competitiveness of FCEVs requires reducing production costs, increasing investments in infrastructure, and providing government incentives.

Automotive companies have made substantial investments to enable the commercial deployment of hydrogen-powered vehicles, with many manufacturers aiming to mass-produce and market FCEVs [6]. Honda launched the CR-V e model in 2025, which integrates both plug-in charging and hydrogen fuel cell technology, offering a hybrid system that operates electrically for short distances and on hydrogen for longer trips [7]. Hyundai's Nexo SUV, introduced in 2018, is a hydrogen-powered model that reached over 10,000 units sold in South Korea by 2020. In the same year, Hyundai unveiled the Xcient Fuel Cell Truck, the world's first mass-produced hydrogen fuel cell truck, and delivered seven units to Switzerland [8]. By May 2024, Hyundai had surpassed 40,000 global sales of hydrogen vehicles [9] and announced its ambition to become the first automaker to integrate fuel cell systems into all commercial vehicle models by 2028, and to achieve cost parity between FCEVs and battery electric vehicles (BEVs) by 2030 [10]. BMW, which began testing its iX5 Hydrogen fleet in 2024, plans to commence mass production by 2028 [11]. The Volkswagen Group, aiming to achieve carbon neutrality by 2040, filed a patent in 2024 for a hydrogen fuel cell stack offering a driving range of 2,000 km [12], [13]. Ford Motor Company has announced that it will continue testing its eight-fuel cell E-Transit vehicles throughout 2025 [14]. Toyota, a pioneer in the hydrogen sector, launched its MIRAI FCEV in 2014 and has since sold over 28,000 units across more than 30 countries and regions [15]. In November 2023, the company also released the Crown FCEV model in Japan [16].

An emerging approach in hydrogen refueling technology is the use of hydrogen swapping systems, which aim to overcome the limitations of conventional on-site production and compression-based refueling infrastructure. Notably, the French-Moroccan startup NamX has introduced a hydrogen utility vehicle concept that integrates six removable hydrogen capsules in addition to a fixed main tank. This modular system enables users to replace depleted hydrogen units quickly, thereby reducing reliance on fixed refueling stations and enhancing vehicle autonomy, especially in regions with limited infrastructure [17]. Similarly, Toyota, in collaboration with Woven Planet, is developing portable hydrogen cartridges designed to supply hydrogen energy for a range of mobility and domestic applications. These cartridges are intended to be lightweight, easy to swap, and safe for everyday use, thereby promoting decentralized hydrogen access and enhancing flexibility in hydrogen distribution [18].

Highlights

- Hydrogen refueling stations
- Hydrogen transportation
- International hydrogen policies

However, there is a vicious cycle between the adoption of hydrogen vehicles and the expansion of hydrogen refueling infrastructure. Manufacturers are hesitant to sell hydrogen-powered vehicles at scale without a sufficient refueling network, while investors are reluctant to fund infrastructure without a large vehicle fleet. To break this cycle, targeted infrastructure investments supported by public subsidies in specific regions are recommended [19]. HRSs are critical to the operational sustainability of hydrogen vehicles, and the launch of commercial hydrogen vehicles and the simultaneous establishment of a refueling network are required [20].

The paper's organization is presented as follows: Section 2 presents HRS types along with their respective advantages and disadvantages. The studies currently available in the literature for micro mobility vehicles are given in Section 3. Section 4 provides an overview of HRSs worldwide, including hydrogen infrastructure, hydrogen transportation, and national hydrogen policies. Concluding remarks are provided in Section 5.

CLASSIFICATION OF HYDROGEN REFUELING STATIONS

HRSs are infrastructure facilities designed to supply energy to hydrogen-powered vehicles. These stations are generally classified into two main categories based on the method of hydrogen production and supply: on-site (produced at the station) and off-site (externally sourced) systems. These types of stations differ in terms of energy supply, cost, infrastructure dependency, and environmental impact. In the comparative evaluation of on-site and off-site systems, factors such as economies of scale, access to energy resources, investment budget, supply security, and sustainability goals play a critical role. There are also hybrid stations that incorporate both on-site and off-site hydrogen supply systems [20], [21].

Hydrogen Refueling Stations with On-Site Hydrogen Production

On-site HRSs are systems in which hydrogen is produced directly at the point of consumption, i.e. directly at the station site, as illustrated in Figure 1. This production is typically carried out using methods such as electrolysis (the separation of water into hydrogen and oxygen using

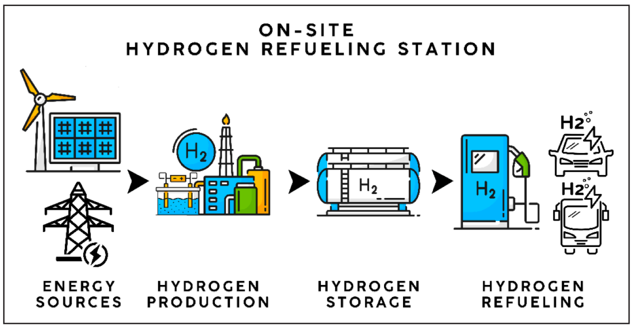

Figure 1. On-site hydrogen refueling station.

electricity) or steam methane reforming of natural gas [22]. The primary advantage of electrolysis is its ability to produce hydrogen with zero emissions when integrated with renewable energy sources (RES), significantly reducing the carbon footprint [23]. However, electrolysis systems require high electricity consumption and substantial capital investment. On-site production offers operational flexibility, particularly in rural or remote areas where transportation infrastructure is limited, and reduces logistical operations such as hydrogen compression, transportation, and storage. Nevertheless, limited production capacity, restricted economies of scale, and maintenance requirements can hinder the widespread adoption of on-site systems.

Hydrogen Refueling Stations with Hydrogen Delivery

Off-site HRSs are systems in which hydrogen is produced at a centralized production facility and then transported to refueling stations for storage and distribution, as illustrated in Figure 2. This transportation is typically carried out via compressed gas cylinders, tube trailers, cryogenic liquid hydrogen tankers, or, in large-scale projects, dedicated pipeline networks [24]. Off-site systems benefit from the efficiencies of large-scale production and lower unit costs. Furthermore, implementing carbon capture and storage technologies is more feasible at centralized production facilities, potentially enhancing the overall environmental benefits [21]. However, hydrogen transportation is not only costly but also requires stringent engineering measures to ensure safety. Additionally, potential disruptions in the supply chain may pose risks to supply security.

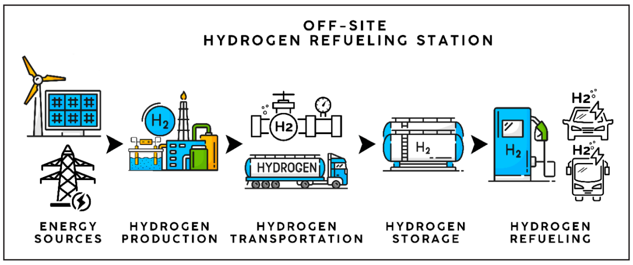

Figure 2. Off-site hydrogen refueling station.

LITERATURE OVERVIEW

The prevalence, location, operational costs, and hydrogen transportation expenses of HRSs are significant factors influencing the widespread adoption of hydrogen-powered vehicles. Accordingly, the literature includes numerous studies focusing on the installation and operational costs of HRSs, their optimal siting, the unit price of produced/sold hydrogen, and hydrogen supply logistics.

On-Site Hydrogen Refueling Station

In the first part of the literature overview, studies focusing on on-site hydrogen production at HRSs are presented. Since hydrogen is produced on-site in these studies, they primarily focus on the production stage, excluding transportation costs. Hai et al. [25] investigated the optimal design of an HRS located along a roadside and modeled the system using TRNSYS software. The station model, which produces hydrogen on-site using a solar-powered electrolyzer, introduced innovative approaches such as multi-stage storage tanks, pressure-temperature control, and minimization of environmental emissions. Zhou et al. [26] conducted a detailed study of the molten-medium-catalyzed pyrolysis of natural gas technology for hydrogen production and highlighted its potential for low-carbon hydrogen production. It was noted that on-site HRSs can eliminate hydrogen transportation costs and that locating the station near a natural gas infrastructure can also minimize the cost of transporting raw materials (natural gas). Erdinç [27] analyzed an energy management strategy of an independent service station focused on minimizing the comfort violation using the MILP (Mixed-integer linear programming) model. The service station serves different types of vehicles such as EV and FCEV, and has a PV (Photovoltaic) system, electric storage systems and electrolyzer as the main power source. The study emphasized the impact of component sizing and relaxing fairness constraints on system performance through different case study results. This study offers a comprehensive management strategy for renewable-powered standalone stations. Çiçek [28] modeled the cost minimization of an all-in-one station providing hydrogen refueling for FCEVs and plug-in charging or battery swapping services for SBEVs using MILP. The station generates electricity from PV panels and purchases power from the grid at variable prices. The study enhances operational efficiency through flexibility features such as energy transfer between batteries in the battery swapping station and hydrogen storage. This study presents a comprehensive management strategy for stand-alone stations operating with renewable energy. Barhoumi et al. [29] conducted an economic analysis of a PV-powered HRS belonging to a transportation company in Tunisia. Considering the initial cost and operational cost of the equipment, the project would pay off in 10 years if the hydrogen selling price is 8 €/kg. The study emphasized that, thanks to Tunisia's high solar potential, green hydrogen can be a sustainable alternative to fossil fuels in the transportation sector. Similarly, Barhoumi et al. [30] conducted an economic analysis of a PV-powered and grid-connected HRS. In countries like Tunisia with high photovoltaic potential, the study aimed to show that such projects, though having high initial investment costs, can yield high future profitability. Marcos et al. [31] proposed a novel stochastic-interval model to optimize energy management of a PV-supported HRS. The study addressed uncertainties in power generation from PV and energy prices using interval notation and modeled FCEV demand through a scenario-based approach. The station is powered by PV panels and the grid, and electricity produced from the fuel cell and PV panels can be sold back to the grid when necessary. The developed method provides operational flexibility by supporting both risk-averse and risk-taking strategies. Results show that on-site hydrogen production and energy sales to the grid significantly improve the economic efficiency of the station. Li et al. [32] conducted a technical and economic analysis of an HRS in China based on a hybrid PV/wind energy system to determine the optimal system configuration and minimize hydrogen production costs. Various combinations of scenarios were analyzed, including PV panels, wind turbines, grid connection, and fuel cells. While the scenario involving PV and wind turbines without grid connection was advantageous in terms of renewable energy, it was found to have very high initial investment costs. Additionally, the energy output from renewable sources is not easily predictable. As a result, the best system configuration was found to be a grid-connected setup with PV panels, wind turbines, hydrogen tanks, and electrolyzers. Mobasseri et al. [33] presented a hybrid robust-stochastic energy management model for a multi-energy microgrid integrating electricity, heat, hydrogen, and gas sub-networks. The study proposed an innovative framework for managing multiple energy carriers and uncertainties in multi-energy microgrids, addressing FCEV demand with stochastic programming, electricity/heat demand using information gap decision theory and PV output uncertainties with the Hong 2m+1 method—managing different types of uncertainties with an integrated approach. Dadkah et al. [34] analyzed the techno-economic feasibility of an HRS in Belgium using an MINLP model. The modeled station draws power from the electricity market, supplies hydrogen for mobility, can inject into the natural gas system, and participates in the ancillary services market. The study concluded that profits could be increased by up to 16%. Although renewable energy was not used as a direct source, RES are mentioned as part of the grid. Zhu et al. [35] examined an optimization strategy for a composite energy station integrating PV, charging, and hydrogenation, combined with demand response. While hydrogen refueling for FCEVs was done with stored hydrogen, energy demands for fixed loads and EVs were met with available power. The proposed optimal operation strategy, considering demand response, evaluated changes in comprehensive operation costs and load fluctuation. The model, solved using the Improved Moth-Flame Optimization algorithm, reduced operating costs by CNY 1051.5 and load fluctuation by 17.8%. Xu et al. [36] modeled a fuel station for BEVs and FCEVs that produces hydrogen/electricity using only PV panel-generated energy and without access to the electricity grid. The study used scenario-based stochastic optimization to handle PV output and demand uncertainties and used Conditional Value at Risk (CVaR) for risk management. In this MILP-modeled system, penalty costs for unmet demand were considered while maximizing the profit.

Tao et al. [37] proposed a model that jointly considers the electricity distribution network and transportation system to achieve low carbon emissions at minimal cost. Hydrogen was produced using Power-to-Gas stations and RES were integrated. The study aimed to minimize total system emissions by optimizing the penetration rates of internal combustion vehicles, EVs, and hydrogen FCEVs. Results showed a 30.3% reduction in carbon emissions, a payback period of 6.8 years, and a 14.6% return on investment. Genovese and Fragiacomo [38] proposed a multi-modular hydrogen energy station model consisting of three main parts: hydrogen production from power, power and heat production from hydrogen, and hydrogen refueling for mobility. The model provides hydrogen at 700 bar, 350 bar, and 30 bar for FCEVs, forklifts, and bicycles, respectively. As a result, a 5.2-year payback period and a 16.11% return on investment within 10 years were achieved. Although it is emphasized that the system is suitable for renewable integration, an alkaline electrolyzer powered by grid electricity was used. Shoja et al. [39] presented a hybrid risk management model to optimize sustainable energy supply for EV charging parks and HRSs within local multi-energy systems. The study managed uncertainties in wind energy, hydrogen demand in HRSs, and energy prices using a Hybrid Multi-Objective Information Gap Decision Theory/Robust Optimization approach. Notably, the combination of storage systems and Integrated Demand Response programs increased flexibility in energy demand and reduced total costs. The study in [40] examined the fast charging and the optimal sizing of HRSs in a multi-energy microgrid system. The system is powered by wind and solar RES and uses hybrid storage systems (battery and hydrogen). The objective function focused on minimizing the loss of power supply probability and total life-cycle cost.

Gökçek et al. [41] analyzed an on-site HRS supported by PV and wind turbines to meet the hydrogen demand of FCEVs in Niğde, Türkiye, and Zaragoza, Spain. The study provided a techno-economic analysis. Using HOMER (Hybrid Optimization of Multiple Energy Resources) Pro software, scenarios involving individual and combined use of RES were evaluated, and the Levelized Cost of Hydrogen and Net Present Cost were optimized. In the model proposed in [42], the installation cost, penalty cost for unmet demand and the cost paid for electricity were tried to be minimized in on-site production HRSs established by taking into account renewable energy integration (PV modules), distribution network and traffic network. Unlike other studies, Zhang et al. included a scenario in which hydrogen is transported between stations via trailers in cases of imbalance between hydrogen production and demand, aiming to reduce penalty costs and meet maximum demand. The redistribution of hydrogen was formulated using the classical pickup and delivery traveling salesman problem to minimize travel distance.

