MASS AND FLIGHT ENDURANCE OPTIMIZATON OF A HYDROGEN POWERED SEARCH AND RESCUE QUADCOPTER

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ABSTRACT

Increased flight time of search and rescue quadcopters is essential for critical missions that endanger public safety. An inhouse mathematical model was built to analyse the drone's performance using both batteries and hydrogen fuel cells. The aim of this study is to determine the viability of utilizing hydrogen fuel cells in drones to extend their flight time. The analysis was done by modelling power equations to find the drone's flight time as it was the most important performance parameter. A Li-Po battery with a specific energy density of 200Wh/kg was compared with hydrogen fuel cells to obtain the drone's endurance. The results of this study determined that fuel cells are desirable above a critical mass point of 1.32 kg of the energy system while batteries are more suitable below this point. A mass sensitivity analysis was conducted to investigate the importance of mass savings on the endurance of the quadcopter. Peak endurance is achieved when the mass of the energy system is precisely two-thirds of the total quadcopter's mass.

Keywords: Search and Rescue (SAR), Hydrogen Fuel Cell, Quadcopter, Endurance.

INTRODUCTION

In this modern age, Unmanned Aerial Vehicles (UAVs) have revolutionized the aerospace industry by integrating into various applications in sectors such as agriculture, search and rescue, transportation, surveillance, and many others. Experts predict that the market for these UAVs, better known as drones, will grow up to $6.3 billion by 2026 [1]. Drones are extensively used in search and rescue missions as they can explore inaccessible terrains. SAR operations are unpredictable as missions include objectives such as locating a missing person, scanning the surrounding area for any threats, and helping injured individuals. SAR drones are fitted with advanced camera and tracking systems so that they can search rapidly compared to ground search teams. Quick deployment is crucial as time is of the essence in these types of missions. 96% of drones sold worldwide are battery powered and thus have limitations on flight times and range [2]. Current standard SAR drones only have a flight time of less than an hour which may not be sufficient for extended missions that require a larger search area [3]. This is due to the limited capacity of the battery installed. In many drone applications the Lithium Polymer (Li-Po) battery is used more often than the Lithium Ion (Li-ion) battery as it provides an improved energy density of 200Wh/kg compared to 150Wh/kg of the Li-ion battery [4]. SAR drones come in different configurations such as fixed wing and rotary wing. Fixed wing drones can fly at a higher altitude and for longer durations compared to rotary wing drones, however fixed wing drones need a runway or a mechanism that is able to launch the drone into the air, hence slowing the deployment of the fixed wing drone. Moreover, fixed wing drones cannot hover at a specific area which reduces its versatility [5]. Rotary wing UAVs are preferred in SAR missions and thus will be considered in this study.

Alternative power sources such as using hydrogen fuel, solar power or micro gas turbines are being tested to replace batteries. Hydrogen propulsion has been suggested as the way forward as it does not emit any carbon dioxide as highlighted by Cecere [6]. Moreover, hydrogen fuel has been gaining popularity due to its high energy density (Wh/kg) thus making it an attractive option for researchers and industries. With the growing demand for SAR drones to increase public safety, optimizing the power sources to achieve longer endurance remains a priority. Hydrogen fuel is the best alternative to a Li-Po battery as it boasts a higher energy per mass ratio [7]. Kang et al. determined the energy density of liquid hydrogen to be within the range of 2000-2500Wh/kg while Apeland has shown that hydrogen fuel cell systems exhibit an energy density of 250-540Wh/kg [8-9]. Fuel cell systems have lower energy per mass because the mass of the additional equipment was accounted for rather than just the mass of hydrogen as shown by Kang et al. Fitting a hydrogen fuel tank on a SAR drone can increase the flight time however storage of hydrogen is a complication especially on a drone where weight is critical. Zhao et al. proposed an optimization algorithm for mass and power of a hydrogen powered quadcopter. This study has shown that the optimal design has a mass reduction of 25% while maintaining the same high-level performance [10]. Similarly, Wang et al. showed, using a mathematical model, a mass reduction of 30% can be achieved [11]. Hydrogen can be stored either as a liquid cryogenically at -252.8°C or as a gas, in insulated high pressurized containers with pressures ranging from 350-700 bar due to its low volumetric density. Brewer concluded his study by showing that an aircraft fueled with liquid hydrogen instead of kerosene is beneficial in terms of weight reduction [12]. Lee et al. have investigated weight optimization for hydrogen storage vessels using genetic algorithm. The limitation of their study is that they did not consider the total mass of the drone [13]. Storing hydrogen requires additional apparatus that may hinder the endurance and the maneuverability of the drone due to the increase in overall mass. Another alternative is to explore hydrogen fuel cells for mass optimization. In Huang's study a hybrid power system of a quadcopter, consisting of a hydrogen fuel cell and a Li-ion battery, improved endurance and reduced the total mass [14]. A particle swarm optimization algorithm has been proposed by Boston et al. to show that a mass reduction of 15% of a hydrogen powered quadcopter is possible [15]. In this study, a basic quadcopter concept was created, shown in Figure 1, will be used to find the optimized performance of the quadcopter with an installed hydrogen storage. The aim of this project is to show how small can a hydrogen powered SAR quadcopter be without compromising the flight time.

Figure 1: CAD design of a basic quadcopter concept.

Basics of Hydrogen Fuel Cells

Figure 2 shows how a basic hydrogen fuel cell work. The stored hydrogen fuel is compressed and fed into the fuel cell and combined with oxygen obtained from the air at the cathode. In this example, a Proton Exchange Membrane (PEM) fuel cell is shown, and it uses a proton conducting polymer membrane as the electrolyte. A catalyst breaks down the hydrogen atoms into protons and electrons. The electrons flow at the external circuit towards the cathode to generate and electric current while the protons move across the selectively permeable membrane. This membrane blocks the electrons and prevents mixing of the hydrogen and oxygen gas by having separate cathode and anode compartments.

The protons and electrons are combined again at the cathode with the introduction of oxygen to produce water and heat as by-products.

