Modeling and Performance Assessment of an HT-PEMFC-Based CHP System for Residential Energy Communities

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Abstract - Renewable Energy Communities (RECs) allow citizens to jointly produce, consume and trade local green power, boosting self-sufficiency and grid resilience. To stabilize the variable output of solar and wind, RECs need flexible, dispatchable technologies. Hydrogen-fueled Combined Heat and Power (CHP) units equipped with High-Temperature Proton Exchange Membrane Fuel Cells (HT-PEMFCs) can deliver both electricity and high-grade heat with zero direct emissions.

This study presents a simulation-based assessment of an HT-PEMFC CHP unit designed for residential use and future integration into REC-oriented architectures. The system was dynamically modeled in MATLAB Simscape, incorporating realistic electrochemical, thermal and auxiliary components. The model was tested under three control strategies (load-following, fixed-power and operation at maximum electrical efficiency) against a high-resolution load profile representative of a multi-apartment building in Rome. The aim was to evaluate the unit's standalone behavior in terms of net electrical output, thermal energy recovery, hydrogen consumption and impact on residential self-consumption.

Results reveal that while the load-following strategy offers real-time responsiveness, it suffers from low electrical efficiency due to continuous auxiliary loads. Conversely, operating the system at optimized and constant power setpoints significantly improves its performance. In the maximum-efficiency scenario, the fuel cell achieves an electrical efficiency close to 45% and meets over 70% of the building's thermal demand, confirming its strong cogeneration potential. These findings support the inclusion of HT-PEMFC units as key assets in hybrid energy systems aimed at decarbonizing the residential sector through resilient, flexible and locally autonomous microgrids.

Keywords – Renewable Energy Communities; High-Temperature PEM Fuel Cell; Hydrogen Combined Heat and Power; Microgrid Flexibility; Decarbonization Technologies.

Introduction

The transformation of the energy sector is essential to achieving climate neutrality targets and ensuring long-term sustainability in the face of growing environmental and geopolitical pressures [1]. As traditional fossil fuel-based systems are progressively replaced by renewable sources, new challenges emerge, particularly in the integration of non-programmable energy generation, the electrification of final uses and the need for real-time balancing of distributed energy systems [2]. Within this evolving landscape, the concept of energy flexibility has gained strategic importance: systems capable of dynamically adjusting production, storage and consumption patterns are key enablers of secure, efficient and decarbonized energy networks [3].

One of the most promising responses to these challenges lies in the development of local energy ecosystems based on Renewable Energy Communities (RECs) [4]. These are legal entities where groups of citizens, enterprises and public bodies collaborate to produce, share and manage energy from renewable sources at the local level. RECs are inherently decentralized and aim not only at technical performance but also at social inclusiveness, economic resilience and active consumer engagement. Technologies enabling energy autonomy and flexibility at the building or district level, such as electric storage, vehicle-to-grid systems and combined heat and power (CHP) units, are therefore fundamental building blocks of these communities.

Hydrogen is rapidly emerging as a strategic vector in this context, due to its versatility, high energy density and compatibility with long-duration storage and sector coupling [5, 6]. When used in fuel cells, hydrogen can generate electricity and heat with zero direct emissions, making it particularly suited for local cogeneration in residential areas. High Temperature Proton Exchange Membrane Fuel Cells (HT-PEMFCs) offer specific advantages for REC integration [7]. Operating at 140–180 °C, they tolerate fuel impurities, allow efficient thermal recovery and reduce system complexity by eliminating external humidification. These characteristics make them ideal candidates for integration into hybrid, multi-vector systems, where electricity and heat demand coexist and interact with local renewable generation. Furthermore, recent techno-economic analyses of hydrogen-integrated building multi-energy systems have shown that increasing the penetration of hydrogen technologies can lift the resilience index

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to about 85 % while simultaneously maximizing on-site self-consumption of renewable electricity, thereby confirming hydrogen's pivotal role in enabling autonomous and robust energy operation at the building scale [8].