Off-Site Hydrogen Refueling Station

In the literature, studies in which hydrogen is transported from an external source to the point of demand have been examined in this section. Rezaei et al. [43] focused on optimal site selection for a wind-powered HRS. The aim was to achieve more effective outcomes from infrastructure-heavy projects such as hydrogen fuel stations and wind turbines, which require significant time, financial investment, and labor. The study specifically addressed the transportation of hydrogen produced at a wind farm to a station located in the capital city, considering hydrogen transport distance as one of the geographical criteria. Elomiya et al. [44] focused on optimizing the placement of HRSs in the Prague region. In their study, criteria weights were determined using the Fuzzy Analytic Hierarchy Process, suitability maps were generated through GIS (Geographic Information System) based spatial analyses, and site selection was automated using the integration of Fuzzy C-Means (FCM) clustering with GA-TOPSIS. For the off-site station, hydrogen transportation was evaluated based on criteria such as adaptation of existing gas networks and proximity to logistics centers (e.g., industrial zones, railway stations). Timalsina et al. [45] proposed an optimization model for the transportation of green hydrogen produced via water electrolysis using wind-generated electricity and blue hydrogen produced through Steam Methane Reforming, the model considers hydrogen pipelines, natural gas pipelines, and variable numbers of trucks per facility. Using a combination of MILP and ROA (Real Options Analysis) methods, the study concluded that new pipelines are optimal for long-distance hydrogen transport, trucks are more suitable for short distances, and repurposed natural gas pipelines present the lowest-cost alternative. Karthikeyan et al. [46] developed an optimization model aiming to minimize the production, storage, and transportation costs of green hydrogen by optimizing large-scale solar-powered PEM electrolyzer systems. While the study attempted to minimize hydrogen delivery costs to various cities, it only considered station locations to reduce delivery costs by truck and did not propose an optimal delivery or routing solution. Zhou et al. [47] optimized the location of HRSs along highways under both continuous and discrete conditions by integrating hydrogen sources and transport costs. In the study aiming to minimize the unit hydrogen cost, cost analyses were conducted in case of transporting hydrogen produced from RES (wind/solar) in gaseous form with trailers or liquid tankers. Although transportation costs were calculated by considering distance, vehicle capacity and driver costs, optimal routing was not included. Zhen et al. [48] considered HRSs location optimization under uncertain demand scenarios using a two-stage stochastic model. The study aimed to minimize construction costs, transport costs, and operational constraints, focusing on off-site hydrogen supply. Hydrogen transportation costs were optimized using high-pressure tube trailers, and the scheduling of hydrogen transport from production facilities to HRSs was conducted under varying demand scenarios. The model proposed in [49] uses multiple data sources including existing gas station network data, GIS data, population data and regional economic data to select the optimum location for HRSs in China. The aim is to reduce costs by suggesting the sharing of infrastructures such as existing gas stations. The study emphasizes the importance of strategic location of HRSs, especially due to high investment costs. Indirect solutions such as integrating stations into the transportation network and placing them based on demand are prominent in order to reduce transportation costs. Although hydrogen demand is met by off-site supply in this study, it does not provide a concrete solution for hydrogen production or transportation to the stations. Sahraie and Kamwa [50] proposed a hydrogen transportation system model in which hydrogen tube trailers are routed via a vehicle routing problem (VRP), considering traffic density and road availability constraints. The study, which provides a cost-reliability balance in the transportation of hydrogen produced from RES, offers optimization especially for hydrogen FCEVs filling stations. Zhang et al. [51] developed an optimization model considering the strategic placement of HRSs along highways, hydrogen supply, transport, and consumption. The objective function minimizes unit hydrogen cost. The model uses genetic algorithms to determine station locations, scales, and the number of distributors, while hydrogen transportation costs are calculated based on distance and transport mode. Shao et al. [52] proposed an optimal operational model combining time-based hydrogen production with event-based hydrogen delivery. Hydrogen produced from wind energy is transported using tube trailers, and the transportation cost is incorporated into the VRP. In hydrogen production, wind spillage/load shedding, and in hydrogen transportation with trailers, delivery cost and capacity constraints were taken into account. The model accounts for wind spillage/load shedding during production, delivery costs and capacity constraints during transportation. Li and Ning [53] proposed a two-stage electricity and hydrogen trading model integrating multiple microgrids (MMG) with off-site HRSs. Electricity trading among multi grids are modeled using a Nash bargaining approach, while hydrogen trading is modeled with a Stackelberg game, solved using distributed algorithms. Hydrogen is produced within MGs and delivered to HRSs via pipelines; transportation costs and line pack capacity are optimized. The system, supported by RES, achieves both carbon emission reduction and cost minimization.

In Li et al. [54], a hydrogen supply chain model was developed to meet the hydrogen demand of FCEVs by integrating with the electricity network. The model uses electricity from RES (particularly hydropower) to produce hydrogen via electrolyzers. Seasonal hydrogen storage systems have been used to eliminate seasonal imbalances. The study suggests that transporting electricity and producing hydrogen near demand centers reduces transportation costs and increases system efficiency by minimizing fuel costs, distances, and the number of trailers required.

On-Site/Off-Site (Hybrid) Hydrogen Refueling Stations

Considering the studies in which hydrogen demand is met both by hydrogen produced at the location of the station and by hydrogen transported from an external source, there are studies in the literature in which transportation cost is taken into consideration. Erenoğlu [55] aimed to minimize the overall costs of operating the R2 station integrated with a multi-energy carrier system to supply electricity and heat to stationary energy consumers and hydrogen and electricity to the transportation sector with a real-time optimization model. The MILP-based model provides a capacity-constrained routing algorithm for hydrogen logistics, while meeting the energy needs of EVs and FCEVs through renewable sources (PV/wind). Ryu et al. [56] developed a two-stage, web-based decision support system for the optimization of HRSs and the hydrogen supply chain in South Korea. While locations of HRSs were determined using max-coverage and p-median models, a multi-product transportation model was used to optimize hydrogen distribution from production facilities to stations. The study evaluated gaseous/liquid hydrogen transport costs, on-site production options, and renewable energy integration potential, enabling the placement of 450 to 660 HRSs nationwide and linking stations to production sources. Zhou et al. [57] aimed to minimize the unit hydrogen cost by considering two different types of HRSs, off-site and on-site, and the location and equipment costs of these HRSs. In the results obtained from the solution of a highway example with MINLP, it was seen that considering different station types reduces the UHC compared to a single station type. For off-site stations, transportation costs were minimized by factoring in vehicle usage fees, driver hiring costs, and the optimal number of transportation vehicles according to delivered hydrogen volume. Gaseous hydrogen trailers were preferred for short distances, while liquid hydrogen tankers were more suitable for long distances. The study highlights the critical role of station type selection and transportation optimization in hydrogen infrastructure planning. Kuvvetli [58] developed an optimization model focusing on Adana, Türkiye, aiming to maximize population coverage while minimizing total cost and risk in HRSs siting. The model included on-site production via renewable energy-powered electrolysis and off-site delivery options. For off-site delivery option, transportation costs were optimized based on capacity and distance. Li et al. [59] jointly addressed hydrogen supply chain and refueling station planning through a model that seeks to minimize the levelized cost of hydrogen, considering capital investment, feedstock procurement, operational costs, transportation technologies, and emission costs. The study analyzes both on-site production and road-delivered hydrogen HRSs. The model optimizes transport costs including fuel, labor, and maintenance, and evaluates trade-offs between gaseous and liquid transport modes. In [60], the operational cost of a hydrogen-electricity coupled with MMG model using hydrogen tube trailers and power lines was minimized. The model aims to enhance MMG economic efficiency by minimizing electricity purchase, equipment maintenance, and hydrogen logistics costs. Hydrogen transport costs were directly linked to the number of trailers and transported hydrogen volume. The optimization balances delivery time and capacity utilization, achieving cost savings by reallocating excess hydrogen from micro grid to other microgrids. The integrated energy systems in [61] can exchange electricity and hydrogen with external suppliers or peer-to-peer. A Nash bargaining model enables each integrated energy system to negotiate optimal outcomes at lower cost. Electricity is traded via power lines, and hydrogen is delivered by trailers on roadways. Incorporating road traffic data, the scenario achieves the lowest costs using a VRP-based approach combined with peer-to-peer trading and external supply. Lai et al. [62] introduced a hydrogen credit trading system for green hydrogen-based transportation. Infrastructure investments, transport, and vehicle costs were optimized using three business models based on life-cycle assessments. The use of hydrogen credit enables revenue generation in carbon markets, subsidizing transportation costs and reducing Levelized Cost of Driving by up to 50%. The model includes benefit-sharing among producers, transporters, and users. While hydrogen transport costs were integrated via pipeline and trailer delivery scenarios and included in life-cycle assessment, no specific logistics or routing optimization model was proposed. Nuñez-Jimenez and De Blasio [63] analyzed three scenarios—energy independence, cost optimization, and energy security—to meet the EU's future renewable hydrogen needs. Using the MIGHTY optimization model, the study evaluated production potential, cost curves, and transport costs, including pipelines and ammonia/LH_2 maritime shipping. Results indicate that while full hydrogen independence is achievable for the EU, regional imports can reduce costs, and long-distance imports may enhance supply security. Integration of renewable-based production and transport infrastructure was a central theme of the study.

Focusing on mobile hydrogen energy resources, Wang et al. [64] proposed a model for the economic and disaster-resilient planning of hydrogen-supported power distribution networks. Hydrogen produced via electrolysis from renewable sources was integrated into stationary and mobile storage systems, emphasizing the flexibility of mobile hydrogen energy resources under disaster scenarios. Using a two-stage risk-averse stochastic programming model with the CVaR criterion, operational risks were minimized. Simulations on a 33-bus test system showed that mobile sources reduced outage risks by up to 75%. Hydrogen transport costs were integrated to the model in relation to fuel consumption rates and optimal routing. Sarwar et al. [65] designed a mobile HRS powered by marine turbines on Ouessant Island, France. The system produces hydrogen using the anion exchange membrane electrolyzer and electrochemical compression to supply fuel cell bicycles. It offers a unique, scalable model for remote hydrogen delivery due to its portability and low energy consumption. While the study emphasizes the technical feasibility of micro-scale hydrogen mobility solutions, it adopts an on-site production and storage model to minimize transport costs. Results suggest that a 53-liter tank can support ten bicycles for a total range of 1,500 km.

In [66], which did not specify the type of HRSs, a hybrid p-median and max coverage model was applied to address the strategic placement of limited HRSs across general roads, expressways, and bus lines in South Korea. The number of HRSs needed to meet the government-designated demand was calculated, and the model aimed to shorten travel time for FCEV drivers while maximizing demand/area coverage. However, the study did not indicate whether hydrogen was supplied on-site or off-site, focusing solely on station siting and capacity planning.

Some studies focused on hydrogen demand met through both on-site production and external suppliers did not emphasize transportation costs. Song et al. [67] modeled an HRS in Shanghai supplying up to 500 kg/day of hydrogen to heavy-duty trucks, logistics vehicles, buses, and passenger cars. Hydrogen was partly produced using PV panels and electricity from the grid and partly delivered by trailer. While hydrogen was transported from 100 km away, the study did not propose a solution to reduce transport costs. It is stated that HRS has economic benefits in scenarios where the hydrogen price is not less than 6.23 US dollars and in addition, the refueling station can reduce 1,237.28 tons of carbon emissions in a year. Abdulnasser et al. [68] proposed a two-level optimization model for the planning and operation of energy hubs and on-site green/blue HRSs. Considering criteria such as demand response and fuel cell vehicle-to-grid, the study found that although green on-site HRSs (with RES) involved higher capital investment than blue HRSs (without RES, with carbon capture), they were more advantageous in terms of operational and carbon emission costs. While some hydrogen was purchased from the market in certain scenarios, the transportation cost of this hydrogen was not analyzed.

Table 1 lists all studies mentioned in the Literature Overview section, including their HRS type, renewable energy integrations, objective functions, methodologies, and if performed, their contributions to hydrogen transportation.

HYDROGEN AROUND THE WORLD

Overview

Hydrogen demand continued its upward trend in 2023, surpassing 97 million tons with a 2.5% increase, thereby setting a record. This growth highlights the strengthening role of hydrogen in the industrial and transportation sectors following the temporary slowdown caused by the pandemic. As of 2024, global hydrogen demand is projected to approach 100 million tons [21].

The use of hydrogen in road transportation is also advancing in parallel with this growth. The majority of FCEVs are located in Asia, particularly in South Korea and China. In contrast, the number of FCEVs in Europe and North America remains relatively limited. By the end of 2023, Asia accounted for more than 70% of the global FCEV fleet, followed by North America with 20% and Europe with less than 10%. China has distinguished itself through substantial investments in fuel cell heavy-duty vehicles, leading to a significant increase in hydrogen usage in the truck and bus segments. In 2023, China's demand in this segment grew at approximately twice the rate of the United States and three times that of Europe. South Korea, the leading country in terms of fuel cell passenger car stock, has an average fleet exceeding 33,000 vehicles. The United States hosts around 18,200 FCEVs, nearly all of which are fuel cell passenger cars. On a global scale, as of June 2024, the total stock of FCEVs has reached approximately 93,000 units [69].

As of the end of 2024, the number of operational HRSs worldwide has reached approximately 1,160. The num-

Table 1. Comparison

Ref.	HRS Type	RES	Objective	Method	Transportation Cost
[25]	On-site	PV	Optimal design of HRS	TRNYSYS	-
[26]	On-site		The economic feasibility of hydrogen production in HRS	e Peng-Robinson, IAPWS-95, REQUIL	-
[27]	On-Site	PV	Minimize comfort viola-tion for EV owners	MILP	-
[28]	On-Site	PV	Minimize the total oper-ating cost of HRS	MILP	-
[29]	On-site	PV	The economic feasibility of HRS	-	-
[30]	On-site	PV	The economic feasibility of HRS	HOMER MILP,	-
[31]	On-site	PV	Maximize the profit of HRS	Quadratic-programming	-
[32]	On-site	PV, WT	Determine optimal sys-tem configuration, min-imize the total net pre-sent cost	HOMER	-
[33]	On-site	PV	Minimize the total oper-ating cost of HRS	MILP	-
[34]	On-site		Minimize the cost with hydrogen break-even price	MINLP	-
[35]	On-site	PV	Minimize the operating cost and load fluctuation	Improved moth–flame optimization algorithm	-
[36]	On-site	PV	Maximize profit of hy-drogen/ electricity refuel-ing station	MILP	-
[37]	On-site	PV, WT	Minimize investment, operation, system loss and carbon environmen-tal costs	MILP	-
[38]	On-site		The economic feasibility of HRS	MATLAB/Simulink	-
[39]	On-site	WT	Minimize the total oper-ating cost of HRS	MILP	-
[40]	On-site	PV, WT	Minimize loss of power supply probability and total life cycle cost	MILP	-
[41]	On-site	PV, WT	The economic feasibility of HRS to minimize net profit cost	HOMER	-
[42]	On-site	PV	Minimize total cost	MILP	Minimize distance in hydrogen redistribution via classical pickup delivery traveling salesman prob-lem
[43]	Off-site	WT	Optimal location plan-ning of HRS	FVIKOR, FTOPSIS	Hydrogen transport distance is taken into consideration in HRS location selection
[44]	Off-site		Optimal location plan-ning of HRS	FAHP, FCM, Genetic Algorithm, TOPSIS	Proximity to main industrial cen-ters and railway stations to reduce hydrogen transport cost
[45]	Off-site	WT	Minimize the total cost for the hydrogen transport infrastructure.	MILP, ROA	Transportation cost optimization for different distances and differ-ent types of transportation
[46]	Off-site	PV	Minimize the cost of hydrogen production, storage and transportation.	NSGA-II, CRITIC, TOPSIS	Hydrogen transport distance is taken into consideration via HRS location selection
[47]	Off-site	PV, WT	Minimize unit hydrogen cost and optimal location planning of HRS	MINLP	Minimize transportation cost

Table 1. Comparison (Cont.)

