Enhancing Unmanned Aerial Vehicle (UAV) Endurance with Hybrid Hydrogen Fuel Cells and Lithium Batteries for Extended Flight Time

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***Abstract*—This paper presents a comparative analysis of hybrid hydrogen fuel cell and lithium battery power systems for enhancing the endurance of unmanned aerial vehicles (UAVs). Compared to a battery-only configuration, the study evaluates the performance of a UAV powered by a $500-W$ proton exchange membrane (PEM) fuel cell integrated with a lithium polymer battery. Experimental tests, including static bench evaluations and flight trials, were conducted to assess key performance metrics such as flight duration, energy density, power distribution efficiency, and hydrogen consumption rate. The results demonstrate that the hybrid system extends flight endurance by 25%, increasing operational time from 20 to 25 minutes. However, challenges related to hydrogen storage constraints and limited peak power output necessitate further optimization. The cost-benefit analysis highlights a higher initial investment for hydrogen fuel cells than battery-only systems, yet fuel cells offer a longer operational lifespan and reduced battery replacement frequency. The break-even point for the hydrogen system, at which a fuel cell-only configuration achieves the same energy density as the battery-only system, is observed at $3.5-L$ of hydrogen stored at $350 bar$. The findings suggest that hybrid hydrogen fuel cell-powered UAVs offer a promising alternative for long-endurance missions, provided that key storage and power management limitations are addressed.**

***Index Terms*—Drones, Hydrogen fuel cells, Lithium batteries, UAV power systems, Energy efficiency, Elight endurance.**

I. Introduction

Unmanned Aerial Vehicles (UAVs) are widely used in surveillance, logistics, and environmental monitoring, making flight endurance and power efficiency critical factors in their performance. Lithium batteries are the most common power source due to their high energy density and ease of integration, but they have limitations in endurance for long UAV flight durations. Hydrogen fuel cells offer an alternative with higher energy density and longer flight durations. Unlike batteries, fuel cells enable rapid refueling and produce only water vapor, making them a more sustainable option. However, challenges such as hydrogen storage and system complexity must be addressed to optimize UAV performance.

This paper compares lithium batteries and hydrogen fuel cells for UAV applications, analyzing power efficiency, endurance, and hybrid system configurations. The rest of the paper is structured as follows: Section II reviews UAV power sources and storage technologies. Section III outlines the methodology used in the study. Section IV presents the results and discussion. Finally, Section V provides conclusions and future research directions.

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II. Literature Review

A. Power Sources for UAVs

Unmanned Aerial Vehicles (UAVs) rely on efficient power sources to meet the demands of various applications, such as surveillance, delivery, and environmental monitoring. Among batteries, lithium batteries are the most commonly used power source due to their high energy density (120–170 Wh/kg), compact size, and ease of integration. However, their limited flight duration and sensitivity to environmental conditions have prompted the exploration of alternative power sources, such as hydrogen fuel cells [1], [2]. In contrast, hydrogen fuel cells, particularly proton exchange membrane fuel cells (PEMFC), offer significantly higher energy densities ($> 800 Wh/kg$) and longer flight durations compared to lithium batteries [2]. Additionally, hydrogen fuel cells provide the advantage of rapid refueling, meaning UAVs can continue operating as long as fuel is available, with refueling taking only a short period compared to the charging cycles required for batteries [1], [3], [4].

Fuel cells convert hydrogen into electricity through an electrochemical reaction with oxygen, producing water vapor as the only byproduct, making them an environmentally friendly alternative [5]. Different types of fuel cells exist, with Proton Exchange Membrane Fuel Cells (PEMFCs) being the most commonly used in UAV applications due to their low operating temperature ($30-100°C$) and high power output (1-500 kW) [2], [6].

Hybrid systems combining fuel cells and batteries have emerged as a promising solution. These systems leverage the continuous power output of fuel cells and the high power density of batteries to handle transient loads, resulting in extended flight times and improved efficiency. Hybrid power systems, which combine fuel cells with lithium ion batteries, enhance UAV efficiency by utilizing the battery for transient power demands while maintaining fuel cell endurance [7].

