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TECHNO-ECONOMIC EVALUATION OF FUEL CELL SYSTEMS FOR RENEWABLE-BASED GRID BALANCING AND DECARBONIZED MICROGRIDS

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Abstract
This paper presents a techno-economic analysis of fuel cells (FC) as a component of power grid balancing systems. Different types of fuel cells are examined in terms of efficiency, dynamic response, and potential for integration with renewable energy sources. A comparison is made between FC systems and alternative technologies such as batteries and gas turbines. A sample hybrid microgrid scenario (PV 500 kW + FC 200 kW) is analyzed with LCOE calculation and economic assessment. Results indicate that with decreasing green hydrogen prices and optimized operational costs, fuel cells may play a major role in future intelligent energy systems.
Keywords: Fuel cells, Hybrid microgrid, Techno-economic analysis, Renewable energy integration, Carbon emission reduction.

INTRODUCTION

Over the past decade, the energy sector has undergone a profound transformation, driven by the increasing share of renewable energy sources (RES) and the drive to decarbonize power systems. European Union policies, focus on accelerating the deployment of green technologies and building a sustainable hydrogen infrastructure [1-4].

However, this change leads to increasing challenges in balancing the electricity grid, especially with high variability in solar and wind generation. Classic methods of regulation using fast-acting turbines and battery systems have limitations in terms of capacity, discharge duration and service life.

In this context, fuel cells (FC) are a promising technology capable of providing flexible and sustainable conversion of energy from chemical to electrical form with high efficiency and minimal emissions. Thanks to their modularity and ability to respond quickly, they can be integrated into both centralized and decentralized microgrids, operating in conjunction with RES and storage systems [5-6].

The use of hydrogen as an energy carrier further expands the possibilities for long-term storage and seasonal energy balance. The Power-to-Gas-to-Power (P2G2P) concept allows integration between electrolyzers, hydrogen tanks and fuel cells, ensuring full energy flexibility [7-9].

The present work aims to perform a technical and economic analysis of different types of fuel cells and their application for balancing the electricity system. The emphasis is placed on the assessment of efficiency, costs (LCOE and LCOS) and their potential for integration into hybrid microgrids, including photovoltaic sources and storage systems. The analysis aims to contribute to a deeper understanding of the economic viability of FC technologies and their role in the transition to smart, low-carbon energy systems [10,11].

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TECHNICAL CHARACTERISTICS OF FC

FC are electrochemical devices that convert the chemical energy of a fuel, most often hydrogen, directly into electricity, without an intermediate combustion process. As a result, they are characterized by high efficiency (40–65%), low emissions and the possibility of modular operation at various scales from small domestic systems to megawatt installations.

The main types of fuel cells are classified according to the electrolyte used, temperature range and application characteristics. Table 1 presents a summary of their parameters and areas of use.

One of the key advantages of FC systems is the flexible dynamic response. PEMFC and AFC respond within seconds, making them suitable for balancing short-term load and frequency fluctuations. On the other hand, SOFC and MCFC demonstrate higher efficiency but with slower dynamics, making them more suitable for base and long-term load.

The typical lifetime of the systems varies between 10,000 and 60,000 hours depending on the type and operating conditions. Degradation is mainly due to membrane wear (PEMFC), thermal stress (SOFC), chemical corrosion (MCFC).

The application of intelligent control and predictive maintenance allows for an extension of the operational lifetime by up to 20%.

Fuel cells can also be used in Combined Heat and Power (CHP), where the total efficiency (electric + thermal) reaches 80–90%. This makes them particularly suitable for microgrids and industrial plants where there is a constant need for heat.

Also, through a modular architecture, FC systems can be connected in parallel for power scaling, which facilitates their integration into decentralized energy networks.