Ref.	HRS Type	RES	Objective	Method	Transportation Cost
[48]	Off-site		Minimize installation and operation cost of HRS	SA based meta-heuristic algorithm and MILP	Hydrogen transportation schedul-ing under variable demand scenar-ios
[49]	Off-site		Optimal location planning of HRS	Genetic algorithm, the greedy algorithm, the annealing algorithm	Demand-oriented placement of HRSs in the transportation net-work
[50]	Off-site		Minimize total operating cost and the delay costs in case of hydrogen load loss.	MILP	Minimize transportation cost with VRP that considers road traffic
[51]	Off-site		Minimize the unit cost of hydrogen	Genetic Algorithm	Minimize transportation costs depending on distance and hydro-gen amount
[52]	Off-site	PV, WT	Minimize total operating cost	ADMM	Minimize transportation cost
[53]	Off-site	PV, WT	Minimize total operation cost and carbon emission	ADMM	Transport costs and line pack ca-pacity are optimized
[54]	Off-site	Hydro Power	Minimize transportation and production costs by optimizing installation costs	MILP	Minimize transportation costs depending on distance and hydro-gen amount
[55]	Hybrid	PV, WT	Minimize the total oper-ating cost of HRS	MILP	The capacitated routing problem is taken into consideration for hydrogen delivery.
[56]	Hybrid		Minimize the hydrogen transportation cost and HRS construction cost	The max covering model, p-median model, flow-refueling location model	Reducing the travel time or dis-tance of FCEVs to reach HRS
[57]	Hybrid	PV, WT	Minimize unit hydrogen cost	MINLP	Minimize transportation cost
[58]	Hybrid		Minimize total cost and risk, maximize popula-tion coverage	Set-covering problem, mixed integer mathematical programming models	-
[59]	Hybrid		Minimize the least cost of hydrogen	MILP	Minimize transportation cost
[60]	Hybrid	PV, WT	Minimize total operating cost	LP	Minimize transportation costs with time and capacity constraints
[61]	Hybrid	PV, WT	Minimize total operating cost	ADMM	Minimize transportation cost with VRP that considers road traffic
[62]	Hybrid	PV, WT	Minimize levelized cost of driving	Life Cycle Assessment	Minimize carbon emissions re-sulting from the transportation to reduce cost
[63]	Hybrid	PV, WT	Minimize costs	Model for International Green Hydrogen Trade	Minimize hydrogen transportation cost with electric transmission with the integration of electric network
[64]	Hybrid	PV, WT	Minimize cost and operational risks	Stochastic MILP	Mobile Hydrogen Energy Re-source
[65]	Hybrid	Hydro Power	The economic feasibility of HRS	PID Controller	Mobile Hydrogen Energy Re-source
[66]	Not defined		Maximize served FCEVs minimize station number and travel time	Max cover, p-median models, the mixed-integer programming models	Reducing the travel time or dis-tance of FCEVs to reach HRS

Table 1. Comparison (Cont.)

Ref.	HRS Type	RES	Objective	Method	Transportation Cost
[67]	Hybrid	PV	The economic feasibility of HRS	-	-
[68]	Hybrid	PV, WT	Minimize investment, operation and carbon emission cost	NSGA-II	-

RES: Renewable Energy System; WT: Wind Turbine; NSGA-II: Non-Dominated Sorting Genetic Algorithm; LP: Linear programming; MINNLP: Mixed-integer non-linear programming; FAHP: Fuzzy Analytic Hierarchy Process; TOPSIS: Technique for Order Preference by Similarity to Ideal Solution; FTOPSIS: Fuzzy Technique for Order Preference by Similarity to Ideal Solution; TRNYSYS: Transient System Simulation Tool; IAPWS-95: Internation-al Association for the Properties of Water and Steam – 1995 Formulation; REQUIL: Reaction Equilibrium; CRIT-IC: Criteria Importance Through Intercriteria Correlation; ADMM: Alternating Direction Method of Multipliers.

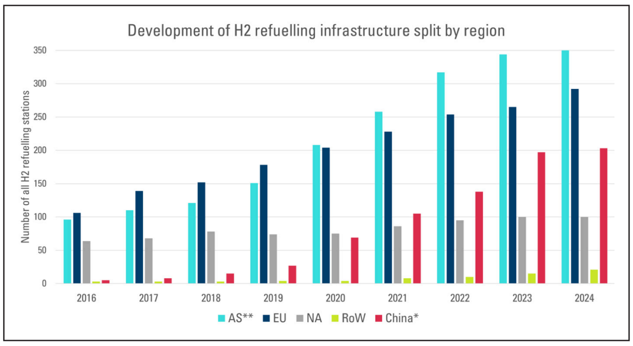

Figure 3. Numbers of hydrogen refueling stations Worldwide [70].

bers of HRSs by continents and years are shown in Figure 3. Asian continent numbers do not include China; China is stated separately because it has a high HRS number. A considerable number of additional stations are also under construction [70,71]. In terms of geographical distribution, Europe, China, South Korea, Japan, and North America stand out as leading regions, as shown in Figure 4.

In 2024, approximately 125 new HRSs were opened worldwide [71]. Although the number of stations has increased annually, this growth remains limited due to the closure or modernization of existing stations. For instance, in 2023, Shell shut down all of its HRS facilities in the United Kingdom, and in February 2024, it closed all its hydrogen stations in California due to high operational costs and low utilization rates. Similarly, Everfuel discontinued its operations in Denmark owing to low demand, which subsequently left around 100 Danish taxis unable to refuel [21,69].

Another critical factor influencing the widespread adoption of FCEVs is hydrogen pricing. In recent years, hydrogen prices (particularly in California) have experienced a significant surge, with pump prices more than doubling between 2021 and 2023. Similar challenges are observed in

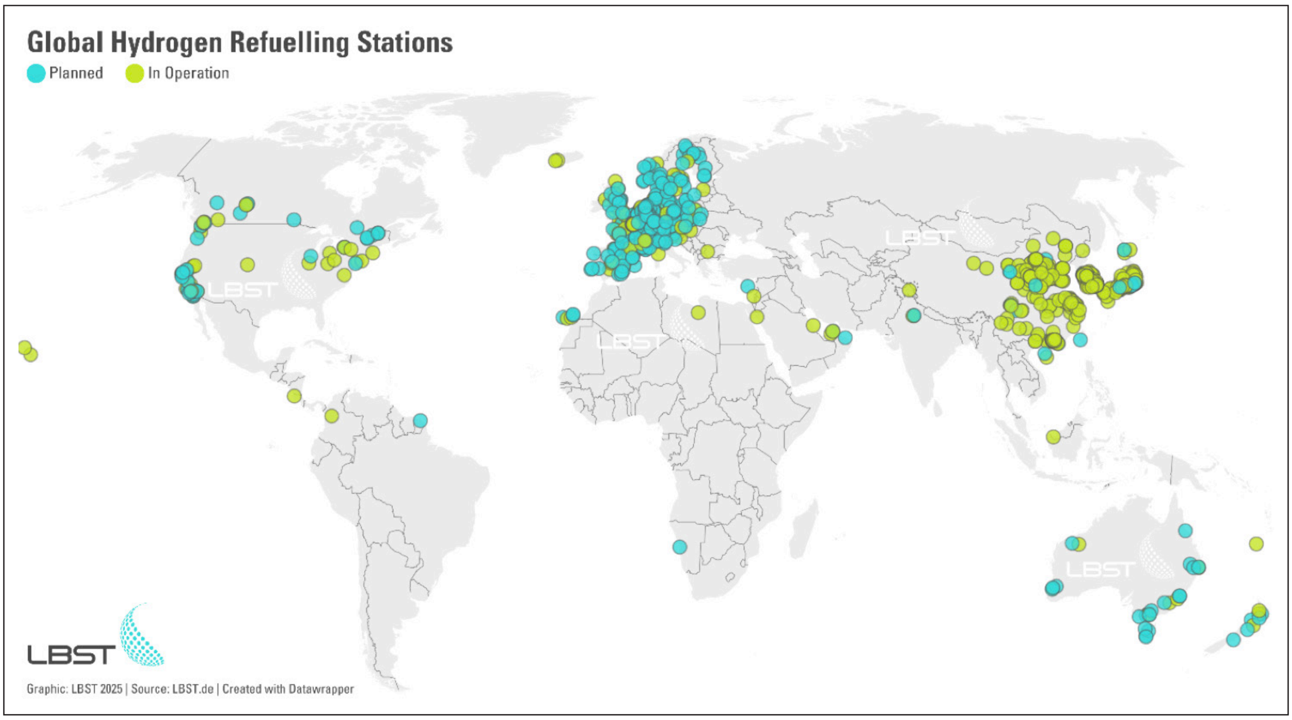

Figure 4. Hydrogen refueling stations Worldwide [71].

Europe, where dynamic pricing systems have been introduced to stabilize costs. For example, as of October 2023, hydrogen produced from renewable sources was offered at a price 25–30% lower than the standard rate.

These developments highlight the strong interdependence between the number of FCEVs and the hydrogen refueling infrastructure. Manufacturers remain cautious in expanding vehicle fleets due to the insufficient number of refueling stations, while the establishment of new stations is hindered by the limited user base. This situation creates a self-reinforcing cycle that constrains sectoral growth, underscoring the need for more coordinated and bold actions from both public policy and private sector investments [21,69].

The remainder of this section presents detailed insights into the hydrogen strategies, HRS networks, and FCEV deployment in countries across Europe, Asia, and North America.

Hydrogen in Europe

By the end of 2024, the total number of HRSs across Europe had reached 294. The distribution of operational and planned HRSs by countries in Europe is given in Figure 5. Among these, 113 stations are in Germany, making it the leading country in Europe in terms of HRS infrastructure. France follows in second place with 65 stations. In 2024, the number of stations in the Netherlands increased to 25, while Switzerland reported 19 operational HRS facilities. Bulgaria and Slovakia inaugurated their first HRS in their respective capitals during the same year. Although many projects across Europe remain in the planning phase, a general upward trend in the number of stations has been observed [21].

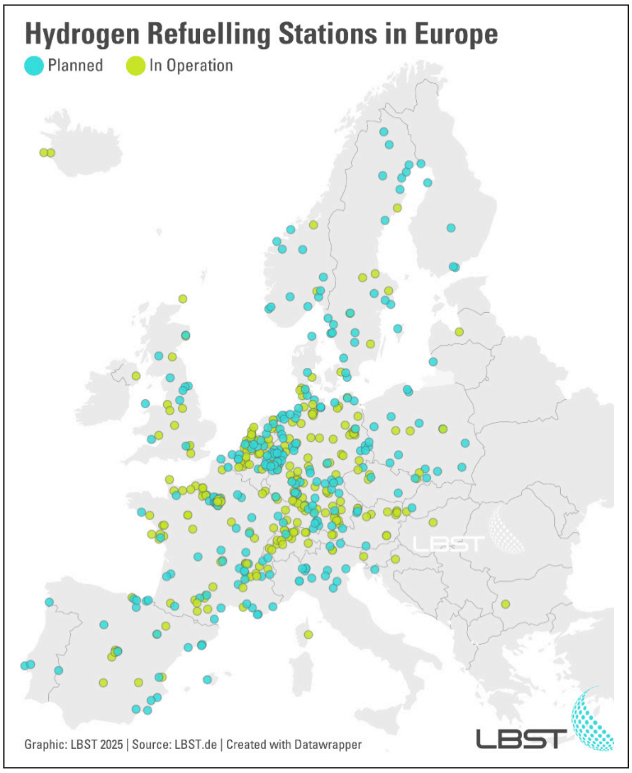

Figure 5. Hydrogen Refueling Stations in Europe [71].

According to data presented in [72], 88% of hydrogen trade in Europe in 2023 was captive, while 12% were merchant. All transactions were intra-European, and the total trade volume amounted to 29,767 tons. Compared to 2022, this reflects a 12.9% decrease in trade volume. Hydrogen distribution via pipelines is common, with the largest trade route running from Belgium to the Netherlands. Europe's largest hydrogen pipelines are in Belgium, with an average length of 600 km, followed by Germany with 400 km. In addition, small- and medium-scale distribution is typically carried out using tube trailers. In areas without pipeline infrastructure, hydrogen is mostly transported by trucks. Although most of the hydrogen is still produced for on-site use (captive), the merchant market is rapidly expanding. The EU's 2030 target is to import 10 million tons of renewable hydrogen from outside the Union.

Germany's long-term goal is to become globally competitive in hydrogen technologies and to promote hydrogen-based solutions across industries such as manufacturing, transportation, and energy production, ultimately aiming to achieve a climate-neutral economy by 2045. Germany positions hydrogen technologies as a cornerstone of its energy transition and aims to be a global leader in this field by 2030. In line with this ambition, the country has adopted a comprehensive strategy covering hydrogen production, distribution, and utilization. The Federal Government is implementing extensive research, development, and application policies, particularly focusing on the production and industrial integration of green hydrogen [73].

Under the National Hydrogen Strategy, Germany is leading large-scale projects covering the entire hydrogen value chain. Among these are the H2Giga, H2Mare, and TransHyDE initiatives, which focus respectively on the serial production of electrolyzers, offshore hydrogen production, and technological solutions for hydrogen storage and transport. Furthermore, the establishment of the Hydrogen Innovation and Technology Center aims to expand hydrogen infrastructure and increase the scope of applications.

To promote the use of FCEVs, the National Innovation Program for Hydrogen and Fuel Cell Technologies is being continued, complemented by regional programs such as HyLand to support hydrogen-based transport applications. These efforts are considered concrete steps toward the widespread adoption of decarbonized transport systems [74,75].

The Netherlands, recognizing the critical role of green hydrogen in its energy transition, is rapidly increasing infrastructure investments. The country aims to increase the number of HRSs to 50 by 2025 and 100 by 2030, with a particular focus on serving heavy-duty vehicles. By 2030, the Netherlands plans to deploy 300,000 FCEVs, primarily for use in public transport and the logistics sector. The country is also taking significant steps to improve hydrogen transport, including adapting its existing natural gas pipelines for hydrogen transmission and positioning the Port of Rotterdam as Europe's main hydrogen import hub. Additionally, domestic green hydrogen production will be supported through the installation of 4 GW of electrolysis capacity by 2030 [76].

Belgium has set a strategic course to become a key hub for hydrogen transportation and imports within Europe. Currently hosting five public HRSs, the country plans to increase this number in the coming years. The use of hydrogen in heavy transport and industrial sectors has been identified as a priority. Although there are no specific targets for the number of FCEVs, it is anticipated that FCEV technology will be widely adopted in professional transport, especially for trucks and buses. Regarding hydrogen transportation, Belgium plans to establish a pipeline network spanning 100 to 160 kilometers by 2026 and to integrate this network with Germany, France, and the Netherlands by 2028. Significant public investments are being made to support this infrastructure, along with the development of port and energy transfer facilities for the import of green hydrogen [77].

The United Kingdom regards hydrogen as a cornerstone of a low-carbon energy system and is implementing a comprehensive strategy in this context. While the country currently has only around 15 HRSs, this number is projected to reach 1,150 by 2030. The expansion primarily targets highway networks and logistics centers to ensure efficient use of hydrogen in transport. According to government plans, by 2030, a total of 1.6 million FCEVs will be on the road, most of which will be fleet vehicles, buses, and heavy-duty trucks. To enhance hydrogen mobility, regional pipeline projects are being supported, and pilot areas are being developed to test hydrogen-based heating systems in residential zones. The UK also aims to reach 10 GW of low-carbon hydrogen production capacity by 2030, with half of this capacity sourced from green hydrogen [78].

