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Investigating PEM Fuel Cells as an Alternative Power Source for Electric UAVs: Modeling, Optimization, and Performance Analysis

Pavel Shuhayeu, Aliaksandr Martsinchyk, Katsiaryna Martsinchyk and Jaroslaw Milewski *

Faculty of Power and Aeronautical Engineering, Institute of Heat Engineering, Warsaw University of Technology, 21/25 Nowowiejska Street, 00-665 Warsaw, Poland; pavel.shuhayeu.dokt@pw.edu.pl (P.S.); aliaksandr.martsinchyk.dokt@pw.edu.pl (A.M.); katsiaryna.razumkova.dokt@pw.edu.pl (K.M.)
* Correspondence: jaroslaw.milewski@pw.edu.pl

Abstract: Unmanned aerial vehicles (UAVs) have become an integral part of modern life, serving both civilian and military applications across various sectors. However, existing power supply systems, such as batteries, often fail to provide stable, long-duration flights, limiting their applications. Previous studies have primarily focused on battery-based power, which offers limited flight endurance due to lower energy densities and higher system mass. Proton exchange membrane (PEM) fuel cells present a promising alternative, providing high power and efficiency without noise, vibrations, or greenhouse gas emissions. Due to hydrogen's high specific energy, which is substantially higher than that of combustion engines and battery-based alternatives, UAV operational time can be significantly extended. This paper investigates the potential of PEM fuel cells as an alternative power source for electric propulsion in UAVs. This study introduces an adaptive, fully functioning PEM fuel cell model, developed using a reduced-order modeling approach and optimized for UAV applications. This research demonstrates that PEM fuel cells can effectively double the flight endurance of UAVs compared to traditional battery systems, achieving energy densities of around 1700 Wh/kg versus 150–250 Wh/kg for batteries. Despite a slight increase in system mass, fuel cells enable significantly longer UAV operations. The scope of this study encompasses the comparison of battery-based and fuel cell-based propulsion systems in terms of power, mass, and flight endurance. This paper identifies the limitations and optimal applications for fuel cells, providing strong evidence for their use in UAVs where extended flight time and efficiency are critical.

Keywords: unmanned aerial vehicle; electric propulsion; proton exchange membrane fuel cell; hydrogen; modeling

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1. Introduction

1.1. Unmanned Aerial Vehicle

An unmanned aerial vehicle (UAV) implies the absence of a human presence (neither pilot nor passengers) on the aircraft [1].

UAV utilization has a wide range of potential applications in numerous sectors. In civilian applications, UAVs are utilized for a variety of tasks, including scientific research, wildfire monitoring, cartography, photography, search and rescue operations, etc. Future potential applications for unmanned aerial vehicles (UAVs) include package delivery, cargo transportation, construction, and others [2–4]. Endurance is a factor that can raise the UAV's overall efficiency. It is the total amount of time a UAV can spend in flight. Numerous factors, including weight, size, payload, and power supply source, affect endurance. Currently, while the majority of UAVs rely on combustion engines or batteries as their primary power source, an increasing number of UAVs are also being developed and utilized that are powered by fuel cells [5]. Only the battery-based solution will be taken into consideration in this work. Although the technical specifications of the batteries are acceptable, they often fail to provide stable, long-duration flights due to limited energy density and increasing system mass with payload. Although the technical specifications of the batteries are fairly acceptable, they often fail to provide stable, long-duration flights due to limited energy density and increasing system mass with payload. Recent studies have proposed various methods to address these limitations, highlighting the need for innovative solutions to enhance UAV endurance [6–8]. While these solutions offer promising improvements, the integration of fuel cells has far higher specific energy and power, allowing UAVs to carry heavier payloads or travel farther [9].

1.2. Battery-Based Propulsion

Lithium-ion (Li-ion) batteries are the most common choice among battery-based solutions. High power and energy density, low self-discharge rates, long life, and recycling potential make Li-ion batteries suitable for UAV applications [10,11]. There is an excellent variety of choices for Li-ion batteries; Table 1 presents an overview of some of them as well as two non-Li-ion batteries for comparison [12].

Table 1. Batteries overview [12].

Type	Cell Voltage,	Specific Energy, $\frac{Wh}{kg}$	Specific Power, $\frac{W}{kg}$
$LiCoO_2$	3.6	125	200+
$LiMn_2O_4$	4.00	150	200
$LiFePO_4$	3.5	120	100
$LiTiS_2$	2.15	125	65
LiS	2.10	300	200
$NaNiCl_2$	2.58	90	90–155
Zn–NiOOH	1.74	50–80	200–300

Li-ion batteries surpass other batteries in terms of key parameters for UAVs, such as cell voltage and specific energy. According to trends, Li-ion batteries' specific energy will increase to 300 Wh/kg within the next few years [13]. Batteries are a great option for the UAV power supply system due to their simplicity, high efficiency and specific energy, thermal stability, reliability, and low emissions [14].

Battery-based propulsion systems have several limitations, including limited energy density, shorter flight times, and the need for frequent recharging. These limitations restrict the range and mission capabilities of electric UAVs, necessitating the exploration of alternative power sources that offer improved performance and endurance.

