Fuel Cell Powered Drone

Use of Fuel Cells to Extend Multirotor Drone Endurance

by

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Preface

This research was carried out in the framework of an Industrial PhD program, funded by the Research Council of Norway (project 286603) and Nordic Unmanned AS. The project was initiated in April 2018 and concluded in May 2021.

Prof. Dimitrios Pavlou and Prof. Tor Hemmingsen from the University of Stavanger, Department of Mechanical and Structural Engineering, Faculty of Science and Technology, supervised the project.

The research work was carried out at Nordic Unmanned, a provider of unmanned aerial systems and services, and the University of Stavanger. To strengthen the experimental activities and gain access to a relevant research community, a research-stay at FFI, the Norwegian Defence Research Establishment, was organized from September to November 2020.

In association with this research project, a "Drone Lab" was established at the University of Stavanger, and 8 BSc and 4 MSc students' projects were co-supervised. These efforts led to Nordic Unmanned being awarded the "Tekna Educational Award 2020" from the local Tekna division.

The research project was inspired by three former MSc and BSc projects from the University of Stavanger [1-3].

Acknowledgments

I would like to thank family and friends for continued support and for enduring times with hard priorities and a strong research focus.

Prof. Dimitrios Pavlou and Prof. Tor Hemmingsen have provided excellent supervision in shaping the research to meet academic standards and good support in evolving the research from initial research questions to published papers.

I am also grateful for the support and dedication from Nordic Unmanned through a challenging business period with strong growth. The enthusiasm and engagement from colleagues and management have really helped move the project forward. Willingness to invest in relevant hardware and use of internal resources for design, manufacturing, and piloting – as well as travels before the corona period to Austin, Texas, and Singapore for fuel cell-related acceptance testing and training has been critical to reaching the project outcome and is highly appreciated.

The University of Stavanger has supported with critical hydrogen refueling infrastructure. Knut Erik Giljarhus and Jørgen Grønsund have been key resources to establish the Drone Lab and supervising the associated student projects.

I appreciate the fruitful discussions and assistance with experiments from the whole power supply research group at FFI, with special thanks to Helge Weydahl and Arvid Melkevik for organizing the research stay.

Abstract

Unmanned aerial systems can be used for a range of industrial applications to reduce risk, cost, and time. Fuel cell-based propulsion systems are outlined as a solution to extend mission endurance, one of the current main barriers for further adoption. This coincides with a general societal push towards more sustainable aviation and the use of fuel cells and hydrogen as important zero-emission enablers.

In this thesis, results from research about the use of fuel cells to extend multirotor drone flight endurance are presented. This application entails certain challenges compared to fixed-wing drones, which has been the scope of most previous research. The research explores the performance threshold between batteries and a fuel cell-based propulsion system, the prospects of further adoption, and how the performance can be improved.

A prototype fuel cell system is developed and integrated into an X8 multirotor drone with a take-off mass of 21 kg and flight-tested. The specific energy on a power plant level was 243 Wh/kg, and the gross endurance for the current system is estimated to be 76 minutes, a 90% increase from the comparable endurance of the battery-powered alternative. The performance of the 2 kW fuel cell hybrid system is characterized in laboratory testing and exposed to relevant load profiles with a peak load of 2.8 kW.

This is one of few independent third-party multirotor drone integrations of a fuel cell-based propulsion system. Based on experimental data from laboratory testing and full-scale flight in a realistic operating environment, a unique overview of associated challenges and further work is provided. As there is little published research on this topic, the work should be valuable for the research community, as well as drone operators and technology providers.

List of Papers

Paper I

J. Apeland, D. Pavlou, and T. Hemmingsen, "State-of-Technology and Barriers for Adoption of Fuel Cell Powered Multirotor Drones," in 2020 International Conference on Unmanned Aircraft Systems (ICUAS), Athens, Greece, 2020, pp. 1359-1367, DOI: 10.1109/ICUAS48674.2020.9213971.

Paper II

J. Apeland, D. Pavlou, and T. Hemmingsen, "Suitability Analysis of Implementing a Fuel Cell on a Multirotor Drone," Journal of Aerospace Technology and Management, vol. 12, e3220, 2020, DOI: 10.5028/jatm.v12.1172.