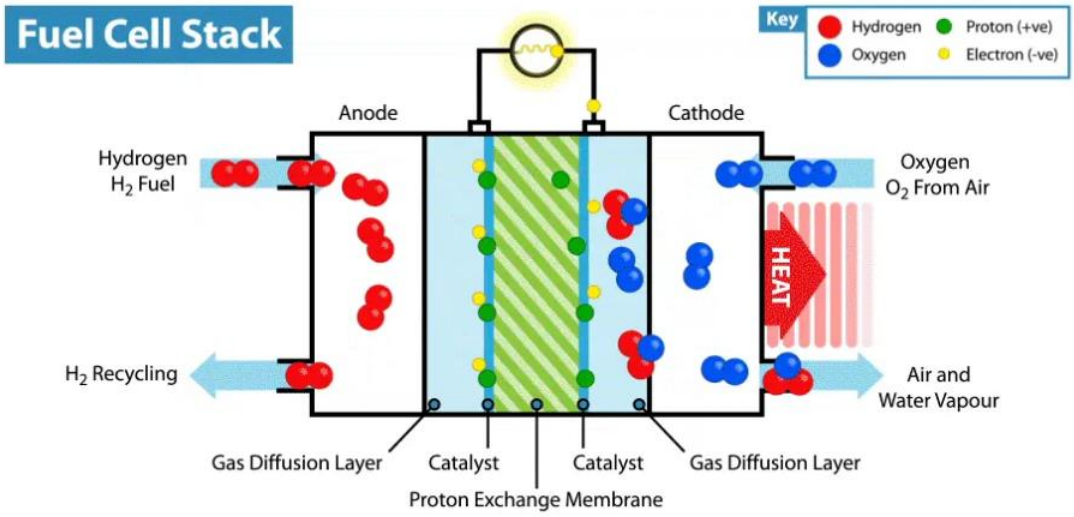

Figure 2: PEM fuel cell process reproduced by Unmanned® Systems Technology [16].

Fuel cells are devices that convert chemical energy into electrical energy through an electrochemical reaction. They are most viable for drones as fuel cells have a higher energy density and a longer operating time compared to batteries. Moreover, fuel cells are lightweight which is critical for drone applications as it results in an increase in payload capacity and an extended flight range.

METHODOLOGY

Analytical methods were used to optimize the mass of the hydrogen powered quadcopter by comparing with a battery powered counterpart. A mathematical model was created based on simple model equations and was validated with data from reliable literature sources published from manufacturers and experimental results. This resulted in correlations between different design parameters. The initial analysis was based on the battery powered Mavic 3 to validate the model which is then used to analyze the hydrogen powered quadcopter and make performance comparisons.

Parameters Initial Sizing

The Mavic 3 drone was used as the baseline concept as it boasts a flight time of 45 minutes and has a battery capacity of 5000 mAh. The total mass of the quadcopter (m_{total}) is decomposed into the fixed mass of the SAR equipment (m_{SAR}), the fixed mass of the drone's frame and avionic subsystem (m_{EW}) and the mass of the onboard energy system (m_{ES}) which is essentially the propulsion system. The dimensions and the mass distribution of the Mavic 3 drone will be shown in Table 1 [17].

$$m_{total} = m_{SAR} + m_{EW} + m_{ES} \tag{1}$$

Drones used for SAR missions are equipped with a 4K camera, a thermal imaging camera, a GPS system (RTK module), a radio transceiver, and other essential rescue gear which include first aid kits and harnessing equipment. The m_{SAR} is fixed as there is no priority to reduce weight on SAR essential equipment as it is vital for rescue missions. m_{EW} is fixed in this study although it could be altered by choosing different materials. The airframe and its components can be manufactured with lighter materials leading to a smaller m_{EW}. m_{ES} is a variable as it changes with respect to the mass of the energy system used whether it is a battery or hydrogen fuel cells. Figure 3 shows the system architecture of the Mavic 3 SAR quadcopter.

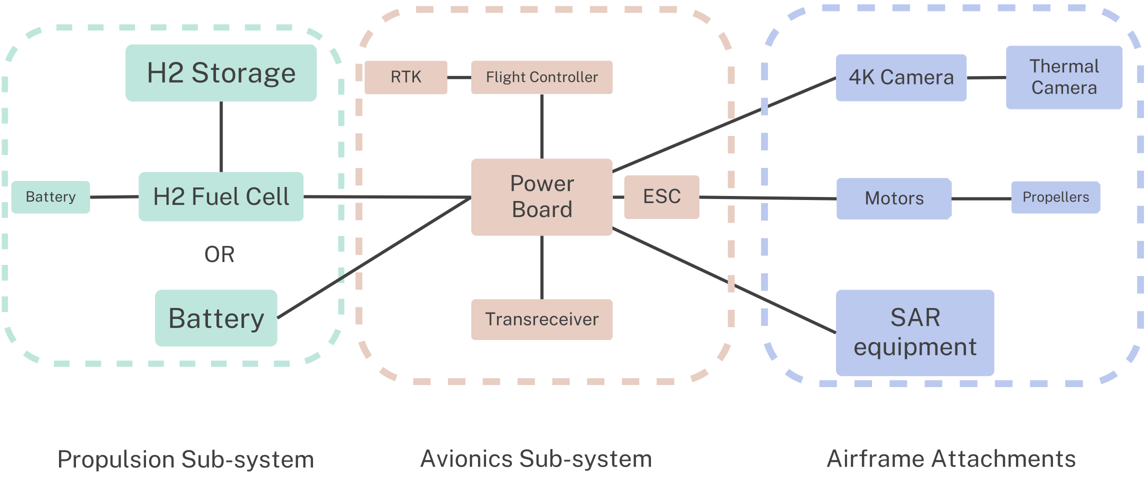

Figure 3: System architecture of the Mavic 3 SAR quadcopter which includes three sub-systems that were considered in the mass decomposition of this study. The mass of the propulsion system is the independent variable which is altered based on the power required to fly the drone.

Mathematical Modelling
An inhouse mathematical model was created in MATLAB to find the endurance of the quadcopter powered by the two different energy sources individually. Power equations were implemented in the model to find the required power of the drone under different design parameters. The equations used will be expanded and explained in the following sections. This model was validated by obtaining published literature from industries and compared to the experimental results of various sources. Assumptions such as stable hover, absence of wind speed, and maximum power consumption were made to simplify the model. To find the endurance of the quadcopter, the power required is essential as that determines how much battery or fuel the quadcopter needs.

Battery and Fuel Cell Specifications
This study required generated data about batteries and hydrogen fuel cells such as specific energy density and mass to perform analyses on the energy systems. As a result, data was taken from several manufacturers and a correlation between the specifications was established. Moreover, different fuel cells were compared to determine the most suitable fit on the quadcopter.

