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Recent Advancements and Current Status of Hydrogen Fuel Cells: Materials, Systems, Applications, and Commercialization Prospects

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Abstract

In the transportation, stationary electricity, and industrial sectors, hydrogen fuel cells have become a crucial clean-energy technology that can help achieve worldwide decarbonization. Significant progress has been made in catalyst design, membrane engineering, stack architecture, system optimization, and hydrogen generation pathways throughout the last ten years. Platinum group metal (PGM) loading has been significantly reduced, single-atom and transition-metal-nitrogen-carbon (M-N-C) catalysts for oxygen reduction have been developed, proton exchange membranes in membrane electrode assembly (MEA) have been improved for durability, and green hydrogen has been scaled using sophisticated electrolyzers. Strong legislative support and global electrolyzer deployment have advanced commercial demonstrations in fuel cell vehicles, stationary solid oxide fuel cell systems, and micro combined heat and power. However, there are still major challenges, including cost, long-term durability, the lack of necessary materials, infrastructure gaps, and the carbon intensity of upstream hydrogen generation. This overview summarizes recent advancements in materials, cell designs, hydrogen supply, applications, techno-economic trends, and future research directions. The report identifies key commercial challenges, outlines research objectives, and offers a roadmap for accelerating fuel cell commercialization in developing hydrogen economies. Applications across transportation, stationary power, residential combined heat and power systems, industrial backup power, and emerging maritime and aviation sectors are analyzed to assess real-world performance and deployment trends. Environmental and techno-economic considerations, including lifecycle emissions, system costs, and policy-driven market enablers, are evaluated to identify remaining barriers to widespread adoption. The review concludes by outlining key research gaps, durability challenges, infrastructure limitations, and strategic priorities, and proposes a forward-looking roadmap to accelerate the transition of hydrogen fuel cells from niche demonstrations to large-scale commercial energy solutions.

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INTRODUCTION

Global plans to lower greenhouse gas emissions and improve energy security rely heavily on hydrogen fuel cells (HFCs). They are attractive for transportation, stationary power, industrial decarbonization, and distributed generation, owing to their high efficiency and zero tailpipe emissions when converting hydrogen and oxygen into electricity [1]. Global commitments to net-zero pathways, significant investments in large-scale hydrogen production and storage infrastructure, and sharp drops in the cost of renewable electricity have contributed to the revival of fuel cell research and commercialization since 2018 [2].

Although hydrogen currently accounts for only 4% of the world's final energy consumption, estimates suggest that by 2050, depending on the policy and electrolyzer deployment, its share could increase to 10–20% [3]. The use of fuel cell cars, buses, micro-combined heat and power (CHP) units, and solid oxide systems is growing as more than 40 nations have announced national hydrogen strategies [4]. Reducing platinum loading, enhancing catalyst stability [5] and membrane durability [6], and creating less expensive stack architectures [7] have received much research attention.

From a policy standpoint, governments are accelerating demonstration projects in areas such as the EU, Japan, South Korea, and the US by providing incentives such as tax credits, hydrogen banks, and guaranteed offtake agreements [8]. However, upstream hydrogen production is crucial to the environmental benefits of HFCs. Compared to grey hydrogen, green hydrogen produced by renewable-powered electrolysis significantly lowers lifecycle emissions [9].

A thorough analysis is required to highlight developments in materials, system engineering, electrolyzers, applications, modeling, techno-economics, and prospects, given this rapid evolution. To assess the maturity and commercialization potential of HFCs, this study synthesizes evidence from peer-reviewed studies, review papers, and techno-economic frameworks. It covers the developments from 2018 to 2025.

HISTORICAL BACKGROUND AND FUNDAMENTALS OF HYDROGEN FUEL CELLS

Although the concept of HFCs dates back to the 19th century, modern development began during space missions in the middle of the 20th century [1]. The only byproducts of the electrochemical reactions of modern HFCs, which produce electricity, heat, and water, are the oxidation of hydrogen at the anode and the reduction of oxygen at the cathode [10].

Basic Electrochemical Principles

In conventional proton exchange membrane fuel cells (PEMFC), hydrogen dissociates into protons and electrons at the anode interface. Protons traverse the membrane, whereas electrons navigate through an external circuit to facilitate the generation of electrical energy. At the cathode interface, oxygen interacts with protons and electrons to yield water [6]. The operational efficacy of PEMFCs is influenced by the activation loss, ohmic loss, and concentration polarization phenomena [11].

Solid oxide fuel cells (SOFCs), as illustrated in Figure 1, function at elevated temperatures (600–1000°C), where oxide ions migrate through a ceramic electrolyte such as yttria-stabilized zirconia [12]. Their elevated operational temperature permits internal reforming and enhances electrical efficiency [13] (Figure 1).

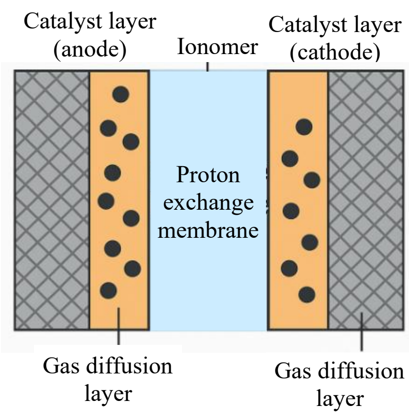

Figure 1. MEA cross-section layout diagram.