B. Hydrogen Storage Technologies

Efficient hydrogen storage is crucial for UAV applications, with multiple storage methods available, each offering distinct advantages and challenges. High-pressure gas storage in "Type IV" vessels, which use carbon fiber-reinforced plastic (CFRP) and non-metal liners, is a widely adopted method. Lee et al. optimized these vessels using a genetic algorithm, achieving a weight reduction of 23.79% while maintaining structural integrity at 30 MPa pressure [8]. This makes them suitable for long-endurance UAV missions that require lightweight and high-capacity storage. Alternative storage methods include metal hydrides and liquid hydrogen. Metal hydrides offer compact low-pressure storage, but are limited by lower power output at high-demand stages [9]. Liquefied hydrogen storage allows for high energy density, but requires cryogenic tanks and advanced thermal management systems, making it complex for UAV integration [10].Chemical hydrogen storage, using compounds like sodium borohydride ($NaBH_4$), offers safe, low-pressure storage with high packing density [10].

C. UAV Power System Configurations

UAV power systems can be categorized into single power sources and hybrid configurations. Single power sources are simpler but often lack the versatility required for diverse mission profiles. For example, lithium batteries are ideal for short-duration missions due to their high power output and ease of use. At the same time, fuel cells excel in long-endurance applications due to their higher energy density [1], [11]. Hybrid systems, which combine fuel cells and batteries, offer a balanced approach. These systems optimize the strengths of both technologies: fuel cells provide continuous power, while batteries handle peak loads. Apeland et al. demonstrated that hybrid systems significantly increase specific energy, enabling longer flight times [7]. For example, a $250-W$ PEMFC hybrid system achieved a flight duration of 5 hours, showcasing the potential of hybrid configurations for high-power UAV applications [12].

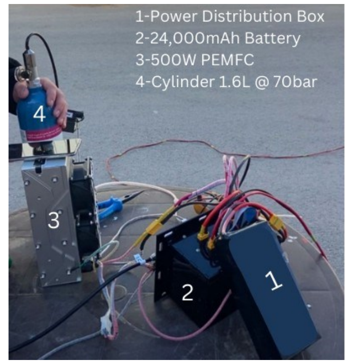

Fig. 1. The experimental setup showing all the key components

III. METHODOLOGY

A. Research Design and Approach

This research employs a quasi-experimental design to compare the performance of hydrogen fuel cell-powered UAVs with lithium battery-powered UAVs under real-world operational conditions. The approach integrates both static and dynamic testing methodologies to evaluate power efficiency, endurance, and feasibility for UAV applications.

1) Experimental Setup: The UAV prototype used in this study is a custom-built hexacopter designed to accommodate a lithium battery-only system and a hybrid hydrogen fuel cell-battery hybrid system. The setup is shown in Figure 1 and includes:

- A 500W Horizon H-500 PEM fuel cell.
- 2 6S 24,000mAh lithium battery.
- A power management system allows the fuel cell to provide a continuous 500W output while the battery supplements peak power demands.
- A hydrogen storage system consisting of a 1.6L cylinder pressurized to 70 bar.
- A boost converter to step up the fuel cell's output voltage to match the UAV's operational voltage requirements.
- A telemetry system to monitor power consumption, flight duration, and system efficiency in real-time.

Figure 2 illustrates the designed UAV power management system, which integrates a hydrogen fuel cell and a lithium battery to enhance endurance and efficiency. The fuel cell provides a continuous 14.4V at 35A, while the lithium battery supplements peak loads. A DC-DC converter steps up the fuel cell's output to 22.2V at 20A, which, along with the battery-managed 22.2V at 100A, supplies a maximum load of 22.2V at 120A.

A fuel cell controller regulates hydrogen consumption, and an Arduino-based power management unit ensures smooth energy distribution. The hydrogen storage system, consisting of a 1.6L, 70-bar cylinder, supplies fuel to the $500-W$ PEM fuel cell for sustained operation. The system dynamically manages power, optimizing UAV flight endurance while maintaining voltage stability.