Current research focuses on reducing the content of platinum catalysts (to <0.1 mg/cm²), developing new membranes with increased CO_2 resistance and high

Table 1 Parameters and areas of use of fuel cells

Type FC	Work. Temperature	Efficiency	Response time	Typical application	Advantages	Disadvantages
PEMFC (Proton Exchange Membrane)	60–80 °C	40–60%	seconds	transport, households	fast start, compactness, low temperature	sensitivity to CO, membrane degradation
SOFC (Solid Oxide)	600–1000 °C	50–65%	minutes	stationary systems	high efficiency, flexible fuel (H_2, CH_4, biogas)	long warm-up time, material stresses
MCFC (Molten Carbonate)	~650 °C	45–55%	minutes	industrial applications	uses CO_2 and CH_4, good corrosion resistance	heavy construction
PAFC (Phosphoric Acid)	~200 °C	40–50%	minutes	utilities	stable operation, mature technology	average efficiency, expensive maintenance
AFC (Alkaline)	60–90 °C	50–60%	seconds	space applications, laboratory	high efficiency with pure H_2	strong sensitivity to CO_2

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conductivity, hybridizing FC with batteries or supercapacitors for better dynamics, introducing AI-based control and fuel flow optimization.

It is expected that by 2030 the price of PEMFC systems will drop below 700 €/kW, and of SOFC – to around 1000 €/kW, which will make them competitive with lithium-ion systems in long-term operating modes.

ROLE IN GRID BALANCING

With the increasing share of renewable energy sources (RES), the electricity system is facing serious challenges related to the variability and unpredictability of generation. Traditional control methods with gas turbines and pumped storage plants cannot always provide the necessary speed of response and environmental sustainability.

Fuel cells (FC) stand out as an innovative tool for flexibility, capable of providing both short-term and long-term balancing through reversible energy conversion Power-to-Gas-to-Power (P2G2P). In this cycle, electrical energy from RES is used to produce hydrogen through electrolysis (Power-to-Gas), which is subsequently stored and, when necessary, converted back into electrical energy through fuel cells (Gas-to-Power).

Fuel cells can participate in several levels of regulation and market segments. Primary frequency regulation through fast-acting PEMFCs, reacting in seconds and compensating for fluctuations in real time. Secondary regulation for medium-term load changes (within minutes), where SOFC and MCFC demonstrate stability and high efficiency. Tertiary regulation/back-up use of FC systems as backup capacity in case of shortages or planned repairs. Flexibility Market, decentralized FC installations in microgrids can offer voltage stabilization and load management services.

In decentralized microgrids, fuel cells play the role of a buffer source between the variable production from photovoltaics or wind and dynamic consumption. A typical configuration includes a PV or wind generator, an electrolyzer for H_2 production, a storage tank, a fuel cell for recovering electricity when needed.

Such an approach ensures local energy balance, reduces transmission losses and improves site autonomy. In industrial applications, FC systems can also provide cogeneration (CHP), where the heat is used for technological needs or heating.

From the perspective of the power system, fuel cells have very low inertia, but high controllability. Through appropriate current and voltage management, they can actively participate in frequency and voltage regulation, reactive power compensation, fast backup in the event of generator failure, and improvement of power quality (Power Quality) by filtering harmonics.

It is also possible to combine FC with batteries or supercapacitors, where the battery absorbs momentary fluctuations, and FC provides continuous balancing, the so-called hybrid FC–Battery architecture.

Model simulations show that with a share of FC systems above 10% in a local microgrid, a significant reduction in frequency deviations (up to 40%) and an improvement in overall energy stability are observed. The main challenges remain related to the need for optimal hydrogen flow management, the high cost of electrolyzers, and ensuring safety in hydrogen storage.

However, the trend towards digitalization and the use of AI-based controllers allows for adaptive and predictive regulation, which increases system efficiency and reliability.