Türkiye's hydrogen strategy is focused on increasing green hydrogen production and becoming an international player in line with its net-zero carbon emissions target by 2053. The country aims to reach an electrolysis capacity of 2 GW by 2030, 5 GW by 2035, and 70 GW by 2053. It also plans to reduce green hydrogen production costs to below 2.4 USD/kg by 2035 and 1.2 USD/kg by 2053. The strategy includes adapting the existing natural gas infrastructure for hydrogen use, developing storage systems based on local resources such as boron, and replacing fossil fuels with hydrogen across various sectors, primarily industry. A wide range of policy instruments will be implemented simultaneously, including regulatory frameworks, domestic technology development, international cooperation, and capacity building. Türkiye also aims to play an active role in the global hydrogen economy by leveraging its strategic location for green hydrogen exports, particularly to the European market [79].

Hydrogen in Asia

The Asian continent plays a leading role in shaping the global hydrogen economy. In particular, China, Japan, and South Korea have emerged as pioneering countries in the development of FCEVs, HRSS, and hydrogen transportation. In 2024, China, South Korea, and Japan expanded their HRS infrastructures with 30, 25, and 8 new stations, respectively. By the end of 2024, a total of 748 HRSs were operational across Asia. Among these, 384 were located in China, 198 in South Korea, and 161 in Japan [71]. The distribution of operational and planned HRSs by countries in Asia is given in Figure 6.

In the field of FCEVs, South Korea accounts for more than 50% of the global stock. This dominance is attributed to the country's early adopter strategies and government-supported fleets. On the other side, China has prioritized light commercial vehicles, particularly trucks, which represent 95% of this segment globally. Between 2023 and 2024, the number of FCEVs increased by more than 50%. In Japan, the FCEV market has remained relatively stagnant; however, operational efficiency is maintained through a high station-to-vehicle ratio.

To strongly support its 2030 carbon peak target, China aims to promote the widespread use of hydrogen production from RES. With an annual output of 33 million tons, China currently holds the position as the world's largest hydrogen producer [80]. The national strategy prioritizes green hydrogen (climate-neutral production), promoting sustainable alternatives over gray and blue hydrogen. According to the national plan, China intends to establish 1,200 HRSs across the country by 2025. Additionally, local governments such as Shanghai and Guangdong have set respective goals of 70 and 300 stations by 2025. On a national level, the target is to have 50,000 FCEVs on the roads by 2025. Jilin Province plans to deploy 1.2–1.5 million FCEVs by 2035, while both Guangdong and Shanghai aim for 10,000 vehicles by 2025 [81], [82]. In 2024, construction began on a 700 km hydrogen pipeline connecting Zhangjiakou and the Caofeidian port, which, upon completion, will become the world's longest hydrogen transport pipeline. Valued at 845 million USD, the project represents a milestone in mobile hydrogen infrastructure development [21].

Japan holds a globally leading position in hydrogen policy, having published the world's first national hydrogen strategy in 2017. The updated Basic Hydrogen Strategy, released in 2023, is built upon three core principles: energy security, economic efficiency, and environmental sustainability. Japan aims to consume 3 million tons of hydrogen annually by 2030, 12 million tons by 2040, and 20 million tons (including ammonia) by 2050. The country plans to reduce the hydrogen supply cost to approximately 334 yen per kilogram by 2030 and to 222 yen per kilogram by 2050.

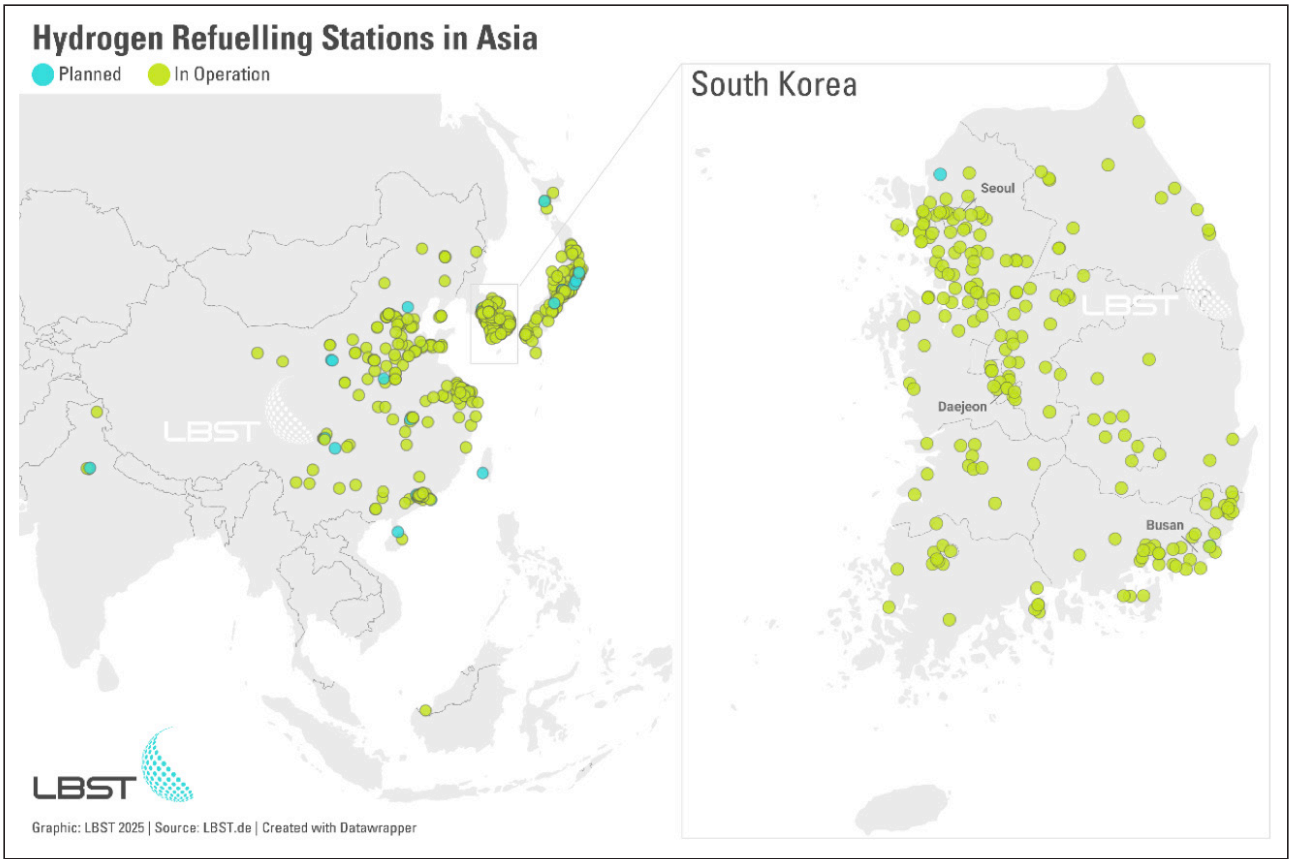

Figure 6. Hydrogen Refueling Stations in Asia [71].

As the global leader in fuel cell technology patents, Japan promotes the deployment of FCEVs, with a particular focus on heavy-duty vehicles, public transportation, and logistics applications [83].

South Korea positions hydrogen energy as a strategic instrument for achieving its goal of a carbon-neutral economy by 2050. The Hydrogen Economy Roadmap, published in 2019, along with the subsequent Hydrogen Economy Promotion and Safety Management Act (2020), laid the legal foundations of the country's hydrogen policies. This legislation introduced a comprehensive support framework encompassing safety regulations for hydrogen infrastructure, R&D incentives, tax reductions, and financial facilitation mechanisms. Although South Korea currently produces only grey hydrogen—approximately 220,000 tons as of 2020—it aims to diversify this mix with green and blue hydrogen by 2030. By 2050, grey hydrogen is planned to be completely phased out, with a total annual hydrogen supply of 27.9 million tons, of which approximately 3 million tons will be green hydrogen, 2 million tons blue hydrogen, and 22.9 million tons imported green hydrogen.

South Korea is a global leader in FCEVs. As of 2020, more than 10,000 FCEVs are on the road. By 2040, the country aims to deploy 2.9 million domestically produced FCEVs, 30,000 fuel cell trucks, and 40,000 fuel cell buses. In parallel with these targets, there are plans to significantly increase the number of HRSs. In 2022, the country aimed for 310 stations, and by 2040, the target is 1,200 stations [84]. Although South Korea did not fully meet its target in 2022, it constructed approximately 50 new stations, aiming for a balanced distribution with one station for every 200 vehicles [21].

In light of this data, the Asian continent possesses a strong potential both in production and consumption for the widespread adoption and commercialization of hydrogen technologies. China's industrial-scale investments, Korea's fleet-supported transportation policies, and Japan's regulatory-focused approach all demonstrate the existence of a multifaceted hydrogen strategy in the region.

Hydrogen in North America

North America, particularly the United States and Canada, has made certain advancements in hydrogen infrastructure and the FCEV sector. However, structural and economic barriers persist in terms of widespread adoption and scalability [21]. In 2024, 13 new stations were opened in North America, with nine in the US and four in Canada. The total number of HRS in Canada increased to twelve. Despite the opening of nine new stations in the US, the number of operational HRSs decreased to 89 due to the closure of twelve stations [71]. The distribution of operational and planned HRSs in North America is shown in Figure 7.

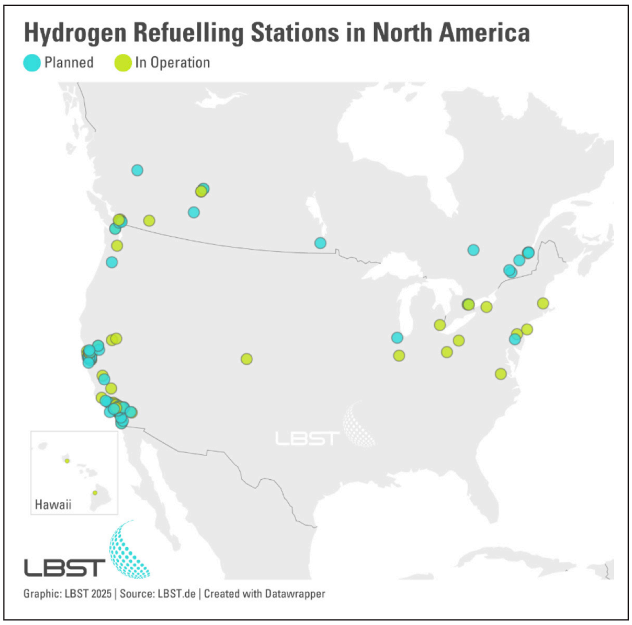

Figure 7. Hydrogen Refueling Stations in North America [71].

In the United States, the distribution of FCEVs is concentrated primarily in the state of California, parallel to the distribution of HRSs. Over 25% of the global FCEV stock is located in the US, which can be explained by state-level incentive mechanisms and early infrastructure investments. Notably, there has been significant growth in the heavy-duty vehicle segment: the number of fuel cell trucks, which was around 10 in 2022, reached 170 by mid-2024. However, this growth has had a limited impact due to infrastructure instability, with station closures affecting user satisfaction [21].

The "National Clean Hydrogen Strategy and Roadmap" prepared by the U.S. Department of Energy details the infrastructure needed for the widespread adoption of FCEVs. According to the document, one of the main barriers to the adoption of these vehicles is the limited number of distribution networks and refueling stations. Currently, there are approximately 50 publicly accessible HRSs across the US, most of which are located in California. Outside California, station access is extremely limited, restricting the use of FCEVs. To expand the hydrogen distribution infrastructure by 2030, an $8 billion investment in regional hydrogen hubs is planned. Additionally, the existing 1,600-mile hydrogen pipeline network is targeted for expansion, particularly around industrial areas and transportation corridors. In addition to pipelines, methods such as liquid hydrogen tankers and chemical carriers (ammonia, liquid organic hydrogen carriers) are also being considered for hydrogen distribution. For large-scale storage, underground hydrogen storage facilities, particularly salt caverns, are emerging as a key solution. In fact, a salt cavern in Texas, with a hydrogen storage capacity of 7,000 tons, is currently the largest such facility in the world [85].

In the United States and Canada, hydrogen production costs vary depending on the technology type and local resources. According to the Stated Policies Scenario based on current policies, production costs generally range between 3–7 USD/kg. In a more ambitious transformation scenario, the Net Zero Emissions 2050 scenario, it is estimated that these costs will decrease to a range of 2–5 USD/kg by 2030 [21].

However, final consumer prices are highly volatile. In California, the pump price of hydrogen increased by over 100% in 2023, making it economically unappealing for FCEV users. This price fluctuation is due to supply disruptions and inadequate distribution infrastructure, which hinder investments from both individual and institutional users.

In Canada, the development of hydrogen refueling infrastructure is progressing very slowly. Although some new station projects have been announced in provinces like Alberta and British Columbia, most of these projects have not yet become operational. Planned station projects in Edmonton have been canceled or delayed significantly. The FCEV market in Canada remains weak, with pilot projects such as the hydrogen bus in Edmonton being canceled and only a limited number of hydrogen vehicles being made available to the public. The lack of hydrogen infrastructure severely restricts the adoption of FCEVs at both individual and fleet levels [21].

According to Canada's strategic report [86], for automotive manufacturers (OEMs) to introduce hydrogen FCEVs on a large scale, a network of at least 7-8 stations per region needs to be established. The medium-term goal is to build a comprehensive and accessible fuel refueling infrastructure nationwide. To achieve this, the report suggests supporting region-based incentives, public-private partnerships, and publicly funded pilot projects.

In line with zero-emission vehicle (ZEV) targets, Canada assigns a strategic role to hydrogen FCEVs. Under federal goals, 10% of light vehicle sales will be classified as ZEVs by 2025, 30% by 2030, and 100% by 2040. In this context, FCEVs stand out as an ideal solution for transportation scenarios that require long-range driving, operate in cold climates, and need fast fuel refueling. Although BEVs will occupy a larger share of the market in the short term, the advantages offered by FCEVs mean they will be prioritized in heavy transportation, public transit, and commercial fleet applications.

The transportation of hydrogen from the production point to the end user is a critical component of the strategy. Currently, hydrogen is typically transported in steel cylinders at pressures of 180-250 bar, but the goal is to increase this capacity and reduce costs using next-generation 450 bar composite tanks. Options for developing the distribution infrastructure include adapting existing natural gas pipelines to transport hydrogen, building dedicated hydrogen pipelines in the long term, and storing hydrogen in large volumes in underground infrastructures such as salt caverns. The integration of regional hydrogen production centers with distribution systems is also recommended.

While the United States and Canada have taken a leadership role in hydrogen technologies in the early stages, they face significant challenges in scaling up these technologies. High costs, infrastructure gaps, and market uncertainty are hindering the expansion of hydrogen-based transportation solutions. Future progress will likely depend on strong public policies, targeted infrastructure investments, and mechanisms to support the demand side [21].

CONCLUSION

Hydrogen fuel presents a significant solution in the fight against climate change and in reducing the share of road transportation in global carbon emissions. Although OEMs have made substantial technological progress in FCEVs, their widespread adoption has been slow due to the limited availability of HRSs. This has resulted in a mutual dependency problem: vehicle fleets do not expand without sufficient HRS infrastructure, while investments in HRSs are not economically viable without an adequate number of FCEVs.