The present work is conceived as a preliminary simulation study aimed at exploring the operational potential of an HT-PEMFC-based CHP unit designed for residential applications. A dynamic model of the system has been developed in Simscape (MATLAB/Simulink), incorporating realistic thermal, electrochemical and balance-of-plant components. The system is tested under various control strategies and building load profiles, simulating the real consumption of a multi-apartment residential building located in Rome. The primary objective is to characterize its electrical and thermal performance and assess its suitability as a flexible asset to be integrated into future REC configurations. By enabling bidirectional energy flows, supporting self-consumption and contributing to local energy balancing, hydrogen-based CHP systems such as the one presented here can play a key role in realizing resilient, zero-emission energy communities.

Materials and methods

The present study is conducted within the framework of the FlexBIT project [9], a collaborative initiative involving research institutions, universities, and industrial partners from Germany, Greece, Italy, Malta, and Poland. The project aims to develop cost-effective solutions for the transition to a zero-carbon energy system, with a particular focus on the creation of a digital platform for cross-sectoral flexibility management.

As part of this initiative, our research group focuses on the integration of hydrogen technologies as a source of flexibility within RECs. These communities promote decentralized generation and consumption of renewable energy, supported by intelligent and adaptive infrastructures. Within this context, hydrogen is investigated as a key enabling vector for short- and long-term energy storage, sector coupling, and energy sharing among multiple buildings or end-users.

The overall system architecture, illustrated in Fig. 1, includes a photovoltaic-powered electrolyzer for green hydrogen production, metal hydride tanks for solid-state hydrogen storage and a range of hydrogen-consuming subsystems characterized by different levels of operational flexibility, depending on the technologies installed within each energy system. These include low- and high-temperature fuel cell stacks, lithium-ion batteries, and smart power electronics. All devices are interconnected through a common DC bus and coordinated via a centralized energy management system that enables real-time monitoring, load balancing and data acquisition. The system is equipped with flow meters, smart meters and current/voltage sensors (CVS) that allow for fine-grained energy monitoring and control at each subsystem level. A smart grid interface is also implemented to simulate data exchange with external platforms, such as demand response aggregators or REC digital twins.

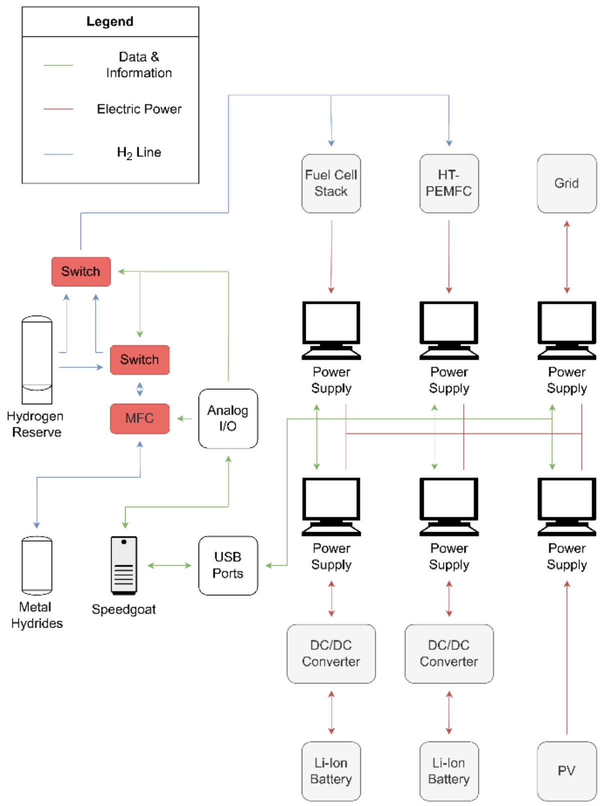

Fig. 1. Overview of the hybrid hydrogen-based microgrid architecture integrating electrolyzer, metal hydride storage, fuel cells, batteries and monitoring systems for REC applications.

The HT-PEMFC-based CHP unit was modeled in the Simscape environment of MATLAB/Simulink due to its capability to handle multi-domain physical systems and to represent the interactions between the thermal, electrical and fluid dynamic subsystems in a physically coherent way. The simulation platform includes the electrochemical core (MEA), the balance of plant (BoP) and the thermal management system. The BoP components consist of compressors, heat exchangers, hydrogen/air management valves, pumps and a thermal circuit using MultiTherm 503 as the working fluid.