Paper III

J. Apeland, D. Pavlou, and T. Hemmingsen, "Sensitivity Study of Design Parameters for a Fuel Cell Powered Multirotor Drone," Journal of Intelligent & Robotic Systems, vol. 102, p. 6, 2021, DOI: 10.1007/s10846-021-01363-9.

Paper IV

J. Apeland, D. Pavlou, and T. Hemmingsen, "Characterization and Flight Test of a 2 kW Fuel Cell Powered Multirotor Drone," *Manuscript.*

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Abbreviations

BoP	Balance of Plant
BVLOS	Beyond Visual Line of Sight
CONOPS	Concept of Operations
DC	Direct Current
DMFC	Direct Methanol Fuel Cell
EASA	European Aviation Safety Agency
FC	Fuel Cell
FCHS	Fuel Cell Hybrid System
FFI	The Norwegian Defence Research Establishment
LHV	Lower Heating Value
Li-Ion	Lithium-Ion, battery
LiPo	Lithium-Polymer, battery
PEM	Proton Exchange Membrane
RQ	Research Question
SOFC	Solid Oxide Fuel Cell
SORA	Specific Operation Risk Assessment
TRL	Technology Readiness Level
UAV	Unmanned Aircraft Vehicle

1 Introduction

1.1 Background

There is an increase in industrial use of unmanned aircraft systems (UAS) and an interest in how they can create value compared to traditional methods. Typical benefits are reduced risk, higher quality inspections and services, while also being time- and cost-efficient. The global drone market is forecasted to reach $42.8B by 2025 [4], and new industry achievements are frequently reached. One recent milestone that highlights the potential in drone technology was a flight to Troll A, an offshore installation located 80 km from shore. In this flight, a 3D-printed spare part was delivered, search and rescue capabilities were demonstrated, and a structural inspection was carried out [5]. A SINTEF report provides further examples of how drones can be used in the offshore industry, along with development trends and associated challenges [6].

There is a wide range of drones available and possible applications [7]. Each configuration has different strengths and will be better suited for certain missions than others. Thus, it is reasonable to assume that moving forward; there will be an ecosystem of various drones used for different applications. It is also important to consider that to gain societal acceptance, aspects related to safety and privacy must be addressed, and stakeholders should take into consideration how drones can serve the broad interests of society [8].

Multirotor drones have the advantage of a small take-off and landing footprint, good positioning control, being able to hover in the same geographical location, and carrying payloads at both low and high velocities [9]. These multirotor drones can typically have a take-off mass of up to 25 kg and a payload capacity of 5 kg. To improve performance and achieve higher mission endurance and range, research efforts have been focused on the power plant.

The most common power plant used for these systems are pouch cell Lithium-Ion batteries, often referred to as LiPo batteries, with a typical specific energy of 130-200 Wh/kg [10]. Adding more batteries will increase system energy, but above a certain mass, this will not increase endurance due to the increased power consumption from the added mass. To further improve the endurance, the power plant's specific energy must be improved – more energy must be added without adding more mass.

Fuel Cell Hybrid Systems (FCHS) have emerged as one viable option to extend endurance on multirotor drones. Fuel cells are the primary power source that provides continuous power, and a 'hybrid battery' is the secondary power source that handles transient loads and power peaks. For proton exchange membrane (PEM) fuel cells, hydrogen is used as fuel. Fuel cell hybrid systems can provide a specific energy of 250-540 Wh/kg [11] on a power plant level and give better endurance than batteries. The exact threshold is further investigated in Paper II.

The use of hydrogen has been gaining much momentum lately, and in 2020 EU published a hydrogen strategy [12] that is important for reaching the 2050 climate-neutrality goal outlined in the European New Green Deal. If produced from renewable energy sources, hydrogen is referred to as 'green' and can play an essential role in decarbonization and moving towards a more sustainable future. The strategy outlines how investments, regulations, market creation, and research and innovation can be leveraged to accelerate the use of hydrogen.

The aviation industry is also moving towards more sustainable mobility solutions. Through the ZEROe program, Airbus explores multiple hydrogen-powered options [13]. The DLR HY4 project has been active since 2015, and recently their sixth-generation four-seater aircraft conducted successful test flights [14]. ZeroAvia carried out a flight in 2020 with a fuel cell-based six-seat aircraft and has received funding for a fuel cell-powered certifiable nineteen-seat aircraft to be ready by 2023 [15].