In this study, on-site and off-site HRS types are introduced to better understand the current state of HRS infrastructure. Subsequently, recent literature is reviewed to present various optimization approaches, economic analyses, and system modeling methods used in HRS planning. The contributions of hydrogen transportation costs and their effects on HRS planning are evaluated. These studies highlight the necessity of integrating production, distribution, and consumption processes for the sustainable development of hydrogen infrastructure.

In the last section, the expansion of HRS networks and national hydrogen strategies in Europe, Asia, and North America are examined. The policies and infrastructure investments pursued by different countries emphasize the critical role of public-private cooperation and long-term strategic planning in this field.

In conclusion, the widespread and effective adoption of hydrogen as an energy carrier in the transportation sector depends not only on technological advancements but also on economic incentives and coherent public policies. The findings presented in this review provide practical insights for policymakers and infrastructure planners. Specifically, integrated planning across production, distribution, and refueling systems, combined with long-term public-private partnerships, is essential to achieve economically viable and scalable hydrogen mobility. Future research should prioritize the development of holistic planning approaches that encompass the entire hydrogen value chain from production to end use. In this way, hydrogen fuel can fully realize its potential as a low-carbon mobility solution.

AUTHORSHIP CONTRIBUTIONS

Authors equally contributed to this work

DATA AVAILABILITY STATEMENT

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

CONFLICT OF INTEREST

The author declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

ETHICS

There are no ethical issues with the publication of this manuscript.

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Clean Energy Technologies Journal
Web page info: https://cetj.yildiz.edu.tr
DOI: 10.14744/cetj.2025.0002

CLEAN ENERGY TECHNOLOGIES JOURNAL

Review Article

The use of hydrogen-powered vehicles in natural disasters: A review

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ARTICLE INFO

Article history
Received: 10 June 2025
Accepted: 22 June 2025

Key words:
Energy Flexibility; Fuel Cell Electric Vehicles; Hydrogen Energy; Load Prioritization; Resilience; Sustainable.

ABSTRACT

Ensuring energy continuity in the aftermath of disasters is a growing global concern, particularly as extreme weather events and infrastructure disruptions become more frequent. Hydrogen-powered mobile energy systems, especially Fuel Cell Electric Vehicles (FCEVs), offer a promising solution due to their clean operation, high mobility, and capability to function independently of damaged grid infrastructure. This study presents a comprehensive review of hydrogen-based mobile technologies in the context of disaster resilience. It categorizes key technologies—including hydrogen production methods, storage solutions, and fuel cell types—and explores their integration into microgrid and vehicle-to-load (V2L) applications. Real-world implementations in Japan, South Korea, the United States, Germany, and Puerto Rico are examined to identify operational benefits and constraints. A SWOT (Strengths, Weaknesses, Opportunities, Threats) analysis is conducted to evaluate technical, economic, and regulatory factors, and research gaps are discussed with emphasis on the lack of real-time task-routing models and AI-supported dispatch systems. The paper concludes with a strategic roadmap and policy recommendations to facilitate the deployment of hydrogen-powered mobile units in future emergency response frameworks.

Cite this article as: Yüce DZ, Prencuva B, Erdinç O. The use of hydrogen-powered vehicles in natural disasters: A review. Clean Energy Technol J 2025;3(1):20-29.

INTRODUCTION

In recent years, the frequency and severity of natural disasters have increased significantly, placing considerable pressure on urban energy infrastructures. Events such as earthquakes, floods, wildfires, and hurricanes often cause substantial damage to transmission and distribution networks, leading to prolonged outages in critical services [1]. In such emergency situations, maintaining an uninterrupted energy supply is crucial not only for humanitarian operations but also for the continued functioning of essential infrastructure such as hospitals, communication systems, water supply, and disaster management centers.

Traditional energy solutions have long been employed in disaster scenarios. However, these systems are typically limited by their stationary nature, high carbon emissions, fuel supply challenges, and lack of flexibility in the face of widespread infrastructure failures [1]. As urban systems become more complex and climate-related risks more pronounced, the need for mobile, sustainable, and resilient energy solutions is growing rapidly [1].

At this point, hydrogen-based technologies, particularly FCEVs, are emerging as strategic alternatives for ensuring post-disaster energy continuity. With their zero-emission operation, long driving range, rapid refueling capability, and ability to operate independently of the grid, FCEVs

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offer promising mobile energy solutions under crisis conditions [2-4].

While numerous studies have explored hydrogen production and stationary fuel cell applications [5], limited attention has been given to hydrogen-powered mobile units for disaster resilience [3,4,6,7]. Existing reviews often focus on either technical specifications or policy aspects, but a unified analysis linking technological capabilities, real-world use cases, and deployment barriers is lacking. Moreover, integration with AI-driven task routing and V2L-based microgrid models remains underexplored in disaster contexts [3].

This review investigates the capabilities of hydrogen-powered vehicles in enhancing energy continuity during post-disaster conditions. It synthesizes findings from recent academic literature and real-world applications, identifies technological and operational gaps, and outlines strategic directions for future research. In contrast to previous reviews, this study places a particular emphasis on the integration of FCEVs into disaster-resilient microgrids, the application of optimization and artificial intelligence (AI) strategies, and the development of hybrid, renewable-powered systems for emergency energy delivery [6].

A structured literature search was carried out to ensure comprehensive coverage of hydrogen-powered vehicles and their role in disaster resilience. The review focused on studies published between 2010 and 2024, covering both foundational research and recent developments. Major scientific databases, including IEEE Xplore, ScienceDirect, Web of Science, SpringerLink, and Google Scholar, were utilized. The search was conducted using combinations of keywords such as "hydrogen fuel cell," "FCEV," "disaster resilience," "mobile energy supply," "post-disaster energy continuity," "hydrogen microgrid," and "AI-supported routing." To complement the database search, backward snowballing was performed by examining the reference lists of key papers. Priority was given to peer-reviewed journal articles, high-impact conference proceedings, and official reports from recognized institutions, such as the International Energy Agency and the European Union Hydrogen Strategy [2].

Highlights

- Fuel Cell Electric Vehicles (FCEVs) offer a clean, mobile, and resilient alternative for post-disaster energy supply, especially where stationary infrastructure is compromised.
- Hydrogen technologies provide zero-emission, high-energy-density solutions that can integrate with renewable sources for decentralized energy resilience.
- The operational success of FCEVs in emergencies depends on factors like hydrogen availability, dynamic task routing, and AI-supported energy management systems.
- Electrolyzer-integrated microgrids powered by solar photovoltaic (PV) can produce green hydrogen locally, enhancing autonomous energy continuity after disasters.
- Current literature lacks real-time implementation models and integrated optimization strategies, limiting the practical deployment of FCEVs in emergencies.
- SWOT analysis reveals that while FCEVs offer environmental and operational advantages, challenges remain in infrastructure, cost, and system integration.

UNDERSTANDING ENERGY CONTINUITY IN DISASTER SCENARIOS

Energy continuity refers to the capacity of an energy system to provide users with a stable, reliable, and uninterrupted energy supply even during disruptions or crisis situations. This concept holds strategic importance not only for maintaining the comfort of daily life but also for ensuring the operability of critical systems such as healthcare services, water supply, and communication infrastructure under all conditions [8].

The International Energy Agency (IEA) defines energy continuity as the "provision of energy services in a continuous, affordable, and environmentally responsible manner to meet the needs of present and future generations" [9]. This definition highlights that energy continuity is not merely a technical performance metric but also a fundamental component of economic, environmental, and social sustainability.

Energy continuity is particularly tested during extraordinary events such as natural disasters, cyberattacks, extreme weather conditions, or technical failures. In such scenarios, the flexibility, resilience, and recoverability of the energy system become decisive factors for maintaining continuity [10]. Thus, energy continuity encompasses not only the continuous supply of energy but also the delivery of energy at the required quality, timeliness, and quantity [11]. In this respect, energy continuity and energy system resilience are interrelated concepts.

As climate change increases the frequency and severity of disasters, the limitations of static and fossil-fuel-based systems have become more apparent. Consequently, the demand for new technologies and flexible energy infrastructures is growing. FCEVs, battery storage systems, and renewable-powered microgrids are increasingly preferred to ensure energy continuity in disaster scenarios [12]. FCEVs, in particular, offer high flexibility during rapidly changing conditions such as disasters, as they can function both as a means of transportation and as mobile energy sources. Hydrogen fuel, which can be produced on-site and supported by renewable energy sources (e.g., solar or wind), enhances both energy autonomy and system resilience [13]. With advantages such as mobility, zero emissions, and local energy supply, hydrogen-powered vehicles are becoming a preferred option for delivering fast and environmentally friendly solutions to ensure energy continuity during emergencies.

HYDROGEN TECHNOLOGIES

Hydrogen technology is a multidisciplinary field encompassing production, storage, transportation, and energy conversion processes. Due to its high energy density, zero carbon emissions, and ability to integrate with renewable energy sources, hydrogen is considered a key alternative in the development of sustainable energy systems [14].

Hydrogen Production Methods

Fossil fuel-based methods

Currently, these methods account for approximately 95% of global hydrogen production [15].

- Steam methane reforming (SMR): The most widely used method. In this process, high-temperature steam reacts with natural gas (mainly methane), producing hydrogen, carbon monoxide, and a small amount of carbon dioxide. In a secondary step, carbon monoxide reacts with steam to yield additional hydrogen and carbon dioxide (known as the water-gas shift reaction). While this method is efficient and cost-effective, it generates a significant amount of carbon emissions [16].
- Coal Gasification: Coal is reacted with a limited amount of oxygen under high temperature and pressure to produce synthesis gas (syngas), which consists of hydrogen, carbon monoxide, and carbon dioxide. Similar to SMR, a water-gas shift reaction is used to extract hydrogen. Due to its carbon-intensive nature, this method is less favored from an environmental perspective [17].

Electrolysis methods

Electrolysis involves splitting water into hydrogen and oxygen using electrical energy. Since it does not emit carbon, it is the most preferred method for green hydrogen production.

- Alkaline water electrolyzer (AWE): This is the most commercially mature electrolyzer type. It is cost-effective but has limited current density and low tolerance to dynamic load changes, which restricts its integration with renewable sources [18].
- Proton exchange membrane (PEM) Electrolyzer: Known for high current densities, fast response times, and compact design, making it suitable for integration with photovoltaic and wind systems. However, the use of platinum group metals increases capital cost [19].
- Solid oxide electrolyzer (SOE): Operates at high temperatures (700–1000°C) and can utilize thermal energy sources, thereby achieving higher efficiency with lower electricity consumption. However, this technology is still in its early development stages [20].

Thermochemical and photoelectrochemical methods

These are alternative and still experimental methods, offering potential for more sustainable hydrogen production in the future.

- Thermochemical cycles: Rely on the chemical splitting of water at high temperatures (e.g., 800–1000°C) using metal oxide cycles. They can be integrated with solar concentrator systems [21].
- Photoelectrochemical (PEC) production: An innovative method where semiconductor materials use sunlight to directly split water. Still under development in terms of efficiency and material stability [22].

Table 1 provides a comparison of the main features of hydrogen prductiın methods.

Hydrogen Storage and Transportation

When examining the storage and transportation of hydrogen, it emerges as one of the most significant technical challenges limiting its widespread use in energy systems. Due to hydrogen's low volumetric density, it must be either compressed to high pressures (typically 350–700 bar) or liquefied at -253 °C for transportation. These processes are highly energy-intensive and require specialized equipment and safety systems [23].

As alternatives, solid and chemical storage methods such as metal hydrides and Liquid Organic Hydrogen Carriers (LOHCs) are also being developed. However, these technologies have not yet reached widespread commercial adoption [24]. For example, benzyl toluene-based carriers developed by Hydrogenious LOHC Technologies enable the safe transport of hydrogen in liquid form and offer solutions compatible with existing fuel infrastructure [25].

In addition, companies like Toyota and Hyundai have successfully implemented composite high-pressure tanks in their commercial vehicles, improving energy efficiency in hydrogen transportation [26]. Effective and safe storage and transportation solutions are critically important for scaling up the hydrogen economy, and innovations in this field directly influence the success of the energy transition. In Figure 1 provides a comparison of the hydrogen storage and transportation.

Table 1. Comparison of hydrogen production methods

Method	Efficiency (%)	CO_2 Emissions	Cost ($/kg H_2)	Technology readiness level
Steam methane reforming (SMR)	65–75	High	1–2	Commercial
Coal gasification	50–60	Very High	<1.5	Commercial
PEM electrolysis	60–80	None (green)	4–6	Commercial/growing

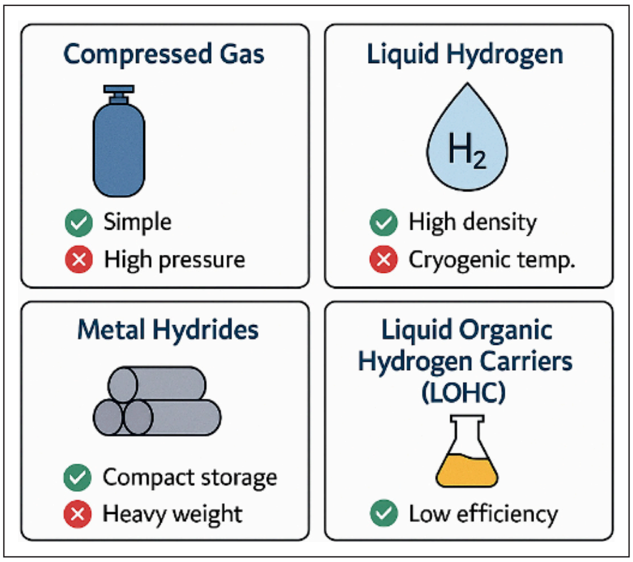

Figure 1. Hydrogen storage and transportation [Figure designed by the authors using digital illustration tools]

Operating Principles of Fuel Cell Types

Fuel cells are devices that convert the chemical energy of fuels, such as hydrogen, directly into electrical energy. Every fuel cell contains two electrodes: an anode and a cathode. At the anode, the fuel is oxidized, while at the cathode, the oxidizing agent (typically air/oxygen) is reduced. The electrolyte in between allows only specific ions to pass, thus completing the charge transport process.

PEMFC (Proton exchange membrane fuel cell)

PEMFCs, known for their compact design and suitability for mobile applications, operate at relatively low temperatures (~60–80°C) and rely on a polymer membrane that selectively transports protons during the electrochemical reaction. At the anode, hydrogen is split into protons and electrons; protons pass through the membrane to the cathode, while electrons travel through an external circuit, generating electricity. Due to their rapid response time and compact design, PEMFCs are ideal for automotive applications [27].

SOFC (Solid oxide fuel cell)

SOFCs employ ceramic-based electrolytes and function at high temperatures (~600–1000°C). Oxygen ions move from the cathode to the anode, where they react with hydrogen to form water. Thanks to their high operating temperature, they can directly use a variety of fuels, including methane and biogas. Their high efficiency makes them suitable for stationary power generation and cogeneration applications [28].

AFC (Alkaline fuel cell)

These cells operate in an alkaline environment (typically a KOH solution), with hydroxide ions (OH-) serving as charge carriers. Although they can achieve very high efficiency, they are highly sensitive to carbon dioxide contamination and are thus mainly used in aerospace or other ultra-pure environments [29].