Key Performance Metrics

The performance of fuel cells is assessed using various parameters, including voltage-current polarization, power density, efficiency, fuel utilization, cold-start capability, and durability [14]. The longevity objectives for automotive PEMFC stacks are set to exceed 5,000–8,000 h, whereas stationary SOFCs aspire to achieve lifespans ranging from 40,000 to 80,000 h [15]. Enhancements in durability are fundamentally dependent on the mitigation of catalyst degradation, fortification of membrane mechanical integrity, and optimization of water and thermal management systems [16].

Degradation Mechanisms

Catalyst degradation occurs due to sintering, Ostwald ripening, carbon support oxidation, and poisoning by CO, NH_4, and sulfur [17]. Membrane failure arises from chemical attack by peroxide radicals and mechanical fatigue induced by humidity cycles [18]. In SOFCs, thermal cycling and interfacial reactions between the electrodes and ceramic electrolyte cause long-term degradation.

Fundamentally, improving durability while reducing costs remains a central research challenge that drives innovation across materials and systems.

HYDROGEN PRODUCTION: SUPPLY-SIDE CONTEXT

The viability of HFCs is closely related to hydrogen production pathways. Approximately 99% of today's hydrogen is grey hydrogen produced from fossil fuels, but major global efforts aim to scale low-carbon (blue) and renewable (green) hydrogen sources [19].

Grey, Blue, and Green Hydrogen

Grey hydrogen is produced through steam methane reforming (SMR), whereas blue hydrogen incorporates carbon capture and storage (CCS) to reduce emissions [20]. Green hydrogen, produced through water electrolysis using renewable electricity, offers the lowest lifecycle emissions when powered by wind, solar, or hydropower [9].

Electrolyzer Technologies

Recent reviews identify four major electrolyzer types [3, 21]:

- *Alkaline water electrolysis (AWE):* Mature and low-cost, but slower dynamics.
- *Proton exchange membrane electrolysis (PEMEL):* Faster response, higher purity hydrogen.
- *Anion exchange membrane electrolysis (AEMEL):* Promising lower-cost alternatives with non-PGM catalysts.
- *Solid oxide electrolysis cells (SOECs):* high efficiency and potential for integration with industrial waste heat.

Anion exchange membranes (AEM) electrolysis is gaining research attention because of its ability to eliminate expensive iridium and noble metal components [22], although membrane stability requires improvement (Figure 2).

Economics and Deployment Trends

The cost of green hydrogen depends on the electrolyzer CAPEX- Capital Expenditure, renewable electricity cost, system efficiency, and capacity factor [23]. Industry analyses show major electrolyzer manufacturing expansion worldwide, led by Europe and China [24]. Pipelines for electrolyzer projects are growing rapidly, yet operational capacity remains low, and supply chain constraints persist.

Link to Fuel Cell Commercialization

The carbon intensity of upstream hydrogen directly determines the environmental benefits of fuel cell vehicles and stationary systems [20]. The widespread adoption of green hydrogen will accelerate the deployment of HFCs in heavy transport, industrial power, and microgrid applications (Table 1).

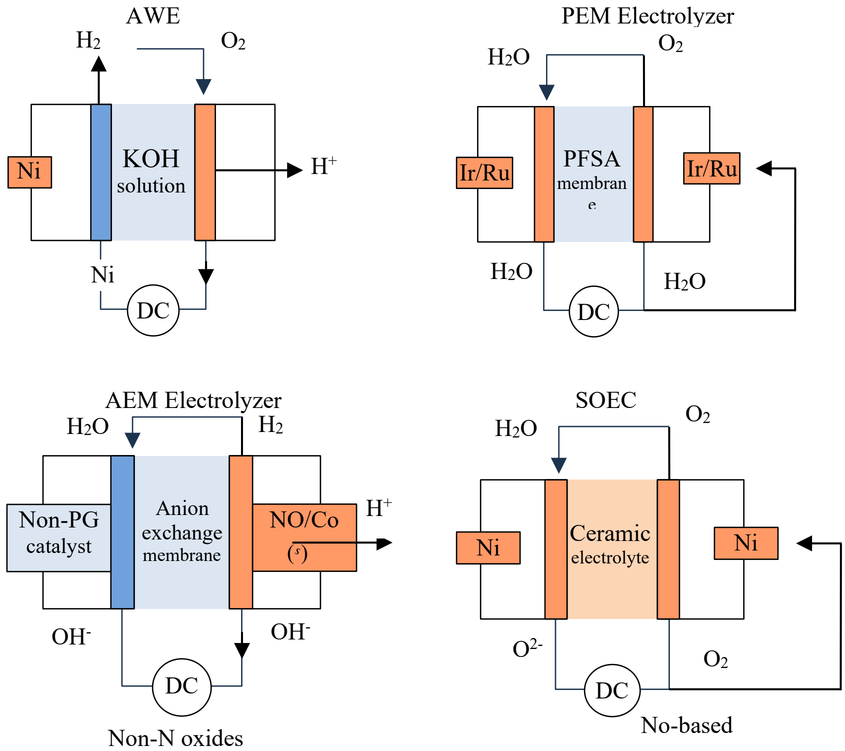

Figure 2. Schematic representation of major water electrolysis technologies (AWE, PEMEL, AEMEL, and SOEC).