Performance Analysis
Determining the endurance of the quadcopter requires the energy stored by the energy system (E_{ES}) and the power required for the drone (P_{hover}) as shown in Equation 2. To find out how much of power the quadcopter requires, the thrust (T), and the rotor area (A_{rotor}) should be known.

$$Endurance(min) = \frac{E_{ES}(Wh)}{P_{hover}(W)} \times \frac{60(\text{min})}{1(h)} \tag{2}$$

Equation 3 is used to find how much energy is stored in the battery ($E_{battery}$), where the specific energy density ($\sigma_{battery}$), and the depth of discharge (η_{DOD}) is known. The Li-Po batteries are preferred in weight sensitive applications as the energy density is 200Wh/kg compared to the Li-ion battery which has an energy density of 150Wh/kg [18]. The depth of discharge of Li-Po batteries affects the battery's lifespan and a value of 0.8 was chosen as it is the maximum discharge the battery can endure before it experiences permanent damage and a reduced capacity [19].

$$E_{battery} = \sigma_{battery} m_{battery} \eta_{DOD} \tag{3}$$

A substitute approach of computing the energy stored in the battery involves determining the nominal voltage (V) and the battery capacity (C) which is widely published by manufacturers. Equation 4 shows the relationship between the battery specifications mentioned. The units of nominal voltage are in Volts and the battery capacity is in milliampere-hours (mAh).

$$E_{battery} = \frac{CV\eta_{DOD}}{10^3} \tag{4}$$

To calculate the energy stored in the hydrogen fuel cell (E_{H_2}), Equation 5 is used. The density of hydrogen (ρ_{H_2}) is a function of the pressure and can be found in Eric and Marcia's article about standardized equations for hydrogen gas densities in fuel consumption applications [20]. The volume of the hydrogen storage (V_{H_2}) is calculated in liters and the efficiency of the fuel cell (η_{FC}) is based on the quality of the materials used to manufacture and is taken as 0.5 to ensure consistency of the study [21]. η_{H_2} is the hydrogen fuel utilization factor which shows that not all the hydrogen will be used in the electrochemical reaction and was assumed to be 0.95 [9]. h_{H_2} is the lower heating value (LHV) of hydrogen which equates to 33.3kWh/kg at standard temperature and pressure (STP) conditions. (i.e., 25°C and 0.1 MPa). The LHV is a measure of energy released when a substance is burned in excess oxygen.

$$E_{H_2} = \rho_{H_2} V_{H_2} \eta_{FC} \eta_{H_2} h_{H_2} \tag{5}$$

To calculate the thrust required, the weight, the initial acceleration during takeoff and the drag needs to be known. The acceleration depends on the weight and the power available by the motors. As it is the first iteration this is simplified by calculating the thrust during hover condition by using the rule of thumb of drone manufacturers shown in Equation 6 [22]. This allows the drone to perform basic operations and maneuvers including takeoff.

$$T = 2 \times m_{total} g \tag{6}$$

The rotor area (A_{rotor}) is the total area of the four propellers. The energy system of a battery powered drone only includes the battery whereas for the hydrogen one it includes the mass of the fuel cell along with the weight of the hydrogen storage. A small battery is included in the propulsion system of the fuel cell, but this is neglected as the mass is negligible compared to the mass of the hydrogen storage. In addition, this study compared between the power sources individually and as a result the small battery was not considered. As the mass increases the rotor area or the rotor speed should increase as the propellers now need to produce more lift. However, the area is kept constant to have a fair comparison on the endurance against the weight of the energy system rather than on the drone's capability. The power required during hover is calculated using Equation 7.

$$P_{hover} = \frac{T^{\frac{3}{2}}}{\sqrt{2\rho A_{rotor}}} \times \eta_{total} \tag{7}$$

η_{total} is the total efficiency of the drone's ability to create lift which is primarily affected by the product of the motor and propellers efficiencies shown in Equation 8. Since the motors and propellers used are constant the efficiency value will remain the same throughout this study.

$$\eta_{total} = \eta_{motors} \times \eta_{propeller} \tag{8}$$

Figure 4 shows a flowchart of the essential parameters considered in this study ranging from masses to efficiencies in the energy systems.

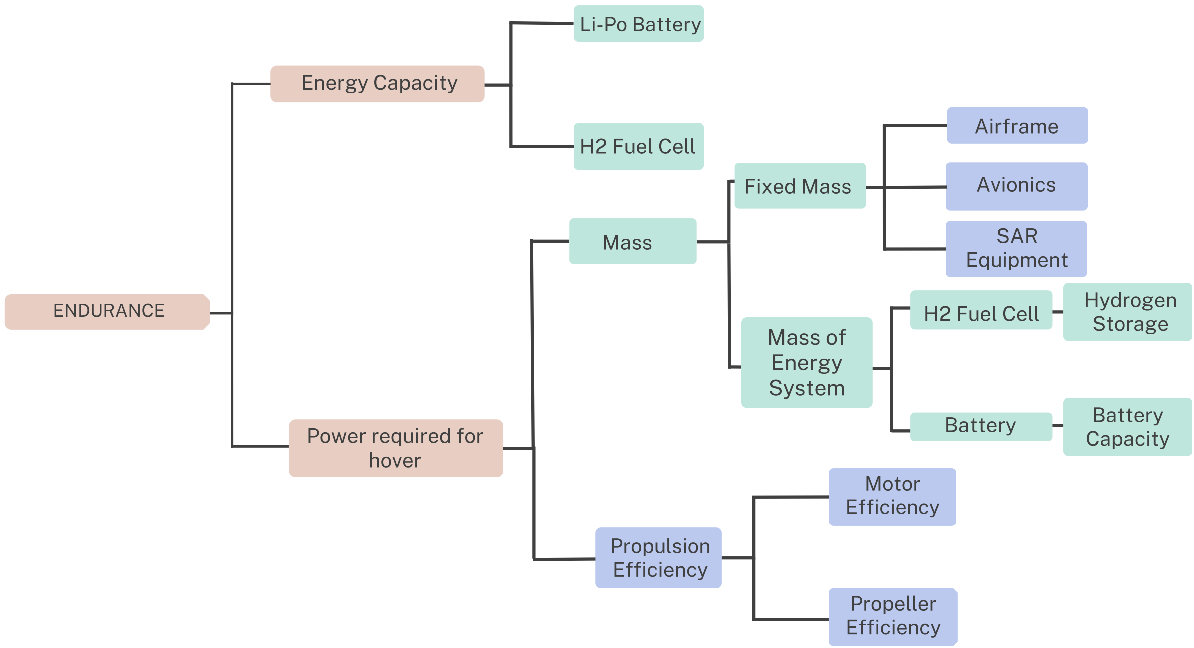

Figure 4: Endurance is affected by the energy capacity available by the power source and the power required for the quadcopter. The power required heavily depends on the total mass of the drone. One key component of the total mass is the mass of the energy system which is a function of the capacity of the energy system.