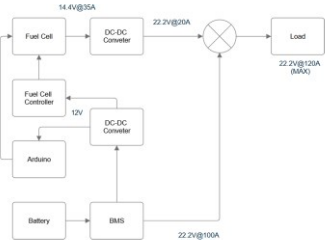

Fig. 2. Hybrid power system architecture of the UAV integrating a hydrogen fuel cell and a lithium battery

Fig. 3. The hexacopter UAV used in testing

2) Key Performance Metrics: To assess the feasibility and efficiency of hydrogen fuel cells as a power source for UAVs, the study focuses on the following key performance metrics:

- **Flight Duration:** The time from takeoff until the system reaches critical battery levels or hydrogen depletion.
- **Energy Density:** Comparison of specific energy (Wh/kg) between the battery-only and hybrid power configurations.
- **Power Distribution Efficiency:** Analysis of how effectively the hybrid system manages power between the fuel cell and battery.
- **Hydrogen Consumption Rate:** Measurement of hydrogen usage per minute of flight to determine system efficiency.
- **Environmental Impact:** Assessment of emissions and sustainability advantages compared to lithium batteries.

The methodology includes static ground testing to validate system stability under controlled conditions, followed by flight tests to evaluate real-world performance. The collected data provide insights into the viability of hydrogen-powered UAVs and highlight potential areas for further optimization.

B. UAV Prototype and System Specifications

The UAV prototype utilized in this study is a hexacopter designed for medium-endurance applications, incorporating both battery-only and hybrid hydrogen fuel cell-battery configurations. The following subsections describe the key components and specifications.

1) Airframe and Structural Design: The UAV airframe is constructed from lightweight carbon fiber to ensure structural integrity while minimizing overall weight, see Figure 3. The hexacopter configuration provides enhanced stability and payload capacity. The total weight distribution of the system, including the hybrid power source, is optimized for maximum endurance.

2) Power System Components: The hybrid power system integrates a $500W$ Horizon H-500 PEM fuel cell and a 2 6S $24,000mAh$ lithium polymer battery (LiPo) battery, configured to provide a stable energy supply under varying power demands. This system consists of the fuel cell, the LiPo battery, the boost converter, and the hydrogen storage.

3) Propulsion System: The UAV is equipped with six high-efficiency brushless motors, paired with $16 - inch$ carbon fiber propellers. These components are selected to maximize thrust efficiency and energy conservation which is crucial for extended flight missions.

4) Weight Distribution and Energy Density: The total maximum takeoff weight of the drone, integrating the hybrid power system, is 18.5 kg. This figure includes a designated payload capacity of 2 kg. equivalent to $181.685N$, with the following component breakdown:

TABLE I
UAV MASS DISTRIBUTION

Component	Mass (kg)
Airframe	3.0
Fuel Cell + Hydrogen Cylinder	7.0
LiPo Battery	6.5
Payload	2
Other Electronics	0.5
Total Mass	18.5

The calculated energy density of the UAV in hybrid configuration is $90.5 Wh/kg$, providing a significant endurance advantage over lithium-only systems, which typically offer around $164 Wh/kg$ yielding shorter flight times.

5) Power Distribution and Efficiency: The UAV's hybrid power system is designed to manage energy dynamically:

- Cruising Power Mode: The fuel cell provides continuous power while slowly recharging the battery.
- High-Demand Phases (Takeoff, Maneuvers): The LiPo battery supplements the fuel cell to meet power surges above $500W$.
- Regenerative Energy Use: The excess power from the fuel cell is redirected to charge the battery when demand is low.

This configuration ensures extended endurance, stable voltage supply, and efficient energy utilization, making it a promising solution for long-endurance UAV applications.

C. Testing Procedures

The testing procedures were designed to evaluate the performance, endurance, and efficiency of the UAV power systems under controlled and real-world conditions. The experiments were divided into static bench testing and flight tests to analyze power stability, energy consumption, and system reliability.

1) Static Bench Testing: The static bench tests were conducted to validate the fuel cell and battery system performance under controlled conditions before integrating the system into the UAV. The objectives of the static tests included:

- Assessing the stability of the power output from the fuel cell and battery.

- Measuring voltage and current fluctuations under different load conditions.
- Evaluating the response time of the fuel cell when transitioning between power modes.
- Monitoring the hydrogen consumption rate at various power loads.

The test setup consisted of a programmable electronic load to simulate UAV power demands. The hybrid power system was subjected to varying loads, mimicking flight conditions such as cruising and high-thrust maneuvers. Power delivery consistency, efficiency, and temperature variations were recorded throughout the tests. The data collected provided insight into the optimal power-sharing strategy between the fuel cell and the battery.

