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"Advancing Stationary Applications with Hydrogen Fuel Cells: A Path Toward Sustainable Energy Systems"

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ABSTRACT:

Hydrogen fuel cell technology has emerged as a promising solution to meet the energy demands of stationary applications in a sustainable and efficient manner. As climate change accelerates and traditional energy sources face growing limitations, hydrogen offers a clean alternative with high efficiency and low emissions. This paper reviews the potential of hydrogen energy for powering stationary systems such as buildings and critical infrastructure. A SWOT analysis was conducted to evaluate internal strengths, weaknesses, and external opportunities and threats impacting its adoption. Strategies are proposed to increase hydrogen's role in the stationary energy sector. Key implementation factors include policy frameworks, cost reduction, infrastructure expansion, and public awareness. The findings highlight hydrogen's potential to shape a low-carbon, resilient energy future through stationary applications.

Keywords : alternative energy, energy efficiency, fuel cell, hydrogen energy, stationary application

Introduction

As global efforts intensify to transition toward cleaner and more sustainable energy systems, hydrogen fuel cell technology has emerged as a promising solution, particularly for stationary power applications. This shift is largely fueled by concerns over climate change, the depletion of fossil fuels, and the need for decentralized and efficient energy solutions [1–9].

Hydrogen, when used in fuel cells, offers a high-efficiency, low-emission alternative capable of generating both electricity and heat from a clean electrochemical process. Unlike traditional energy systems, hydrogen fuel cells can operate using a variety of feedstocks, support combined heat and power (CHP) applications, and integrate seamlessly with renewable energy sources, making them a strategic component of modern energy infrastructure.

Despite significant technological advancements, hydrogen fuel cell deployment still faces notable barriers—including infrastructure limitations, high costs, and regulatory gaps. To better understand the potential and challenges of adopting this technology, a comprehensive SWOT (Strengths, Weaknesses, Opportunities, and Threats) analysis is essential. This analysis not only highlights the internal capabilities and limitations of hydrogen fuel cells, but also examines the external factors that could drive or hinder their implementation in stationary energy applications.

Materials and Methods

The research methodology adopted in this study draws from an extensive review of scientific literature, technical reports, and strategic documents relevant to hydrogen fuel cells, particularly in the context of stationary energy applications. The sources include peer-reviewed journals, conference proceedings, and online academic databases such as Google Scholar, ScienceDirect, Scopus, and MDPI, along with institutional resources from the European Union (EU), International Energy Agency (IEA), and other key stakeholders in hydrogen energy research, including E4Tech, IAHE, and ICSI Râmnicu Vâlcea, Romania.

Figure 1. The SWOT process.

A SWOT (Strengths, Weaknesses, Opportunities, Threats) analysis was employed as the primary analytical tool to evaluate hydrogen energy's integration into stationary energy systems. This tool provided a structured assessment of internal and external factors influencing the adoption of hydrogen fuel cells as sustainable alternatives to conventional power generation methods.

The SWOT framework helped uncover critical strategic directions by identifying:

- Key internal strengths (e.g., high energy efficiency, zero emissions),
- Internal weaknesses (e.g., infrastructure gaps, high costs),
- External opportunities (e.g., renewable integration, policy support),
- External threats (e.g., fossil fuel competition, safety concerns).

This approach guided the formulation of actionable strategies, such as leveraging strengths to exploit opportunities (S&O), mitigating weaknesses via external supports (W&O), using strengths to reduce threats (S&T), and minimizing vulnerabilities in face of threats (W&T). These insights form the basis for recommending pathways to accelerate the deployment of hydrogen fuel cells in stationary applications.

Hydrogen Fuel Cell Technology

Hydrogen as an Energy Vector in Stationary Systems

Hydrogen is increasingly recognized as a versatile, non-polluting energy carrier capable of supporting a wide array of applications, particularly within stationary energy systems. Its ability to be produced from a range of renewable sources and stored over long durations positions it as a key enabler of future sustainable infrastructure.

Hydrogen's high energy-to-mass ratio, zero carbon emissions when produced cleanly, and compatibility with distributed energy systems make it ideal for stationary uses such as:

- Microgrid power supply,
- Backup energy for critical facilities,
- Grid balancing and long-duration storage.