The sizing of the hydrogen storage was also considered in this study as it has a significant impact on the quadcopter's endurance. Different shapes, sizes and types of hydrogen storage containers were considered and studied from various resources to obtain the most viable option while maintaining safety and complying with the EU regulation standards.

Sensitivity Analysis

The performance of the drones powered by either a battery or a fuel cell can be compared by examining the flight times. A mass sensitivity analysis was conducted to see how the endurance is affected when the masses of different sub-systems were altered. The graph obtained for these energy systems was plotted with the mass of energy system on the x-axis and the endurance on the y-axis. This graph is essential as it provides a visual representation of the point where it is beneficial to use a hydrogen fuel cell or a battery.

RESULTS

The results section of this study aims to provide an insight in determining the critical mass point of the two energy systems compared to see which energy system is more efficient in terms of endurance. The main parameter for performance in this project is the endurance, also known as the flight time, and was calculated in minutes. Table 1 shows the masses of the equipment onboard the battery powered Mavic 3 quadcopter. The masses of the power sources were varied as storing hydrogen requires additional equipment that contributes to the increase in total mass of the quadcopter. Industrial standard hydrogen fuel cells were considered as well. The original battery powered Mavic 3 drone dimensions were used to conduct this study.

The drone is equipped with various components such as brushless motors and propellers which are used for lift generation and control. The RTK module is a device that enhances the navigation system so that the location is more precise. The beacon is used for signal detection, the spotlight for illumination and the speaker for noise alerts. The camera is used for imaging to send visual data to the user. The airframe holds all these components together and provides structural stability.

Table 1: Mavic 3 Dimensions and Specifications [17].

Components	Mass (g)
Brushless Motors	80
Thermal Camera	127
Frame	170
RTK module	26
Beacon	5.5
Spotlight	16
Speaker	87
Total Weight	915
Max Take Off Weight	5000

Battery	Type	Li-ion 4S
	Capacity	5000 mAh
	Weight	335.5 g
	Voltage	15.4 V
Propeller	Diameter	23.9 cm
	Area	0.179 m^2
	Weight	68 g
	Number	10
Max Hovering Time		40 min

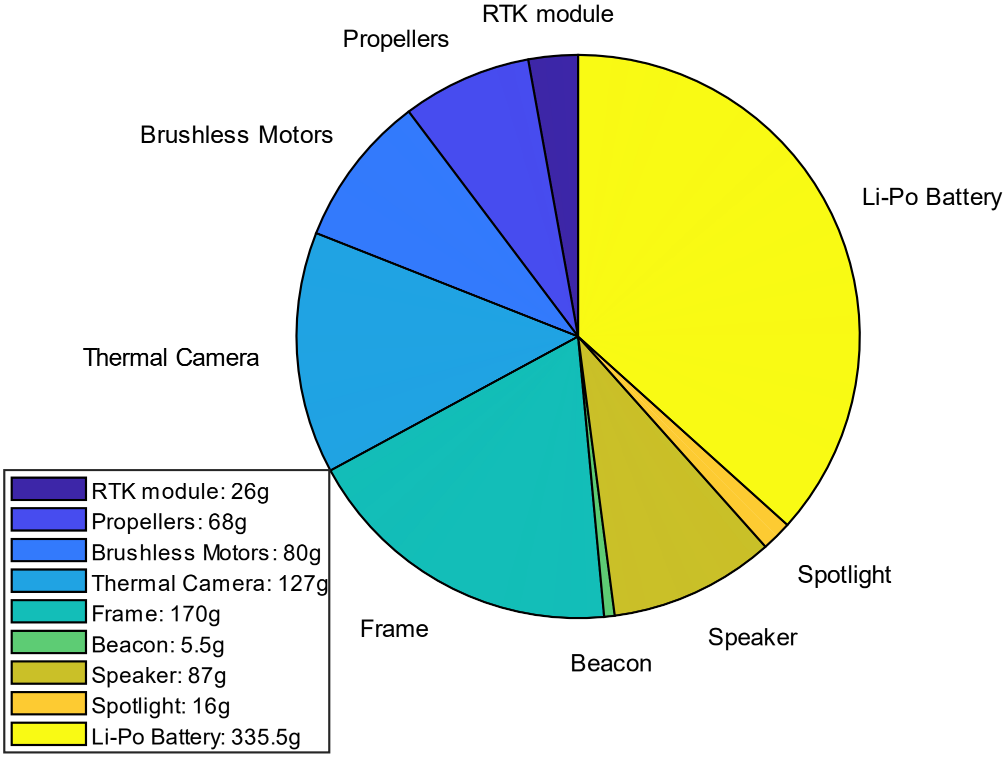

Figure 5: Mass distribution of a 0.915 kg battery powered Mavic 3 quadcopter.

As mentioned above the specific energy density (σ_{LiPo}) of Li-Po batteries is 200Wh/kg and Li-ion is 150Wh/kg. As weight is a critical parameter in rotary powered drones, Li-Po was preferred although it was compared to Li-ion to show the effect of specific energy density on the flight endurance.

Hydrogen Fuel Cells

There are various types of fuel cells such as Polymer Electrolyte Membrane (PEM), Solid Oxide Fuel Cell (SOFC) and Phosphoric Acid Fuel Cell (PAFC). PEM fuel cells are known for their high efficiency, low operational temperatures and are lightweight. SOFC are fuel cells that operate at temperatures between 600°C and 1000°C and due to the high operating temperatures, natural gas or hydrogen can be used. Although hydrogen is not ideal for this fuel cell due to its need for cryogenic temperatures, so propane is preferred. However, the efficiency is as low as 20% as there are thermal losses and takes a considerable amount of time to heat up. Table 2 shows a summary of the fuel cells compared and for this study the PEM fuel cell was chosen due to its high efficiency and high specific power.

Table 2: Fuel Cell Comparisons [23].

Fuel Cell Types	Operating Temperature (°C)	Max Efficiency (%)	Minimum Specific Power of Fuel Cell (W/kg)
PEMFC	30-100	60	500
SOFC	500-100	50	300
PAFC	150-200	40	200

Table 3 shows examples of mass comparisons of the PEM fuel cells. Fuel cells from different manufacturers have different power ratings and are studied to compute the performance of the drone by varying the amount of battery capacity or hydrogen it carries. These fuel cells are commercial off the shelf items (COTS) and are obtained from manufacturers such as Intelligent Energy and HES.[9,24-25].