Table 1. Comparison of electrolyzer technologies.

Parameter	AWE	PEM electrolyzer	AEM electrolyzer	SOEC
Electrolyte	KOH solution	PFSA membrane	Anion exchange membrane	Ceramic electrolyte
Operating temperature	60–90°C	50–80°C	40–70°C	650–850°C
Catalysts	Ni-based	Ir/Ru oxides	Non-PGM (Ni, Co)	Ni-based
Efficiency	62–82%	60–75%	55–70%	80–90%
CAPEX	Low	High	Medium	High
Advantages	Cost-effective, mature	High purity H_2, dynamic response	Low-cost materials	Highest efficiency, heat integration
Limitations	Lower dynamic response	Uses precious metals	Membrane stability	Durability, high temperature
Applications	Large industrial H_2	Mobility-grade H_2	Future low-cost green H_2	Industrial integration

FUEL CELL TYPES AND COMPARISON

HFCs exist in several technologically distinct forms, each defined by electrolyte material, operating temperature, and targeted application. PEMFCs and SOFCs dominate research and commercialization, while phosphoric acid fuel cells (PAFCs), molten carbonate fuel cells (MCFCs), alkaline fuel cells (AFCs), and direct methanol fuel cells (DMFCs) play important roles in specific niches [1].

Proton Exchange Membrane Fuel Cells

PEMFCs operate at relatively low temperatures (60–90°C) and use perfluorosulfonic acid (PFSA) membranes such as Nafion for proton conduction [10]. Their advantages include fast startup, high-power density, compactness, and rapid responsiveness, making them ideal for automotive applications, such as fuel cell electric vehicles [9]. As highlighted in the investigation by Wei (2024) [25], PEMFCs represent the most mature transportation technology.

Key challenges:

- Platinum group metal (PGM) catalysts cost and scarcity [25, 26].
- Membrane chemical degradation from radicals and contaminants [6].
- Water management and flooding/drying cycles affect the ohmic and mass transfer losses [1].
- Operating durability under repeated cold-start cycles [1].

Recent advances, such as reinforced PFSA membranes, PGM-free catalysts, and optimized flow-field architectures, have substantially improved the durability and power density of PEMFCs [22, 27].

Solid Oxide Fuel Cells

SOFCs operate at high temperatures (600–1000°C) using a ceramic electrolyte, typically yttria-stabilized zirconia (YSZ), to conduct oxygen ions. Their high efficiency and ability to internally reform hydrocarbons make them attractive for stationary power generation [15]. Advanced modeling and material studies [28, 13] have demonstrated rapid improvements in intermediate-temperature SOFCs (IT-SOFCs), which aim to reduce the operating temperature to 500–700°C.

Advantages

- Fuel flexibility, including natural gas, ammonia, and biogas.
- High electrical efficiency (up to 60% in standalone mode).
- Excellent suitability for distributed generation and CHP systems.

Challenges

- Thermal cycling, electrolyte degradation, and interfacial reactions [15].
- Long startup times due to high operating temperature.
- Higher system cost compared with PEMFCs.

Nonetheless, SOFC commercial roll-out for micro-CHP and data center backup has accelerated owing to its performance, low noise, and reliability.

Phosphoric Acid Fuel Cells

PAFCs operate at moderate temperatures (~200°C), using liquid phosphoric acid as the electrolyte. They were among the first fuel cells to reach commercial deployment, particularly in stationary CHP applications [1].

Advantages

- High tolerance to fuel impurities.
- Good cogeneration efficiency.

Limitations

- Lower electrical efficiency than PEMFCs and SOFCs.
- High system cost and complex water/thermal management.

Molten Carbonate Fuel Cells

MCFCs utilize molten carbonate salts as electrolytes and operate at 600–700°C [15]. Their high temperatures enable internal reforming of natural gas and excellent fuel flexibility.

Challenges

- Complex high-temperature sealing and corrosion issues.
- Relatively slow commercial uptake due to system complexity.

Alkaline Fuel Cells

AFCs use potassium hydroxide (KOH) as the electrolyte and operate at 60 °C–120°C. Historically used in space applications, AFCs provide high efficiency, but have poor tolerance to CO_2, which limits their widespread adoption [29].

Direct Methanol Fuel Cells

DMFCs operate at low temperatures (~60°C) using methanol as the fuel and are attractive for portable electronics [30]. However, their low efficiency and methanol crossover are limitations.

Comparative Assessment

Recent reviews [1, 25] suggest that PEMFCs dominate transportation, SOFCs dominate stationary, and other types hold niche roles.

Table 2 shows a consolidated summary of the major fuel cell types, comparing various parameters.

MATERIALS AND COMPONENT-LEVEL ADVANCEMENTS

Advances in materials, catalysts, membranes, gas diffusion layers (GDLs), bipolar plates, and MEAs have driven many of the recent performance gains in fuel cells. Research between 2018 and 2025 has focused on reducing the critical material dependence, increasing durability, and improving microstructural control [25, 26, 28].