The characteristics that make hydrogen well-suited for stationary energy systems include:

- Clean combustion producing only water,
- High gravimetric energy density,
- Versatile storage and transport methods,
- Integration potential with renewable sources (e.g., solar, wind).

Table 1. Hydrogen characteristics

Characteristics	Unit	Value
Density	kg/m^3	0.0838
Higher Heating Value (HHV)/liquid hydrogen (LH_2)	MJ/kg	141.90–119.90
HHV/cryogenic hydrogen gas (CGH_2)	MJ/m^3	11.89–10.05
Boiling point	K	20.41
Freezing point	K	13.97
Density (liquid)	kg/m^3	70.8
Air diffusion coefficient	cm^2/s	0.61
Specific heat	kJ/kg K	14.89
Ignition limits in air	% (volum)	4–75
Ignition energy in the air	Millijoule	0.02
Ignition temperature	K	585.00
Flame temperature in air	K	2318.00
Energy in explosion	kJ/g TNT	58.823
Flame emissivity	%	17–25
Stoichiometric mixture in air	%	29.53
Air/fuel stoichiometry	kg/kg	34.30/1
Burning speed	cm/s	2.75

Power reserve factor	-	1.00

In order to highlight the advantages that hydrogen has, compared to other fuels, the main properties of the various fuels currently used are presented in Table 2.

Fuel Type	Energy/Mass Unit (J/kg)	Energy/Volume Unit (J/m^3)	Energy Reserve Factor	Carbon Emission Specific (kgC/kg Fuel)
Liquid hydrogen	141.90	10.10	1.00	0.00
Hydrogen gas	141.90	0.013	1.00	0.00
Fuel oil	45.50	38.65	0.78	0.84
Gasoline	47.40	34.85	0.76	0.86
Jet fuel	46.50	35.30	0.75	-
GPL	48.80	24.40	0.62	-
GNL	50.00	23.00	0.61	-
Methanol	22.30	18.10	0.23	0.50
Ethanol	29.90	23.60	0.37	0.50
Biodiesel	37.00	33.00	-	0.50
Natural gases	50.00	0.04	0.75	0.46
Coal	30.00	-	-	0.50

Table 2. Comparison between the main properties of hydrogen and other fuels

Fuel Cells: Hydrogen Conversion Technologies

Fuel cells enable the direct conversion of chemical energy (from hydrogen) into electricity and heat through electrochemical processes. This section outlines the types of fuel cells, their characteristics, and their applications in stationary systems.

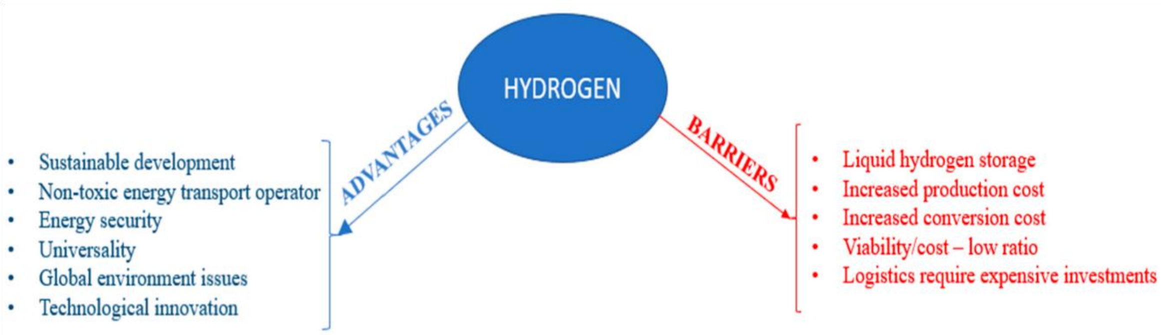


Figure 2: Advantages and barriers regarding the use of hydrogen as energy vector

A. *Main Types of Fuel Cells Used in Stationary Applications*

Fuel cells are categorized by their electrolyte type and operating temperature:

PEMFC, SOFC, PAFC, MCFC, and DMFC are commonly used in stationary contexts. PEMFCs and SOFCs dominate small and large applications, respectively.