Table 3: Specifications of COTS fuel cells.

Manufacturer	Fuel Cell	Power (W)	Mass (g)	Specific Power (W/kg)
Intelligent Energy	IE-800W	800	1450	552
	IE-1.2kW	1200	2700	444
	IE-2.4kW	2400	4800	500
HES	A-1000	1000	1800	556
	A-1500	1500	2800	536
	A-2000	2000	4400	457
Ballard	FCair 600	600	1800	333
	FCair 1200	1200	4000	300

Hydrogen Storage Cylinders

Hydrogen storage vessels are categorized in four types, as compressed hydrogen gas storage is the most mature technology used in industries. Type I is a steel cylinder and is the heaviest option storing hydrogen at 175-200 bars. Type II is a metal tank made with either steel or aluminum with glass or carbon fibers winding around the metal cylinder, and stores at pressure ranges of 260-300 bars. Type III is a tank made out of composite materials such as carbon fiber and epoxy resin and lined with metal. The pressure stored ranges from 300-700 bars and offers a mass reduction of 25%-75% compared to Type I cylinders[26]. Finally Type IV cylinder is a carbon fiber tank lined with polymer and the max pressure of hydrogen stored is 700 bars. Type IV is the lightest option available and can withstand a pressure of 1000 bar however it is the most expensive option due to the cost of carbon fiber manufacturing. Type I and Type II are unsuitable for vehicle applications due to their low hydrogen storage density which makes it unfeasible for drones.

Table 4: Summary of the 4 types of hydrogen storage cylinders.

Types	Materials	Traits
I	Steel cylinder	Heaviest with high durability
II	Metal cylinder with composite liner	Lighter and untransportable
III	Composite cylinder with metal liner	Lightweight and portable
IV	Composite cylinder with polymer liner	Lightest and highest strength to weight ratio

Storage vessels can take any shape but for this application, a lightweight solution is needed to withstand high pressures and not be prone to structural failure. Cylinders are great for hydrogen storage as they are equipped with materials that can withstand the stress of the pressurized gas. Rectangular tanks will lead to high stress concentrations at the corner points and is not space efficient compared to cylinders [27]. The rounded edges in cylinders distribute the stress concentrations and reduce the risk of structural failure. Additionally, cylinders are simple to fill and empty making it the ideal choice for a SAR quadcopter. Studies have optimized hydrogen storage using algorithms and experimental analysis [28-30]. In this study a Type IV cylinder is used as the storage option for hydrogen fuel.

Hydrogen Power

After choosing the PEM fuel cell and the type of storage the power can be calculated. The energy produced by the hydrogen fuel cell was calculated by using Equation 5 based on the sizing of the hydrogen storage. The values were obtained from CEN and was defined as the European Standard (EN 12245) [31].

Table 5: Hydrogen storage in Type IV cylinder.

Cylinder Volume (L)	Cylinder Mass (kg)	Mass of H_2 (g)	Energy capacity (Wh)	Power required (W)	Endurance (min)
1.0	1.2	20.9	209	428	30
2.0	1.4	41.7	417	487	51
3.0	1.6	62.5	624	550	68
6	2.7	125.0	1249	933	80
6.8	2.9	141.7	1416	1009	84
7.2	3.0	150.0	1499	1049	86
9.0	4.0	187.6	1874	1465	76

The mass of hydrogen was neglected as compared to the cylinder’s mass it was negligible. For a Type IV cylinder the mass of hydrogen only accounts for 5% of the weight [32]. The fixed mass of the SAR drone was taken to be 1kg to account for safety margin requirements as it may need to carry extra rescue gear. The equations listed above under power analysis were used to calculate these parameters and plotted in Figure 6 below.

Table 6: Efficiency values [21,33].

Efficiencies	Value
η_{FC}	0.50
η_{H_2}	0.95
η_{motors}	0.85
$\eta_{propellers}$	0.95
η_{total}	0.81

Even with a total efficiency of 0.3 of the hydrogen fuel cells, the high specific energy density increases the endurance compared to batteries with a depth of discharge of 80% to prevent damaging the battery. The mass of the fuel cell was constant as the only change was the amount of hydrogen stored. The power rating of the fuel cell varies as there is more hydrogen stored as the maximum power is used. The maximum power was calculated for one hour based on the energy capacity of the hydrogen stored.