PAFC (Phosphoric acid fuel cell)

Operating at intermediate temperatures (~150–200°C), PAFCs use a phosphoric acid-based liquid electrolyte. In addition to generating electricity, they allow for effective utilization of waste heat. Their most common applications are in stationary buildings such as hospitals and hotels [30].

MCFC (Molten carbonate fuel cell)

MCFCs operate at approximately 650°C and use molten carbonate salt electrolytes. They can directly use carbon-based fuels. The high operating temperature makes them well-suited for cogeneration systems and large-scale power plants. However, they face challenges related to thermal management and material durability [31].

Vehicles Utilizing Hydrogen Technologies

• *Hydrogen-Powered Trucks*

Battery weight and long charging times present major disadvantages for long-haul trucking. In this context, FCEV trucks are seen as an ideal solution for long-distance freight transport. Models developed by companies such as Nikola Motor Company, Hyundai (XCIENT Fuel Cell), and the Toyota-Kenworth partnership offer ranges of 400–800 km and payload capacities of up to 30 tons [32]. Hydrogen-powered trucks offer advantages such as short refueling time (~10 minutes), long range (400–800 km), and lower weight compared to batteries. However, the limited hydrogen refueling infrastructure and high system costs continue to delay widespread adoption.

• *Hydrogen-Powered Trains*

In rail transport, especially on lines where electrification is not economically feasible, hydrogen trains present an environmentally friendly alternative to diesel-powered counterparts. The Coradia iLint model by Alstom is already in operation in Germany and France and is a fully emission-free train with a range of 600–1000 km [33]. Countries such as Japan, the UK, and China are also developing similar prototypes. However, the integration of refueling infrastructure and hydrogen production and storage systems into rail networks still requires substantial investment.

• *Hydrogen-Powered Aircraft*

Aviation is both one of the most challenging sectors for carbon reduction and one of the most receptive to technological innovation. Battery-powered aircraft are limited in terms of range and payload capacity, whereas hydrogen's high specific energy (120 MJ/kg) makes hydrogen-based flight systems increasingly attractive. Several major companies around the world are actively pursuing projects in this area. Airbus has announced its goal to produce the first hydrogen-powered commercial aircraft by 2035 [34]. In 2020, ZeroAvia successfully flew a six-seat hydrogen aircraft, and models with capacities of 20–40 passengers are being developed for regional flights beyond 2025.

• *Hydrogen-Powered Cars (Passenger FCEVs)*

Today, hydrogen fuel cell systems stand out among environmentally friendly solutions developed as alternatives to internal combustion engines. Commercial passenger car models such as the Toyota Mirai, Hyundai NEXO, and Honda Clarity operate on Proton Exchange Membrane Fuel Cell (PEMFC) technology and offer driving ranges of 500–600 km with just 4–5 kg of hydrogen. One of their key advantages is the ability to refuel in only 3–5 minutes [35]. While they benefit from shorter refueling times and require lighter batteries compared to battery electric vehicles, their widespread adoption is hindered by limited infrastructure and high initial investment costs [25].

In this context, hydrogen-based mobile energy systems such as FCEVs and portable hydrogen generators offer clean and flexible alternatives for both disaster scenarios and applications that require continuous power supply. Thanks to their low carbon emissions, silent operation, and high energy density, these systems are considered promising solutions for supplying critical loads with mobile energy sources during emergencies. The effective deployment and operation of FCEVs in post-disaster scenarios depend on multiple parameters, including available hydrogen stock, critical load priorities, and time constraints. Therefore, modeling approaches such as Mixed-Integer Linear Programming (MILP), multi-objective optimization, and decision support systems are commonly used.

At the heart of hydrogen-powered mobile energy systems lies fuel cell technology, which converts hydrogen into electrical energy through electrochemical reactions. In a fuel cell, hydrogen is oxidized at the anode, producing protons and electrons; protons travel through an electrolyte membrane to the cathode, where they combine with oxygen to form water. The energy released in this process is directly converted into electricity [36].

In mobile applications, these systems are typically composed of FCEVs, portable hydrogen generators, high-pressure hydrogen tanks, and electrolyzer units. The vehicles generate electricity through fuel cells powered by their onboard hydrogen tanks, which can then be used either to directly supply critical loads or to charge battery systems.

The long-term sustainability of FCEV infrastructure is directly linked to the hydrogen production source. In particular, microgrid systems integrated with PV systems and electrolyzers are crucial for on-site and renewable hydrogen production in post-disaster conditions. In this regard, islanded microgrids composed of PV + battery + electrolyzer configurations can ensure clean and continuous energy supply during emergencies [37]. This system is visualized in Figure 2. At the same time, FCEVs can serve as backup sources within such systems, enhancing the flexibility and security of microgrids supported by renewable energy. Hybrid FCEV systems, with their high efficiency, long range, and mobility advantages, serve as versatile solutions acting both as energy carriers and mobile generators [36].

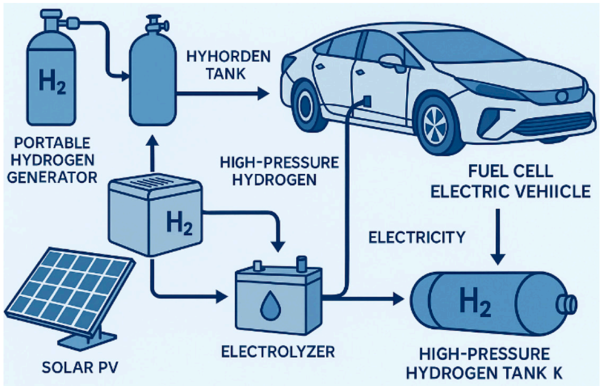

Figure 2. Hydrogen-powered mobile energy systems [Figure designed by the authors using digital illustration tools]

ROLE OF FCEVS IN POST DISASTER ENERGY SUPPLY

Today, strategies designed to ensure energy continuity after disasters adopt a multidimensional approach that integrates both stationary and mobile solutions. Among the stationary solutions, microgrids, renewable energy systems (such as solar and wind), energy storage technologies (including batteries and fuel cells), real-time energy management algorithms, and automated load management systems are particularly prominent. Access to energy in the first 72 hours following a disaster is critical for coordinating emergency response teams and supplying critical loads. Therefore, systems designed for energy continuity must be equipped not only for generation but also with capabilities in flexibility, mobility, and load prioritization [38].

Microgrids, as part of these solutions, play a vital role thanks to their ability to operate independently from the main grid. In post-disaster "island mode," they can supply power to critical infrastructure such as hospitals, fire stations, and police departments [39]. When combined with locally sourced renewables like solar energy, these systems contribute to reducing both carbon emissions and dependence on external energy supply.

Mobile solutions are critically important in situations where fixed infrastructure is damaged and repair times may be prolonged. In this context, new-generation technologies such as portable generators, mobile battery stations, fuel cell or battery-powered electric vehicles, and even energy-carrying drone systems are being developed [40]. These systems can be directed to regions in need of energy, providing flexible and on-site solutions. Moreover, AI-supported decision support systems and optimization algorithms play a strategic role in distributing energy resources based on priority levels. In regions like Germany, Japan, South Korea, and California, hydrogen refueling stations are being expanded, and policies are being implemented to encourage the use of FCEVs for both individual and public transportation purposes [41].

Applications and Literature Approaches on the Use of FCEVs for Ensuring Energy Continuity in Disaster Scenarios

Following large-scale disasters, the damage to energy infrastructure significantly increases the importance of flexible and mobile solutions to ensure energy continuity. In this context, both real-world implementations and academic studies highlight the potential of FCEVs in disaster response and recovery. This section presents a comprehensive overview of practical examples and scholarly approaches regarding the use of FCEVs in post-disaster scenarios.

Following the 2011 Tokyo Earthquake and subsequent tsunami, Japan faced a severe crisis regarding energy continuity. In response, energy independence and emergency energy supply became national priorities. Toyota developed and modified the Mirai FCEV model to serve as a mobile energy source in disaster-affected areas. The vehicle reportedly provides up to 9 kW AC output, enough to power the essential needs of a household for several days [42].

Additionally, through its "Moving e" project, Toyota designed hydrogen-powered buses to function both as transport vehicles and mobile energy generators. These buses can supply electricity to run communication devices, refrigerators, or medical equipment in disaster zones [43].

As part of its hydrogen infrastructure enhancement policies, South Korea deployed hydrogen buses developed in collaboration with Hyundai. In 2020, these buses were used as mobile health centers in the aftermath of COVID-19. When needed, they provided off-grid electricity, ensuring the continuity of health services. The country aims to expand the use of this system nationwide for use in other disasters, such as earthquakes and floods [44].

California frequently experiences large-scale power outages due to wildfires and storms. In this context, Pacific Gas and Electric (PG&E) has deployed microgrids, especially in rural and hard-to-access areas, to ensure energy continuity. For instance, during the 2020 outage near Paradise, microgrids allowed hospitals and fire stations to continue operating without interruption [45].

In Germany, R&D projects are underway focusing on renewable-powered microgrids for disaster resilience. One such project in Freiburg integrates PV panels, batteries, and hydrogen electrolyzers in a system capable of operating in island mode during extended outages. The system was designed to meet the energy needs of both residential areas and emergency response centers [46].

Hurricane Maria in Puerto Rico, which struck Puerto Rico in 2017, nearly destroyed the island's entire energy infrastructure. In the aftermath, Tesla and several NGOs established solar + battery microgrids that helped maintain operations in health centers and schools. These systems, deployed by SolarCity, provided 24/7 power without relying on the main grid and played a significant role in post-disaster recovery [47].

Table 2 summarizes real-world case studies implemented in different countries to ensure energy continuity after disasters. These examples highlight a variety of technological solutions, including fuel cell electric vehicles, microgrids, and hybrid renewable systems.

Sharma et al. [47] presented an agent-based simulation that models interactions between mobile energy sources and microgrids, simulating various damage scenarios and incorporating prioritization mechanisms to enable priority-based load dispatch. These AI-supported routing and optimization models collectively demonstrate the potential to improve hydrogen efficiency and reduce energy delivery times by approximately 15–25% in simulation environments, although real-time data integration and field validation are still required for practical deployment.

Bicer and Dincer examined the applicability of hydrogen as a clean energy source in disaster scenarios, focusing on the integration of PV systems with electrolyzers for hydro-

Table 2. Comparison of real-world implementations of FCEVs and related technologies in disaster energy management

Country	Application	Technology	Purpose/contribution
Japan	Mobile FCEV energy support with Toyota Mirai & Moving e	FCEV (Fuel cell vehicles), Mobile AC output	Provide mobile energy to disaster zones
South Korea	H2 Bus Project – Mobile energy for health centers	FCEV bus, hydrogen-powered mobile generator	Ensure sustainability of off-grid emergency health services
USA (California)	PG&E microgrids – Post-disaster energy continuity	Microgrid, backup generator and battery systems	Uninterrupted public service during wildfires, etc.
Germany	Islanded operation scenario with PV + Battery + Electrolyzer	Integration of PV, battery, and hydrogen electrolyzer	Island mode operation during long outages
Puerto Rico	Solar + Battery microgrids for hospital/school support	PV panels + Tesla Powerwall batteries	Continuous supply of critical loads after disasters

gen production. Their work highlights how hydrogen-powered systems, such as FCEVs, can enhance the sustainability of post-disaster energy supply. However, the study does not include any simulation or optimization work, which limits its operational depth [48].

In the comprehensive textbook Fuel Cell Fundamentals, O'Hayre and colleagues detail the operating principles, design, and application areas of fuel cells. The book also discusses the technical potential of FCEV systems as mobile energy providers in emergency scenarios, serving as a fundamental reference for understanding system architecture. Different types of fuel cells such as PEMFC and SOFC are examined in terms of their chemical and physical mechanisms [49].

Yu et al. [50] provided a comprehensive analysis on resilience enhancement strategies for hydrogen-penetrated multi-energy systems, emphasizing that hydrogen can act not only as an energy carrier but also as a strategic element that strengthens flexibility and recovery capabilities of energy systems, particularly during extreme events such as natural disasters. Their work highlighted the potential of integrating hydrogen with renewable energy sources to contribute to long-term system resilience.

Naseri et al. [51] demonstrated that green hydrogen systems integrated with islanded photovoltaic microgrids can play a critical role in achieving net zero emission targets while ensuring energy security. Their proposed energy management strategy showed the technical and environmental advantages of using green hydrogen alongside PV systems, particularly for maintaining energy continuity in post-disaster conditions.

Dhankar et al. [52] conducted a detailed study on the impact of green hydrogen storage on microgrid resilience and found that integrating such systems could enhance critical load continuity by up to 95% and reduce system costs by 6% to 22%. The study underscored the importance of treating hydrogen not just as a supportive component but as a fundamental element of energy security in post-disaster recovery processes.

Qi et al. [53] proposed a long-term online energy management model for hybrid hydrogen-battery storage systems, demonstrating that such integration could significantly reduce operational costs while improving system flexibility and critical load continuity. Their work suggested that these hybrid systems offer more reliable and sustainable alternatives compared to ad-hoc energy solutions typically used in post-disaster scenarios.

Recent real-world implementations, such as the hydrogen-powered Energy Observer vessel and GM's fuel cell heavy-duty vehicle prototypes, illustrate that hydrogen technologies are evolving from conceptual solutions to practical, scalable, and environmentally friendly options in the transportation sector [54]. These examples further strengthen the applicability of hydrogen technologies in emergency and post-disaster energy supply contexts.

When all these studies are examined collectively, several limitations can be identified. Most models lack real-time decision-making mechanisms and hybrid system integration. Additionally, logistical constraints and economic analyses are often omitted, leaving critical gaps in practical applicability and system design.

When these studies [47–49] are collectively examined, they provide valuable insights into the potential of FCEVs and hydrogen technologies in supporting post-disaster energy supply. Nonetheless, they share notable limitations, particularly the lack of real-time operational mechanisms, limited integration of hybrid system components, and insufficient economic and logistical analyses, all of which restrict their practical applicability for large-scale energy resilience planning. To address these gaps, recent studies [50–53] have increasingly emphasized the integration of hydrogen-based systems with renewables and advanced management strategies, offering solutions that tackle both resilience and operational challenges.

FUTURE DIRECTIONS

To enhance the resilience of energy systems in disaster scenarios, research should increasingly focus on the integration of hydrogen-based mobile power Technologies particularly FCEVs into intelligent and adaptive energy infrastructures. In this context, establishing clear priorities and targeted improvements is essential for developing robust systems.

FCEVs are now being considered not only as mobile energy carriers but also as active components of smart grid systems. With their bidirectional power transfer capabilities, these vehicles can support microgrids, participate in demand-side management (DSM) programs, and contribute to post-disaster energy continuity [48]. However, the current literature lacks sufficient focus on real-time implementation. Future systems should be optimized using AI to enable dynamic routing, load forecasting, fault prediction, and autonomous fault response under unpredictable conditions.

One of the main constraints in post-disaster deployment of FCEVs is the limited accessibility and transportability of hydrogen fuel. For this reason, the development of solar-powered mobile electrolyzer systems is recommended. These systems can be integrated into islanded microgrids and used to produce green hydrogen locally [47]. Moreover, detailed techno-economic feasibility analyses must be conducted to evaluate the practical and financial viability of such systems under emergency conditions. These investments are of strategic importance for national energy security and economic resilience. In Table 3 , SWOT analysis is conducted to evaluate technical, economic, and regulatory factors. In this way, the system is evaluated from different aspects.

