Semina
Ciências Exatas e Tecnológicas

e-ISSN 1679-0375
ENGINEERINGS

ORIGINAL ARTICLE | DOI 10.5433/1679-0375.2026.v47.54642
iThenticate

Hybrid PEM Fuel Cell and Ultracapacitor Propulsion System for Energy-Efficient Vehicles

Sistema de Propulsão Híbrido com Célula de Combustível PEM e Ultracapacitor para Veículos de Eficiência Energética

Vitor Gabriel Fonseca Pereira[1], Sebastião Ribeiro Júnior[2]

Received: February 19, 2026 *Received in revised form: May 31, 2026* *Accepted: July 13, 2026* *Available online: September 01, 2026*

ABSTRACT

This article details the development, operation and optimization strategies of a hybrid propulsion system based on a hydrogen fuel cell (PEMFC), designed for an ultra-efficient electric vehicle prototype from a university team. Developed for the Shell Eco-marathon Brazil 2025 competition, the project aimed to maximize energy efficiency through a pragmatic and robust power management architecture. The system integrates a PEMFC as the primary energy source, a lithium-ion battery, DC-DC converters and an ultracapacitor bank. These components provide load leveling, managing current peaks during startup and absorbing regenerative braking energy, thereby protecting the fuel cell from abrupt transient demands that compromise its lifespan. The methodology encompassed a simplified analytical estimation, favoring foundational electronic integration over computationally intensive controls. The study discusses the technical challenges and implemented solutions, highlighting the efficiency and viability of applying this technology by other university teams. In addition to proposing applicable approaches for sustainable hybrid propulsion systems, the research demonstrates that highly expressive results can be achieved even when development is carried out pragmatically by a student team.

keywords power management, fuel cell, energy storage, sustainable mobility, thermal analysis

RESUMO

Este artigo detalha o desenvolvimento, a operação e as estratégias de otimização de um sistema de propulsão híbrido baseado em uma célula a combustível de hidrogênio (PEMFC), projetado para um protótipo veicular elétrico de ultraeficiência de uma equipe universitária. Construído para a competição Shell Eco-marathon Brazil 2025, o projeto visou maximizar o desempenho energético através de uma arquitetura de gerenciamento de energia robusta e pragmática. O sistema integra uma PEMFC como fonte primária, uma bateria de íons de lítio, conversores CC-CC e um banco de ultracapacitores. Estes componentes promovem o nivelamento de carga, gerenciando picos de corrente em partidas e absorvendo energia de frenagem regenerativa, preservando a célula de demandas transientes abruptas que comprometem sua vida útil. A metodologia abrangeu estimativas analíticas simplificadas, priorizando a integração eletrônica fundamental em detrimento de controles computacionalmente intensivos. O trabalho discute os desafios técnicos e as soluções implementadas, destacando a eficiência e a viabilidade da aplicação desta tecnologia por outras equipes universitárias. Além de propor abordagens aplicáveis a sistemas de propulsão híbrida sustentável, o estudo demonstra que resultados expressivos podem ser alcançados mesmo quando o desenvolvimento ocorre de forma pragmática por uma equipe de estudantes.

palavras-chave gerenciamento de energia, célula de combustível, armazenamento de energia, mobilidade sustentável, análise térmica

[1]Undergraduate Student, Department of Electrical Engineering, UFPR, Curitiba, PR, Brazil. gabriel.vitor@ufpr.br
[2]Prof. Dr., Department of Electrical Engineering, UFPR, Curitiba, PR, Brazil. sebastiao@ufpr.br

Introduction

In a world increasingly moving towards the energy transition, characterized by the replacement of fossil fuels with renewable sources, it is imperative to deepen the search for new sources and the strategic use of existing clean technologies. In this panorama, hydrogen fuel cells (PEMFC) emerge as a solution for sustainable mobility.

In this context, these systems are an excellent alternative for reducing greenhouse gas emissions and promoting more sustainable mobility, gaining prominence not only in the automotive sector but also in distributed generation, whether as a primary or auxiliary source of energy supply. As highlighted by Lü et al. (2020), efficiency in the use of this equipment is fundamental to maximizing the performance of electric vehicles, extending the hybrid system's lifespan, and significantly reducing both operational costs and environmental impacts.

Hydrogen fuel cells, particularly Proton Exchange Membrane (PEM) types, convert chemical energy directly into electrical energy through the oxidation of hydrogen, generating only electricity and water. However, as highlighted by Xin et al. (2024), the independent operation of fuel cells in automotive applications faces a critical challenge: a slow dynamic response to sudden load variations. This inability to respond instantaneously to power peaks not only degrades the component but also compromises the overall system efficiency. To mitigate this, the authors emphasize that hybridization with high-power density devices, such as ultracapacitors or batteries, is essential. The cell used in this project is a PEM type, selected specifically to implement this robust hybrid architecture.

While the current literature extensively explores sophisticated, computationally intensive energy management strategies for these hybrid vehicles, such as AI-driven algorithms, neural networks, and Model Predictive Control (MPC) (Maaruf et al., 2025), the direct application of these advanced techniques in ultra-efficient competition prototypes faces strict hardware, weight, and reliability constraints. In scenarios like the Shell Eco-marathon, minimizing the computational overhead and the physical footprint of embedded systems is as critical as the electrochemical efficiency itself.

Therefore, the present work details the pragmatic, robust power management architecture developed to meet transient demands and maximize the energy efficiency of the vehicle prototype Sirius, used in the Shell Eco-marathon Brazil 2025 competition. The Shell Eco-marathon is one of the largest university competitions in the world, and its main objective is to bring together students from all over the world to create the most efficient vehicles, being able to compete in three propulsion categories: battery electric, internal combustion engine, and hydrogen fuel cell.