2) Flight Tests: Flight tests were conducted to assess the real-world endurance and efficiency of the UAV under operational conditions. These tests aimed to:

- Measure total flight duration under the two configurations.
- Analyze power distribution between the fuel cell and battery during different flight phases.
- Evaluate UAV stability and handling performance with the hybrid power system.
- Record hydrogen consumption rates and compare them to static test results.

The UAV was flown in a controlled outdoor environment with minimal wind interference to ensure repeatability of test conditions. Two flight configurations were tested:

1) **Battery-Only Mode:** The UAV operated solely on the LiPO battery to establish a baseline for endurance and power consumption.
2) **Hybrid Mode:** The UAV utilized both the fuel cell and battery, with the fuel cell providing continuous power while the battery managed peak loads.

During the flights, real-time telemetry data, including voltage, current, altitude, and power distribution, were recorded. The hybrid system demonstrated improved flight endurance compared to the battery-only configuration, validating the advantages of integrating a hydrogen fuel cell.

The results from both static and flight tests provided a comprehensive understanding of the system's capabilities, efficiency, and potential areas for optimization.

D. Data Collection and Analysis

To comprehensively evaluate the performance of the UAV power system, key metrics were collected and analyzed from static bench tests and flight experiments. The data analysis focused on quantifying energy efficiency, flight duration, and power density to assess the advantages of the hybrid hydrogen fuel cell-battery configuration compared to a battery-only system.

1) Energy Efficiency: Energy efficiency was measured by evaluating the power conversion and utilization within the hybrid system. The following parameters were recorded:

- **Fuel Cell Efficiency:** The ratio of electrical power output to the hydrogen energy input is calculated to determine the fuel cell's effective utilization.
- **Battery Discharge Rate:** The rate at which the battery discharged under different flight conditions, indicating the efficiency of power-sharing between the fuel cell and battery.
- **Boost Converter Efficiency:** The effectiveness of stepping up the fuel cell voltage to meet UAV operational requirements, minimizing energy losses.

The energy efficiency was compared across different power demands, including steady-state cruise and high-thrust maneuvers, to identify optimal power distribution strategies.

2) Flight Duration: Flight duration was a critical performance indicator and was measured under two configurations:

1) **Battery-Only Configuration:** The UAV operated solely on a 2 6S 24,000mAh lithium battery to establish a baseline flight endurance.
2) **Hybrid Fuel Cell-Battery Configuration:** The UAV operated with the fuel cell providing continuous power while the battery supported transient loads.

The total flight time was recorded for each configuration, with particular attention to:

- The impact of hybridization on extending flight duration.
- The fuel cell's ability to sustain continuous flight without battery depletion.
- Variability in flight time based on environmental factors such as wind resistance.

3) Power Density: The power density was analyzed to evaluate the trade-off between added fuel cell weight and endurance benefits. The calculation involved:

$$P/m = \frac{P_{\text{total}}}{m_{\text{total}}} \tag{1}$$

where:

- P_{total} is the combined power output from the fuel cell and battery (in Watts).
- m_{total} is the total UAV takeoff weight, including the airframe, propulsion system, battery, fuel cell, and hydrogen storage (in kg).

This metric was compared between the battery-only and hybrid configurations to determine whether the added weight of the fuel cell justified the endurance improvements.

4) Data Logging and Analysis Tools: Real-time telemetry and onboard logging systems were used to capture power, voltage, current, and hydrogen consumption. Data analysis was performed using:

- **MATLAB:** For processing and visualizing power consumption trends and efficiency metrics.
- **Excel and Python:** For statistical analysis and comparative performance evaluation.
- **Telemetry System:** For monitoring of power distribution and UAV performance in flight.

The analysis provided insights into system optimization, highlighting areas where fuel cell performance could be improved for greater UAV endurance.

IV. Results and Discussion

The results obtained from both static bench testing and flight experiments are analyzed in this section to assess the performance of the UAV power systems. The discussion focuses on flight duration improvements and power management efficiency in hybrid hydrogen fuel cell-battery configurations compared to battery-only systems.