1.3. Fuel Cells

One of the most promising and highly investigated technologies nowadays is the fuel cell. It offers a variety of scales and options, including vehicular and stationary motive power. Proton exchange membrane fuel cells offer several key benefits as an alternative power source for electric UAVs, including high efficiency, zero-emission, high specific energy density, longer flight endurance, adaptability to different power requirements, and zero noise pollution [15]. Table 2 [15] demonstrates that fuel cells have greater energy and power density than batteries, making them suitable for UAV applications [16]. In this article, we will investigate these benefits in greater detail through modeling, optimization, and performance analysis of a PEM fuel cell for UAV applications.

Table 2. Energy and power density of the fuel cell [15].

Specific Energy		Specific Power	
Wh/kg	Wh/L	W/kg	W/L
800–20,000	500–3000	500+	500+

1.4. Literature Overview

This paper [17] provides a review that focuses on the use of fuel cells as alternative power sources for UAVs. While UAVs offer numerous advantages, their performance is limited by their propulsion systems. Fuel cells are an attractive option due to their higher efficiency, better reliability, and low emissions. The review covers the working principle of fuel cells, two types of propulsion systems involving fuel cells (pure fuel cell and hybrid), design methods and simulation cases, and practical flight tests.

This paper [18] describes the current developments in FC hybrid propulsion systems applied to UAVs. The review covers topics such as the operating principles and characteristics of the three typical FCs (PEMFC, SOFC, and DMFC), issues faced by FC-powered UAVs, potential impacts of various flight factors, and energy management strategies of FC hybrid propulsion systems. It was found that the PEMFC is the best candidate for small commercial UAVs, but the low power performance, slow response, and low efficiency of the low/high power output mode of the FC can limit the overall performance of FC propulsion systems in UAVs. Therefore, hybrid propulsion systems with FCs and other electric power sources, such as batteries and supercapacitors, are essential to achieve stable output and deal with emergency power supply requirements.

The article [19] discusses a study of a commercial PEM fuel cell system designed for unmanned aerial vehicles with a rated power of 258 W and a maximum efficiency of 47%. The fuel cell stack consists of 40 individual cells, and the individual voltage of all cells was measured at different currents. No significant variation was observed between them, indicating good cell balance. However, the efficiency of the system decreases at low power outputs (<80 W) due to energy losses through unreacted hydrogen. The energy losses due to heat generation become the primary contributor to lower efficiency at higher power outputs. This study found that heat losses, unreacted hydrogen (from purging and short-circuit), and balance of plant (BOP) energy consumption accounted for 41%, 10%, and 2% of the input energy at maximum efficiency, respectively. This study also provides a flight simulation based on actual UAV flight data. The fuel cell system was able to meet the simulation's energy requirements without issues.

This study [20] develops a hybrid system combining a PEM fuel cell and a Li-Po battery to increase the flight endurance of UAVs. Three architecture models were evaluated, and ground and air tests were performed. The fuel cell provided approximately 160–170 W of 250 W power, and the battery was selected based on estimated flight profiles to avoid critical voltage. Safety measures, such as measuring and controlling fuel cells and battery parameters, were recommended. The hybrid system was tested repeatedly under static and dynamic loads.

Due to the relatively poor energy density of lithium-ion batteries, this research by C. Depcik et al. [21] explores the potential use of hydrogen-fueled power plants for small UAVs. This study examines lithium-ion and lithium-air batteries, an internal combustion engine with an integrated generator, a parallel hybrid ICE, a free piston engine with an integrated linear generator, and a proton exchange membrane fuel cell. The authors discovered that while the ICE has superior performance characteristics, the FPE and PEMFC designs have the advantage of being able to produce power directly without a complex energy conversion system, hence lowering total weight. The Li-air battery pack would provide the longest flight time and have the simplest configuration; however, it cannot be implemented in practice.

This paper [22] analyzes various mathematical models to simulate electrochemical processes and predict system performance. Model 1 [23], developed by the CRIEPI research group, provides a detailed analysis of mass transport associated with oxygen reduction but may oversimplify complex interactions, leading to deviations in high current densities. Model 2 by Yuh and Selman [24] focuses on activation overpotentials and the effects of reactant composition, though it struggles with accuracy at high current densities due to its simplified approach to concentration losses. Model 3, from the University of Genoa [25], emphasizes ohmic resistance and neglects fuel electrode losses, offering computational simplicity at the expense of accuracy in more complex scenarios. Model 5 [26] provides a comprehensive approach by including detailed polarization losses, aligning well with experimental data, but requires extensive parameter fitting, which can be a limitation. The 4th model [27], however, stands out for its balance of simplicity and predictive power. It simplifies the cell voltage calculation by focusing on a small number of key parameters, making it computationally efficient while still providing reliable predictions. This makes that model a particularly suitable choice for simulating PEM fuel cells in our study, where a balance between accuracy and computational efficiency is crucial.

The literature review revealed that while fuel cells show promise as an alternative power source for UAVs, there is limited research on the optimization and performance analysis of PEM fuel cells specifically designed for UAV applications. Our research aims to address this gap by developing an adaptive, fully functioning model of a PEM fuel cell for electric UAVs, optimizing its parameters, and analyzing its performance in comparison to battery-based propulsion systems.