To achieve this purpose and preserve the fuel cell's lifespan, the adopted methodology, detailed in the subsequent section, progressed systematically from theoretical evaluation to practical implementation. The approach began with an analytical estimation of the PEM cell's electrochemical behavior aligned with the vehicle's kinetic load profile. Subsequently, the hardware architecture was designed and integrated, focusing on the sizing of DC-DC converters (Boost and Buck/Boost) for robust bus stabilization and the implementation of an ultracapacitor bank, responsible for absorbing regenerative energy and supplying peak power. Finally, the system's efficiency and autonomy were validated through laboratory characterization of thermal and electrical parameters, as well as by the efficiency mark obtained in the competition.

Material and methods

The theoretical foundation of this study was established through a targeted literature review focused on hydrogen energy storage, PEMFC-based hybrid systems, and power management architectures. A systematic search across primary scientific databases (e.g., Web of Science and Google Scholar) was conducted following methodological guidelines adapted from Almeida (2021). The initial screening yielded 43 articles, which were subsequently filtered based on thematic relevance, citation metrics, and recency (Harzing, 2021). Through a critical analysis of methodologies and core findings, this process distilled 18 high-impact studies that directly supported the conceptualization, component sizing, and control strategy of the hybrid vehicle prototype.

The methodological approach for developing the hybrid propulsion system was structured in chronological stages, ranging from theoretical foundation to field validation. The process began with an extensive literature review focused on PEMFC-based hybrid systems, DC-DC converters, and ultracapacitor applications in power electronics. Recent foundational studies, such as the comprehensive review on advanced FCHEV control strategies by Maaruf et al. (2025) and the dynamic power-sharing models proposed by Xin et al. (2024), were analyzed to establish component sizing parameters and energy management strategies for the hybrid bus.

After the theoretical analysis phase, experimental tests were initiated on a laboratory bench to characterize the electrochemical behavior of the fuel cell. To ensure rigorous validation, tests were conducted under controlled laboratory conditions, with hydrogen gas supplied at a strictly regulated pressure between 0.55 and 0.65 bar. The instrumentation setup employed dedicated data acquisition hardware powered by an isolated 3.3 V measurement circuit to prevent noise interference. Non-invasive Hall-effect current sensors and precision voltage dividers were utilized, alongside 500 W resistive loads, to map polarization curves (voltage vs. current). Additionally, a digital oscilloscope was used to capture high-frequency transient responses, while a thermal imaging camera monitored the operating temperature gradient. This stage was critical, as thermal management, extensively discussed by Omran et al. (2021) in mathematical models, was a primary concern for participating in the Shell Eco-marathon, requiring the system to maintain stable efficiency under various energy demand conditions. The electrical system performance under these conditions also took into account benchmarks from Banda et al. (2016).

With the cell characterization completed, the project moved to electronic prototyping and component integration. Different ultracapacitor banks were experimentally assembled and tested to optimize regenerative energy absorption and peak power supply. In parallel, a gas leakage detection board was developed, a mandatory safety requirement of the Shell (2025) official rules to protect the pilot and the system. Various electrical connection configurations between the power management boards, the Buck/Boost converters, and the ultracapacitor bank were evaluated to minimize conversion losses and ensure operational viability.

For power conditioning of the energy generated by the fuel cell, an essential step due to the natural variability of the stack's output voltage, a Buck/Boost DC-DC converter topology was employed. The power management logic adopts a semi-active hybrid architecture. The DC-DC converter actively operates in a voltage regulation loop, stepping up or stepping down the stack's variable output to stabilize the main DC bus at a constant 40 V. This ensures that the brushless DC (BLDC) motor controller of the vehicle receives a reliable steady-state power supply directly from the PEMFC.

The final stage consisted of vehicular integration and commissioning after the physical fabrication of the chassis by the team. This process involved the assembly of the electrical harness and verification of the mechanical and electromagnetic robustness of all modules installed in the Sirius prototype. To ensure long-term durability and fuel economy, control strategies were refined based on the multi-mode approaches proposed by Xu et al. (2014) and the optimization algorithms reviewed by Lü et al. (2020). The final validation was carried out through the transition from static laboratory measurements to dynamic track tests, similar to the energy management studies for ultra-efficient vehicles performed by Punov and Gechev (2021).

The project utilizes the H-1000 PEM fuel cell stack Horizon Fuel Cell Technologies (2024), with a nominal power of 1000 W. Based on Proton Exchange Membrane (PEM) technology, the stack converts hydrogen into electricity through an electrochemical reaction, producing only water and heat as byproducts. The system is managed by an integrated electronic controller that performs energy management via IGBTs and safety monitoring. This unit controls thermal management, cooling activation, and protection against critical failures such as overload and low supply pressure. The main technical information for the fuel cell can be found in Table 1.

The hydrogen fuel cell system integrates an IGBT connected in parallel to its output, designated as the Short-Circuit Unit (SCU). Its function is to promote short-duration short circuits between the positive and negative terminals of the cell. As comprehensively investigated by Zhang et al. (2021), this process induces transient electrochemical conditions that act directly on membrane conditioning and catalyst recovery. The periodic short-circuiting strips inactive oxides from the platinum surface, thereby increasing the effective electrochemically active surface area, while generating rapid hydration to mitigate localized membrane dehydration. This active water and surface management effectively prevents cell flooding and performance degradation, maintaining optimal stack voltage and extending the device's operational lifespan.