Table 3. Suitability in practical applications of the fuel cells types adapted from

Fuel Cell Type	Typical Electrical Efficiency (LHV)	Power (kW)	Applications	Advantages	Disadvantages
AFC	60%	1–100	Back-up power; Electromobility; Military; Space.	Stable materials allow lower cost components; Low temperature; Quickly start-up.	Sensitive to CO_2 in fuel and air; Electrolyte management (aqueous); Electrolyte conductivity (polymer).

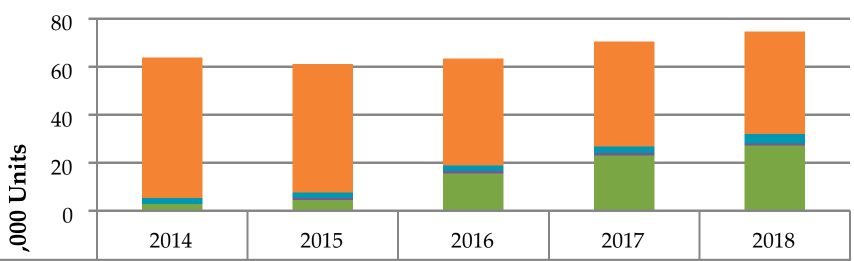
MCFC	50%	300–3000	Electric utility; Distributed generation.	Fuel flexibility; High efficiency; Suitable for hybrid/gas turbine cycle; Suitable for carbon capture; Suitable for CHP.	High temperature corrosion and breakdown of cell components; Long start-up time; Low power density.
PAFC	40%	5–400	Distributed generation.	Suitable for CHP; Increased tolerance to fuel impurities.	Expensive catalysts; Long start-up time; Sulfur sensitivity.
PEMFC	60% direct H_2 40% reformed fuel	1–100	Back-up power; Distributed generation; Electromobility; Grid support; Portable power; Power to power (P2P).	Solid electrolyte reduces corrosion & electrolyte management problems; Low temperature; Quickly start-up.	Expensive catalysts; Sensitive to fuel impurities.
SOFC	60%	1–2000	Auxiliary power; Distributed generation; Electric utility.	Fuel flexibility; High efficiency; Potential for reversible operation; Solid electrolyte; Suitable for CHP; Suitable for hybrid/gas turbine cycle.	High temperature corrosion and breakdown of cell components; Long start-up time; Limited number of shutdowns.

Practical Deployment and Market Trends

Reports from Fuel Cell Today and the Fuel Cells and Hydrogen Joint Undertaking show increasing global deployment of fuel cells, especially in the stationary sector. Notable trends:

- *Japan's ENE-FARM* program supports residential micro-CHP systems.
- From 2014 to 2018, global shipments of stationary fuel cells rose from 39,500 to 57,500 units.
- PEMFCs dominate in versatility and adoption due to fast start-up and compact size.
- SOFC deployments are also increasing due to their efficiency and fuel flexibility.
- Application (portable, transport, stationary),
- Region (Asia, North America, Europe),
- Fuel cell type (PEMFC, SOFC, etc.),
- Total installed capacity in megawatts.

Figure 3 :Shipments by fuel cell type.



	2014	2015	2016	2017	2018
PEMFC	58.4	53.5	44.5	43.7	42.6
DMFC	2.5	2.1	2.3	2.8	3.7
PAFC	0.05	0.1	0.1	0.2	0.2
SOFC	2.7	5.2	16.2	23.7	27.8
MCFC	0.1	0.03	0.07	0.05	0.08
AFC	0.01	0.08	0.1	0.1	0.11

Modalities of Energy Supply through Hydrogen Fuel Cells

Fuel cell systems serve as primary and backup energy sources in:

- Residential microgrids (PEMFC, SOFC),
- Commercial and industrial cogeneration (MCFC, PAFC, SOFC),
- Community-scale distributed energy systems.

Table 4. A brief summary of the CHP performance of fuel cells adapted

	MCFC	PAFC	PEMFC	SOFC
Electrical capacity (kW)	300+	100–400	0.75–2	0.75–250
Electrical efficiency (LHV)	47%	42%	35–39%	45–60%
Thermal capacity (kW)	450+	110–450	0.75–2	0.75–250
Thermal efficiency (LHV)	43%	48%	55%	30–45%
Application	Residential & Commercial	Commercial	Residential	Residential & Commercial
Degradation rate (per year)	1.5%	0.5%	1%	1–2.5%
Expected lifetime (hours)	20,000	80,000–130,000	60,000–80,000	20,000–90,000

CHP (Combined Heat and Power) applications enable efficient dual-use of electricity and heat. *Table 3* outlines the suitability of fuel cell types across different use cases, with their advantages and limitations.