Catalyst Innovations

Platinum Group Metal Optimization

Platinum is essential for the oxygen reduction reaction (ORR) in PEMFCs; however, its scarcity and cost reduce the PGM content. Strategies include:

- Alloyed catalysts (PtNi, PtCo) with enhanced ORR activity [22].
- Core-shell structures reduce Pt use while maintaining surface activity [25, 26].
- High-surface-area carbon supports distribute Pt more efficiently [11].

Yadav et al. [14] showed that optimized Pt loading can achieve acceptable durability for automotive cycles.

Table 2. Comparison of major fuel cell types.

Parameter	PEMFC	SOFC	PAFC	MCFC	AFC	DMFC
Electrolyte	PFSA membrane	YSZ/ceramic	Phosphoric acid	Molten carbonate salts	Aqueous KOH	Polymer membrane
Operating temperature	60–90°C	600–1000°C	~200°C	600–700°C	60–120°C	~60°C
Efficiency	40–60%	50-65% (electric); 85% CHP	40–45%	50–60%	60%	20–30%
Fuel	H_2	H_2, CH_4, NH_3	H_2	H_2, CH_4, CO	Pure H_2	Methanol
Advantages	Fast startup; high-power density; compact	High efficiency; fuel flexibility	Good for CHP	Internal reforming	High efficiency	Easy fuel handling
Limitations	Cost; durability	Thermal cycling; startup time	Low power density	Corrosion; molten salt handling	CO_2 sensitivity	Methanol crossover
Applications	Vehicles, small stationary	Stationary, micro-CHP, industry	CHP	Large stationary	Space, niche	Portable devices

PGM-Free Catalysts

Transition metal-nitrogen-carbon (M-N-C) catalysts have attracted immense attention owing to their cost-effectiveness. Wang et al. [28] demonstrated that Fe-N-C catalysts can achieve ORR activities approaching Pt-based performance, although their long-term durability remains inferior [5].

Single-Atom Catalysts

Single-atom catalysts (SACs) provide near-100% metal utilization. Studies "(Wu et al., 2022)" have shown that Fe-based SACs significantly enhance the ORR activity through tailored coordination environments. However, the challenges include catalyst stability and susceptibility to metallization.

Catalyst Degradation and Poisoning

Degradation occurs via:

- Sintering and Ostwald ripening [17].
- Carbon support oxidation [5].
- CO and sulfur poisoning in reformate hydrogen streams [16].

Advanced diagnostics, such as in situ spectroscopy, have improved our understanding of degradation [31–34]. Table 3 summarizes the advances in catalyst technologies in recent years, and Table 4 shows a consolidated summary of the key degradation mechanisms in PEMFCs and SOFCs.

Membranes and Ionomers

Membranes govern the proton transport and durability. PFSA membranes, such as Nafion, remain dominant; however, alternatives are emerging.

Table 3. Catalyst advances in hydrogen fuel cells.

Catalyst category	Example materials	Key advantages	Limitations	Representative references
Pt-based alloy catalysts	Pt-Co, Pt-Ni, Pt-Cu	Higher ORR activity; lower Pt loading	Cost; long-term stability	[25, 33]
Core-shell catalysts	Pt shell/Ni core	High specific activity	Shell stability issues	[25]
PGM-free catalysts (M-N-C)	Fe-N-C, Co-N-C	Extremely low cost	Durability under cycling	[28, 35]
Single-atom catalysts (SACs)	Fe SACs, Co SACs	Near-100% metal utilization	Demetalization	[28]
SOFC electrode catalysts	Ni-YSZ, LSCF	High-temp stability	Redox cycling degradation	[13]

Table 4. Comparison of electrolyzer technologies.

Parameter	AWE	PEM electrolyzer	AEM electrolyzer	SOEC
Electrolyte	KOH solution	PFSA membrane	Anion exchange membrane	Ceramic electrolyte
Operating temperature	60–90°C	50–80°C	40–70°C	650–850°C
Catalysts	Ni-based	Ir/Ru oxides	Non-PGM (Ni, Co)	Ni-based
Efficiency	62–82%	60–75%	55–70%	80–90%
CAPEX	Low	High	Medium	High
Advantages	Cost-effective, mature	High purity H_2, dynamic response	Low-cost materials	Highest efficiency, heat integration
Limitations	Lower dynamic response	Uses precious metals	Membrane stability	Durability, high temperature
Applications	Large industrial H_2	Mobility-grade H_2	Future low-cost green H_2	Industrial integration

1. *PFSA membranes:* Reinforced PFSA membranes with enhanced mechanical stability have been developed to survive humidity cycling [10]. Chemical degradation, primarily via peroxide radicals, remains a challenge [18].
2. *High-temperature PEM membranes:* Wan et al. [26] have demonstrated that phosphoric-acid-doped membranes allow operation at 140–180°C, improving CO tolerance and reducing water management issues.
3. *Anion exchange membranes:* AEMFCs use OH^- rather than H^+ conduction, enabling the use of cheaper non-PGM catalysts. However, determining the chemical stability of membranes in alkaline environments is challenging [29]. Recent AEM developments [22] include improved quaternary ammonium functional groups, crosslinking to resist degradation, and nanocomposite reinforcement.
4. *Ionomer distribution:* Sebastian Raab [36] showed that the ionomer distribution within the catalyst layers strongly influences both proton conductivity and mass transport.