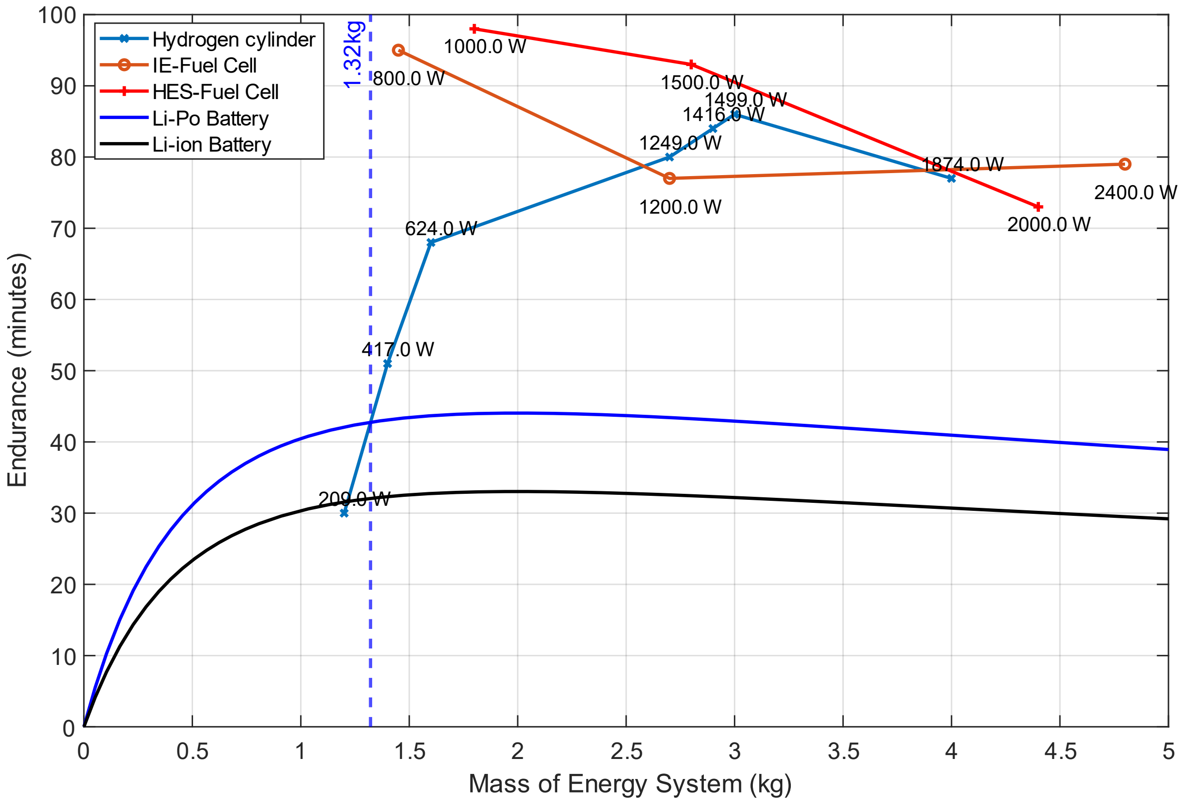

Figure 6: This graph shows how the mass of the energy systems affect the endurance of the drone. Batteries were compared with different hydrogen fuel cells to find the point where one technology is more efficient than the other. The critical point found was at 1.32 kg as it is the intersection between fuel cells and batteries. Batteries are more efficient below this point and fuel cells are more efficient for a heavier mass of the energy system.

Table 7: Comparison between a Li-Po battery and 3.0 L Hydrogen Storage Cylinder at m_{ES}=1.6kg.

Parameters	Li-Po Battery	H_2 Fuel Cell	% Change from battery
$E_{battery/H_2}$	320Wh	624Wh	95%
P_{hover}	550W	550W	0%
m_{total}	2.6kg	2.6kg	0%
$Endurance$	35 mins	68 mins	94%

Figure 6 provides an insight on how different hydrogen fuel cells and batteries affects the endurance of SAR quadcopters. The commercially available fuel cells offer very high endurance with respect to their mass. However, as the power capacity increases the endurance reduces due to the increased mass of the fuel cell. The Li-Po battery will inherently have a longer flight time compared to Li-ion battery due to their higher specific energy density. The crossover point of the hydrogen tanks and the Li-Po battery is when the mass of the energy system is at 1.32 kg. For systems that weigh below this point batteries are more efficient whereas hydrogen fuel cells are more attractive as the mass exceeds the critical point. The fuel cells by Intelligent Energy have the highest endurance for the mass but it decreases rapidly when the power increases as the mass increases much more quickly. The findings show that there are implications on the type of energy system as they highlight tradeoffs between the total mass and the flight endurance.

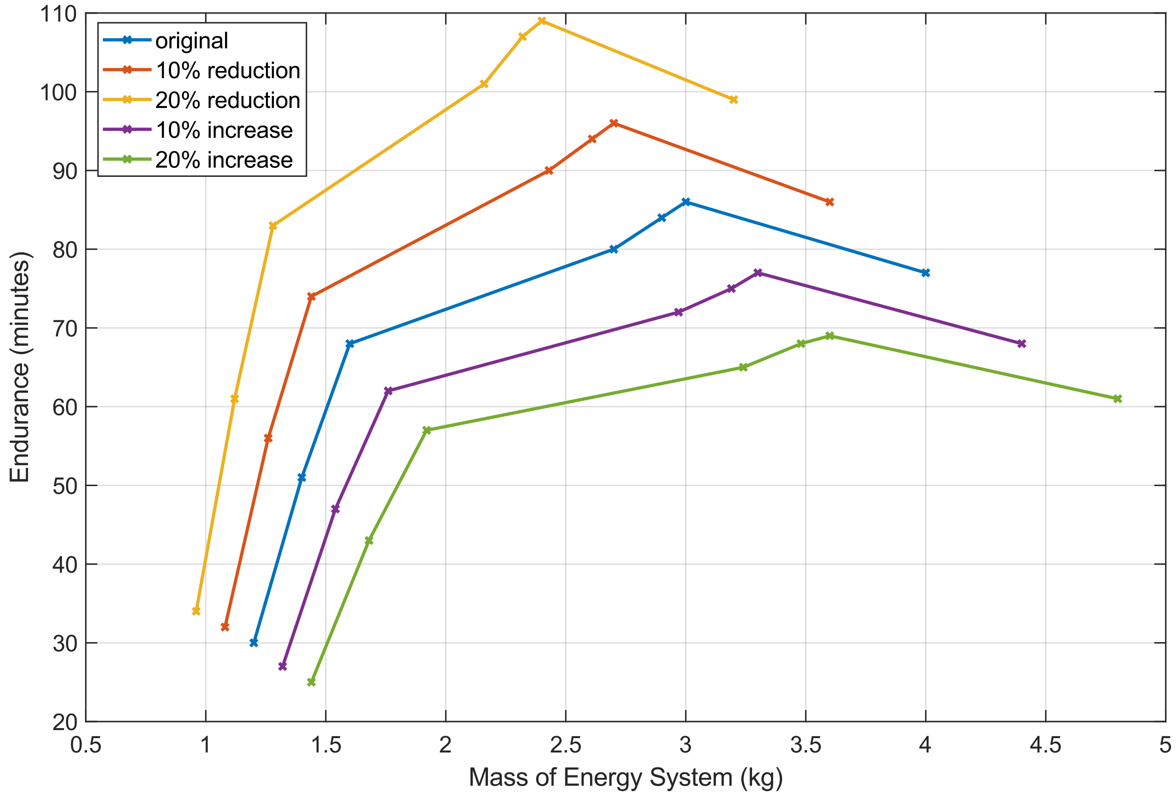

Figure 7: A mass sensitivity analysis was conducted on the hydrogen fuel cells with different storage volumes. Longer flight time is experienced due to the decrease in total mass as the power required reduces while the energy capacity stays the same.

In addition, a sensitivity analysis was conducted to study the effect of the quadcopter's performance. The mass sensitivity analysis of the hydrogen storage was conducted using the percentage change in the fixed mass of the drone which includes the mass of the hydrogen storage. As shown in Figure 7 above, when the mass of the drone reduces the endurance increases. It illustrates how important is mass reduction on the flight time. For smaller masses the endurance changes slightly and is more noticeable when the hydrogen storage gets larger. For example for a storage of 7.2L, a mass reduction of 10% improves the endurance from 86 minutes to 96 minutes. Table 8 shows the percentage change of endurance of two hydrogen storage examples. Weight reductions come from substituting the fixed mass components with lightweight materials [34].