The use of hydrogen as a power source in aviation presents significant challenges, including safety concerns, weight limitations, and the need for specialized infrastructure. These challenges are particularly pronounced in manned aviation, where stringent regulations and passenger safety are paramount. However, unmanned aerial vehicles (UAVs) offer a unique opportunity to explore the potential of hydrogen fuel cells in a more flexible and less regulated environment. This study seeks to fill the existing knowledge gap by conducting a detailed feasibility analysis of integrating Proton Exchange Membrane (PEM) fuel cells into UAVs. Given the absence of passengers in UAVs, there is greater flexibility in design, which allows for innovative approaches to overcoming the traditional barriers associated with hydrogen fuel cell technology.

1.5. Novelty of This Paper

In this study, a theoretical investigation of the integration of a PEM fuel cell into a UAV is presented. Through the utilization of a novel mathematical model, the design of the PEM fuel cell can be optimized for maximum power output and efficiency within the constraints of the UAV's compact size and weight. Moreover, the successful implementation of this optimized PEM fuel cell into a small UAV is demonstrated, achieving extended flight duration and increased payload capabilities compared to traditional battery power systems. The results pave the way for further research into the integration of PEM fuel cells into a variety of small-scale aerospace applications. Thus, the novelty of this work lies in its comprehensive approach to optimizing and integrating Proton Exchange Membrane (PEM) fuel cells into Unmanned Aerial Vehicles (UAVs), focusing on enhancing power efficiency, endurance, and overall performance. While PEM fuel cells have been explored for various applications, their specific use in UAVs remains underdeveloped, with many existing studies focusing primarily on theoretical or small-scale practical tests without fully optimizing the system for real-world UAV applications.

This study introduces an innovative mathematical model tailored for UAV integration, optimizing the PEM fuel cell design to maximize power output and efficiency while adhering to the constraints of UAV size and weight. This model not only predicts the performance but also guides the practical implementation, showing that the optimized fuel cell significantly extends flight duration and increases payload capacity compared to traditional battery systems. The work demonstrates a clear advancement over conventional battery-based UAV propulsion systems, which are limited by shorter flight times and lower energy densities.

Furthermore, this study's novelty is highlighted by its detailed feasibility analysis, showing that the PEM fuel cell can achieve these performance gains with only a modest increase in overall system weight. This finding is particularly important as it opens new possibilities for longer-duration UAV missions, making fuel cell-powered UAVs a viable alternative for applications where extended endurance is critical.

This paper is structured as follows: Section 2 discusses the theory of PEMFC and the Reduced Order Model used, and it presents introductory information about the investigated UAV. Section 3 covers the model simulation, scale-up process, and feasibility study. Section 4 discusses the integration of the fuel cell into the UAV. Sections 5 and 6 present the discussion and conclusion, respectively.

2. Theory

2.1. Proton Exchange Membrane Fuel Cell

A fuel cell is an electrochemical device that converts chemical energy fully into electrical energy without any intermediate stages (Figure 1a) [28,29].

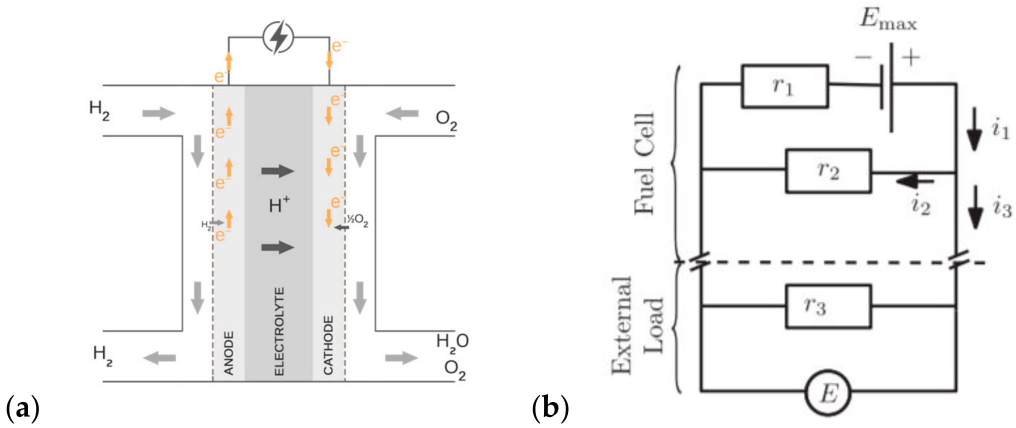

Figure 1. (**a**) PEMFC operation principle, (**b**) reduced order model scheme.

A fuel, typically H_2, is going to the anode side, where it oxidizes and splits into electrons and ions (Equation (1)). Electrons then go through an external circuit, while ions go through the electrolyte (the ion exchange membrane, Nafion®, which is a perfluorosulfonic acid polymer [30]) to the cathode side, where an oxidant, which is normally ambient air, is supplied. At the cathode side, oxygen meets with the ions and electrons to complete the reaction and produce water and heat as a bypass product (Equation (2)) [31]. The overall cell reaction is presented in Equation (3) [28].

$$2H_2 \rightarrow 4e^- + 4H^+ \qquad E^0 = -0.000\text{ V} \tag{1}$$

$$4e^- + 4H^+ + O_2 \rightarrow 2H_2O \qquad E^0 = +1.229\text{ V} \tag{2}$$

$$H_2 + \frac{1}{2}O_2 \rightarrow H_2O \qquad E^0 = 1.229\text{ V} \tag{3}$$

The maximum voltage of the fuel cell can be estimated according to the Nernst equation (Equation (4)):

$$E_{max} = E^0 + \frac{RT}{2F} ln \frac{p_{H_2} + p_{O_2}^{\frac{1}{2}}}{p_{H_2O}} \tag{4}$$

where E^0—ideal standard Nernst potential, R—universal gas constant, T—temperature, F—Faraday's constant, p—partial pressure of the reactants and products. The ideal standard Nernst potential for the PEMFC is $E^0 = 1.229$ V [32]. It is assumed that the temperature of the process in the cell is constant, so the process needs to be considered isothermal.