A. Performance Analysis

1) Flight Duration Comparison: Flight endurance is a critical factor in UAV performance, and the comparison between the battery-only and hybrid configurations demonstrated significant differences:

- **Battery-Only Configuration:** The UAV achieved an average flight duration of 20 minutes under standard operating conditions.
- **Hybrid Configuration:** The integration of the 500W hydrogen fuel cell extended the flight duration to 25 minutes, marking an improvement of approximately 25%.

The increase in endurance results from the continuous power supply provided by the fuel cell, reducing the battery discharge rate. However, the total energy-to-weight ratio plays a crucial role in determining system feasibility.

As shown in Table II, the break-even point for the hydrogen system, considering its energy efficiency and weight constraints, is observed at **3.5L of hydrogen stored at 350 bar**. This threshold represents the minimum hydrogen capacity required to achieve comparable energy storage to lithium batteries in long-endurance UAV applications. The significantly lower energy-to-weight ratio of the hydrogen system (22.14 Wh/kg) compared to the lithium battery system (164 Wh/kg) highlights the need for further advancements in lightweight hydrogen storage solutions to enhance overall feasibility.

TABLE II
Comparison of Energy Storage Systems for UAV Power Sources

Activity	LiPo Battery	Hybrid System	Hydrogen System
Energy Stored	1066 Wh (2 lipo)	1221 Wh	155 Wh
Weight	6.5 kg	13.5 kg	7 kg
Energy Density	164 Wh/kg	90.5 Wh/kg	22.14 Wh/kg
Break-Even Point	-	-	3.5L @ 350 bar

2) Power Management Efficiency: Efficient power management is essential for ensuring UAV stability and optimizing energy distribution between the fuel cell and battery. The hybrid system's power-sharing strategy was evaluated based on:

- **Voltage Stability:** The fuel cell maintained a steady output voltage of $14.4V$, which was stepped up to $22.2V$ using a boost converter to match the UAV's operational requirements.
- **Battery Load Reduction:** The fuel cell supplied continuous power, reducing battery discharge rates and extending its lifespan.
- **Redundancy and Reliability:** The battery acted as a backup power source, ensuring system redundancy in case of fuel cell voltage fluctuations or temporary performance dips.

During high-thrust maneuvers, power demand exceeded the $500W$ limit of the fuel cell, requiring additional energy from the battery. The system effectively transitioned between power sources, preventing sudden voltage drops and ensuring uninterrupted operation.

The results indicated that the hybrid system not only enhanced flight duration but also improved power reliability by dynamically adjusting power distribution based on flight conditions. The combination of fuel cell and battery power sources created a more resilient UAV energy system, reducing risks associated with single-source failures.

These findings demonstrate that hybrid hydrogen fuel cell-powered UAVs offer substantial advantages in endurance and energy efficiency. However, further research is required to optimize hydrogen storage solutions and enhance the power density of fuel cell technology for broader UAV applications.

B. Environmental Impact

The environmental impact of UAV power sources is key to their sustainability. This subsection compares the lifecycle emissions of lithium batteries and hydrogen fuel cells, outlining their advantages and challenges.

1) Emissions Comparison: Lithium batteries and hydrogen fuel cells differ significantly in their environmental footprints:

- **Lithium Battery Emissions:** The production of lithium batteries involves energy-intensive mining of lithium, cobalt, and nickel, contributing to high carbon emissions and environmental degradation. Battery disposal remains a challenge due to toxic waste and limited recycling infrastructure.
- **Hydrogen Fuel Cell Emissions:** Fuel cells produce zero operational emissions, with water vapor as the only byproduct. However, their environmental impact depends on the hydrogen production method. Gray hydrogen, derived from fossil fuels, has a high carbon footprint, whereas green hydrogen, produced via electrolysis with renewable energy, has minimal emissions.
  While green hydrogen is cleaner, electrolyzer manufacturing involves energy-intensive processes, particularly for catalyst materials like platinum and iridium. Additionally, the production of electrolyzers requires steel, polymers, and specialized membranes, contributing to indirect carbon emissions. Advancements in electrolyzer technology, such as solid oxide and proton exchange membrane (PEM) electrolyzers, are reducing material demands and energy consumption, enhancing sustainability.

Table III summarizes the lifecycle emissions of both power sources.