Gas Diffusion Layers

The GDLs ensure reactant diffusion, electronic conduction, and water management. Studies conducted by Shin-Woo Myeong [22]. (2019) highlighted advances in microporous layer (MPL) coatings, hydrophobicity optimization, and porosity grading to control water balance. Carbon paper and carbon cloth GDLs with tailored pore structures exhibit improved water removal and increased cell durability (Lim et al., 2016).

Bipolar Plates

Bipolar plates contribute significantly to the stack cost, mass, and electrical resistance. Recent innovations include metallic bipolar plates with corrosion-resistant coatings [35], graphite-polymer composites for lightweight designs [7], and additive manufacturing for flow-field structures [37]. Metallic bipolar plates allow thinner geometries and improved compactness but require stable anti-corrosion coatings.

MEA Engineering

The membrane electrode assembly (MEA) integrates catalyst layers, GDLs, and membranes.

1. *Catalyst layer fabrication:* Improved ink formulations, solvent selection, and ionomer-to-carbon ratio optimization directly influence the catalyst layer microstructure [11]. Advanced coating techniques, such as ultrasonic spraying, slot-die coating, and roll-to-roll processing [38], have lowered the variability and operating costs.
2. *Water and thermal management:* Water flooding and membrane drying pose major mass transport limitations. Advanced flow-field designs [27] and optimized GDL hydrophobicity [16] have improved the water balance.

Durability and Degradation

Durability remains the primary barrier to wide commercialization.

Key Degradation Mechanisms:

- Catalyst sintering and carbon corrosion [5].
- Membrane chemical attack from radicals [18].
- Mechanical degradation due to pressure and humidity cycling [6].
- GDL compression fatigue [16].
- SOFC electrode delamination due to thermal expansion mismatch [13].

Recent efforts have focused on developing accelerated stress tests (ASTs) that correlate strongly with field performance [16].

SYSTEM-LEVEL AND MANUFACTURING ADVANCES

Although material advances have driven improvements in electrochemical performance, commercialization ultimately depends on system-level engineering, stack design, manufacturability, and balance-of-plant (BOP) optimization. Between 2018 and 2025, significant progress was made in flow-field engineering, thermal management, stack modularization, and automated MEA fabrication [7, 37].

Stack Architecture and Flow-Field Design

The flow-field design influences the reactant distribution, water removal, pressure drop, and thermal uniformity. Computational fluid dynamics (CFD) and multi-physics simulations are widely used to optimize channel geometries [12].

Advancements Include

- 3D-printed flow fields with improved gas distribution [37].
- Interdigitated and tapered channels for enhanced mass transport [27].
- Bio-inspired patterns mimic leaf venation to improve the reactant flow uniformity [11].
- Thermal homogenization strategies to minimize hotspots are essential for both PEMFC and SOFC stacks [39].

Flow-field design is particularly critical under dynamic load conditions in fuel cell vehicles. Jun Shen et. al [39] showed that improved thermal management extends the stack lifetime by reducing the membrane mechanical stress during transients [40].

Balance-of-Plant Improvements

The compressors, humidifiers, pumps, sensors, and power converters) contribute 30–50% of the fuel cell system cost [1].

Key BOP Advancements

- Low-parasitic compressors for automotive PEMFCs [39].
- Membrane-less humidifiers reduce water management complexity [27].
- High-efficiency DC-DC converters enabling integration with batteries [41].
- Advanced control algorithms for dynamic load following.
- BOP thermal integration in SOFCs for improved heat recovery [15].

[41] emphasized that integrated electrolyzer-fuel cell hybrid systems are emerging for microgrid and backup applications.

Manufacturing Scale-Up

Manufacturing readiness has improved markedly due to automation and precision techniques.

Major Developments Include

- Roll-to-roll MEA fabrication with uniform catalyst loading [38].
- Laser welding for metallic bipolar plates, improving durability [35].
- Automated quality control using machine-vision and inline diagnostics [7].
- Standardized stack modules enabling modular assembly [14].

Global supply chains are rapidly expanding. Sugawara et al. [24] highlighted intense geopolitical competition in electrolyzer manufacturing, which also affects the fuel cell supply chain regionalization.

Reliability and Real-World Validation

Long-term performance under field conditions often deviates from laboratory projections. Liu et al. [16] found that cold-start cycles and start-stop transitions significantly accelerate PEMFC catalyst degradation. Studies on bus fleets [19] have shown that water flooding and under-humidification remain key causes of performance deterioration.

For SOFCs, thermal and redox cycling lead to electrode delamination [13]. Improved sealing materials, graded electrodes, and thermal buffering strategies have been increasingly adopted [12].

The validation of systems under realistic environmental, humidity, and load conditions is essential for their commercialization.

APPLICATIONS AND DEMONSTRATION PROJECTS

HFCs are gaining traction for mobility, stationary power, industrial, maritime, and emerging aviation applications. Between 2018 and 2025, real-world deployment increased significantly, supported by government incentives, falling electrolyzer costs, and improved system reliability [8].

Transportation Applications

Fuel Cell Electric Vehicles (FCEVs)

PEMFCs dominate the automotive market because of their high-power densities and low operating temperatures. Commercial FCEVs include the Toyota Mirai and Hyundai Nexo, with ranges exceeding 600 km and refueling times of 3–5 minutes [4].