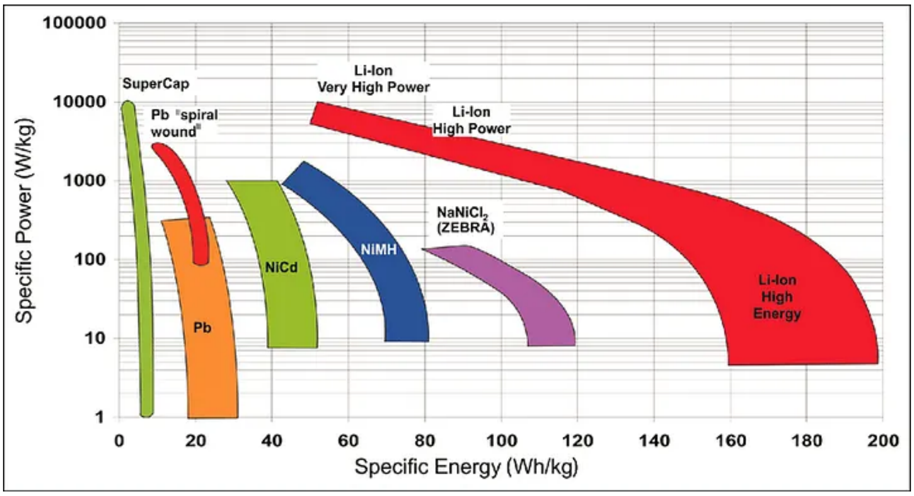
Table 1 - Technical specifications of the H-1000 PEMFC stack.

Parameter	Value
Cell Type	PEM
Number of Cells	48
Nominal Power	1000 W
Max. Performance	28.8 V / 35 A
Max. Stack Current	42 A
H_2 Purity	99.995%
Efficiency	40%
Flow rate at max. power	13 L/min
Hydrogen Pressure	0.55 - 0.65 bar

From "*H-1000 fuel cell stack user manual (v. 1.3)*," by Horizon Fuel Cell Technologies, (2024).

An electrical circuit developed by the manufacturer, known as the cell controller, is required to monitor and control the state of the hydrogen fuel cell. This circuit requires an external power supply independent of the fuel cell. The project utilizes a lithium-ion battery for this purpose, as this material offers superior performance in terms of specific power and specific energy compared to other battery types. The relationship between these parameters for the most commonly used battery materials is illustrated in Figure 1.

Figure 1 - Comparative graph of specific power and specific energy of energy storage devices.



From "*Baterias Íon-Lítio: uma revisão*," by A. Carvalho, (2025), *Medium*.

For the auxiliary subsystem, a lithium-ion battery with a nominal voltage of 12 V and a capacity of 10.4 Ah was selected. This battery was sized to meet the manufacturer's power requirements, which specify a range of 12–14 V and peak currents between 5 A and 8 A. The assembly integrates a Battery Management System (BMS) responsible for monitoring the State of Health (SoH) and providing active protection against overcurrent and undervoltage. This integration mitigates thermal risks and ensures the component's longevity.

The auxiliary subsystem also includes a hydrogen leak detection circuit, designed to automatically manage the fuel cell controller's power supply. This safety mechanism utilizes a hydrogen gas sensor that monitors the environment near the stack's intake; upon detecting an increase in gas concentration, the sensor's output voltage rises, triggering a relay that immediately disconnects the system's power. Given that hydrogen is a highly flammable gas, this proactive safety measure is critical for preventing hazardous conditions and ensuring the integrity of both the prototype and the laboratory environment.

Furthermore, the overarching control strategy integrates a 5.53 F ultracapacitor bank (rated for 48 V) directly coupled to the DC bus to passively manage transient dynamics. The power-sharing strategy is dictated by the bus voltage fluctuations: during sudden vehicle accelerations, the instantaneous current demand causes a momentary voltage dip on the bus. This automatically prompts the ultracapacitors to discharge, supplying the required peak power and buffering the fuel cell from severe current spikes that cause membrane degradation. Conversely, during regenerative braking, the ultracapacitors absorb the reverse current, preventing bus overvoltage. This cooperative management strategy ensures that the PEMFC operates predominantly within its optimal steady-state efficiency range.

Results and discussion

The performance and efficiency analysis of the hybrid system was studied based on mathematical modeling and theoretical simulation of the fuel cell, applying conservation equations (mass, energy, and charge) and thermodynamic criteria to predict electrochemical behavior under different regimes. These computational estimates established the necessary comparison for subsequent experimental validation and project optimization.

Specifically, to quantify the fuel consumption required for the vehicle's autonomy, a simplified analytical estimation of the theoretical mass consumption of hydrogen (Δm_{H_2}) was performed based on the electrical power supplied by the cell (P_{cell}), its efficiency (η_{cell}), and the Lower Heating Value (LHV_{H_2}) of hydrogen, according to Xin et al. (2024). Using the Ideal Gas Law under Normal Temperature and Pressure (NTP) conditions, the mass was converted to volume to allow for a direct comparison with the fuel cell manual. The mass consumption of hydrogen was calculated using equation (1):

$$\Delta m_{H_2} = \int_{t_0}^{t} \frac{P_{cell}}{\eta_{cell} \cdot LHV_{H_2}} dt \quad [\text{kg}]. \tag{1}$$

Considering the Lower Heating Value (LHV_{H_2}) of 33.33 kWh/kg, the fuel cell power (P_{cell}) of 1000 W and the fuel cell efficiency (η_{cell}) of 40 %, according to Horizon Fuel Cell Technologies (2024), the calculated mass flow ($\dot{m}_{H_2}$) is 0.075 kg/h. To convert this mass flow into a volumetric flow rate ($\dot{V}_{H_2}$) under Normal Temperature and Pressure (NTP) conditions (0 °C and 1 atm), the density of hydrogen (ρ_{H_2}) of 0.0899 kg/m^3, approximately, was applied in equation (2):

$$\dot{V}_{H_2} = \frac{\dot{m}_{H_2}}{\rho_{H_2}} \quad [\text{m}^3/\text{h}]. \tag{2}$$

The result is 0.8343 m^3/h, converting to L/min, the flow rate at maximum power was 13.91 L/min, approximately. This value is remarkably close to the 13 L/min specified in the manufacturer's manual (Horizon Fuel Cell Technologies, 2024). The slight difference of 0.91 L/min is justified by the efficiency overhead and the hydrogen purge cycles required to maintain membrane hydration and remove impurities during high-power operation, thus validating the mathematical model used for autonomy and fuel management projections.