TABLE III
LIFECYCLE EMISSIONS COMPARISON OF LITHIUM BATTERIES AND HYDROGEN FUEL CELLS

Factor	Lithium Batteries	Hydrogen Fuel Cells
Extraction	High (mining lithium, cobalt, nickel)	Moderate (platinum, iridium for electrolyzers)
Manufacturing	High carbon footprint	Moderate to high (electrolyzer and fuel cell production)
Electrolyzer Manufacturing	Not applicable	Material-intensive (steel, membranes, catalysts)
Operational Emissions	None	None (only water vapor)
Energy Source Dependency	Grid electricity (may include fossil fuels)	Depends on hydrogen source (green hydrogen is low-emission)
Disposal	Toxic waste, limited recycling	Minimal waste, some recyclable components
Infrastructure	Well-established but requires battery replacement	Requires hydrogen storage and refueling infrastructure

Lithium batteries are practical for short-duration UAVs but have high production and disposal impacts. Hydrogen fuel cells offer a cleaner alternative, particularly when powered by green hydrogen.

2) Sustainability of Hydrogen Fuel Cells: The sustainability of hydrogen fuel cells depends on production, storage, and infrastructure advancements:

- **Renewable Hydrogen Production:** Electrolysis using renewable energy eliminates carbon emissions. Efficiency improvements and cost reductions will determine feasibility.
- **Storage and Transport Challenges:** Hydrogen's low energy density necessitates high-pressure or cryogenic storage. Lightweight, high-pressure tanks and solid-state hydrogen storage could improve UAV applications.
- **Infrastructure Development:** Hydrogen fuel cells require a refueling network, which is currently limited. Expanding hydrogen production and distribution will enhance scalability.

Despite these challenges, hydrogen fuel cells offer a sustainable solution for long-endurance UAVs in logistics, environmental monitoring, and defense. Continued advancements in hydrogen storage and production will improve their viability as an environmentally friendly alternative to lithium batteries.

C. Cost-Benefit Analysis

A comprehensive cost analysis was conducted to compare the financial feasibility of a hybrid hydrogen fuel cell-powered UAV versus a battery-powered UAV. The evaluation includes initial investment, operational costs, and long-term sustainability.

1) Initial Investment and Operational Costs: Transitioning from a battery-powered UAV to a hybrid fuel cell-battery system involves a significant upfront investment. The cost breakdown is as follows:

- **Fuel Cell Cost:**
  - 500W PEM fuel cell: $3,905
  - 1kW PEM fuel cell (potential upgrade): $5,200
- **Hydrogen Storage and Refueling:**
  - 1.6L 70 bar cylinder: $451 (providing 18 min flight time)
  - 3L 150 bar cylinder: $155 (allowing 75 min flight in static tests)
  - Hydrogen refueling cost: $1.4 per liter ($2.24 for 1.6L, $4.2 for 3L)
- **Battery System:**
  - 6S 24,000mAh lithium battery: $1,565 per unit
  - Two batteries required: $3,130
  - Battery replacement every 1 year: $565 - $987 per unit
- **Power Electronics and Circuit Components:**
  - Boost Converter (14.4V to 22.2V): $40
  - Buck Converter (Fuel cell controller 13V ±1V, 5 A): $7
  - Arduino and Relay for power management: $9
  - Battery Management System (BMS): $80
  - Total estimated electronics cost: $130
- **Printed Circuit Board (PCB) Development:**
  - Moving from plug-and-play to PCB reduces weight and improves reliability.
  - Estimated PCB development cost: $280

Total Initial Investment:

- Minimum cost: $4,624
- Maximum cost (with upgrades): $5,800

Operational Costs:

- Hydrogen refueling per flight: $2.24 (1.6L cylinder) or $4.2 (3L cylinder)
- Battery replacements every 1 year: $565 - $987 per battery
- Electronics maintenance and part replacements: $35 - $71 per year

While battery-powered UAVs have lower hydrogen-related costs, they incur higher expenses due to frequent battery replacements.

2) Maintenance and Longevity of Power Systems: Fuel cells have a longer lifespan than lithium batteries but require maintenance and refueling infrastructure.