Table 3. SWOT analysis: use of hydrogen FCEVs in disaster scenarios

Strengths	Weaknesses	Opportunities	Threats
Zero-emission energy: Hydrogen fuel cells produce only water vapor, reducing local emissions to zero.	Limited refueling infrastructure: Hydrogen stations constitute <1% of refueling points in disaster-prone regions (IEA, 2021).	AI + IoT integration: Real-time adaptive routing and dynamic load assignment improve energy dispatch efficiency by ~10–20% (simulation studies).	Access disruption risk: Damaged infrastructure and blocked roads can delay vehicle deployment.
High mobility: Suitable for regions with compromised infrastructure.	High initial cost: FCEVs typically cost 1.5–2 times more than equivalent diesel or BEV vehicles (e.g., Toyota Mirai ~$50,000).	Integration with PV electrolysis: Mobile solar electrolyzer systems can generate ~10–50 kg H_2/day (pilot projects).	Lack of safety regulations: Hinders rapid deployment.
Quiet operation: <50 dB noise level enables use near hospitals and shelters	Safety risks in hydrogen storage: Requires special logistics and containers.	Development of V2G/V2H systems: Enhances bidirectional energy use.	Public skepticism: Hydrogen safety concerns may limit social acceptance.
Long operational range: FCEVs offer driving ranges of 400–800 km (e.g., Nikola, Hyundai Xcient, Toyota Mirai).	Limited grid integration: Many FCEVs lack built-in V2G compatibility.	Policy incentives: Opportunity for strategic disaster integration.	Supply chain instability: Hydrogen production and supply depend on stable economic/ geopolitical conditions.
Supports off-grid microgrids: Acts as a mobile hub for local energy supply.	Static routing models: Need for real-time adaptive energy dispatch.	Scalable deployment: Modular mobile units (e.g., 5–10 kW fuel cell generators) can be rapidly dispatched.	Personnel shortage: Maintenance requires specialized training.

CONCLUSION

Hydrogen-powered mobile energy systems particularly FCEVs emerge as viable and environmentally sustainable alternatives for ensuring uninterrupted energy supply during and after disasters. Each component of the hydrogen ecosystem offers distinct technical, economic, and environmental advantages and limitations. In line with global carbon neutrality goals, green hydrogen production is increasingly supported and promoted. Ensuring energy continuity in the aftermath of disasters is vital not only for humanitarian response but also for the timely restoration of infrastructure. In this context, mobile hydrogen-based systems offer clean, flexible, and deployable alternatives that have the potential to replace traditional methods.

Ensuring energy continuity through hydrogen mobility requires not only technical readiness but also strategic planning for deployment routes, fast refueling infrastructure, and clear regulatory frameworks for emergency energy dispatch.

FCEVs, in particular, are no longer limited to zero-emission transport; they are now being recognized as strategic components that enhance the resilience, flexibility, and sustainability of energy systems. Especially in post-disaster scenarios where the electric grid is non-operational, FCEVs can autonomously generate electricity through onboard fuel cells. When integrated with intelligent energy management algorithms, these systems can support optimized task assignment, routing, and energy distribution playing a critical role in post-disaster energy continuity.

To fully realize this potential, future efforts should focus on the integration of AI-supported control mechanisms, real-time optimization capabilities, and modular renewable hydrogen production systems. Overcoming regulatory and infrastructural barriers, along with conducting comprehensive techno-economic feasibility studies, is essential for large-scale deployment. As academic research and field applications continue to expand, hydrogen technologies are increasingly demonstrating their applicability not only in stationary and transport sectors but also as reliable, mobile energy solutions in emergency conditions. A coordinated approach involving technology, policy, and planning will be key to leveraging FCEVs in building low-carbon and disaster-resilient energy systems of the future.

AUTHORSHIP CONTRIBUTIONS

Authors equally contributed to this work.

DATA AVAILABILITY STATEMENT

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

CONFLICT OF INTEREST

The author declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

ETHICS

There are no ethical issues with the publication of this manuscript.

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Clean Energy Technol J, Vol. 3, No. 1, pp. 30-38, June, 2025

Clean Energy Technologies Journal
Web page info: https://cetj.yildiz.edu.tr
DOI: 10.14744/cetj.2025.0003

CLEAN ENERGY TECHNOLOGIES JOURNAL

Review Article

Dibenzyltoluene- based liquid organic hydrogen carrier systems: Recent advances, challenges and future perspectives

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ARTICLE INFO

Article history
Received: 08 June 2025
Revised: 17 July 2025
Accepted: 21 August 2025

Key words:
Dibenzyltoluene-Perhydrodibenzyltoluene; Hydrogenation and Dehydrogenation; Hydrogen Storage and Release; Liquid Organic Hydrogen Carrier.

ABSTRACT

This review provides a comprehensive overview of dibenzyltoluene (DBT)-based liquid organic hydrogen carrier (LOHC) systems, a promising technology for the safe, efficient, and scalable storage and transportation of hydrogen. Owing to their high thermal and chemical stability, low toxicity, and compatibility with existing energy infrastructure, DBT and its fully hydrogenated form (H_{18}-DBT) are among the most advanced candidates for industrial LOHC applications. Despite these advantages, several technical challenges remain, including high dehydrogenation temperatures (>300 °C), catalyst deactivation (coke formation and sintering), and slow molecular diffusion within porous supports. Recent progress in catalyst design — particularly through the development of bimetallic catalysts (e.g., Pd–Ni) and nanostructured supports — has significantly improved reaction efficiency and cycle stability. In addition, the integration of thermo-electrochemical hybrid approaches and process intensification strategies offers further potential for enhancing system performance. This review critically assesses the current state of DBT-based LOHC systems, highlights ongoing advancements, and identifies future research directions needed to overcome existing limitations and enable the commercial-scale deployment of this technology within a sustainable hydrogen economy.

Cite this article as: Al K, Kantürk Figen A. Dibenzyltoluene- based liquid organic hydrogen carrier systems: Recent advances, challenges and future perspectives. Clean Energy Technol J 2025;1:30-38.

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INTRODUCTION

The rapid advancement of technology, transportation, industry and artificial intelligence have considerably increased energy demand across various sectors. Data from the International Energy Agency (IEA), show that 81% of global energy production still relies on fossil fuels [1]. However, the rapid depletion of fossil fuel reserves, the continuous rise in energy consumption, and fluctuations in energy supply pose significant challenges to energy security. Moreover, the increase in greenhouse gas emissions resulting from fossil fuel use contributes to environmental threats such as global warming and climate change. In particular, global policies to reduce carbon emissions (such as the Paris Agreement) and sustainable energy targets necessitate the development of alternative energy sources [2]. In this context, while the proliferation of renewable energy sources (solar, wind, etc.) is an important development, the discontinuous nature of these sources (the sun shines at certain hours, the wind is variable) has created the need for energy storage. With its high bulk energy density (120 MJ/kg), zero carbon emissions at the point of use and compatibility with fuel cells, hydrogen is considered a key component of the energy infrastructure of the future. However, the safe, economical and efficient storage and transportation of hydrogen poses a significant barrier to large-scale deployment [3].

Hydrogen storage is critical for the efficient and safe utilization of hydrogen as an energy carrier. In this context, many hydrogen storage systems have been developed, such as compressed hydrogen storage (CH_2), liquid hydrogen storage (LH_2), metal hydrides, chemical hydrides, liquid organic hydrogen carriers (LOHCs) and carbon material hydrogen storage (CMH2) [4]. Among these, LOHCs stand out as an innovative technology that enables the chemical storage and transportation of hydrogen under atmospheric conditions. Compared to conventional systems (compressed hydrogen storage, liquid hydrogen storage, etc.), LOHCs chemically bind hydrogen in liquid organic compounds under atmospheric conditions, making it safe and easily transportable. One of the major advantages of LOHC technology is that it is compatible with existing fossil fuel infrastructure because it can be stored in conventional fuel tanks, transported via pipelines and easily integrated into industrial processes. In addition, LOHCs are non-explosive and non-volatile liquids, making them much safer than transporting hydrogen in liquid and compressed gas form. However, hydrogenation and dehydrogenation processes that require high temperatures and catalysts for efficient operation of LOHC systems are still under investigation. Current research focuses on developing catalysts that can operate at lower temperatures, consume less energy and have long lifetimes.

LOHC systems operate by hydrogenation (H_2 storage) and dehydrogenation (H_2 release) reactions of suitable organic compounds. The compounds used in these systems are in the liquid phase and show stable behaviour at atmospheric pressure and ambient temperatures. Many LOHC candidates (toluene/methylcyclohexane, N-ethylcarbazole/perhydro-NEC, dibenzyltoluene/perhydrodibenzyltoluene) have been investigated in the literature. Among these compounds, Dibenzyltoluene (DBT) and its fully hydrogenated form Perhydrodibenzyltoluene (H_{18}-DBT) stand out on an industrial scale with their superior properties such as high thermal and chemical stability, low toxicity and wide liquid phase working range. Notable advantages of the DBT system include high boiling point (~390 °C), low vapor pressure, low environmental risk and long-term availability. Furthermore, its long-standing industrial use as a heat transfer fluid supports the scalability of this system. However, technical challenges such as high dehydrogenation temperatures (>300 °C), slow molecular diffusion, and catalyst deactivation limit the efficiency of the system. Therefore, it is critical to develop more efficient and low-temperature catalysts specific to the DBT system [6,7].

Highlights

- DBT-based LOHC technology is a leading candidate for hydrogen storage.
- High dehydrogenation temperatures challenge system sustainability.
- Recent advances in catalyst and system design improve cycle stability.

This review offers a comprehensive examination of DBT-based LOHC systems, which have emerged as promising candidates owing to their high thermal and chemical stability, low toxicity, and compatibility with existing energy infrastructures. In particular, the study focuses on the structural properties of the catalysts developed for the DBT system, reaction performances, technical limitations encountered (e.g. high temperature requirements, sintering, coking) and current catalyst design strategies (bimetallic systems, mesoporous supports, thermo-electrochemical solutions). Thus, this review aims to technically assess the current status of DBT-based LOHC systems, analyze development trends and provide a guiding perspective for future research. The findings of this study are expected to contribute to the advancement of innovative technologies for the safe and sustainable storage and transportation of hydrogen.

FUNDAMENTALS OF LOHC TECHNOLOGY

LOHC systems operate by reversible hydrogenation (exothermic) and dehydrogenation (endothermic) reactions. Hydrogen-rich (H^{2+}) and hydrogen-poor (H^{2-}) states form a cyclic system in which hydrogen is stored and released using catalysts [8]. Hydrogenation is an exothermic reaction in which the organic compound is mixed with hydrogen in the reactor and this reaction is carried out under a certain temperature and pressure conditions under the influence of the catalyst. The products resulting from the hydrogenation reaction are called hydrogen carriers (Hx-LOHC) (Fig. 1). It is essentially a catalytic process using hydrogen to convert unsaturated bonds into saturated ones [9].

Hydrogenation typically occurs at 80-150°C and pressure 1-5 MPa, utilizing transition with the help of catalysts such as Pd, Pt or Ru [10,11]. In contrast, hydrogenation, dehydrogenation is an endothermic reaction in which, in the presence of a catalyst, hydrogen is extracted from Hx LOHCs in a dehydrogenation reactor [12]. Dehydrogenation takes place at 200-350°C and sub-atmospheric pressure (<1 MPa) with catalysts acting on hydrogen-rich LOHC compounds [13]. The process involves continuous absorption of heat from the outside due to the energy difference between the energy required for the dissociation of hydrogen atoms and the activation energy of C-H bonds. An efficient LOHC system should possess the following characteristics: i) high hydrogen storage capacity (>56kg/m3), ii) Long cycle stability with minimal degradation, iii) low melting point (<-30°C) and high boiling point (~300°C), iv) low energy demand for dehydrogenation, v) high hydrogen purity upon release, and vi) low toxicity and environmental compatibility during use and transport [9].

While early studies predominantly focused on simple aromatic compounds such as benzene and toluene, advancements in molecular design have led to the development of more structurally complex and efficient LOHC candidates, including DBT, N-ethylcarbazole (NEC), and naphthalene/decalin systems. Recent research indicates that the incorporation of heteroatoms—particularly nitrogen—into the molecular framework can reduce dehydrogenation enthalpy and enhance overall system performance [11]. As the field progressed, a diverse array of LOHC systems emerged, including toluene/methylcyclohexane (TOL/MCH), DBT/perhydro-DBT (DBT/H_{18}-DBT), CO_2/methanol, CO_2/formic acid, naphthalene/decalin, and NEV/dodecahydro-NEC [7, 14]. Among these, DBT-based systems have gained significant attention due to their high thermal stability, low vapor pressure, and proven industrial scalability as heat transfer fluids. Alongside DBT, the most extensively studied LOHC candidates in academic and industrial contexts are toluene/methylcyclohexane, NEC/dodecahydro-NEC, and naphthalene/decalin, as summarized in Table 1.

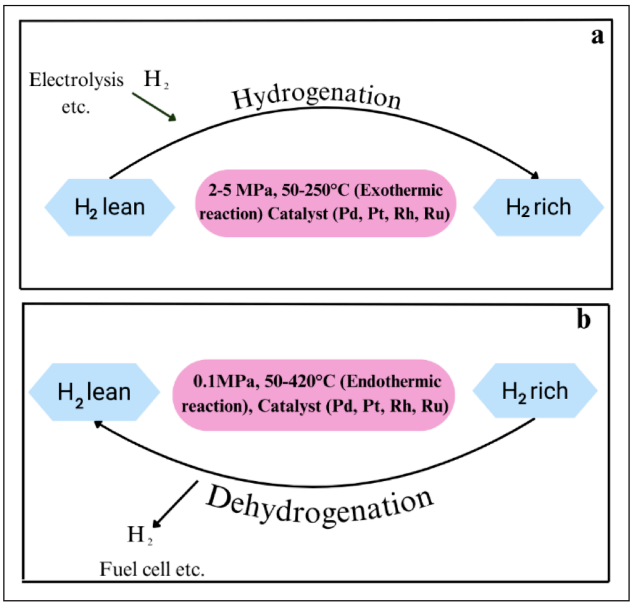

Figure 1. Schematic representation of the LOHC cycle hydrogenation **(a)** and dehydrogenation **(b)**.

DBT SYSTEMS

In the LOHC cycle, catalysts play a critical role for both yield and selectivity in the hydrogenation and dehydrogenation steps of the aromatic compound. An ideal LOHC catalyst is expected to i) ii) Provides high conversion efficiency at low temperatures, ii) Allows pure H_2 to be obtained during dehydrogenation, iii) Maintains its activity during long cycle life iv) Resistance to catalyst poisoning and sintering. The high energy consumption in LOHC technology, the difficulty of catalyst development in hydrogenation and dehydrogenation systems, and the decrease in hydrogen storage performance as the number of cycles increases limit industrial-scale commercialization [20,21]. Therefore, the design of catalysts that minimize energy requirements and offer high efficiency is critical. In addition, carbon-based supports and various carriers such as Al_2O_3 and zeolite are used to enhance the performance of the catalysts [11]. Since hydrogenation and dehydrogenation reactions are reversible in LOHC systems, catalysts with high hydrogenation activity generally exhibit high performance in the dehydrogenation step.