A recent report on hydrogen-powered aviation [16] states that the most promising aviation application of hydrogen-based propulsion systems is short-range aircraft and that entry into service could be around 2035. The climate impact can be reduced by 50 – 90%, and the additional cost will be € 18 per passenger. To scale hydrogen-based propulsion solutions in aviation, a fuel cell system power density target of 2 kW/kg is highlighted. In a Roland Berger report, an energy density target of 500 Wh/kg is stated as a threshold to enable electric propulsion systems [17]. A review by Nazir et al. [18] explores mobile and stationary applications of fuel cells, and predicts that the first commercial aerospace applications will be related to drones.

Thus, this research aligns with two global trends of increased use of drones for industrial applications and the use of hydrogen and fuel cells to advance towards a more sustainable future.

1.2 Literature

Early research efforts have mainly focused on fixed-wing UAVs (unmanned aerial vehicles), with one of the first demonstrator projects carried out in 2003. An overview of relevant demonstration projects, test results, and fundamental design considerations for fuel cell-based power plants for small UAVs is presented by Bradley et al. [19-23]. A more general overview of fuel cell applications and associated considerations are provided by Sharaf and Orhan [24], while Gong and Verstraete [25] present a 2017 status overview and research needs for fuel cell-powered UAVs.

Multirotor drones have more power-intensive propulsion systems than fixed-wing UAVs and a more dynamic power profile. Thus, relevant fuel cell hybrid systems require a higher nominal stack power and a higher degree of hybridization than fixed-wings. With a minimalistic design and high-performance focus, such systems introduce certain challenges to hybrid power management and system sizing. As the dynamic response of fuel cells is limited, hybrid batteries are essential for the maneuverability and flight envelope. Poor hybrid management can lead to fuel starvation and membrane dehydration [26].

There are some research results on fuel cell hybrid systems in the range of 50 W to 500 W [26-31]. Boukoberine et al. [32] provide a general overview of power source alternatives for drones, and Lussier et al. [33] provides some multirotor-specific considerations. Belmonte et al. [34] did a conceptual development of a fuel cell-powered octocopter, and Arat and Sürer [35] integrated and tested a 30 W fuel cell on a small multirotor drone – and recommended further research into more powerful systems. From this, it is clear that there is limited published research on fuel cell systems in the kW range for multirotor applications, which is the power range relevant for drones with 25 kg take-off mass.

1.3 Fuel Cell Powered Demonstrators

Some commercial projects have demonstrated technology and relevant use-cases. The most relevant ones are presented in Paper I, which also provide a good overview of available fuel cell systems and drones. Two factors that currently drive integration and use of fuel cells on multirotor drones are 1) lightweight fuel cell systems with adequate performance are becoming commercially available, creating supply, and 2) multirotor drones with an adequate power plant capacity is now emerging and becoming more popular for industrial use, creating demand.

In project RACHEL, a 70 minutes flight endurance with a 5 kg payload and a take-off mass below 20 kg was demonstrated [36]. US-based Harris Aerial has a Carrier H6 Hydrone with a 5 kg payload capacity, powered by a 2.4 kW fuel cell from Intelligent Energy. The Hycopter from HES is powered by a 1500 W fuel cell and has a maximum take-off mass of 15 kg [37]. In April 2019, a multirotor drone powered by liquid hydrogen carried out a 12 hours and 7 minutes flight using an 800 W fuel cell, which at the time was a new Guinness World Record [36].

The fuel cell-powered drone that appears to have the highest technological maturity is the DS30 from Doosan Mobility Innovation (DMI). It has a stated endurance of 2 hours, a payload capacity of 5 kg, and a maximum take-off weight of 24.9 kg. This has been used in several demonstrations [38-41], where one was a 90-minute gas pipeline inspection over 44 km, and another was a 69 km medical delivery between two islands

It should be noted that the actual technology readiness level (TRL) and certification status for these systems are unknown. It does not appear like any systems are in full-scale operational use, and some demonstration flights have been carried out indoors or in a regulatory vacuum. However, new milestones are continuously reached, and with large commercial aviation actors like Airbus looking into fuel cell technology, ripple effects are expected to benefit unmanned aviation and drones as the market grows and certification aspects are addressed.