- **Fuel Cell Lifespan:**
  - Expected operational life: 4,000 - 8,000 hours
  - Membrane replacement: $705 - $1,400 after extensive use
- **Battery Degradation and Replacement:**
  - Battery lifespan: 1 year with frequent use
  - Replacement cost: $565 - $987 per cycle
- **Circuit Reliability and Optimization:**
  - Boost and buck converter replacements: $40 - $47 per cycle

- Switching to PCB: \$280 improves durability and reduces weight
- **Hydrogen Storage Considerations:**
  - Cylinders require periodic safety inspections
  - Future improvements include higher-pressure (350 - 700 bar) or lightweight composite tanks

3) Final Cost-Performance Comparison: The prices for the drone, supporting systems, and battery were provided by Jordan Design and Development Bureau (JODDB) in their quotation.The fuel cell retail price was taken from horizon. Table IV compares the cost and performance of battery-powered and fuel cell-powered UAVs.

TABLE IV
FINAL COST-PERFORMANCE COMPARISON

Comparison	Battery-Powered UAV	Fuel Cell-Powered UAV
Initial Cost	\$3,130 - \$3,600	\$4,624 - \$5,800
Flight Duration	20 min	25 min (Hybrid)
Battery Life	1 year	-
Fuel Cell Life	N/A	4,000 - 8,000 hours
Refueling Cost	\$0.07 (electric charge)	\$1.4 per liter
Long-Term Cost	Frequent battery replacements	Lower maintenance but higher hydrogen costs

In addition to the cost and maintenance considerations discussed, the hybrid hydrogen fuel cell system introduces a reduction in payload capacity due to its increased weight. The total weight of the hybrid power system, including the fuel cell, hydrogen storage cylinders, and associated power electronics, is approximately 13.5 kg. In comparison, the original battery-powered system weighs around 6.5 kg. This results in a net reduction of 7 kg in available payload capacity. While this reduction impacts the economic feasibility for payload-dependent applications, the design of the hybrid UAV focused primarily on achieving extended flight endurance. For missions where flight time is prioritized over payload capacity, this trade-off was considered acceptable within the scope of this project. Nonetheless, future developments could investigate weight optimization techniques to further enhance both endurance and payload capabilities.

Battery-powered UAVs remain cost-effective for short-range applications due to their lower initial investment and easy recharging. However, frequent battery replacements (\$565 - \$987 per unit annually) make them less viable for long-endurance operations.

Hybrid fuel cell-powered UAVs provide extended endurance (25 min vs. 20 min for battery-only systems) and longer operational life (4,000 - 8,000 hours for fuel cells), reducing battery dependence. However, higher initial costs (\$4,624 - \$5,800) and the need for hydrogen refueling infrastructure pose adoption challenges.

Future advancements, including higher-capacity fuel cells (e.g., 1kW instead of 500W) and lightweight composite hydrogen tanks (350 - 700 bar), could enhance efficiency. Additionally, mass production of PEM fuel cells by companies like Siemens is expected to lower costs and expand hydrogen UAV adoption.

D. Key Limitations and Challenges

While hydrogen fuel cell technology presents significant advantages for UAV applications, several key limitations and challenges must be addressed to improve its practicality and scalability. The primary constraints include fuel cell power output limitations, hydrogen storage capacity, and system integration complexities.

1) Fuel Cell Power Output Limitations: Hydrogen fuel cells provide a continuous power output but are inherently limited in their peak power capacity. The major challenges associated with fuel cell power output include:

- **Limited Peak Power Handling:** The 500W PEM fuel cell used in this study delivers a steady-state power output but struggles to handle sudden surges in power demand, particularly during takeoff and rapid maneuvers.
- **Slow Response Time:** Unlike batteries, which can quickly discharge high amounts of current, fuel cells have a slower response time to changes in power demand, requiring additional power buffering mechanisms.
- **Hybrid Power Management Complexity:** The need to integrate a lithium battery to compensate for peak power demands adds complexity to the power management system, requiring efficient control algorithms to balance power sources effectively.

Potential solutions to mitigate these challenges include increasing the rated power of the fuel cell, improving hybrid energy management strategies, and developing more responsive fuel cell architectures with rapid power delivery capabilities.

