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Review Article

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

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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.

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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

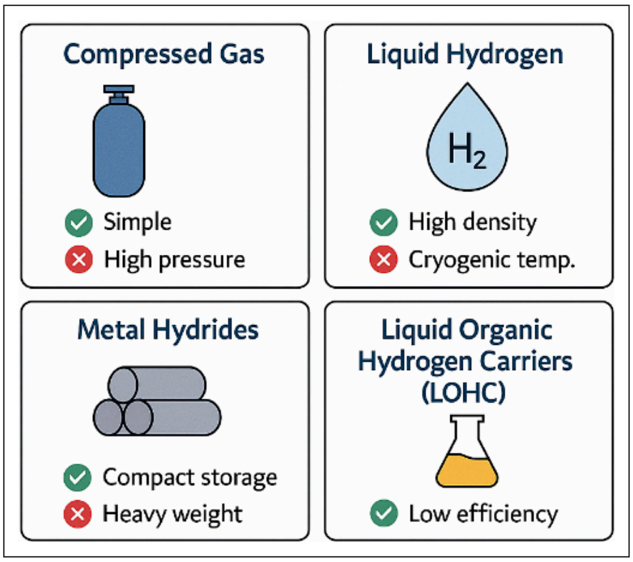

Figure 1. Hydrogen storage and transportation [Figure designed by the authors using digital illustration tools]

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].

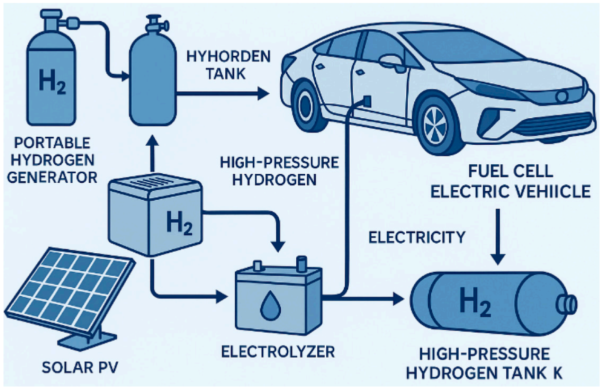

Figure 2. Hydrogen-powered mobile energy systems [Figure designed by the authors using digital illustration tools]

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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