2.2. Reduced Order Model

Besides the simplicity of the fuel cell at first sight, it is not easy to model the operation of the fuel cell. The fuel cell encompasses various scientific disciplines, such as thermodynamics, physics, chemistry, fluid mechanics, etc. There are many different models of fuel cells proposed [33–38]. This work will refer to the approach described in [27]. The reduced-order model (ROM) offers simplicity and physical response. It states that if hydrogen ions are the charge carriers, an equivalent electric circuit can be created describing the fuel cell (Figure 1b).

Using Ohm's and Kirchhoff's laws and solving the set of equations, we can write an equation for the real cell voltage for PEMFC (Equation (5)):

$$E_{PEMFC} = \frac{E_{max} - i_{max}\eta_f r_1}{1 + \frac{r_1}{r_2}\left(1 - \eta_f\right)} \tag{5}$$

$$i_{max} = \begin{cases} \frac{2 \cdot F \cdot \dot{n}_{H_2,\ eq}}{A_{cell}} \\ \frac{4 \cdot F \cdot \dot{n}_{O_2,\ eq}}{A_{cell}} \\ \frac{2 \cdot F \cdot \dot{n}_{CO_2,\ eq}}{A_{cell}} \end{cases} \tag{6}$$

where E_{max} is the Nernst Voltage (Equation (4)), i_{max}—maximum current density (Equation (6)), η_f—fuel utilization factor, r_1—area specific internal ionic resistance, and r_2 is an area specific internal electronic resistance.

2.3. Investigated UAV

The chosen UAV for fuel cell reconfiguration is A.R.C.H.E.R. (Figure 2), designed by a team of students at Warsaw University of Technology. One of the main features of this UAV is its reconfigurability, meaning that the design of the UAV itself might be changed. The cruise power of the UAV is about 800–1000 W, at a full payload estimated to take 1300 W. Without a payload, on two 6S LiPo batteries, this UAV is capable of 28 min of flight endurance.

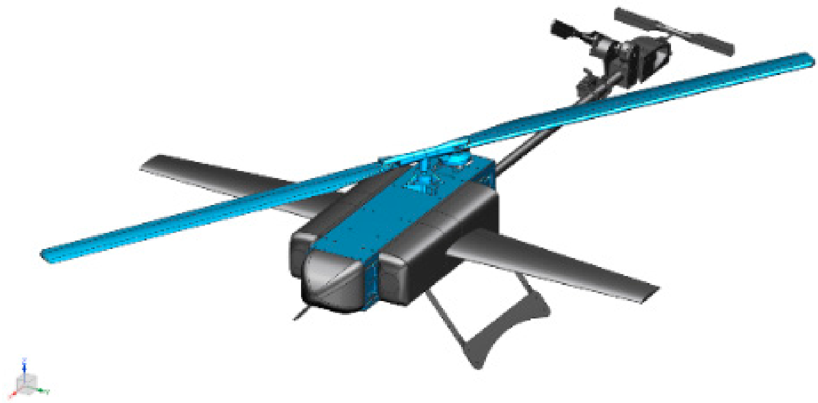

Figure 2. Investigated UAV A.R.C.H.E.R.

The initial parameters of the UAV are listed in Table 3.

Table 3. Initial parameters of investigated UAV.

Parameter	Value
Power	1500, W
MTOW	12.5, kg
Voltage	22.2, V
Battery capacity	2 × 7000, mAh
Mass of one battery	756, g
Flight time without payload	28, min

3. Model Simulation

3.1. Simulation Preparations

The theoretical model was realized in Aspen HYSYS v2.4.1 software. This paper proposes a new tool for fuel cell electrochemical process simulation, together with the possibility of stack mechanical dimensions and property scalability. The model integrates the electrochemical simulation approach with construction development. The novel feature of this model is its ability to optimize the objective mechanical and electrochemical parameters of the fuel cell stack together. The model provides a tool to simulate and select the scale of the fuel cell stack for applications where both performance and size are crucial.

A complete scheme of the simulation is presented in Figure 3. The initial parameters of pressure across the fuel cell, the molar flow of hydrogen, and the inlet temperatures of the flow can be set up. The rest of the parameters are calculated by the software. The inlet parameters were assumed to match the required power input of the UAV by the fuel cell system, taking into account the operation conditions of actual atmospheric PEM fuel cells and hydrogen delivery systems. The flow rate of hydrogen was adjusted to match the requested power of the system, while the fuel utilization factor was used to adjust the appropriate operation point of current and voltage. The operating temperature of the fuel cell as well as the composition of the outlet gases were calculated numerically using the reduced-order model of the fuel cell and Gibbs free energy law.