The HT-PEMFC model used in this study was derived from the reference model proposed by Wang et al. in [10], which describes the thermal and electrochemical behavior of high-temperature PEM fuel cells operating in the 140–180 °C range. While our implementation is adapted to the Simscape environment and simplified for system-level integration, the fundamental thermophysical parameters, operating conditions and electrochemical relationships remain consistent with those presented in their detailed simulation study. Future work will focus on a detailed validation campaign using laboratory-scale data currently under acquisition, with the goal of refining the electrochemical and thermal response of the model under dynamic residential load profiles.

Although fuel cell degradation phenomena are not explicitly modeled in the present study, their relevance in long-term performance is well acknowledged. Based on literature data for HT-PEMFC systems, a nominal operating lifetime of approximately 20,000 hours is assumed [11, 12]. Several mechanisms contribute to the gradual performance deterioration of these systems, including catalyst sintering, electrolyte degradation, and phosphoric acid depletion in PBI-based membranes. The voltage drop rate typically ranges between 8 and 19 μV/h, depending on operating temperature and current density, with elevated temperatures above 160 °C accelerating degradation, whereas moderate increases in current density may have mitigating effects. Studies such as the one of Najafi et al. [11] have shown that over a 15,000-hour operation, HT-PEM systems may experience a drop in electrical efficiency from 29% to 24%, accompanied by an increase in thermal output due to enhanced waste heat. Despite the exclusion of these effects from the current simulation, they will be addressed in future developments through the implementation of empirically validated degradation models, enabling more accurate assessment of performance trends, maintenance needs, and replacement strategies for real-world operation.

To realistically represent residential demand, an electric load profile was generated using LoadProfileGenerator [13], simulating the consumption of a building composed of ten apartments in Rome over a 15-day period. This enabled the assessment of system behavior under realistic and time-varying conditions.

The thermal management system includes a preheating phase using an electric heater and a regulation mechanism involving a bypass-controlled three-way valve. The cooling circuit is dynamically modulated by a PID controller that adjusts the pump flow based on stack temperature, ensuring thermal stability during both startup and steady-state operation. A residential air source heat pump (RASHP) was also modeled and integrated to represent the actual usage of recovered heat for space heating purposes.

Results

The simulation campaign focused on evaluating the dynamic behavior of a high-temperature PEM fuel cell (HT-PEMFC) integrated into a residential Combined Heat and Power (CHP) system. Three distinct operating strategies were considered: load-following (LF), fixed power output (FP) and operation at maximum electrical efficiency (ME). These scenarios were selected to explore the trade-offs between responsiveness, conversion efficiency and energy autonomy in different system control conditions.

The model was tested over a 15-day simulation period using a high-resolution electrical load profile generated for a multi-apartment residential building located in Rome. For each scenario, the analysis focused on net electrical energy delivered to the load, thermal energy recovered, hydrogen consumption, conversion efficiencies and the extent to which the system supports household self-consumption. All results discussed in this section refer to the performance of the HT-PEMFC subsystem, isolated from any contribution by photovoltaic or battery storage systems, to evaluate its standalone impact within a hybrid energy architecture.

The net electrical power provided to the residential load is a key indicator of the fuel cell system's effectiveness in reducing reliance on the grid. Net power is calculated as the difference between the gross electrical output of the stack and the total consumption of auxiliary components, including the compressor, coolant pump and electric heater.

As shown in Fig. 2, the three operating strategies yield markedly different performance profiles. In the load-following scenario, the system closely tracks the building's real-time electricity demand. However, the transient nature of the residential load combined with the fixed auxiliary consumption results in frequent operating points where the net power is negligible or negative. This is particularly evident during low-load periods or startup transients, where the stack operates at low efficiency and auxiliaries consume a disproportionate share of the generated energy.