1.4 Scope of Research

The overall objective was to establish knowledge about the use of fuel cells to extend multirotor drone flight endurance. To guide the research, increase the practical relevance, and maximize the research outcome for the relevant boundary conditions, a clear goal was to complete a full-scale prototype and accomplish a successful test flight, giving the research an 'applied' profile.

The industry partner of the project, Nordic Unmanned, owns a drone design that they manufacture, sell, and use in their own operations. It has an empty mass of 8.5 kg and a 25 kg maximum take-off mass, giving a wide permissible mass range and integration freedom for a power plant prototype. By using an established drone design with a certain airworthiness basis, the research efforts could be focused on the fuel cell-based power plant. As the company is an approved drone operator and has experienced test pilots available, flight testing was made possible.

Other high-endurance alternatives are internal combustion engine-based systems or improved battery technology. However, fuel cell-based power plants were found to be a less developed research field where this project would be more likely to gain relevant research contributions. Fuel cells also offer features like low noise levels, low vibrations and are environmentally friendly – which are beneficial for certain operations. Thus, the research was limited to focus on fuel cell-based systems.

As it is a novel and highly multidisciplinary research topic, the project had to take a broad approach and focus on the overall system level to reach the desired research outcome. It was at this level that the most valuable research contributions could be provided. Where relevant to the overall objective, sub-topics are pursued, but efforts have been made to ensure that the research aligns and helps to advance the overall research objective. The research questions were:

RQ1: When will a fuel cell-based propulsion system give a higher endurance than a battery-powered alternative?

RQ2: What is the performance of a fuel cell-powered prototype?

RQ3: What are the prospects of further adoption of fuel cell-based propulsion systems for multirotor drones?

RQ4: How can the performance of fuel cell-powered multirotor drones be improved?

These research questions provide a good framework for this thesis and a solid basis for further research and development. Fig. 1 shows how the research questions and research papers are related.

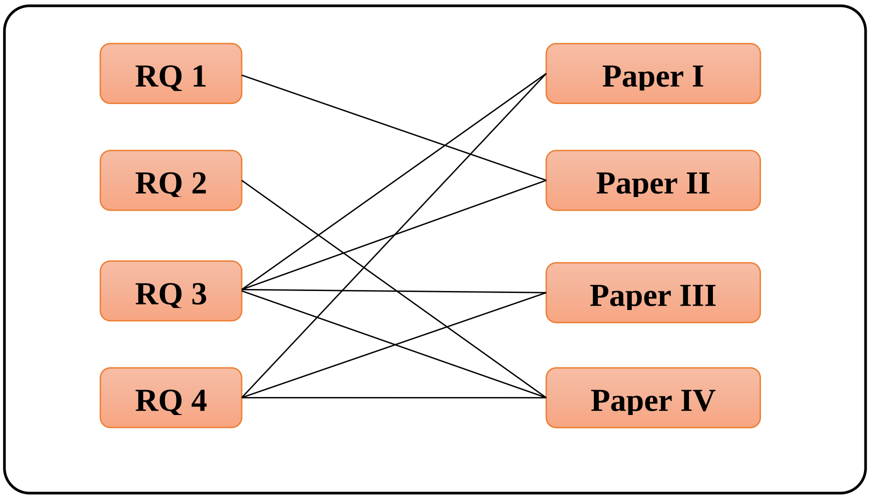

Fig. 1: Interrelation between the research questions and research papers.

1.5 Outreach

As hydrogen-related technology developments and drones are topics that attract the general public's interest, this research project has gained some attention. The press release related to the test flight got covered in at least ten different drone and hydrogen technology-focused media outlets and the journal Fuel Cells Bulletin [42]. The project was also covered by Teknisk Ukeblad and FFI [43, 44]. The test flight video gained 1250 views as of April 2021 [45]. The test flight coincided with the stock exchange listing of Nordic Unmanned and also received some attention in that regard. The project has been presented at the University of Tromsø, at events at the University of Stavanger, and to various company stakeholders.