However, while the fuel cell provides the necessary steady-state power, its slow dynamic response necessitates an energy storage system to handle transient loads. As stated by Ferreira and Pomilio (2005), sizing an ultracapacitor (UC) bank for vehicles can follow two main criteria: transient response stabilization or power peak management. In the latter, the sizing considers the maximum kinetic energy (E) of the vehicle in equation (3):

$$E = \frac{mv^2}{2} \quad [\text{J}]. \tag{3}$$

The required capacitance (C) to absorb or supply this energy is calculated by the voltage variation in the DC bus in equation (4):

$$C = \frac{2E}{|V_{max}^2 - V_{min}^2|} \quad [\text{F}], \tag{4}$$

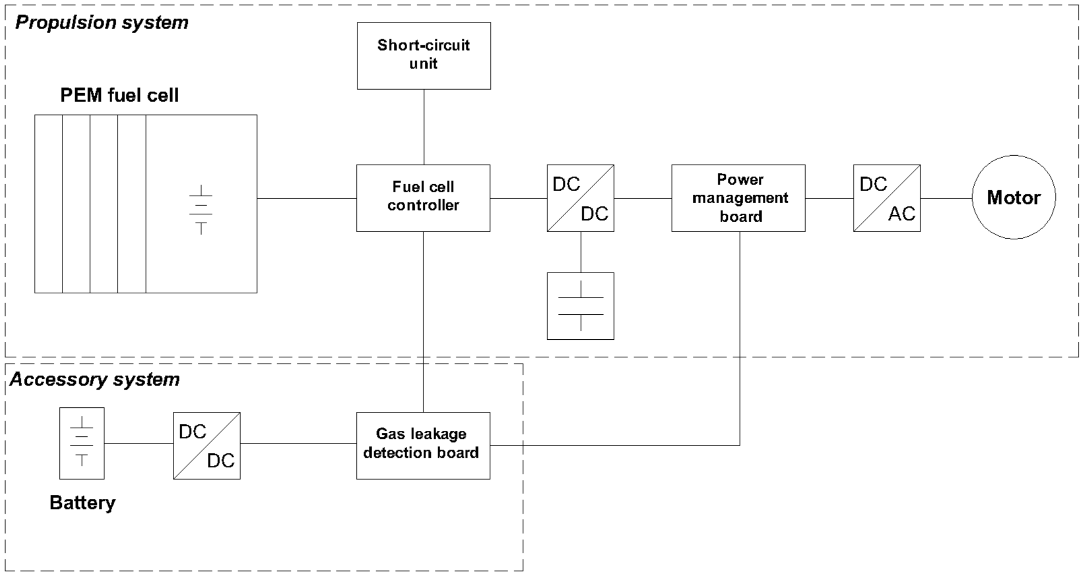
where V_{max} and V_{min} are the maximum and minimum operating voltages, respectively. For the Sirius prototype, considering a mass of 110 kg (measured during competition), including the body and the driver of the vehicle, and a maximum speed of 32 km/h observed in tests, the kinetic energy calculated is approximately 4,346 joules. Applying the voltage limits of the fuel cell (45.6 V as open circuit and 24 V as undervoltage limit), the required capacitance was calculated at 5.78 Farads, which is consistent with the 5.53 Farads bank implemented in the system. These results validate that the implemented ultracapacitor bank effectively satisfies the operational demands of the hybrid propulsion system.

It is important to highlight that this capacitance is ideal to ensure that there is no voltage variation greater than this. However, for greater system efficiency, a higher capacitance would be necessary, further reducing voltage sag on the DC bus. Due to financial and experimental reasons, a 5.53 F ultracapacitor bank was chosen, which worked well in the system.

System configuration and laboratory testing

In compliance with Shell Eco-marathon guidelines, the hybrid architecture was segregated into two functional subsystems: the propulsion circuit (Propulsion system) and the auxiliary circuit (Accessory system). The propulsion circuit manages the power bus for traction, integrating the fuel cell, ultracapacitor bank, Buck/Boost DC-DC converter and the motor inverter. The auxiliary circuit operates as an independent low-voltage system (12 V battery, Boost DC-DC converter and gas leakage detection board), ensuring the stability required for initialization and control of the fuel cell peripherals. The system architecture is shown in Figure 2.

Figure 2 - Simplified electrical diagram of the Sirius vehicle prototype.



The initial characterization trials were conducted to obtain the electrical and thermal parameters of the fuel cell. The electrical load was simulated using a parallel association of five variable resistive banks (330 Ω each), with a gradual current increment up to a plateau of 5 A. The instrumentation employed dedicated data acquisition hardware, utilizing non-invasive current sensors and voltage dividers. The integrity of the analog signals was simultaneously validated using an oscilloscope to ensure data precision. In addition, the thermal profile of the components was observed using a thermal camera. Below, in Figures 3(a) and 3(b), is two images of the first test performed with the fuel cell.