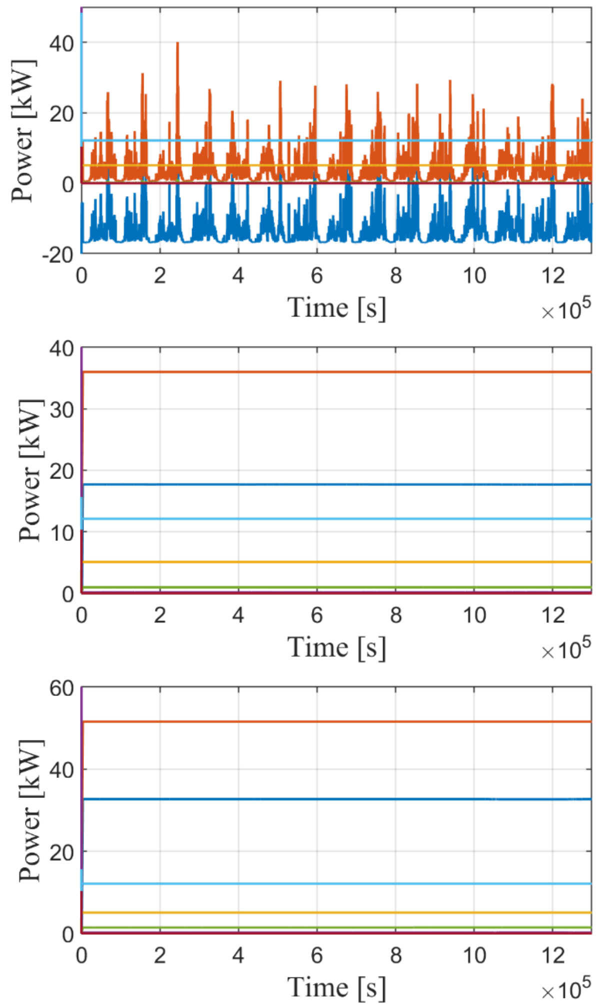

Fig. 2. Net electrical power output of the HT-PEMFC system under the three simulated operating modes: load-following (top), fixed-power at 36 kW (middle) and maximum-efficiency at 51.56 kW (bottom). The curves shown represent the net power gain (blue), the gross electrical output from the fuel cell (orange) and the power absorbed by the air compressor (yellow), the coolant pump (violet), the hydrogen heater (green), the air heater (light blue) and the MultiTherm 503 heater (red).

In contrast, the fixed-power mode maintains a constant operating point, selected to match the average building and auxiliary load. This strategy results in a much more stable net power output, with positive values sustained for most of the simulation period. The scenario representing maximum electrical efficiency offers the best net output performance. By operating the stack at the highest efficiency (51.56 kW), the system not only delivers consistent power but also minimizes hydrogen consumption relative to energy delivered.

One of the most compelling advantages of HT-PEMFCs is their ability to provide high-quality heat due to their elevated operating temperature. This thermal energy can be directly recovered from the cooling system and used for domestic hot water or space heating, significantly contributing to residential energy autonomy.

Fig. 3 quantifies the proportion of the building's total thermal demand that is met by the heat recovered from the HT-PEMFC system in each scenario. Even in load-following mode, where the electrical contribution is limited, the thermal output remains significant due to the continuous removal of heat required to maintain stack temperature stability. However, because the stack frequently operates below nominal capacity in this mode, the average thermal output is lower than in the other scenarios.

In the fixed-power scenario, the system provides a steady thermal output that covers approximately 44% of the total building thermal demand over the simulation period. The performance is markedly improved in the maximum-efficiency scenario, where the system delivers sufficient thermal energy to cover up to 71.7% of the building's needs. This highlights the system's cogeneration potential, especially when operated under conditions that optimize both electrical and thermal energy conversion.