2 Methods and Materials

The research is primarily applied and addresses specific questions related to a defined scope. Descriptive and experimental methods are used. From literature and technology reviews, relevant information about the research topic is collected and analyzed. The relationship between research variables is explored to describe various research outcomes. Both analytic and empirical models are used in the suitability analysis and sensitivity study. A fuel cell-powered drone prototype is developed and flight-tested, and data are collected from laboratory experiments. Experiences from the prototype development, test execution, and performance data are synthesized to present useful insights about a little developed research topic. The key aspects related to methods and materials are outlined in the following sections. More details and further context can be found in Papers I-IV.

2.1 Fuel Cell Hybrid System and Drone

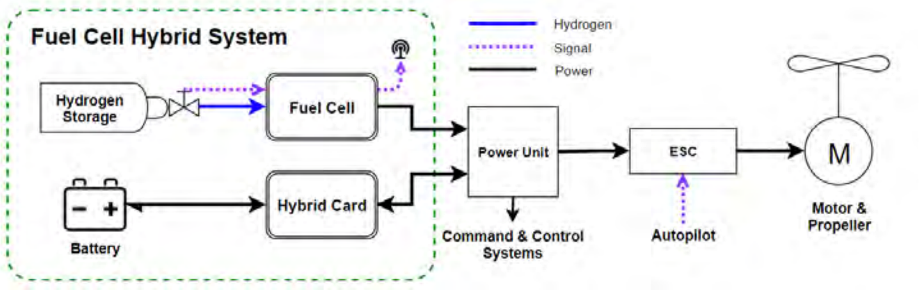

Fig. 2: Simplified layout of a fuel cell-based multirotor propulsion system

The main components of the fuel cell-based propulsion system are shown in Fig. 2 and Fig. 3. Two Aerostak A-1000 proton exchange membrane (PEM) fuel cells are used. Each stack has 65 cells, operates over a voltage range of 39 V - 61.8 V, and is rated for 1 kW of electric power. They are open cathode fuel cells and use ambient air for cooling and as reactant

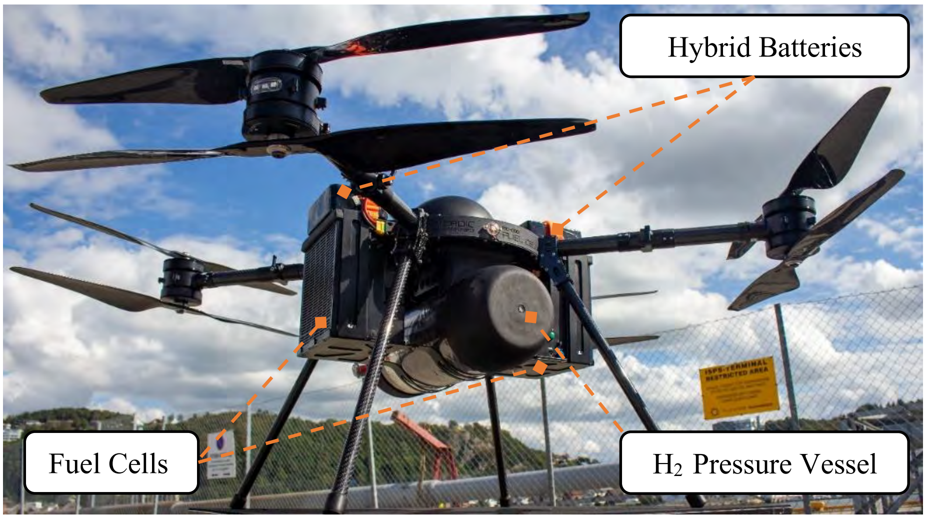

Fig. 3: Staaker BG200 FC prototype with a 2 kW fuel cell system, 7.2 L hydrogen cylinder, and hybrid batteries.

gas. The operating temperature range is 0℃ – 35℃. Each fuel cell has internal control electronics that manage balance-of-plant components and handle thermal and hydration aspects. Paper IV explores their exact performance.

The parallel hybrid system has a Lithium-Ion battery (pouch cell) referred to as 'hybrid battery' connected in parallel with the fuel cells. It provides power for starting the fuel cells, power buffer for rapid load changes and high loads, redundancy for emergency landings, and sustains operation through fuel cell purging. The 'hybrid card' is designed to regulate charge current and voltage into the batteries, which will occur if there is excess power from the fuel cells. A passive hybrid power management strategy is used, which is further investigated in Paper IV.