ECONOMIC ANALYSIS

The LCOS (Levelized Cost of Storage) indicator allows to estimate the real cost of storing and recovering electricity from fuel cells, including both capital and operating costs. In the expression:

$$LCOS = \frac{CAPEX \cdot CRF + OPEX + C_{H_2}}{E_{delivered}} \quad (1)$$

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the CAPEX parameter represents the initial investments for building the system, the cost of the fuel cells, electrolyzer, tanks and supporting infrastructure. Capital Recovery Factor (CRF) is a capital recovery factor that takes into account the interest rate and the operating life, converting one-time capital costs into an annual equivalent. OPEX includes ongoing operating costs for maintenance, repair and management, usually in the range of 2–5% of CAPEX per year. C_{h2} expresses the annual cost of the hydrogen used and is determined by its price and the quantity needed to produce electricity. Finally, E_delivered shows the energy actually delivered to the grid, which depends on the nominal power, operating time and efficiency of the system. In this way, LCOS combines all financial and energy parameters into a single indicator reflecting the economic viability of fuel cells relative to alternative storage technologies.

SCENARIO: PV + FC MICROGRID

To evaluate the potential of fuel cells in real energy systems, a hybrid microgrid was modeled, combining a 500 kW photovoltaic (PV) plant and a 200 kW fuel cell (FC) unit supplying an industrial site with a 400 kW peak and 250 kW average load. The system aims to reduce grid peak demand, provide backup power, and enhance local energy autonomy.

The PV array supplies low-cost electricity during daytime, while surplus energy drives an electrolyzer producing hydrogen for storage. The stored hydrogen is later reconverted into electricity via a PEMFC module, achieving an overall Power-to-Gas-to-Power efficiency of 38–45 %.

Simulations indicate that at a hydrogen price of €3/kg and FC efficiency of 55 %, the system can deliver 280–300 MWh of balancing energy annually—covering up to 40 % of peak demand and improving local voltage stability. The LCOS is about €0.18/kWh, dropping to €0.14/kWh when hydrogen costs fall below €2.5/kg, making the concept economically competitive with lithium-ion batteries.

Operating in combined heat and power (CHP) mode, waste heat recovery raises overall efficiency to 80–85 %, lowering both operating costs and carbon emissions. Environmentally, the PV + FC system reduces CO_2 emissions by over 250 tons per year compared to diesel generation and can participate in flexibility markets for frequency and voltage support.

In summary, the PV + FC hybrid microgrid demonstrates a practical, low-carbon, and cost-effective solution for industrial applications, combining sustainability with operational flexibility and long-term energy independence.

DISCUSSION

The results of the techno-economic analysis confirm that fuel cells (FC) are a promising and flexible solution for power system balancing in the context of increasing renewable penetration. Their main advantages are high efficiency, zero local emissions when operating on green hydrogen, and the ability for long-term energy storage, outperforming batteries in duration and capacity retention.

The economic feasibility of FC systems strongly depends on hydrogen cost. At prices below 3 €/kg, the PV + FC configuration becomes competitive with diesel generators and lithium-ion batteries. With projected reductions in electrolyzer costs and FC efficiency approaching 65% by 2030, the LCOS could decrease to around 0.12 €/kWh, comparable to advanced storage technologies.

Environmentally, FC-based systems achieve substantial CO_2 reductions and improved power quality. The recovery of waste heat in CHP mode further increases total system efficiency and supports industrial energy-efficiency targets.

At the system level, fuel cells enhance flexibility and dispatchability within microgrids through fast power response and participation in frequency and voltage

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regulation. Remaining challenges—such as membrane degradation, high CAPEX, and safe hydrogen storage—are being mitigated through advances in catalyst materials and AI-driven control and predictive maintenance. In the long term, FC integration with PV, batteries, and electrolyzers can enable fully decarbonized smart microgrids, aligned with the EU objective of climate neutrality by 2050.

CONCLUSION

Fuel cells are proving to be an effective and sustainable solution for balancing the electricity grid with a growing share of renewable sources. They provide high efficiency, low emissions and the ability to operate continuously at stable power. The analysis of the hybrid microgrid PV 500 kW + FC 200 kW shows that at a green hydrogen price below 3 €/kg, the system can achieve an LCOS of around 0.18 €/kWh, making it competitive with battery solutions.

From an environmental perspective, fuel cells significantly reduce carbon emissions and allow for a high degree of recycling of components. The application of AI-based management contributes to optimization of operation and extension of service life. As a result, FC technologies have the potential to become a key element of smart microgrids and a major tool for achieving energy independence and decarbonization.

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