Table 8: Percentage change in endurance.

7.2L	Parameter	Original	New	% change
	m_{total}	3.0kg	2.4kg	-20.0%
	P_{hover}	1049W	822W	-21.6%
	$Endurance$	86 mins	109 mins	+26.7%
3.0L				
	m_{total}	1.6kg	1.3kg	-20.0%
	P_{hover}	550W	451W	-18.0%
	$Endurance$	68 mins	83 mins	+22.1%

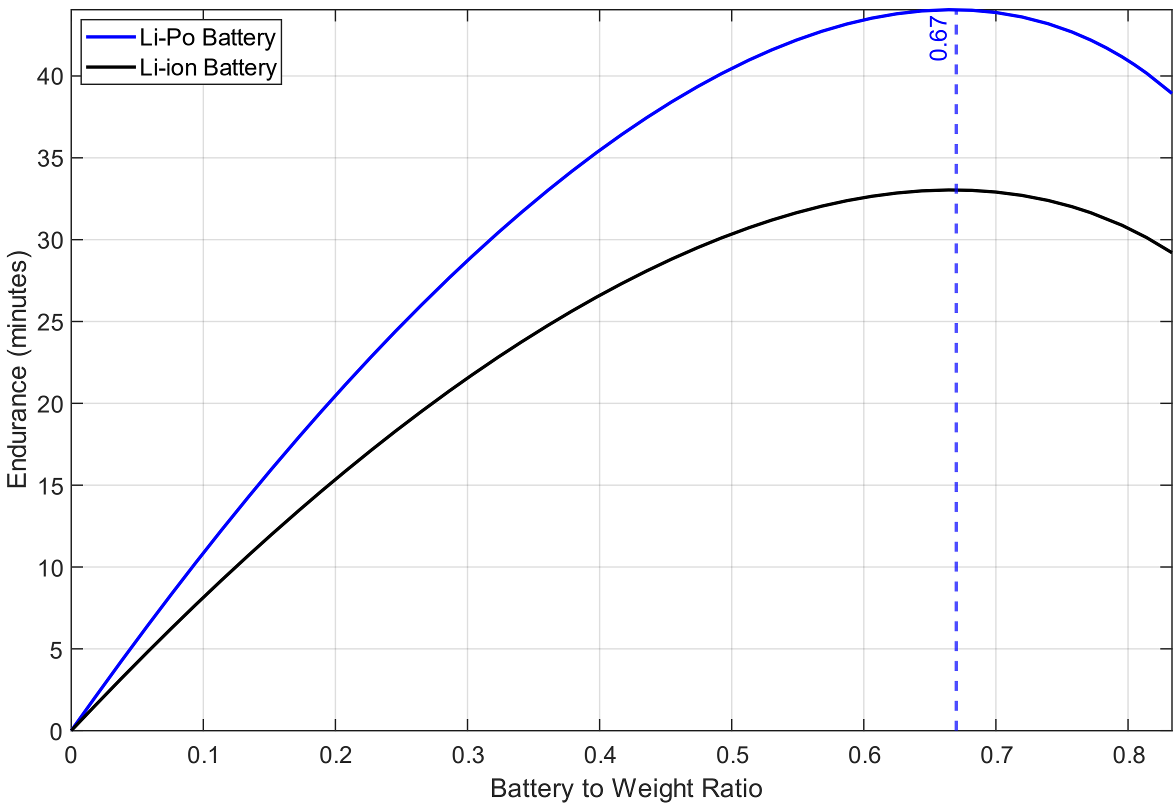

Figure 8: This graph shows the ideal ratio of the mass of the battery system with the total mass of the drone. If the battery weighs two thirds of the total mass, then peak endurance is achieved. Past this point the battery gets heavier and the drone is carrying extra load.

As shown above, increasing battery capacities will not result in an increase in endurance because drone will need more power as the mass of the battery increases. Thus it is compared with the hydrogen fuel cell, an alternative power source that has a higher energy density and can be seen it improved the endurance greatly. The ideal ratio is having two thirds of the total mass dedicated to the energy system as that is the point where the max endurance is achieved.

DISCUSSION

Validity and Improvement of the Mathematical Model

A simple model was created using MATLAB to ensure the endurance was affected by the main parameters of a rotary wing quadcopter with a S8 configuration. This model was based on assumptions such as stationary hovering with no wind, maximum power consumption during hover and neglecting aerodynamic calculations. In addition, the mass of the battery in the hydrogen fuel cell system was neglected as it was taken to be small to understand the effects of a hydrogen fuel cell. A more complex model can be built to find the endurance based on the propulsion system configuration and not limited to one configuration. Apeland et al. showed that the S8 configuration gives a 27% improvement on endurance compared with the X8 configuration [9]. The model can be further improved by comparing it with a hybrid system where hybridization comes into play as shown in Equation 9. The degree of hybridization (β_{hybrid}) ranges from 0 to 1, where 0 is solely fuel cell power and 1 is powered completely by battery. Adding a battery to a fuel cell system allows for smoothing of the power distributed and was investigated by Mi et al [35]. In that study, the model accounted for the dynamic switching between the fuel cell and the battery and resulted in an increase of the overall efficiency by 20%.

$$\beta_{hybrid} = \frac{P_{battery}}{P_{battery} + P_{H_2}} \tag{9}$$

Advanced models may also include the design stage to optimize the SAR drone further and obtain a more accurate analysis on the efficiencies and power required. However, this model needs to be compared with experimental data to check the validity. Test flights were conducted by Liu et al. to predict the endurance of a specific flight part with various flight speeds and distances [36]. Experimental data and Liu's model had a constant difference of around 10%. Since the Mavic 3 quadcopter was used in this study, it was limited because of not including an optimization design process. A study by Hwang et al. included parameters such as drag for steady level flight and maneuverability equations to model the power required for a drone [37]. Alternative approaches were used to see the feasibility of a fuel cell in a drone, Taccani and Ustolin found the energy required for a drone with a fixed mass to complete a mission. This technique will lead to the most lightweight system without prioritizing performance of the drone [38].