A 7.2 L hydrogen pressure vessel rated for 300 bar is used. It is a carbon fiber filament wound cylinder with a polymer liner (Class IV), designed according to EN 12245. Through a pressure regulator, the gas is supplied to the fuel cells at 0.6 – 0.8 barg. A pressure sensor reports the remaining hydrogen pressure through one of the fuel cells.

The fuel cell hybrid system was integrated on a Staaker BG200 multirotor drone [46]. It has an X8 coaxial configuration with 28" propellers, an arm-to-arm width of 1.2 m, and is designed for a maximum take-off mass of 25 kg. The airframe and power electronics are modified to accommodate the fuel cell hybrid system, as shown in Fig. 3. The fuel cell hybrid system weighs 12.5 kg, and a mass breakdown is provided in Table 1. Using an empirical model for the relevant coaxial propulsion system, Eq. 5, the power consumption in static hover at 21 kg take-off mass is found to be 2.4 kW.

Table 1: Mass breakdown of Staaker BG200 w/fuel cell hybrid system

Drone empty mass	8.5	kg
Fuel cell stacks (2 x 1 kW)	4.4	kg
7.2 L pressure vessel (w/regulator)	4.0	kg
Hybrid battery (11 S / 16 Ah)	4.1	kg
Take-off mass	**21**	**kg**

The power demand from motors and motor controllers (ESC) is controlled by the autopilot to achieve the desired maneuvers. Fuel cell data is sent through two radio links (EZ50 radio, 912 Mhz) to a laptop, where status, performance, and remaining hydrogen level can be monitored. The command and control link (C2-link, 2.4 gHz) provides maneuvering commands to the autopilot, and telemetry (433 Mhz) transmits essential flight data to the ground control station.

At the project start in 2018, there were very few lightweight high-power fuel cell systems commercially available. After a customization process with HES Energy Systems, they provided the current 2 kW system in August 2019. One of the modifications made was related to the hybrid power management between the two fuel cells and the battery, and an external 'hybrid card' was introduced. Due to the increase in power from a standard system, a higher hydrogen flow rate was needed, and the pressure reduction valve was upgraded to facilitate this.

More in-depth details about the fuel cell hybrid system and drone aspects relevant to the research are further described in Papers II-IV.

2.2 State-of-Technology and Barriers for Adoption

A review was carried out for Paper I to map relevant research, fuel cell providers, and relevant technology demonstrators. This was important for gaining a clear understanding of the current state-of-technology and identifying what was commercially available. Based on the findings, an analysis was carried out to map and structure barriers for further adoption. The three main categories were: regulatory, technical, and operational barriers.

An analysis was then made for three sub-systems critical to the overall system performance: fuel cell type, cooling strategy, and hydrogen storage. This was to map specific challenges, assess the current selections, and analyze the prospects of advancing the state-of-technology. Altogether, Paper I serve as the primary literature and technology review.

2.3 Suitability Analysis and Case Study

In Paper II, a framework for analyzing the relative performance of a fuel cell and battery-based propulsion system is presented, and a case study is carried out. For a given multirotor drone, the model can identify the performance threshold for when a fuel cell-powered option will provide better endurance than a battery-powered alternative.

The model uses gross endurance t_e as the main parameter and rely on sub-models for the available energy E and power consumption P, as seen in Eq. 1.

$$t_e = \frac{E}{P} \tag{1}$$

Using this basic model, the performance of various energy systems and configurations can be compared. By using endurance as the basis for comparison, the total mass of the energy system and its effect on the power consumption is considered. As it is a theoretical comparison using all the available energy for propulsion and assuming static hovering, transient effects from maneuvering and dynamic effects on the efficiency are not considered. However, the gross endurance is considered to give a reasonable and fair indication of the relative power plant performance.