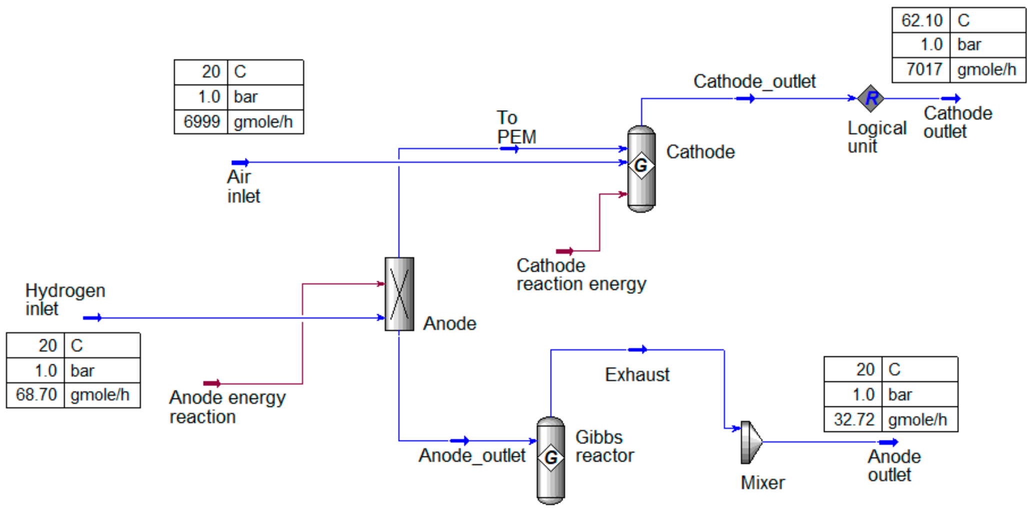

Figure 3. Scheme of the simulation.

Before the simulation of the real problem, a simulation of the process for the case was conducted, where the cell active surface area is 1 cm^2. It gives the opportunity to check the correctness of the model based on the case study analysis. The next step is an optimization of the parameters. With a derived objective function (Equation (7)) as a function of efficiency and power $\eta_{opt} = f(\eta_{eff}, P)$. Using the objective function, it is possible to optimize the key parameters to achieve optimal performance. After applying the objective function to the simulation, a balanced model of the fuel cell with an active surface area of 1 cm^2 was obtained.

$$\eta_{opt} = \eta_{eff} \cdot P = \frac{(E_{real} I_{real})^2}{LHV_{H_2} \dot{n}_{H_2}} \tag{7}$$

where η_{eff}—efficiency, P—power, E_{real}—real voltage, I_{real}—real current, LVH_{H_2}—Lower Heating Value of H_2, and $\dot{n}_{H_2}$ is molar flow of the H_2.

3.2. Scale-Up

Scale-up is the process where the adjustment of the key parameters occurs based on our needs and is the last stage of the modeling process. As an output of scaling-up, the power of 1.5 kW should be produced by the fuel cell. From the ROM, hydrogen molar flow ($\dot{n}_{H_2}$), air molar flow ($\dot{n}_{air}$), and active surface area (A_{cell}) have a direct impact on the power produced by the cell. The key parameters after adjustment and scale-up of the fuel cell are listed in Table 4.

Table 4. Scaled-up parameters.

Parameter	Value	Unit
Power	1500	W
Electrical efficiency	62.03	%
Current	1928	A
Voltage	0.7778	V
Active surface area	5431	cm^2
Temperature	62.10	°C
Molar flow, H_2	68.70	gmole/h
Molar flow, air	6999	gmole/h

From that point on, the adaptive model of the system is finished. It can be used not only for the chosen UAV but practically for every UAV that needs to replace its power source with PEMFC.

It is worth noticing that the active surface area of the cell is quite large (5431 cm^2). The reason for this is that we found out the optimal current density of the cell, and then the system was adjusting A_{cell} to maintain current density at a fixed value. That A_{cell} is comparable to the single square cell with an edge of 74 cm. This square should be equally divided into smaller cells with an appropriate dimension to fit in the UAV. As was mentioned above, hydrogen molar flow has a direct impact on the cell potential; nevertheless, it's bonded together with the air molar flow. If it does not bond, the temperature of the cell will vary. An optimization of this relationship was conducted, and it is estimated to be $\dot{n}_{fuel} = 101.9\dot{n}_{air}$. Hydrogen molar flow was adjusted with respect to the power, and simultaneously, air molar flow was changed to maintain the temperature in the cell.

It should be noted that this system is designed to be air-cooled, leveraging the airflow around the drone during operation to dissipate heat naturally. This approach simplifies the design and reduces weight, contributing to the UAV's efficiency and range. Additionally, the system can incorporate radiators to dissipate excess heat when necessary, ensuring that the operating temperature remains within the optimal range. Effective thermal management through these methods is crucial for maintaining the long-term durability of the PEM fuel cells, as temperature fluctuations can significantly impact their performance and lifespan. By maintaining a stable temperature, the fuel cell can operate more efficiently, reducing energy losses due to heat generation [39].

Despite UAV reconfigurability, initial dimensions need to be considered. After calculating the number of cells, the following results were obtained: N_{cell} = 39, A_{cell} = 142.85 cm^2. A brief analysis was conducted on the lightweight, high-power components that the commercial offers. For comparison, typical thickness parameters of the cell parts are shown in [29]. The thickness of the current collector was taken from [40] The thickness of the single cell is estimated to be 1.44 mm (with the current collector), and the total thickness (casing included) is 66.16 mm.