PEMFCs and SOFCs are most suitable for residential-scale CHP due to compactness, quick start-up, and acceptable efficiency. PAFCs and MCFCs are better suited to large-scale, centralized power generation. CHP applications with fuel cells can reach efficiency levels exceeding those of conventional systems

The Main Modalities for Energy Supply through Hydrogen Fuel Cell Technologies Hydrogen fuel cell technologies, with distinct operational principles and characteristics, are well-suited to a variety of energy generation applications, particularly in combined heat and power (CHP) systems and stationary power generation. The selection of fuel cell type depends on the specific energy requirements, efficiency targets, and application domains. *Table 3* summarizes the suitability, advantages, and limitations of major fuel cell types.

Fuel Cells in Building CHP Systems

Fuel cells are ideal for micro-cogeneration and CHP systems due to their ability to produce both electricity and heat from a single fuel source—hydrogen or even conventional fuels like natural gas. Systems using *PEMFCs* are most common in residential settings due to their low-temperature operation, quick start-up, and modular design. *SOFCs*, while more thermally robust and fuel-flexible, are used where higher operating temperatures and tolerance to fuel impurities are beneficial.

In collective housing or multi-unit buildings, systems under development aim to expand PEMFC and SOFC use to higher power ratings. Their ability to provide stable, decentralized energy generation gives them an edge over traditional separate systems, with cogeneration efficiencies surpassing conventional boundaries. A flagship example is Japan's *Ene-Farm* initiative, which began in the 1990s. Backed by government support, it led to the commercial deployment of city-gas-based hydrogen PEMFC systems for households. By 2018, over *200,000 PEMFC units* had been installed. Future plans include expanding into multi-family dwellings. Inspired by its success, similar demonstrations are underway in *Germany, Denmark, Korea, the UK, and the USA*.

Backup Power Using Renewables or Waste-to-Hydrogen Systems

Hydrogen fuel cells can also stabilize renewable energy systems by storing excess electricity as hydrogen, later used in fuel cells for backup or off-grid power. For instance, the *MYRTE Project in Corsica* integrates photovoltaics, electrolyzers, hydrogen storage, and fuel cells to demonstrate grid-independent power systems. It was developed by a partnership including AREVA and the French Nuclear and Alternative Energy Commission.

Another notable initiative is *HyUnder*, funded by the *Fuel Cells and Hydrogen Joint Undertaking (FCH JU)*. The project assessed the potential for large-scale underground hydrogen storage in Europe. This included geological analysis, safety standards, public perception, and market readiness. Romania's

ICSI Rm. Vâlcea contributed case studies and technical expertise to the project.

Alternative Hydrogen Production Pathways

Electrolysis, while clean, demands significant water—a major barrier in arid regions. Thus, alternative feedstocks like biomass, agricultural waste, and municipal solid waste are being explored. Studies and pilot projects have focused on:

- Catalytic steam reforming of *bioethanol from fir wood* [74]
- *Pyrolysis and gasification* of agricultural residues [75]
- *Municipal/industrial waste conversion* into hydrogen and fuels [76,77]
- *Carbohydrate-to-hydrogen* processes [78]