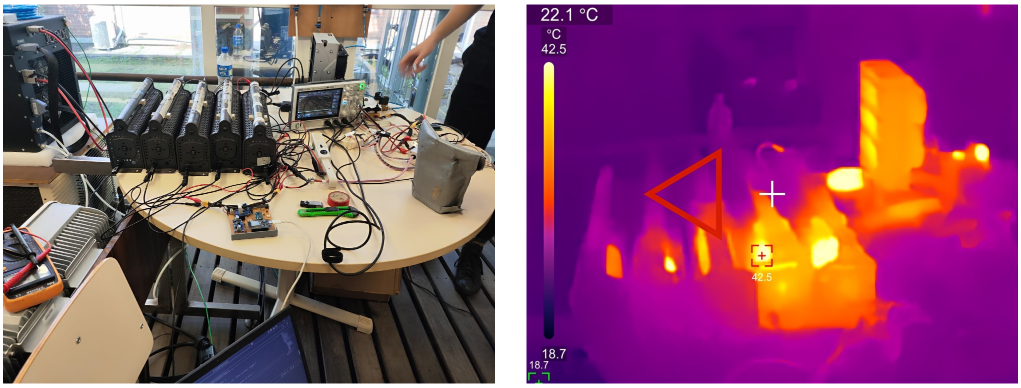
It is interesting to observe the temperature difference in the resistive load banks due to the resistance in each of them operating with the cell, which was not equal. This was one of the first experimental validations of the cell with a very stable and purely resistive load.

Further tests showed that the thermal profile of the fuel cell demonstrated stability, with temperature variations directly proportional to the increments in current and power demand. However, during preliminary trials, the components subjected to the highest thermal gradients were identified as the solenoid valve and the ultracapacitor bank.

In the case of the solenoid valve, the excessive heating is attributed to the Joule effect losses within the winding resistance, given that the component operates in a continuous conduction regime. Beyond the thermal impact, the inductive nature of this load, associated with a lack of drive modulation (PWM control), may generate a constant magnetization current that represents significant parasitic consumption.

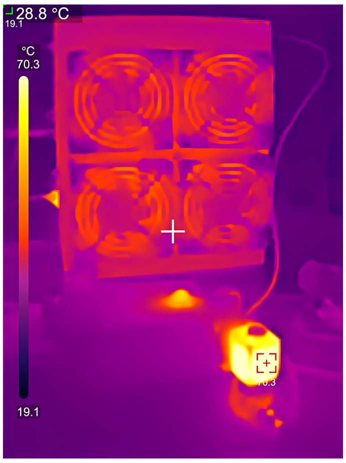
Figure 3 - Experimental laboratory setup: (a) setup for the fuel cell system characterization; (b) thermal camera image illustrating the heat dissipation.

(a) (b)



Furthermore, the valve's operation introduces harmonics and high-frequency noise into the power line, degrading the Power Quality and potentially compromising the signal integrity of the vehicle's analog sensors. Figure 4 shows the temperature of the cell and solenoid valve in one of the system's thermal validation tests.

Figure 4 - Thermal camera image of the fuel cell compartment highlighting the thermal gradient of the solenoid valve during operation.



To solve this problem, the solenoid valve was swapped for a low-power model, yielding satisfactory results; the operating temperature decreased significantly, from 70 °C to 40 °C in continuous work.

During preliminary tests to define the auxiliary power system, before reaching a capacitance of 5.53 F, 1.6 F ultracapacitor modules with compact printed circuit board (PCB) layouts were evaluated. During the validation of different topologies, critical thermal dissipation was observed: component temperatures reached 100 °C within seconds of activation, indicating undersized PCB traces and high initial current density.

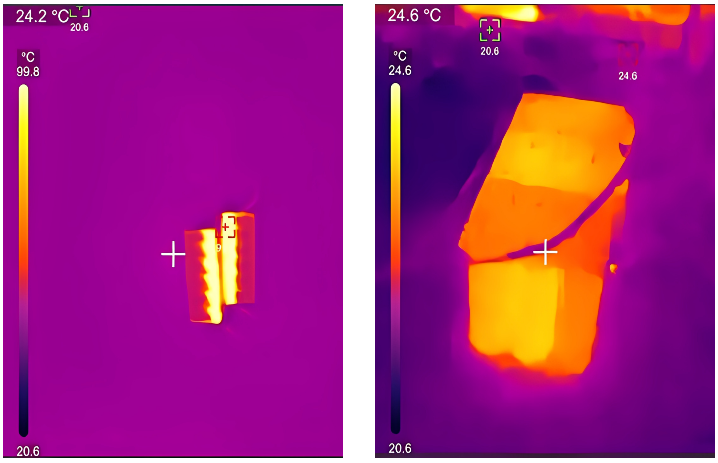
As a corrective measure, the system was redesigned using three 16.6 F banks connected in series (5.53 F), sourced from a different manufacturer and characterized by traces with larger cross-sectional areas. This new configuration effectively mitigated the overheating, resulting in stable thermal behavior with the operating temperature maintained at the 25 °C range. Figures 5(a) and 5(b) show the heating of one bank of ultracapacitors and the thermal stabilization of another bank of ultracapacitors, highlighting distinct behaviors due to their physical construction.

These validations with the two ultracapacitor banks were performed in the same way, using the resistive banks as the system load. This abrupt heating can be explained by the lack of initial charging current limitation of the banks, which generates a high electrical current and consequently significant heating of the component.

The integration of multiple storage devices into a hybrid topology provides load leveling as its primary benefit. In the proposed system, consisting of a hydrogen fuel cell and an ultracapacitor bank, a strategic complementarity occurs: while the fuel cell possesses high energy density, the ultracapacitor bank offers high power density.