To estimate the mass of the stack, research was conducted using open commercial sources. The masses estimated for all components are listed in Table 5.

Table 5. Mass of the components in the stack.

Component	Mass,g
Bolts and nuts	142
Anode and Cathode	76
Membrane	10
Current collector	382
Endplates	289

The overall fuel cell stack is bigger than two combined batteries, but the UAV itself is configurable, which gives a fuel cell an opportunity to be installed into a UAV.

3.3. Feasibility Study

The simulated PEM fuel cell for UAV purposes was able to operate as high as 323 mW/cm^2 with a maximal current density of 0.72 A/cm^2. The simulation environment allowed us to cover all the possible operating points, as indicated in Figure 4.

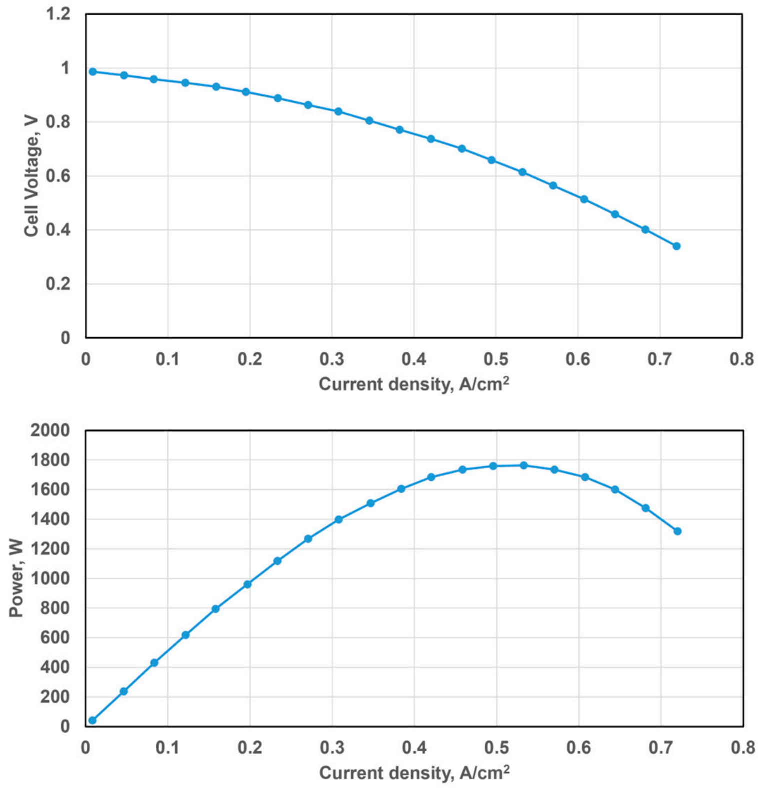

Figure 4. Simulation results of PEM fuel cell: current-voltage (**top**) and current-power (**bottom**) dependency.

One of the parameters that should be compared between battery and fuel cells is energy density. Knowing the parameters of the battery (Table 3), it is possible to calculate its energy density. For two batteries, the energy density (gravimetric) is estimated to be 207 Wh/kg. That amount of energy density gives approximately 30 min of flight time. At the same time, 50 g of hydrogen gives about 1666 Wh/kg (based on LHV). If the volumetric energy density is taken into consideration, hydrogen stored at 300 bars has a density ρ = 20 kg/m^3 [41], which results in an energy density of 666 Wh/L. Two batteries with dimensions listed in Table 3 have a volumetric energy density of 486 Wh/L. Figure 5 shows the comparison of the specific energies of the battery and fuel cell. In order to increase the endurance from 30 min to 1 h, it is necessary to double the mass of the battery. Compared to the battery, which weighs 3 kg, the fuel cell's entire system—fuel cell, fuel, and tank—would weigh roughly 2.2 kg. The further increase in endurance will result in a rapid increase in battery mass and volume. The mass of the fuel cell stack, on the other hand, will remain the same; only the mass of the fuel and tank (with the volume of the tank) will increase. Figure 6 presents the difference in mass depending on the operation time.