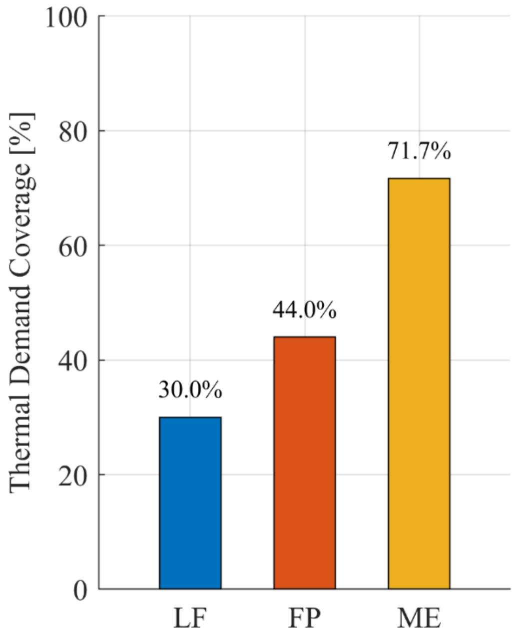

Fig. 3. Percentage of the building's thermal demand covered by heat recovered from the HT-PEMFC system in each operating mode. LF: Load-Following; FP: Fixed Power; ME: Maximum Efficiency.

While absolute power and heat outputs are important, conversion efficiencies offer a more normalized view of system performance. In this work, two efficiency metrics were calculated:

Electrical efficiency, defined as the ratio between net electrical energy delivered and the chemical energy of the hydrogen consumed.

Thermal efficiency, based on the heat recovered and reused by the residential heating system.

The maximum-efficiency model achieves the best overall performance. Electrical efficiency approaches 45% and the thermal efficiency exceeds 70%, placing it well within the typical range of CHP systems based on HT-PEMFC technology as reported in the literature. The fixed-power mode yields lower efficiencies, mainly due to a less favorable ratio between hydrogen input and usable energy. The load-following mode, although responsive, suffers from poor electrical efficiency because of low-load operation and inefficient use of auxiliaries. Nevertheless, its thermal efficiency remains substantial, emphasizing that this mode still has value in systems where thermal needs dominate or where electricity is supplemented by other sources (PV or batteries).

A final but essential performance metric is the system's contribution to residential self-consumption. This is defined as the share of the building's total electrical demand that is met directly by the HT-PEMFC system, without drawing energy from the grid. A high self-consumption rate implies reduced dependency on external supply, greater energy autonomy and more effective use of locally generated energy.

Fig. 4 illustrates this metric for the three scenarios. Load-following operation, despite its conceptual appeal, results in a very limited contribution to self-consumption due to the negative or near-zero net electrical output during much of the simulation. In contrast, the fixed-power and maximum-efficiency scenarios significantly improve this performance. By delivering a sustained and predictable amount of net power, these strategies allow the system to meet a larger portion of the building's electricity needs, thereby increasing energy independence and enhancing the resilience of the local microgrid.

These results demonstrate that operating the HT-PEMFC system at a carefully selected and optimized point significantly improves both electrical and thermal contributions. This, in turn, enhances the system's role within hybrid energy configurations and supports its integration into Renewable Energy Communities as a reliable, efficient and dispatchable cogenerative source.

Conclusions

The ongoing transformation of the energy sector, driven by the need to decarbonize final uses and integrate non-programmable renewable sources, requires new energy paradigms based on local generation, flexibility and active participation of end users. In this context, Renewable Energy Communities (RECs) are emerging as strategic enablers of the energy transition, promoting collective self-consumption, energy sharing and distributed storage. Technologies that support these objectives, such as hydrogen systems, fuel cells and intelligent control infrastructures, are essential to making RECs resilient, autonomous and truly sustainable.

The work presented in this paper fits within this broader vision, investigating the integration of a High Temperature Proton Exchange Membrane Fuel Cell (HT-PEMFC) into a residential Combined Heat and Power (CHP) system. The system is conceived as a cogenerative unit capable of operating flexibly in response to residential energy needs, while simultaneously recovering thermal energy useful for heating or hot water. The HT-PEMFC was modeled within a physically realistic framework in MATLAB Simscape and embedded into a broader hybrid architecture composed of hydrogen storage, power electronics and

auxiliary thermal systems. The goal was to evaluate the behavior of the fuel cell subsystem in different operating conditions and assess its suitability for deployment in REC-aligned energy models.
Three simulation scenarios were explored: a load-following mode, where the system tracks real-time residential demand, a constant power output mode aligned with the building's average energy requirements and an operation mode that maximizes the electrical efficiency of the fuel cell.