In recent years, several LOHC compounds including toluene and N-ethylcarbazole have been investigated. However, the low boiling points and toxic nature of compounds such as toluene and naphthalene present significant disadvantages. N-ethylcarbazole, for instance, has a melting point of 68 °C, which leads to solidification during the dehydrogenation process. Additionally, its high cost limits its feasibility for industrial-scale applications. To overcome these issues, DBT has emerged as a focal point in LOHC research. Dibenzyltoluene (H_0-DBT) is an organic compound classified among cycloalkanes and is extensively used as a heat transfer fluid in industrial applications. Upon hydrogenation, H_0-DBT is converted into its fully hydrogenated form, perhydrodibenzyltoluene (H_{18}-DBT). It is considered a non-toxic and non-flammable environmentally friendly compound.. DBT can store hydrogen up to 6.2 wt%, corresponding to an energy capacity of approximately 2.05 kWh/kg. The market price of DBT is around €4/kg, making it more expensive than

Table 1. Comparision of Liquid Organic Hydrogen Compounds

Systems	Hydrogen storage capacity (wt%)	Advantages	Challenges	References
Benzene-Cyclohexane	7.2	High hydrogen storage capacity, liquid at room temperature, well-studied system, high selectivity and conversion.	High toxicity and corrosiveness, high dehydrogenation temperature, low boiling and flash points	[15]
Toluene-Methylcyclohexane	6.2	High stability and low toxicity, liquid under atmospheric conditions, no CO_2 emissions during dehydrogenation, high flash point, low cost.	Requires high dehydrogenation temperature (300–400 °C), MCH is hazardous to the environment, MCH is in gas phase during dehydrogenation, necessitating hydrogen purification.	[7, 16]
Napthalene-Decalin	7.3	High boiling point minimizes evaporation losses.	Solid at room temperature, requires solvent, prone to side reactions, not suitable for transport and storage due to material properties, high melting point (~80 °C).	[6,7]
N-ethylcarbazole-Dode-N-ethylcarbazole	5.8	Hydrogen storage possible below 200 °C, high stability, low reaction temperatures.	Requires different catalysts for hydrogenation and dehydrogenation, solid at room temperature, H_{12}-NEC cracking during dehydrogenation, high cost.	[17]
Dibenzyltoluene-Perhydrodibenzyltoluene	6.2	Low melting point and high boiling point, long-standing use as heat transfer fluid demonstrates scalability.	High dehydrogenation temperature required, slow molecular diffusion of DBT in porous catalysts.	[18, 19]
CO2- Formic acid	4.4	Low dehydrogenation temperature, low energy consumption, low cost and abundant availability, low toxicity.	Lower hydrogen storage capacity (4.4 wt%) compared to other systems, CO_2 released during dehydrogenation must be captured and managed or reused.	[7]

toluene and benzene but more affordable than N-ethylcarbazole [22]. The benzyltoluene perhydrobenzyltoluene system is being used on an industrial scale for hydrogen storage as a liquid organic hydrogen carrier by Hydrogenious Technologies GmbH (Erlangen, Germany) [23].

Hydrogenation of DBT

Hydrogenation of DBT involves the addition of hydrogen molecules to its aromatic rings, converting it into its fully saturated form, perhydrodibenzyltoluene (H_{18}-DBT). The liquid state of DBT facilitates transportation and storage, while its hydrogen storage capacity is approximately 6.2 wt%. This exothermic reaction typically requires elevated hydrogen pressures (1–5 MPa) and moderate temperatures (150–200°C) to ensure high conversion and selectivity (Fig. 2). The hydrogenation reaction of the compound dibenzyltoluene (H0-DBT), i.e. its saturation with hydrogen (hydrogen charging), can be written as in Eq 1:

$C_{21}H_{20}+8H_2 \rightarrow C_{21}H_{36}$ (1)

The selection of suitable catalysts to carry out the hydrogenation reaction is important. The most widely used as catalysts are noble metals such as Pd, Pt and Ru, which

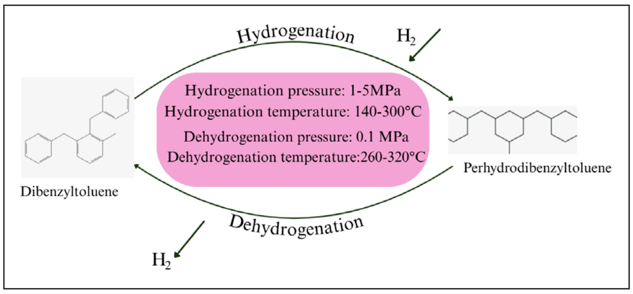

Figure 2. Hydrogenation and dehydrogenation cycles of LOHC compounds.

provide high selectivity and activity. Initially, Ru, Pt or Ni based catalysts supported on alumina were reported as potential catalysts for the hydrogenation of DBT [24]. Various catalysts have been investigated to improve the efficiency of DBT hydrogenation (Table 2). Platinum-based catalysts (Pt/Al_2O_3) are the most extensively studied systems and demonstrate excellent performance across a range of conditions. For instance, the study by Shi et al. [25] revealed that 3% Pt/Al_2O_3, including H_2 and O_2 plasma-modified

Table 2. Hydrogenation catalytic performance of some catalysts for DBT

LOHCs	Catalysts	T (°C)	P (MPa)	Conversion (%)	Selectivity (%)	References
DBT	0.3%Pt/Al_2O_3	270	30	100	100	[30]
	3%Pt/Al_2O_3	140	40	100	100	[25]
	3%Pt/Al_2O3-H_2 plasma	140	40	100	100	[25]
	3%Pt/Al_2O3-O_2 plasma	140	40	100	100	[25]
	5 wt. % Ru/Al_2O_3	170	5	-	100	[26]
	Raney-Ni	170	7	-	100	[31]
	Ni70/AlSiO-1/1	150	7	100	100	[32]
	0.3 wt% Pt/Al_2O_3	270	3	-	100	[33]
	0.3 wt. % Pt/Al_2O_3	230	3	100	-	[34]
	0.3 wt. % Pt/Al_2O_3	300	3	95	-	[35]
	13 wt. % Ni/Al_2O_3	200	4	100	-	[29]
BT	0.5 wt. % Ru/MgO	150	0.5	100	100	[27]
	5 wt. % Ru/Al_2O_3	150	0.5	% 99<	-	[36]

versions, achieved 100% conversion and selectivity at a relatively low temperature (140 °C) and high pressure (40 MPa) within just 15 minutes. This highlights the impact of catalyst pretreatment on reaction kinetics. Similarly, other studies using 0.3% Pt/Al_2O_3 at higher temperatures (230–300 °C) and moderate pressures (3 MPa) also reported conversion values close to 100%, although some lacked selectivity data. Nickel-based catalysts, such as Ni70/AlSiO and 13 wt.% Ni/Al_2O_3, provide a cost-effective alternative to noble metals. Despite being less active at low temperatures, these systems still achieved 100% conversion, albeit at slightly higher temperatures (150–200 °C) and pressures (4–7 MPa). Ruthenium-based catalysts also offer remarkable performance, particularly under milder conditions. For example, 5 wt.% Ru/Al_2O_3 [26] and 0.5 wt.% Ru/MgO [27] demonstrated nearly complete hydrogenation at only 150–170 °C and low pressures (0.5–5 MPa), with 100% selectivity. These results emphasize the high activity of Ru catalysts at lower energy requirements. Liu et al. [28] investigated the hydrogenation of DBT using Al_2O_3-supported catalysts containing 5 wt% of Pd, Pt, Ru, or Rh. The most active catalyst was found to be 5 wt% Rh/Al_2O_3, which achieved a turnover frequency (TOF) of 26.5 h^{-1} and a hydrogenation degree of 92.7% within 2 hours. Support materials also play a key role by influencing metal dispersion, hydrogen adsorption, and heat transfer. Porous supports like Al_2O_3, γ-Al_2O_3 and ZrO_2 are commonly used due to their thermal stability and surface area. In particular, highly acidic or mesoporous supports have been shown to enhance hydrogen diffusion and prevent aggregation of metal particles. In particular, highly acidic or mesoporous supports have been shown to enhance hydrogen diffusion and prevent aggregation of metal particles. These include slow diffusion within the large DBT molecule, metal sintering during prolonged operation, and catalyst deactivation due to impurities. To address these issues, recent research has focused on: i) bimetallic catalysts that balance activity and stability, ii) nano-structured supports that enhance mass transfer and iii) solvent-assisted hydrogenation methods that lower energy requirements [28, 29].

Dehydrogenation of DBT

Dehydrogenation of perhydrodibenzyltoluene (H_{18}-DBT) is a critical step in the LOHC cycle, where hydrogen is released through an endothermic catalytic process. This reaction typically occurs at temperatures ranging from 270 °C to 320 °C and pressures below 1 MPa (Fig. 2). DBT has a melting point of 34 °C and a boiling point of 390 °C, which helps minimize vapor losses due to hydrogen flow. Moreover, its low vapor pressure at room temperature enables the release of high-purity hydrogen. The m ain advantages of the DBT system include: (i) a high boiling point (~390 °C) and low vapor pressure, which minimize vapor losses and system inefficiencies, (ii) lower environmental and toxicity risks compared to nitrogen containing compounds like NEC, and (iii) its long-standing use as a heat transfer fluid, which demonstrates its scalability for industrial applications. However, the system also requires high dehydrogenation temperatures (>300 °C), and molecular diffusion in porous supports can be slow, limiting reaction kinetics. This endothermic reaction can be represented as Eq (2):

$$C_{21}H_{36} \rightarrow C_{21}H_{20} + 8H_2 \quad (2)$$

Lee et al. [37] compared the dehydrogenation performance of 5 wt% Pt/Al_2O_3 and 5 wt% Pt/CeO_2 catalysts in the DBT–perhydrodibenzyltoluene system. The study achieved 100% selectivity, with Pt/Al_2O_3 showing full conversion, whereas Pt/CeO_2 achieved only 37% conversion. Additionally, Sievi et al. [12] developed innovative thermo-electrochemical hybrid systems that enable hydrogen recovery from DBT at lower temperatures. Recent studies have introduced several strategies to enhance the performance of DBT-based LOHC systems, including the development of bimetallic catalysts (e.g., Pd–Ni) to leverage synergistic effects and the utilization of nanostructured supports to increase surface area and improve mass diffusion [38, 39]. Efficient dehydrogenation of DBT remains critical for the practical implementation of LOHC technology. Accordingly, ongoing research efforts focus on optimizing catalyst activity, elucidating reaction mechanisms, and ensuring long-term system stability over multiple hydrogenation–dehydrogenation cycles. Nevertheless, key challenges such as catalyst deactivation (e.g., coke formation), high energy demand, and the necessity to maintain thermal stability continue to limit the widespread adoption of this technology [32].

Table 3 summarizes the catalytic performances of some catalysts used in the dehydrogenation of H18-DBT. Pt/Al_2O_3 (platinum supported alumina) catalysts were mainly used in the studies. However, one of the main findings noted is that higher platinum loading does not always result in higher performance. For example, a catalyst containing 5 wt.% Pt and tested in a flow-type reactor gave only 5% conversion, while a 0.5 wt.% Pt/Al_2O_3 catalyst prepared by precipitation method in supercritical CO_2 environment achieved 89% conversion at the same temperature and pressure. This reveals that the catalyst is directly related not only to the amount of active metal but also to parameters such as preparation method and metal dispersion. In Modisha et al. [40], among various catalyst preparation methods, Pt/Al_2O_3 prepared by SCD (supercritical CO_2 deposition) method stands out with both high conversion (89%) and acceptable selectivity (38%) values. In contrast, the catalyst prepared by wet impregnation with the same Pt ratio yielded only 31% conversion and 15% selectivity. This highlights the decisive influence of metal particle size and surface distribution on catalytic performance. Catalytic dehydrogenation of H_{18}-DBT is highly sensitive to parameters such as metal dispersion, catalyst preparation method, support material and additives. Although Pt-based systems are still the most widely used, their performance can be significantly improved by surface engineering and synthesis techniques. Future work should focus on the development of long-lasting and cost-effective catalyst systems that can operate at lower temperatures.

CONCLUSION

Dibenzyltoluene (DBT)-based Liquid Organic Hydrogen Carrier (LOHC) systems present significant potential for the safe, efficient, and scalable chemical storage and transportation of hydrogen. Thanks to their high thermal and chemical stability, low toxicity, and compatibility with existing energy infrastructure, DBT-based systems have considered as one of the most promising candidates for the commercialization of LOHC technology. The advancement of commercial applications further demonstrates the progress of this technology towards industrial maturity. However, several critical technical challenges continue to limit the large-scale applicability of LOHC systems. High dehydrogenation temperatures (>300 °C), catalyst deactivation (coke formation, sintering), and slow molecular diffusion within porous structures negatively affect the process efficiency and cycle life. Additionally, the high energy demand associated with the dehydrogenation step remains one of the main obstacles to achieving fully sustainable operation.

Table 3. Deydrogenation catalytic performance of some catalysts for H18-DBT.

Compond name	Catalysts	T (°C)	P (MPa)	Conversion (%)	Selectivity (%)	References
H18-DBT	Pt/Al_2O_3	270	0.1	-	58.1	[41]
	W0.22-Pt0.78/ Al_2O_3	270	0.1	-	64.8	[41]
	0.3 wt. % Pt/Al_2O_3	310	0.1	83	-	[42]
	0.5 wt. % Pt/Al_2O_3 (SCD/$scCO_2$)	298	0.1	89	38	[40]
	0.5 wt. % Pt/Al_2O_3 (Wet Impregnation)	299	0.0	31	15	[40]
	0.5 wt% Pt/Al_2O_3 (commercial catalysts)	300	0.1	88	42	[40]
	0.3%Pt/Al_2O_3	310	0.1	85	100	[43]
	5%Pt/Al_2O_3	300	0.1	5	100	[44]
	5%Pt/CeO_2	300	0.1	37	100	[44]
	5%Pt/Al_2O_3	270	0.1	58	100	[45]
	1%La,5%Pt/Al_2O_3	270	0.1	65	100	[45]
	5%Pt/Al_2O_3	300	0.1	48	-	[46]

In recent years, significant progress has been made in overcoming these challenges through the development of bimetallic catalysts (e.g., Pd–Ni, Pt–Ru), nanostructured supports, and thermo-electrochemical hybrid systems. However, further research is still required to ensure the scalability and long-term performance of these solutions. Future research should focus on the following key areas: i) Design of next-generation catalysts with high activity at low temperatures and reduced energy consumption, ii) Enhancement of mass and heat transfer through process intensification, iii) Integration of thermo-electrochemical hybrid systems to improve process efficiency, iv) Development of bio-based or sustainably sourced LOHC compounds, v) Long-term performance and cycle stability studies at commercial scale. In conclusion, LOHC technology — particularly DBT-based systems — has the potential to play a critical role in the future sustainable hydrogen economy. To fully realize this potential, it is essential to advance multidisciplinary research, innovative catalyst design, and integrated system development.

ACKNOWLEDGEMENT

Kübra AL expresses her gratitude to TUBITAK-BIDEB (2211-A) for the doctoral fellowship.

AUTHORSHIP CONTRIBUTIONS

Authors equally contributed to this work.

DATA AVAILABILITY STATEMENT

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

CONFLICT OF INTEREST

The author declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

ETHICS

There are no ethical issues with the publication of this manuscript.

STATEMENT ON THE USE OF ARTIFICIAL INTELLIGENCE

Artificial intelligence was not used in the preparation of the article.

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