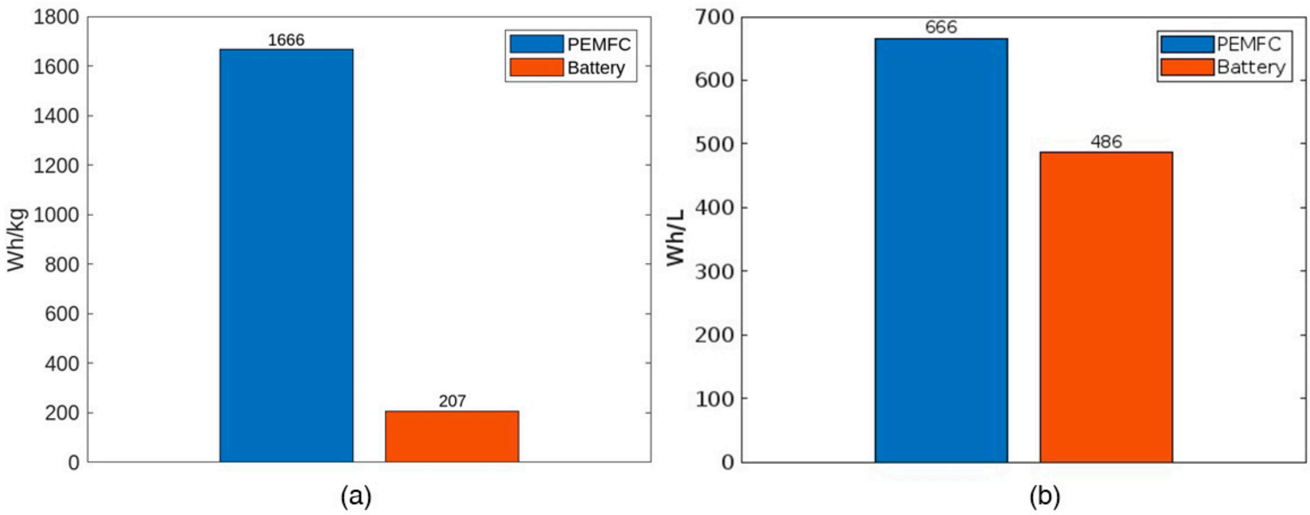

Figure 5. Specific energy of battery vs. fuel cell: (**a**) gravimetric; (**b**) volumetric.

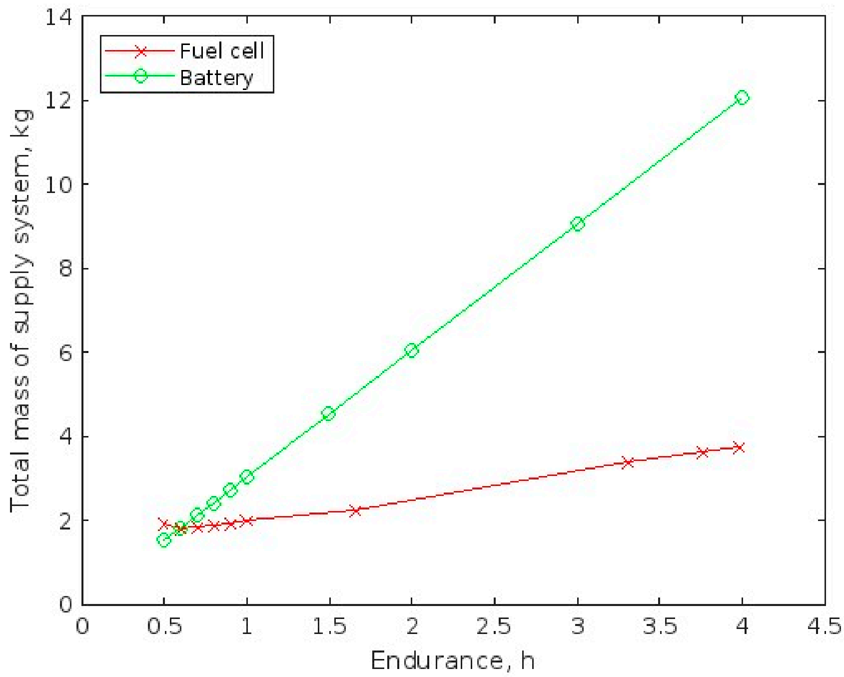

Figure 6. Total mass of the supply system vs. time of operation.

Table 6 provides a concise summary of numerically optimized UAV-dedicated PEM fuel cell stack parameters, indicating a configuration of 39 cells generating a current of 50 A and a voltage of 30 V. Physical dimensions, including a length of 119 mm, a thickness of 66 mm, and a mass of 901 g, are detailed, reflecting the considerations for optimizing both power density and integration within UAV platforms. These parameters are critical for assessing the feasibility and efficiency of using PEM fuel cells in UAV applications.

Table 6. Summary of UAV-dedicated stack parameters.

Parameter	Value	Unit
N_{cells}	39	-
Current	50	A
Voltage	30	V
Acell	142.85	cm^2
Length (Width)	119	mm
Thickness	66	mm
Mass	901	g

An interesting investigation was performed about the feasibility of applying fuel cells to UAVs. Figure 6 shows the point where the application of the fuel cell is not feasible. Particularly if the present set-up (battery and fuel cell) is to be taken at the same cruise power, it appears that below 36 min of operation, the application of the fuel cell is pointless. Even though the estimation procedures for the mass of the tank are complex and nonlinear, we might assume a ±10% error margin, which will result in about 40 min of flight endurance. From a technical point of view, applying fuel cells for 40 min of flight endurance does not make sense either because of fuel cell complexity or high cost. Nevertheless, the fuel cell solution has an advantage over batteries since it can provide more power and better endurance.

While the results presented in this study are at an early stage, they are intentionally positioned to explore the high novelty and potential of hydrogen fuel cells in UAV applications. The exploratory nature of this research reflects the complex and uncharted landscape of integrating hydrogen fuel cells into aviation. By focusing on UAVs, which do not carry passengers, this study takes advantage of the flexibility in design and operational parameters. This approach allows for a practical investigation into the feasibility of using hydrogen as a power source in aviation, paving the way for further advancements in this challenging yet promising area.

4. Propulsion System

Fuel Cell Integration

Based on the parameters of the battery, it was calculated that the mass of the battery is 12% of the MTOW. Up to 20% of the MTOW may occupy the propulsion system. An operation point is 1 kW of cruise power with the ability to access 1.5 kW of maximum power. In order to maintain 1 h of endurance, with the efficiency of the cell achieved during the modeling process ($\eta_{eff} = 62.03\%$), the UAV would need 1612.12 Wh of hydrogen. That is equivalent to 50 g of hydrogen [42].