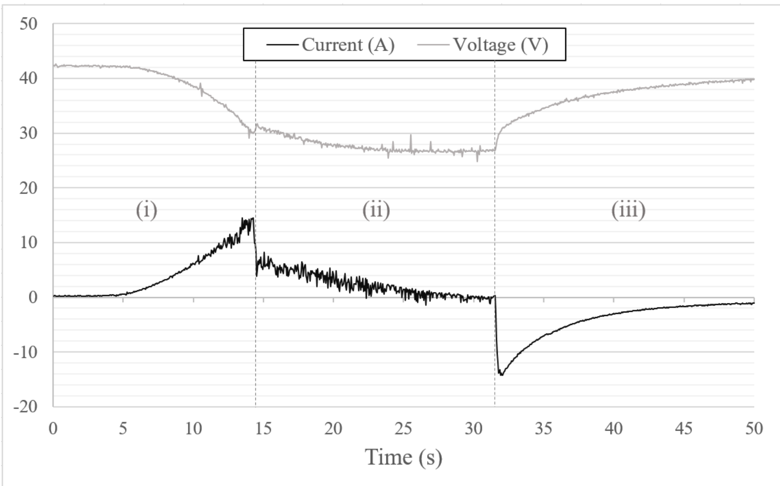
Figure 5 - Thermal camera images: (a) undersized ultracapacitor bank; (b) redesigned 5.53 F bank.

(a) (b)



During load transients, such as sudden accelerations, the ultracapacitor bank assumes the instantaneous peak demand. This is crucial because the fuel cell has a slow dynamic response due to the inertia of electrochemical reactions and gas flow. By preventing the cell from undergoing abrupt current variations, the hybrid system prevents membrane stress, increases the device's lifespan, and mitigates severe voltage drops. Figure 6 shows the operation of the two devices together in the hybrid configuration.

Figure 6 - Oscilloscope graph illustrating three operational stages of the hybrid system: (I) Acceleration peak required by the motor, (II) Gradual reduction in motor speed, and (III) Regenerative braking with the subsequent charging of the ultracapacitor bank.



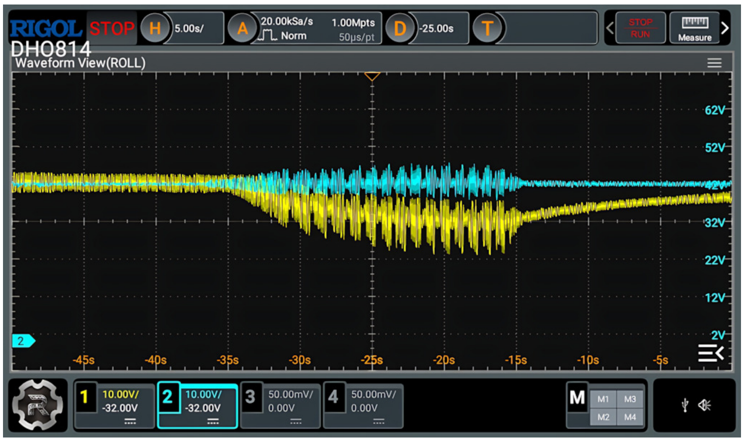
The analysis of the hybrid system's electrical behavior, as illustrated in Figure 6, reveals the dynamic interaction between the motor's current demand and the bus voltage throughout an operational cycle. During the initial acceleration, a positive current peak of approximately 15 A is observed, accompanied by a momentary voltage drop, which demonstrates the high torque requirement necessary to overcome the vehicle's inertia. Following movement stabilization, the most relevant aspect of this trial occurs during the deceleration stage, where regenerative braking takes place. This system behavior was triggered by an experimental Foucault current dynamometer developed by the team for testing the vehicle's electric motor efficiency.

A notable symmetry exists between the peak consumption current at startup and the peak regenerated current during braking, as both reach similar absolute magnitudes in the 15 A range. This correspondence between the startup (positive) and braking (negative) currents highlights the high power density of the ultracapacitor bank and its capability to accept charge at rates as high as its discharge rates. Unlike conventional chemical batteries, which often face limitations in fast recharge rates, the ultracapacitor bank was able to absorb the kinetic energy converted by the motor with the same intensity as it was supplied during acceleration.

This behavior results in immediate bus voltage recovery, validating the system's effectiveness in reclaiming energy that would otherwise be thermally dissipated in mechanical brakes, while protecting the fuel cell from these sudden power transients.

The electrical system utilizes two DC-DC converter topologies to meet distinct demands. In the auxiliary line, a Boost converter was implemented to raise the battery voltage (Li-ion 3S4P) above the critical threshold of 12 V, preventing the premature shutdown of the cell controller and maximizing charge utilization. In the propulsion line, a Buck/Boost converter is employed to stabilize the bus at 40 V, the voltage defined for driving the BLDC motor and management systems. Figure 7 shows the separate behavior of the output voltage of the cell and the converter in the same test, both connected in series.

Figure 7 - Oscilloscope waveforms comparing the fuel cell output voltage (yellow) and the Buck/Boost DC-DC converter output voltage (blue) during a BLDC motor load test, demonstrating bus stabilization despite stack voltage drop.



Analysis of the transient response under dynamometer load (Figure 7) reveals that while the bus voltage exhibits greater stability compared to the sharp decay of the cell voltage, the system suffers from signal quality degradation. The presence of noise and electromagnetic interference (EMI), stemming from the switching of inductive loads (motor and solenoids), underscores the imperative need to implement filtering, and isolation stages. Such measures aim to ensure Electromagnetic Compatibility (EMC) and protect low-power peripherals against high-frequency oscillations.