Although battery-electric vehicles dominate passenger transport, FCEVs offer advantages in:

- Long-distance driving
- Cold climates
- Rapid refueling
- Heavy transport payload

Buses and Heavy-Duty Trucks

Fuel cell buses have been deployed on scale in Japan, Germany, and California [19]. Heavy-duty trucks such as the Hyundai Xcient and Nikola Tre leverage the high gravimetric energy density of hydrogen.

Studies indicate that hydrogen becomes more competitive for payloads >15 tons or ranges >500 km [8].

Rail Applications

Hydrogen fuel cell trains (e.g., Alstom Coradia iLint) operate in an emission-free manner on non-electrified lines. Their adoption in Europe reflects the suitability of hydrogen for long routes, where overhead electrification is cost-prohibitive.

Stationary Power Systems

Micro-CHP and Residential Systems

The SOFC micro-CHP units provide high electrical efficiency and valuable heat for residential and small commercial buildings. Mehran et al. [15] reported SOFC efficiencies of above 55% (electrical) and >85% (combined).

Backup and Remote Power

Fuel cells are used in:

- Telecom Towers
- Data centers
- Remote military bases
- Off-grid microgrids [41]

Their low noise, high reliability, and high-quality DC output make them attractive replacements for diesel generators.

Industrial Applications

Hydrogen-powered SOFCs are increasingly used in industrial backup power and distributed generation. Internal reforming allows the use of natural gas or ammonia, easing the hydrogen infrastructure constraints.

Maritime and Aviation

Maritime

Hydrogen and ammonia are candidates for decarbonizing shipping. Demonstrations include:

- Hydrogen fuel cell ferries (Norway, USA).
- Ammonia-to-hydrogen SOFC systems for maritime propulsion [40].

Aviation

Fuel cell aviation is less mature. Present efforts focus on:

- Auxiliary power units (APUs)
- Hybrid-electric propulsion concepts
- Small regional aircraft

Energy density constraints remain a bottleneck.

Refueling and Infrastructure Deployment

Refueling network growth is essential for transportation adoption.

- Japan, Korea, Germany, and California have the most developed station networks.
- Infrastructure costs remain high, and poor station availability inhibits FCEV consumer uptake.
- Hydrogen pipelines, liquid hydrogen terminals, and ammonia-to-hydrogen cracking infrastructures are emerging.

Aurora Energy Research (2024) reports that more than 1000 global hydrogen refueling stations are planned or under construction, although only a fraction is operational.

Large-Scale Demonstration Projects

- Megawatt-scale PEM electrolyzers power refueling stations.
- Hydrogen valleys integrating production, storage, and end-use [24].
- Island microgrids using electrolyzer fuel cell hybrid systems [41].
- Data center SOFC installations with 24/7 operational capability.

Demonstration projects highlight strong reliability and favorable lifecycle economics under the right conditions. Table 5 provides a summary of fuel cell applications across sectors.

ENVIRONMENTAL, ECONOMIC, AND LIFECYCLE PERSPECTIVES

Environmental performance and techno-economic viability determine whether HFCs can compete with existing technologies. Fuel cells emit only water at the point of use, but upstream emissions vary dramatically depending on the hydrogen source. Demonstration projects highlight strong reliability and favorable lifecycle economics under the right conditions. Table 5 provides a summary of fuel cell applications across sectors.

Lifecycle Assessment

Lifecycle assessment (LCA) studies [9, 20] consistently show that:

- Green hydrogen (renewable-powered electrolysis) produces <2 kg CO_2-eq/kg H_2.
- Blue hydrogen varies widely depending on CCS capture rates [20].
- Grey hydrogen from SMR emits 9–12 kg CO_2-eq/kg H_2.

Thus, fuel cell vehicles offer true climatic benefits only when paired with low-carbon hydrogen.

Component manufacturing also contributes to emissions:

- PFSA membranes involve fluoropolymer processing [18].
- Catalyst production involves PGM mining and refining.
- Bipolar plates manufacturing contributes significantly to embodied carbon [13].

SOFCs tend to have higher manufacturing emissions due to ceramic sintering but compensate for high electrical efficiency [13].

Techno-Economic Analysis (TEA)

Cost of Hydrogen

The cost of hydrogen (LCOH) depends on:

- Electrolyzer CAPEX
- Renewable electricity price
- System efficiency
- Operating hours/capacity factor

The estimate that green hydrogen could reach $1.5–2.5/kg by 2030 under optimistic scenarios, compared to current costs of $4–7/kg.

Fuel Cell System Cost

Fuel cell system cost is composed of:

- Stack cost (catalysts, membrane, plates)
- Balance-of-plant
- Integration with power electronics

PEMFC cost reductions have reached <$100/kW for automotive stacks, Anderson, approaching the US Department of Energy targets.

SOFC stacks remain more expensive owing to ceramic fabrication, although mass manufacturing is improving [15].

Comparisons with Competing Technologies

Fuel cells compete with:

- Battery-electric systems (transport)
- Internal combustion engines
- Gas turbines and diesel generators (stationary)

Studies have shown that fuel cell trucks outperform BEVs stands for Battery Electric Vehicles. in long-haul applications owing to energy density constraints.

Policy and Market Enablers

Strong policy frameworks, including subsidies, tax credits, carbon pricing, and hydrogen banks, are critical.