2) Hydrogen Storage Capacity Constraints: Hydrogen storage remains a critical bottleneck in fuel cell UAV applications, as current storage technologies present limitations in both capacity and weight efficiency. Key challenges include:

- **Low Energy Density Per Volume:** While hydrogen has a high gravimetric energy density, its volumetric energy density is low, requiring high-pressure or cryogenic storage solutions to accommodate sufficient fuel for extended flights.
- **Weight Considerations:** The $1.6\ -L$, $70\ -bar$ hydrogen cylinder used in this study provides a limited flight duration. The hybrid powered UAV developed in this study has a maximum takeoff weight of 18.5 kg, including a 2 kg payload capacity. Although the hybrid system adds weight compared to fully electric UAVs, it was carefully designed to retain practical payload capabilities for real-world use. Most of the added weight comes not from the hydrogen fuel itself, which is negligible, but from its supporting components, such as the high-pressure cylinder, valves, tubing, regulators, and the fuel cell. Advances in storage technology, particularly lightweight composite cylinders, offer a way to reduce this weight. These materials allow higher storage pressures and more hydrogen capacity without significantly increasing or

even reducing the overall system weight, enabling longer flight times without sacrificing payload.

- **Storage Safety and Leakage Risks:** High pressure hydrogen storage poses safety concerns, including risks of leaks and fire hazards, necessitating stringent safety protocols and robust containment systems.
- **Refueling Infrastructure Limitations:** The availability of hydrogen refueling stations remains a challenge, particularly in remote or field-deployed UAV operations, restricting the practicality of hydrogen-powered UAVs in certain applications.

To overcome these constraints, advancements in lightweight hydrogen storage materials (such as metal hydrides or solid-state hydrogen storage), high-pressure composite tanks, and on-demand hydrogen generation technologies are required.

3) System Integration and Operational Challenges: Deploying a fuel cell-powered UAV introduces additional system-level challenges, including:

- **Thermal Management:** Fuel cells generate heat during operation, requiring active cooling solutions to maintain efficiency and prevent overheating.
- **System Complexity:** The integration of multiple power sources, including fuel cells and batteries, demands sophisticated power distribution and control strategies to optimize energy efficiency.
- **Cost Considerations:** The high initial investment in fuel cells, hydrogen storage, and refueling infrastructure remains a barrier to widespread adoption, particularly for cost-sensitive UAV applications.

Despite these challenges, hydrogen fuel cells remain a promising technology for long-endurance UAVs. Continued research into higher-efficiency fuel cells, improved hydrogen storage methods, and cost-effective system integration will be key to unlocking the full potential of hydrogen-powered UAVs for commercial and industrial applications.

V. Conclusion

This study compared lithium batteries and hydrogen fuel cells as UAV power sources, demonstrating that a hybrid system with a 500W PEM fuel cell and a 6S lithium battery extends flight time by 25% (from 20 to 25 minutes). While fuel cells provide continuous power, their limited peak output necessitates battery support, increasing system complexity. Hydrogen storage constraints, particularly with the 1.6L 70 bar tank, restrict further endurance improvements, making storage advancements a priority for future research.

The cost analysis highlights a significant initial investment for fuel cell-powered UAVs ($4,624 - $5,800) compared to battery-only systems ($3,130 - $3,600). However, fuel cells offer a longer operational lifespan (4,000 - 8,000 hours), reducing the need for frequent battery replacements, which range from $284 - $497 per year. While hydrogen refueling adds operational costs, advancements in on-site hydrogen generation and lightweight composite tanks (350 - 700 bar) could mitigate these expenses over time.

Integrating fuel cells with lithium batteries enhances endurance and reliability but introduces challenges in weight distribution, power management, and refueling infrastructure. Hybrid systems are more viable for larger UAVs where increased payload capacity can accommodate fuel cell and storage requirements. Future developments should focus on increasing hydrogen storage efficiency, scaling up fuel cell power output (1kW+), and integrating AI-driven energy management systems to optimize performance.

Despite current limitations, hydrogen fuel cells present a promising pathway for long-endurance UAVs. With advancements in fuel cell technology, hydrogen storage, and sustainable hydrogen production, hybrid UAVs can become a competitive alternative to traditional battery-powered systems. Continued investment in infrastructure and cost-reduction strategies will be essential for the widespread adoption of hydrogen-powered UAVs in commercial and defense applications.

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