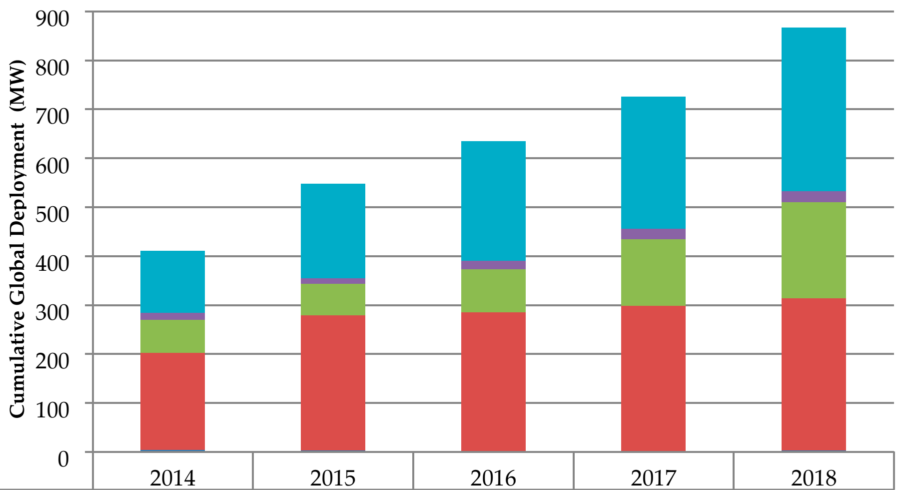
Table 5. Hydrogen production methods-efficiency and energy consumption adapted

	Energy Consumption (kWh/kgH$_2$)	Efficiency (LHV)
Biomass gasification	69–76	44–48
Coal gasification	51–74	45–65%
Electrolysis	50–65	51–67%
Methane reforming	44–51	65–75%

Although fossil and biomass-based hydrogen may contribute to emissions, *carbon capture and storage (CCS)* can help mitigate the impact. For instance, research by *Graz University of Technology* has demonstrated production of *99.997% pure hydrogen*, along with high-purity CO_2 and nitrogen, using post-combustion capture in advanced fixed-bed reactors [82].

Prime Power: Large-Capacity Fuel Cell Stations

Fuel cell technologies are also deployed in centralized power stations. As of 2018, the sector is dominated by *MCFC*, *SOFC*, and *PAFC* systems, with limited large-scale use of *PEMFC* and *AFC* in high-capacity configurations. These systems support distributed electricity generation across commercial, industrial, and utility-scale applications. These fuel cells are favored for large-scale applications because they can operate at high efficiency, tolerate a variety of fuels (like natural gas or biogas), and often support combined heat and power (CHP) systems.In contrast, PEMFC (Proton Exchange Membrane Fuel Cells) and AFC (Alkaline Fuel Cells) are typically used in smaller-scale applications due to their limitations in durability, fuel tolerance, or scalability. Their use in high-capacity settings is still limited.



	2014	2015	2016	2017	2018
SOFC	126	193	244	270	334
PEMFC	14	12	18	21	23
PAFC	68	64	88	137	196
MCFC	198	276	283	297	312
AFC	4	3	2	1	2

Figure 4. Large scale stationary fuel cells.

Table 6. SWOT Matrix for Hydrogen Fuel Cell Technology in Stationary Applications

Strengths	*Weaknesses*
High energy density, on-site generation, low emissions, smart grid integration, noise-free operation	Incomplete infrastructure, high costs, integration complexity, safety concerns, low public acceptance
Renewable integration, potential for energy independence, vast feedstock variety	Lack of regulations, technical standards, policy support, and government cooperation
Opportunities	*Threats*
Green development, energy diversification, intersectoral collaboration, new markets	Immature storage tech, weak public policies, fossil fuel market dominance, lack of fiscal incentives

Strategic Recommendations for Implementation

Based on the SWOT analysis, key strategies (Figure 2) to facilitate hydrogen integration into stationary applications include:

- *Policy Development*: Introduce comprehensive legislation to support hydrogen infrastructure and incentivize adoption.
- *Public Engagement*: Educate communities and stakeholders to improve acceptance and understanding.
- *Innovation Stimulation*: Continue R&D funding, promote demonstration projects, and support cross-border cooperation.
- *Economic Stimulation*: Foster new business models, enhance international collaboration, and attract private and foreign investments.

	Strengths *internal*	**Weaknesses** *internal*
Opportunities *external*	**S&O**	**W&O**
Threats *external*	**S&T**	**W&T**

Figure 6. Strategic Framework for Hydrogen in Stationary Energy Applications

Results and Discussion

The development and implementation of hydrogen fuel cell technology for stationary applications are influenced by a multifaceted set of factors, encompassing technological innovation, environmental sustainability, social perception, and economic viability. These dimensions are schematically represented in *Figure 13*, which outlines the hierarchy of influential elements shaping the progress and adoption of hydrogen-based energy systems.