Interpretation of Results

In Figure 7, the graph illustrates how sensitive the mass is on the drone's flight time. The analysis could be done with a more lightweight vessel to reduce the mass which leads to a decrease in power consumption. As a result, a fuel cell with a lower power rating can be implemented and as seen from Figure 6 it would weigh less. A small multirotor was studied and integrating the batteries into the airframe gives a 41% increase in flight time [39]. For COTS fuel cells, Figure 6 indicates that for a certain value the endurance reduces due to the increase in energy capacity of the fuel cell. This is because the fuel cell stacks get larger and have to store more hydrogen to achieve the desired power rating. Storing more hydrogen will increase the mass of the storage vessel as it may need to be stored under higher pressures thus needing a thicker cylinder wall. The hydrogen cylinder has a peak endurance when the volume is at 7.2L. Although more data could have been included to find a more suitable peak value but the storage vessels compared all came from the same manufacturer to maintain consistency. For a 9.0L cylinder, the endurance reduces by 11 minutes due to the added weight as it increases the power required. Further study could be done on fuel flow rates to obtain a more accurate analysis of the energy transferred.

The critical point is the intersection between the hydrogen energy system and the battery as that is when both energy systems have the same endurance and mass. Beyond that critical point the mass of the energy system increases, making it more advantageous to install a hydrogen fuel cell than a battery as the endurance increases rapidly pass the point. However, for masses of 1.32 kg and below batteries are more suitable as the added weight of the hydrogen storage limits the endurance. This finding proves why most small multirotor drones are battery powered. This was the main result of this study, to show the minimal mass of the quadcopter for the feasibility of installing a hydrogen fuel cell.

Figure 8 shows the ideal ratio of energy system's mass to the total mass of the drone. The peak endurance was found at a weight fraction of 0.67. This result is consistent with the findings of Apeland et al. who showed that for a hybrid powered multirotor drone the ideal fraction is 0.67. [9]. Similarly, research done by Traub found that the maximum range is reached when the optimal battery weight fraction at cruise conditions to be two thirds of the total mass of the fixed wing drone [40]. While this study focused on batteries, it could have been conducted with the hydrogen fuel cells but due to the limited published data it was difficult to determine the ideal mass ratio.

Altered Efficiency Values

The impact of varying efficiency values of the energy system has a major impact on the drone's flight time. To investigate this, the graphs are going to be studied when the efficiency values are altered. As the efficiency of the fuel cell increases the graph of the fuel cells with the hydrogen cylinder storage shall shift upwards leading to an increase in the endurance for the same mass. Similarly, if η_{total} increases then all the lines plotted will shift upwards and towards the left. This is because the power required by the drone reduces as efficiency increases leading to a reduction of the mass of the hydrogen fuel cell or battery which increases endurance. Further research can be conducted to determine the optimal efficiency values for both the energy systems.

Material Selection

Material selection is essential when it comes to drone design as it directly affects the mass and the endurance of the drone. As mentioned above to elongate the flight time the mass has to be significantly reduced and this could be done by using lightweight materials such as carbon fiber and other composite materials while maintaining the strength of the structure. The mass of the power source was kept the same as the goal is to compare between battery power and hydrogen power. As shown above the heaviest components are the power sources, the thermal camera, and the frame. If these are significantly reduced, then the endurance will increase. The mass of the equipment used is essential to show how sensitive changes in mass can affect the flight time of the drone.

Comparisons with Previous Studies

The data obtained above can be compared to previously built quadcopters to evaluate the findings. However, due to the limited data about lightweight hydrogen powered SAR quadcopters, comparisons were made with hydrogen fuel cell multicopters. It is important to note that most of the market comprises of heavyweight drones that range from 8 kg to 25 kg. One example is the Hycopter from HES which has an endurance of 180 minutes, weighs 16.5 kg and is powered by a 1500W fuel cell. It carries a 12 L fuel tank and no payload [41]. Another example is the world's first mass manufactured hydrogen fuel cell drone, the Doosan DS30W. With an endurance of 120 minutes and weighing 20.9 kg with a fuel tank of 7 L it is powered by a 2700 W fuel cell and has a max payload of 3 kg [42]. To increase the flight time of a hydrogen powered drone, a larger hydrogen storage system is required as it is more beneficial for it to be heavier rather than lighter. This is because the added mass allows for a longer flight time contrary to battery powered drones.

Figure 9: Images of a HES Hycopter (left) and a Mavic 3 Drone (right) [17,41].

CONCLUSION

The findings of this study have important implications on the drone industry, especially in the field of renewable energy sources. There is an increase in demand for energy efficient and environmentally sustainable power sources as the use of drones becomes increasingly widespread. The critical mass comparisons produced in this study offers valuable insight for drone development with increased flight endurance between batteries and hydrogen fuel cells. This benefits a variety of applications such as search and rescue operations.
A mathematical model was formulated to find the critical mass of the SAR quadcopter at which it becomes more beneficial to utilize either a battery or a hydrogen fuel cell for extending flight endurance. The findings obtained from this study provides an insight of a preliminary design stage to check the feasibility of lightweight quadcopters carrying hydrogen fuel cells onboard. The critical mass between the battery and the hydrogen fuel cell is a topic of great interest as the drone industry expands into a future where sustainability is a priority. This study analysed the endurance of a SAR quadcopter powered by these two energy sources using key parameters such as energy density and power consumption. Moreover, this can help first time drone manufacturers to have an idea about how much the energy system should weight to obtain peak endurance.

The limitations of this study however pave a way for future research. This study only investigated the effects of power consumption, energy density and the total mass while the cost and the availability of hydrogen fuel were not taken into consideration. Additionally, this study assumed idealized flight conditions where wind and forward flight were not taken into account. Future studies should focus aim to address these limitations and offer an improved evaluation of the viability of installing hydrogen fuel cells in lightweight SAR quadcopters.

FUTURE WORKS

This section provides several potential suggestions that could help expand on the results obtained of implementing hydrogen fuel cells in SAR quadcopters. First, future research can investigate how different flight conditions and varying terrains can affect the performance of the drone in real world scenarios. Factors such as wind speed, temperature, and power consumption can significantly affect the endurance and efficiencies of these energy systems. Secondly, this study investigated the performance of single source energy systems, whereas hybrid configurations of batteries and fuel cells may provide a more practical solution. Future studies should assess the feasibility of using hybrid configurations and analyse how well they operate compared with single source energy systems. Furthermore, a design study could be conducted on hybrid systems to find the ideal size for maximization of performance. Thirdly, this study was constrained to a Mavic 3 quadcopter, and it is essential to know that different drone models could affect the viability of installing hydrogen fuel cells. Therefore, future studies should expand the analysis to include more drone models with various specifications. Lastly, the affordability and availability of hydrogen fuel are significant issues that can affect the integration of hydrogen fuel cells being implemented in drones. As a result, further study is required to analyse the economic aspects of using hydrogen fuel cells taking factors such as fuel costs, maintenance expenses and operational costs per hour into consideration.

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