- *EU:* Hydrogen Strategy targeting 40 GW electrolyzers by 2030.
- *USA:* The Inflation Reduction Act (IRA) provides a production tax credit for green hydrogen.
- *Asia:* Japan and Korea target widespread FCEV and fuel cell heating adoption.

Wei notes that policy stability influences investment decisions more than technology maturity.

STANDARDS, CODES, AND SAFETY CONSIDERATIONS

The physical properties of hydrogen, low ignition energy, high diffusivity, and wide flammability range necessitate strict safety protocols for its production, storage, transport, and end-use. Regulatory frameworks have evolved significantly in parallel with hydrogen technology deployment [42].

International Standards

Key international bodies include:

- ISO/TC 197, Standards for hydrogen technologies

- IEC TC 105, Fuel cell safety and performance
- SAE International, Vehicle and refueling protocols
- ASME, Pressure vessel codes

ISO 19880 governs the hydrogen refueling station design, while IEC 62282 covers performance, safety, and testing for all major fuel cell types.

Fuel Cell Stack and System Safety

Fuel cell safety considerations involve:

- Hydrogen leak detection and ventilation design
- Electrical safety (high-voltage circuits in FCEVs)
- Thermal management to avoid hotspot formation [39]
- Freeze-thaw durability for PEMFCs [14]
- Redox and thermal cycling stress for SOFCs [13]

Standards also specify AST protocols, including 8 catalyst degradation testing, membrane chemical durability assessment, and pressure/flow cycling.

Infrastructure and Refueling Safety

Hydrogen refueling stations (HRS) are governed by strict setback distances, emergency shutdown systems, and grounding requirements. Station reliability and uniform refueling standards have been crucial in Japan's successful adoption of FCEVs.

CURRENT GAPS, CHALLENGES, AND RESEARCH NEEDS

Even with major progress, several fundamental and systemic challenges continue to constrain commercialization.

Hydrogen Supply and Infrastructure

Green hydrogen scale-up remains insufficient to support mass fuel cell deployment (Aurora Energy Research, 2024). Challenges include:

- Electrolyzer manufacturing capacity and supply chains [24]
- Renewable electricity constraints
- High hydrogen transport and storage costs
- Slow roll-out of refueling stations [4]

Research needs to emphasize ammonia cracking, liquid organic hydrogen carriers (LOHCs), and pipeline repurposing [40].

Cost and Critical Materials

PEMFCs depend heavily on platinum catalysts and fluorinated membranes [10, 25, 26]. Cost remains a barrier to large-scale deployment.

Key research areas:

- PGM-free catalysts with improved durability [28]
- Pt recycling and circular material flows [42]
- PGM-support stabilization against corrosion [5]
- PFSA alternatives for membranes [29]

Durability Under Real-World Conditions

Durability under cyclic loads, humidity swings, startup-shutdown, and cold-start conditions remain pressing issue [16].

Key degradation modes include:
- Catalyst poisoning [17]
- Carbon support corrosion [5]
- Membrane thinning and radical attack [16]
- GDL compression fatigue [18]
- SOFC electrode delamination [13]

More predictive correlations between ASTs and real-world ageing are needed.

System Integration and Manufacturing

Large-scale commercialization requires:
- Automated, low-cost MEA and stack production [38]
- Standardized system architectures [7]
- Digital twins for stack monitoring [31]
- Validated multi-physics models

Market and Policy Uncertainty

Policy stability is one of the strongest determinants of industrial investment [24]. Carbon pricing, hydrogen subsidies, and long-term procurement commitments shape the future trajectories.

FUTURE OUTLOOK AND ROADMAP

The next decade is expected to witness a strong growth in hydrogen production, distribution, and end-use technologies. In the short term (2025–2030), PEMFCs will continue to dominate mobility applications, while SOFCs will grow in stationary markets [15].

Near-Term Priorities (2025–2030)
- Reduce PEMFC platinum loading to <0.1 mg/cm² without compromising durability [25, 26].
- Commercialize durable PGM-free ORR catalysts [28].
- Deploy 100+ MW-scale electrolyzer projects for green hydrogen [21].
- Build large-scale hydrogen valleys integrating production, pipelines, and end-use [4].
- Expand hydrogen refueling networks in major industrial regions [9].

Medium-Term Priorities (2030–2040)
- Cost parity of green hydrogen with fossil fuels under favorable renewable conditions [23].
- Widespread adoption of fuel cell heavy-duty trucks and rail and maritime systems [8, 40].
- Mass-market residential and commercial SOFC systems [15].
- Integration of electrolyzer-fuel cell hybrid systems for grid balancing [41].

Long-Term Priorities (>2040).
- Global hydrogen backbone pipelines enabling transnational trade.
- Circular lifecycle for fuel cell materials.
- Full decarbonization of steel, ammonia, and petrochemical industries through hydrogen and SOFC integration [40].

Overall, HFCs are poised to become a central pillar of decarbonized energy systems, providing technological, economic, and policy challenges are addressed strategically. Table 6 shows category-based summary of SOFC vs PEMFC characteristics.