During competition, the prototype achieved an energy efficiency (η) of 132 km/m^3, according to the official telemetry data provided by Shell. Considering the storage in a 6-liter cylinder at 150 bar (approximately 0.9 m^3 at atmospheric pressure of 1 bar) provided during the event, a theoretical autonomy of 118.8 km is projected, subject to operational variations and pressure safety margins. For comparative purposes, the data were converted into equivalent units. The conversion to kWh allows for a direct comparison with battery electric vehicles. Using the volumetric energy density of hydrogen (w_{H_2}) as 2.71 kWh/m^3, the calculation was performed as follows in equation (5):

$$\eta_{kWh} = \frac{\eta_{m^3}\left(\frac{km}{m^3}\right)}{w_{H_2}\left(\frac{kWh}{m^3}\right)} \quad [\text{km/kWh}]. \tag{5}$$

Based on equation (5), the efficiency (η_{kWh}) corresponds to 48.7 km/kWh, allowing for a direct comparison with battery electric vehicles. For comparative purposes, a commercial electric vehicle, such as the BYD Dolphin Mini, presents an urban energy efficiency of approximately 7.5 km/kWh, with a total range of 280 km provided by a 38 kWh lithium-iron-phosphate (LFP) battery (BYD Brazil, 2024). In contrast, the nominal efficiency achieved by the Sirius prototype (48.7 km/kWh) is approximately 6.5 times higher than that of the commercial model. Evidently, this significant discrepancy must be interpreted cautiously, as it stems primarily from the prototype's highly optimized ultra-low drag coefficient, reduced vehicular mass (110 kg), and lack of commercial safety, auxiliary, and structural payloads, which heavily penalize the energy performance of passenger vehicles. Nevertheless, this index underscores the maximum baseline capability of hydrogen-based hybrid systems in optimizing energy performance for sustainable mobility.

To express efficiency in terms of internal combustion, the Lower Heating Value (LHV) of standard competition gasoline is used. According to the official regulation (Shell, 2025), reference gasoline has an LHV of approximately 42.9 MJ/kg and a density of 0.668 kg/L, resulting in a specific energy of 28.6 MJ/L. Considering that 1 m^3 of hydrogen contains approximately 9.76 MJ (Lower Heating Value - LHV) under Normal Temperature and Pressure (NTP) conditions, consistent with the 2.71 kWh/m^3 energy density previously utilized, the conversion factor relative to competition gasoline (31.6 MJ/L) is established as follows in equation (6):

$$\eta_L = \eta_{m^3} \cdot \left(\frac{9.76}{31.6}\right)^{-1} \approx \eta_{m^3} \cdot 3.24 \quad [\text{km/L}]. \tag{6}$$

The result of efficiency in gasoline (η_L) is 427.7 km/L (rounded to 428 km/L), which provides a standard metric for performance comparison against alternative high-efficiency internal combustion prototypes in the Shell Eco-marathon Brazil 2025 and commercial vehicles, whose figures were lower. The demonstrated technical superiority validates the effectiveness of the PEMFC/ultracapacitor hybrid architecture. The ultracapacitor bank managed transient demands, allowing the fuel cell to operate stably in its maximum efficiency range, resulting in significantly reduced specific hydrogen consumption compared to non-hybridized systems. Figure 8 shows the visual appearance of the prototype vehicle in the competition.

Figure 8 - The Sirius vehicle prototype at Shell Eco-Marathon Brazil 2025.

Furthermore, the recorded efficiency of 132 km/m^3 provides a theoretical baseline for the economic viability of hydrogen as a clean energy carrier under idealized conditions. While top-tier teams in Europe and the USA have achieved higher marks in specific Shell Eco-marathon events, the results obtained by Sirius are highly competitive on a global scale. Considering the average price of green hydrogen, ranging from €2.5 to €5.5 per kilogram (Click Petróleo e Gás, 2022; Hyundai Portugal, 2021), which corresponds to approximately $2.70 to $5.90 USD/kg, and given that 1 kg of hydrogen corresponds to roughly 11.12 m^3 at NTP, the prototype could theoretically travel over 1,460 km on a single kilogram of fuel. This yields a theoretical cost-to-distance ratio of roughly $0.003 USD per kilometer. However, it is crucial to emphasize that this economic projection is strictly confined to an ultra-lightweight competition vehicle operating at low speeds on a closed track. While it highlights the maximum thermodynamic potential of the PEMFC/ultracapacitor architecture, it cannot be directly extrapolated to commercial transport economics, which involve significant payload, safety infrastructure, and real-world aerodynamic constraints.

Conclusions

The development of the Sirius prototype confirmed that integrating a PEM fuel cell with an ultracapacitor bank, managed by a semi-active Buck/Boost DC-DC converter topology, represents a highly effective solution for ultra-efficient mobility. By actively stabilizing the 40 V main bus and passively managing transient dynamics, the hybrid architecture successfully decoupled the fuel cell from sudden load variations. This cooperative power sharing allowed the stack to operate steadily within its optimal efficiency range, while the ultracapacitors efficiently absorbed regenerative braking energy and supplied the necessary peak acceleration currents.

The systematic methodology, transitioning from analytical estimations to empirical validation, proved fundamental to the project's viability. Controlled laboratory tests utilizing a digital oscilloscope and thermal camera ensured high-fidelity data acquisition for electrical mapping and thermal analysis. These trials were decisive in identifying and correcting early inefficiencies, guiding critical hardware optimizations such as the substitution of the solenoid valve and the redesign of the 5.53 F ultracapacitor bank to resolve severe thermal gradients.

The transition to dynamic track testing at the Shell Eco-marathon Brazil 2025 validated the system's robustness under real competition conditions. Over a driven distance of 8,500 meters, the vehicle demonstrated outstanding energy management. This performance culminated in an official efficiency of 132 km/m^3 (equivalent to 48.7 km/kWh and 428 km/L of gasoline).