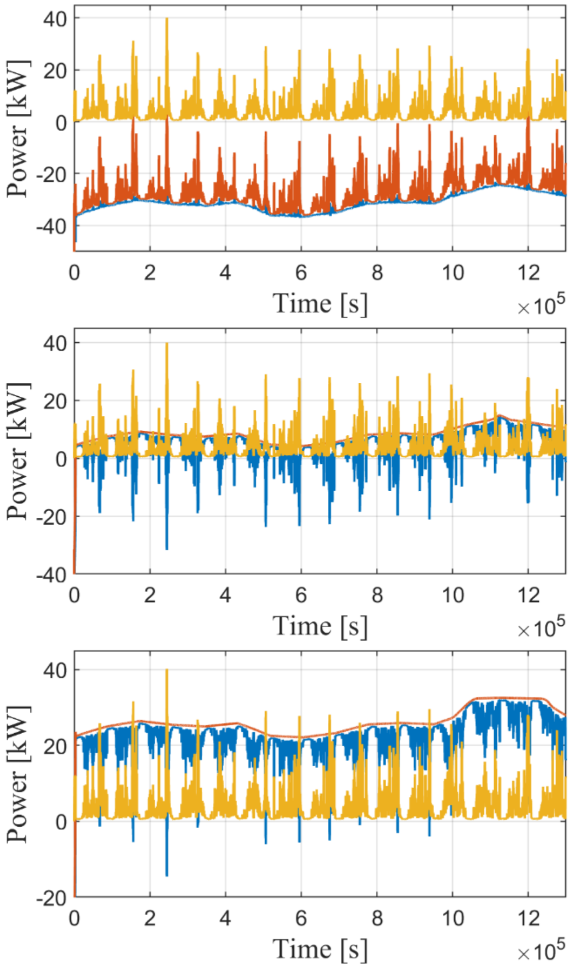

Fig. 4. Electrical power profiles over the 15-day simulation period for the three HT-PEMFC operating strategies: load-following (top), fixed power at 36 kW (middle) and maximum-efficiency operation at 51.56 kW (bottom). In each subplot, the yellow curve represents the building electrical demand, the blue line corresponds to the net electrical power delivered by the fuel cell and the orange line indicates the total power supplied by the HT-PEMFC stack.

The results revealed a clear trade-off between responsiveness and net energy performance. While the load-following strategy ensures alignment with demand, it suffers from reduced electrical efficiency due to the impact of auxiliary consumption. In contrast, the fixed and optimized operation modes demonstrated better performance in terms of net power delivered, hydrogen use and overall efficiency. Across all scenarios, the system showed significant thermal recovery potential, confirming the value of the CHP approach even when electrical autonomy is constrained.

Overall, the simulation results confirm that HT-PEMFC-based cogeneration units can play a valuable role in enhancing energy self-sufficiency and improving energy efficiency in residential settings. Their capacity to provide both electricity and heat, combined with the ability to operate on green hydrogen, makes them highly suitable for REC implementation. The developed model, although not yet experimentally validated, was built upon realistic physical parameters and benchmarked against data from literature. It thus represents a robust starting point for further investigation.

Future developments will focus on the integration of this HT-PEMFC-based cogeneration unit within a broader hybrid energy system currently under development. This system includes a photovoltaic-powered electrolyzer for green hydrogen production, solid-state hydrogen storage in metal hydride tanks, lithium-ion batteries for short-term electrical storage and a coordinated control infrastructure based on a centralized energy management platform. The goal is to implement a fully functional microgrid architecture capable of supporting self-sufficient residential districts, aligned with the principles and operational models of Renewable Energy Communities. Within this framework, the HT-PEMFC will serve as a key generation asset, ensuring high-efficiency energy conversion and valuable thermal recovery, while complementing intermittent renewable sources and storage dynamics through stable, dispatchable operation. In parallel with these technical developments, a detailed techno-economic analysis will be carried out to evaluate the investment viability of the proposed architecture, including capital and operational costs, energy savings and expected payback periods.

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