CONCLUSIONS

In recent years, extraordinary advancements have been made in hydrogen fuel cell technologies, spanning catalysts, membranes, MEAs, stack architecture, system integration, and manufacturing. PEMFCs continue to lead the transportation market, whereas SOFCs dominate stationary and industrial applications. Materials science innovations, particularly PGM-free catalysts, single-atom materials, alkaline membranes, and lightweight bipolar plates, have improved durability and lowered cost barriers. System-level optimization, automated manufacturing, and large-scale electrolyzer deployment further strengthen the commercial readiness of fuel cells. However, critical challenges remain, including green hydrogen supply constraints, high capital costs, durability under real-world operation, and infrastructure underdevelopment. Strong policy frameworks and long-term market signals are essential for scaling fuel-cell technologies.

This review presents a comprehensive assessment of the recent advancements, current technological maturity, and prospects of hydrogen fuel-cell systems, emphasizing their role in enabling low-carbon energy transitions across transportation, stationary power generation, and industrial sectors. Based on the critical synthesis of materials innovation, system integration, hydrogen supply pathways, and real-world deployment trends, the following conclusions were drawn.

1. Significant technological progress has been achieved in the field of fuel cell materials and components. Advances in catalyst engineering, including reduced platinum loading, the development of platinum group metal-free catalysts, and improved catalyst layer microstructures, have substantially enhanced performance while lowering material costs. Parallel improvements in membranes, GDLs, bipolar plates, and membrane electrode assemblies have strengthened durability and operational stability under dynamic conditions.
2. PEMFCs and SOFC have emerged as dominant technologies for distinct application domains. PEMFCs are best suited for transportation and mobile power applications owing to their high-power density, rapid startup, and compact design. By contrast, SOFC demonstrate superior efficiency and fuel flexibility for stationary and industrial applications, particularly in CHP systems.
3. System-level optimization and manufacturing scale-up are central to commercialization. Advances in flow-field design, thermal and water management, BOP integration, and automated manufacturing techniques have significantly improved the system efficiency, reliability, and cost competitiveness. Modular stack architectures and standardized system design further support large-scale deployment.
4. Hydrogen production pathways critically influence the environmental and economic performance. Although fuel cells produce zero emissions at the point of use, their overall sustainability depends strongly on the carbon intensity of the hydrogen supply. The rapid development of electrolyzer technologies and the expansion of renewable-powered hydrogen production are essential for realizing the full decarbonization potential of fuel-cell systems.
5. Real-world deployment demonstrates growing maturity but highlights durability challenges. Demonstration projects across transportation, stationary power, and backup energy applications confirm strong operational performance, yet long-term durability under cyclic loading, thermal stresses, and variable environmental conditions remain a key limitation that requires further research.
6. Policy support, infrastructure development, and certainty markets are decisive enablers. Coordinated policy frameworks, investment incentives, and hydrogen infrastructure expansion are necessary to overcome economic and logistical barriers and accelerate adoption beyond niche markets.

In conclusion, HFCs transitioned from the experimental and early commercial stages toward broader energy-system integration. Continued advances in material durability, system reliability, green hydrogen availability, and supportive policy mechanisms are essential to unlock their full potential as a cornerstone technology for sustainable and resilient energy systems.

Tables 5–7 show category-based advances for HFC, comparison of electrolyzer technologies, degradation mechanism, applications, and a summary of SOFC versus PEMFC Characteristics, respectively.

Table 5. Key degradation mechanisms in PEMFCs and SOFCs.

Component	Degradation mechanism	Description	References
Catalyst (PEMFC)	Sintering	Particle growth reduces the active surface	[17, 26, 33]
Membrane (PEMFC)	Carbon corrosion	Carbon support oxidizes at high potentials	[35]
	Chemical attack	Radical attack thins the PFSA membrane	[11, 27, 35]
SOFC electrodes	Mechanical fatigue	Repeated humidification cycles	[6]
	Redox cycling	Ni re-oxidation causes cracking	[13]
	Thermal mismatch	Electrode delamination at interfaces	[12]

Table 6. Summary of fuel-cell applications across sectors.

Sector	Fuel Cell Type	Status	Examples
Automotive	PEMFC	Commercial demonstration	Toyota Mirai, Hyundai Nexo
Heavy-duty trucks	PEMFC	Early commercial	Hyundai Xcient
Rail	PEMFC	Pilots	Alstom iLint
Maritime	PEMFC/SOFC	Demonstrations	Hydrogen ferries
Residential CHP	SOFC	Commercial	ENE-FARM
Data centers	SOFC	Growing adoption	Microsoft SOFC projects
Telecom backup	PEMFC	Commercial niche	Huawei telecom towers

Table 7. Summary of SOFC versus PEMFC characteristics.

Parameter	PEMFC	SOFC
Operating temperature	60–90°C	600–1000°C
Startup time	Seconds	Hours
Fuel flexibility	Low	High (CH_4, NH_3)
Efficiency	40–60%	50–65%
Main applications	Transport	Stationary, industry
Major challenges	PGM cost, membrane durability	Thermal cycling, materials degradation

However, critical challenges remain, including green hydrogen supply constraints, high capital costs, durability under real-world operation, and infrastructure underdevelopment. Strong policy frameworks and long-term market signals are essential for scaling fuel-cell technologies.

In conclusion, HFCs have reached a pivotal moment where continued innovation and coordinated global policy can accelerate their transition from niche applications to large-scale commercial deployment across mobility, stationary power, and industrial sectors.

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