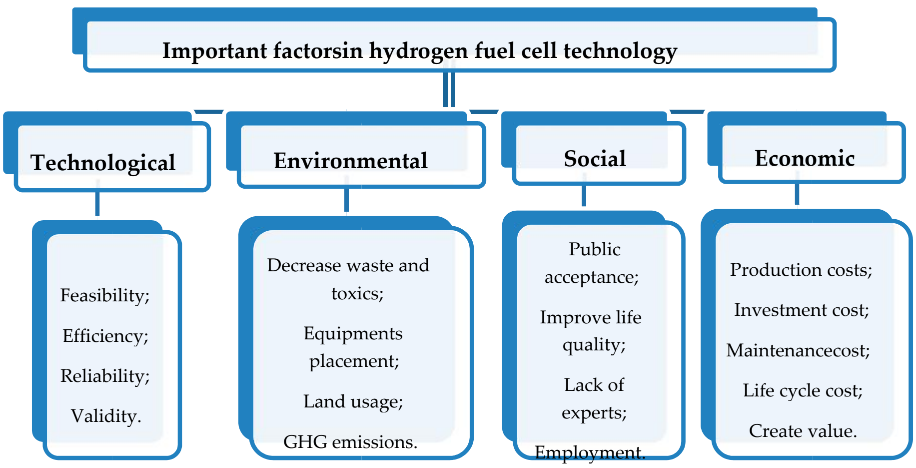


Figure 5. Hierarchy of important factors in hydrogen fuel cell technology.

Insights derived from the SWOT analysis (Section 5) highlight the substantial potential of hydrogen fuel cells in advancing clean and decentralized energy systems. However, they also reveal several persistent barriers that must be addressed to fully leverage these technologies for widespread stationary energy use.

Conclusions

Over the past fifteen years, hydrogen and fuel cell technologies have made significant strides in both research and practical application. Despite this progress, several critical challenges—technical, economic, and infrastructural—remain unresolved, hindering their widespread deployment in stationary energy systems. Nonetheless, policy frameworks at national and international levels increasingly recognize hydrogen and fuel cells as strategic components of future energy systems, capable of contributing to environmental sustainability, energy security, and economic resilience.

This study has reviewed existing literature and institutional reports to assess the development and applicability of hydrogen fuel cell technologies in stationary energy systems. Key findings include:

- By the end of 2018, more than 850 MW of large stationary fuel cell systems (with individual capacities exceeding 200 kW) were deployed worldwide for power generation and combined heat and power (CHP) applications.
- The global stationary fuel cell market is primarily dominated by Molten Carbonate Fuel Cells (MCFCs), Solid Oxide Fuel Cells (SOFCs), and Phosphoric Acid Fuel Cells (PAFCs).
- Alkaline Fuel Cells (AFCs) and Proton Exchange Membrane Fuel Cells (PEMFCs), while promising, are still in earlier stages of development and commercial deployment in stationary applications.
- Integration of hydrogen fuel cell technology into stationary energy systems occurs primarily through:
    - CHP units for residential and small commercial buildings,
    - Backup power systems incorporating renewable energy or waste-to-hydrogen pathways,
    - Large-scale power plants or distributed generation systems supporting grid stability.

The evolution of hydrogen-based stationary energy systems is heavily influenced by a range of external and internal factors, including:

- National and international energy and climate policies,
- The availability and continuity of funding and incentive programs,
- The development of concurrent or competing technologies,
- Market presence of fuel cell system manufacturers,
- The costs of hydrogen production, storage, and system integration.

The SWOT analysis conducted in this study underscores that the successful implementation of a hydrogen economy—particularly in stationary applications—is critically dependent on:

- A supportive and clearly defined legislative and regulatory framework,
- Active involvement of energy policymakers and government authorities,
- Increased public awareness and user engagement,
- Availability of qualified specialists and technical expertise,
- Engagement of investors and industry stakeholders to support commercialization and scalability.

In conclusion, hydrogen fuel cell technology represents a viable pathway toward sustainable stationary energy systems. Achieving its full potential will require coordinated efforts across policy, industry, and research to address current barriers, promote innovation, and accelerate market integration.

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