Only compressed-pressure tanks are taken into consideration for hydrogen storage. Composite tanks (Type III or IV) operating at 300–700 bars of pressure are relatively light and durable. From an economic and technological viewpoint, a Type III carbon-overwrapped aluminum pressure tank operating at 300 bar is a good option for hydrogen storage [43].

5. Discussion

One of the problems with unmanned aerial vehicles is their endurance. Low-temperature fuel cells can solve this problem because of the very high specific energy of hydrogen that is used as fuel. It gives the UAVs a great deal of power and, as a result, better endurance.

The method used in this work is model simulation based on the reduced-order model described in [27]. The ROM has some advantages over the ones that are in use. The model does not give any non-physical values. The change of design or flow parameter does not require changes in all previously used values (as it does in the classical approach).

Simulation and optimization helped achieve the required power capacity of 1500 W with surface active areas such as 5431 cm^2 and an operating current of 1928 A. Later, it was equally divided into squares of active surface area equal to 142.85 cm^2 to fit the initial geometry conditions of the UAV.

Comparing the specific energy and power densities of PEM fuel cells with those of batteries, the PEM fuel cells showed significantly higher values, making them suitable for UAV applications where long endurance and higher payload capacities are required. In comparison, a typical battery-based UAV propulsion system, such as one using lithium-ion batteries, often has a specific energy density of around 200–300 Wh/kg [4] and a specific power density of 200–300 W/kg. The energy density of the PEM fuel cell system developed in this study was significantly higher, with a specific energy density of approximately 1666 Wh/kg (based on the LHV) and a volumetric energy density of 666 Wh/L, compared to 486 Wh/L for the battery system. This increased energy density resulted in a flight endurance of 60 min for the fuel cell system, compared to just 28 min for the battery system under similar conditions.

The mass analysis of the entire power supply system revealed an important consideration: the practicality of using a fuel cell system is limited by the duration of the UAV's operation. Specifically, the application of the fuel cell system becomes less advantageous for flight durations under 36 min due to the additional weight and complexity associated with the system. Even with the complexities of estimating the mass of the hydrogen storage tank, a margin of error of $\pm$10% still indicates that the fuel cell system becomes more practical for flight durations around 40 min or longer. Beyond this threshold, the fuel cell system demonstrates clear benefits, providing significantly more power and better endurance. Specifically, the fuel cell system accounts for 17.6% of the MTOW compared to 12% for the battery-based system, yet it results in a 100% increase in flight endurance, doubling the UAV's operational time.

The findings of this paper align with recent studies where PEM fuel cells have been identified as a viable alternative for UAV propulsion, offering superior performance characteristics compared to conventional batteries and internal combustion engines. However, it is essential to consider the potential limitations, such as the increased complexity and cost of fuel cell systems, which may affect their practicality for certain UAV applications.

6. Conclusions

A PEM fuel cell was investigated as an alternative solution for battery-based electrical UAVs. The results of this research advance the understanding of PEM fuel cells as a power source for UAVs, addressing the limitations of current battery-based systems. By developing a novel adaptive model, this study has optimized the PEM fuel cell design to achieve high power output and efficiency, specifically within the constraints of UAV size and weight. This optimization has led to a significant increase in flight endurance, effectively doubling the operational time compared to traditional battery systems with only a modest increase in overall system mass. PEM fuel cells offer up to 2–3 times the flight endurance of traditional batteries, with energy densities around 1000–2000 Wh/kg compared to batteries' 150–250 Wh/kg. Despite a slight increase in system mass, fuel cells enable significantly longer UAV operations, making them a compelling alternative for extended missions. This work investigated that for a 4 h flight, the mass of the energy system based on batteries will be four times higher than that based on fuel cells. However, for short-term flights up to 1 h, battery-based power systems have strong benefits compared to fuel cells.

Economically, fuel cells may have higher initial costs, but their longer lifespan and reduced operational costs can lead to better cost-efficiency over time. Moreover, the adaptability of fuel cell systems allows for the integration of construction parameters, making them an attractive option for UAV applications requiring extended endurance and reliability.

The findings demonstrate that the high specific energy of hydrogen can greatly enhance UAV performance, making fuel cells a viable alternative to batteries in applications where extended endurance is critical. The comprehensive analysis and modeling conducted in this study fill a crucial knowledge gap, providing a foundation for further research and practical implementation of fuel cell technologies in UAVs.

The summary of key parameters is presented in Table 7, comparing the battery-based solution to the fuel cell-based solution:

Table 7. Summary of this research.

Parameters	Battery Based Solution	Fuel Cell Based Solution
Power, W	1500	1500
Mass of the power supply system, kg	1.5	2.2
Flighttime, min	28	60

This research shows the possibilities for UAV applications, particularly in scenarios where long flight times and higher payload capacities are essential. The contributions of this study provide a valuable reference for future work in the field, supporting the continued development and integration of fuel cell technology in UAVs.

It is important to acknowledge that the findings of this study represent a preliminary exploration into the use of PEM fuel cells in UAVs. The high novelty of our approach inherently results in outcomes that may appear premature; however, this is a necessary step in pioneering new applications for hydrogen in aviation. This research presented here not only addresses current knowledge gaps but also sets the foundation for future studies to build upon, ultimately advancing the viability of hydrogen fuel cells in UAV technology and beyond.

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