While these figures significantly surpass commercial electric vehicle benchmarks and yield an idealized theoretical cost of approximately $0.003 USD per kilometer, they must be cautiously interpreted as the baseline thermodynamic capabilities of an ultra-lightweight prototype rather than direct commercial equivalents. Ultimately, this study presents a promising vehicular system based on clean and renewable energy. By demonstrating that significant efficiency can be achieved through pragmatic electronic integration, this work can provide valuable insights for other Shell Eco-marathon energy efficiency teams. Furthermore, the developed system can inspire future optimizations and sustainable hybrid vehicle propulsion.

Acknowledgments

The authors gratefully acknowledge the Federal University of Paraná (UFPR) for its infrastructural support and commitment to fostering technological research. We are particularly thankful to the Academic Development Fund (FDA - Fundo de Desenvolvimento Acadêmico) for providing the essential financial resources required to acquire materials and construct the prototype. We also extend our thanks to the Mechanical and Electrical Engineering laboratories at UFPR, whose technical assistance and equipment were vital for the successful execution of the bench tests and simulations. Finally, special recognition is given to the coordinating professors and all student members of the Eco Octano UFPR team; their guidance, dedication, and teamwork were the true driving forces behind the success of this project.

Author contributions

V. G. F. Pereira: Conceptualization, Data Curation, Formal Analysis, Investigation, Methodology, Programs, Validation, Visualization, Writing – original draft. **S. Ribeiro Júnior**: Conceptualization, Formal Analysis, Project Management, Resources, Supervision, Validation, Writing – revision and editing.

Conflicts of interest

The authors declare no conflict of interest.

References

Almeida, T. L. d. (2021). *Integração de energias renováveis e armazenamento de energia em smartbuildings* [Tese de Doutorado, Universidade Federal do Paraná]. Repositório Universidade Federal do Paraná. https://www.eletrica.ufpr.br/p/arquivostccs/589.pdf

Banda, J., Salazar, I., & Trinidad, A. (2016). *Hydrogen fuel cell vehicle electrical system performance* [Poster presentation]. Texas State University. https://gato-docs.its.txstate.edu/jcr:d5f27c79-9f5f-4fbe-b3e1-956c44c8acbd/

BYD Brazil. (2024). *Byd dolphin mini: Technical specifications*. https://www.byd.com/br/car/dolphin-mini

Carvalho, A. (2025). *Baterias íon-lítio: Uma revisão*. Medium. https://medium.com/@dri_ird/baterias-%C3%ADon-l%C3%ADtio-uma-revis%C3%A3o-4dee15ae77ab

Click Petróleo e Gás. (2022). *How much does 1kg of hydrogen cost? understand the factors that influence the price*. https://clickpetroleoegas.com.br/blog/hidrogenio/quanto-custa-1kg-de-hidrogenio/

Ferreira, A. A., & Pomilio, J. A. (2005). Estado da arte sobre a aplicação de supercapacitores em eletrônica de potência. *Eletrônica de Potência*, *10*(2), 25–32. https://doi.org/10.18618/REP.2005.2.025032

Harzing, A.-W. (2021). *Publish or Perish* (Version 8.0). https://harzing.com/resources/publish-or-perish

Horizon Fuel Cell Technologies. (2024). *H-1000 fuel cell stack user manual (v. 1.3)*. https://www.horizonfuelcell.com/

Hyundai Portugal. (2021). *Understanding the high price of fuel hydrogen*. Blue Academy by Hyundai. https://blueacademy.hyundai.pt/artigo/preco-hidrogenio-combustivel/

Lü, X., Wu, Y., Lian, J., Zhang, Y., Chen, C., Wang, P., & Meng, L. (2020). Energy management of hybrid electric vehicles: A review of energy optimization of fuel cell hybrid power system based on genetic algorithm. *Energy Conversion and Management*, *205*, 112474. https://doi.org/https://doi.org/10.1016/j.enconman.2020.112474

Maaruf, M., Babangida, A., Ahmed, I., Khalid, M., & Szemes, P. T. (2025). Advanced control strategies for fuel cell hybrid electric vehicles — a review. *Energy Conversion and Management: X*, *28*, 101354. https://doi.org/https://doi.org/10.1016/j.ecmx.2025.101354

Omran, A., Lucchesi, A., Smith, D., Alaswad, A., Amiri, A., Wilberforce, T., Sodré, J. R., & Olabi, A. (2021). Mathematical model of a proton-exchange membrane (pem) fuel cell. *International Journal of Thermofluids*, *11*, 100110. https://doi.org/https://doi.org/10.1016/j.ijft.2021.100110

Punov, P., & Gechev, T. (2021). Energy management of a fuel cell hybrid ultra-energy efficient vehicle. *International Journal of Hydrogen Energy*, *46*(38), 20291–20302. https://doi.org/10.1016/j.ijhydene.2020.09.059

Shell. (2025). Shell Eco-marathon: 2025 Official Rules (Chapter I). *Shell Global*. https://www.shellecomarathon.com/2025-programme.html

Xin, Y., Hu, J., & Wang, Z. (2024). An energy management strategy with considering ultracapacitor ideal state of charge for fuel cell/battery/ultracapacitor vehicle. *Energy*, *304*, 132024. https://doi.org/https://doi.org/10.1016/j.energy.2024.132024

Xu, L., Li, J., Ouyang, M., Hua, J., & Yang, G. (2014). Multi-mode control strategy for fuel cell electric vehicles regarding fuel economy and durability. *International Journal of Hydrogen Energy*, *39*(5), 2374–2389. https://doi.org/https://doi.org/10.1016/j.ijhydene.2013.11.133

Zhang, C., Liu, H., Zeng, T., Chen, J., Lin, P., Deng, B., Liu, F., & Zheng, Y. (2021). Systematic study of short circuit activation on the performance of pem fuel cell. *International Journal of Hydrogen Energy*, *46*(45), 23489–23497. https://doi.org/10.1016/j.ijhydene.2020.10.118