For a fuel cell hybrid system, the sub-model for available energy E have contributions from the fuel cells E_{FC} and hybrid battery $E_{h.batt}$. The fuel cell energy as a function of pressure p and cylinder volume V_{cyl} can be calculated using Eq. 2.

$$E_{FC}(p, V_{cyl}) = \rho_{H2}(p) \cdot V_{cyl} \cdot h_{H2} \cdot \eta_{FC} \cdot \eta_{H2} \tag{2}$$

The density of hydrogen ρ_{H2} is a function of pressure. The specific enthalpy of hydrogen at the lower heating value (LHV) is $h_{H2} = 33.6\ Wh\ g^{-1}$, and together with the fuel cell efficiency η_{FC} and the fuel utilization factor η_{H_2}, the available electric energy can be calculated.

The required energy capacity for the hybrid battery as a function of the fuel cell system energy can be calculated using Eq. 3. This equation assumes a certain degree of hybridization β_{batt}, and includes an energy buffer to manage an emergency landing at full power P_{FCHS} for time t_{emc}.

$$E_{h.batt}(E_{FC}) = \frac{\beta_{batt}}{1 - \beta_{batt}} \cdot E_{FC} + (t_{emc} \cdot P_{FCHS}) \tag{3}$$

The propulsion power model in Eq. 4 is based on momentum theory and is simplified for the case of an X8 configuration with four arms. The propulsion power P_{TOM} as a function of the take-off mass m_{TOM} is:

$$P_{TOM}(m_{TOM}) = \kappa_{int} \frac{(m_{TOM} \cdot g)^{3/2}}{2\sqrt{2 \cdot \rho_{air} \cdot A_{prop}}} \tag{4}$$

The aerodynamic efficiency loss from the coaxial configuration is represented by κ_{int}. Air density is ρ_{air} and A_{prop} is the propeller disk area. It can be noted that the propulsion power will increase to the power of $3/2$ as the take-off mass increase. This model ensures that the impact of various power plants' mass is correctly represented by the gross endurance.

A case study is carried out for a given fuel cell hybrid system and the reference drone using the above models. The case parameters are defined in Paper II. The same models are also used to present an endurance plot for the fuel cell hybrid system with a range of cylinder options. The endurance can then be compared with that of an equivalent battery mass, and the performance threshold where an FCHS will provide superior performance can be identified.

2.4 Sensitivity Study

Using the models presented in the suitability analysis, Paper III carries out a sensitivity analysis on central system parameters. This analysis is useful for system design and for targeting improvements and optimization efforts.

To improve the analysis validity, the momentum theory propulsion power model (Eq. 4) is replaced by an empirical propulsion power model (Eq. 5). The propulsion power P_{exp} for the relevant drone as a function of take-off mass m_{TOM} is:

$$P_{exp}(m_{TOM}) = 2.3369{m_{TOM}}^2 + 64.417m_{TOM} \tag{5}$$

This model is derived from thrust stand measurements of the relevant coaxial motor and propeller configuration. In the sensitivity analysis, the impact of propulsion system configuration and associated propulsion efficiency is investigated. The propulsion efficiency has an impact on the power consumption P in Eq. 1 and how much energy that is needed to keep a certain mass airborne.

The propulsion-power mass sensitivity is investigated, and the impact of changes in mass is quantified. Analysis of the ideal energy system mass fraction explores how endurance is influenced as the power plant becomes a higher mass fraction of the take-off mass.

The power plant specific energy ε_S is an important performance metric, and the sensitivity analysis explores the impact of related parameters. For a fuel cell hybrid system, the relevant energy and mass factors are detailed in Eq. 6.

$$\varepsilon_{S.FCHS} = \frac{E_{FC} + E_{h.batt}}{m_{FC} + m_{H_2} + m_{h.batt}} \tag{6}$$

First, improvements in the specific energy of batteries are analyzed. This influence fuel cell hybrid system performance through the hybrid battery energy $E_{h.batt}$ and mass $m_{h.batt}$.

The impact of higher hydrogen pressure is investigated using Eq. 2. Different storage pressures and lightweight cylinder options are compared, which influence both storage mass m_{H_2} and energy E_{FC}.

Last, the degree of hybridization is investigated, as shown in Eq. 3. That influences the fuel cell mass m_{FC} and hybrid battery energy and mass components. A value of $\beta_{batt} = 0$ means fully fuel cell-powered and $\beta_{batt} = 1$ is fully battery-powered. The standard value used in the case study is 0.17.

2.5 Conditioning Setup

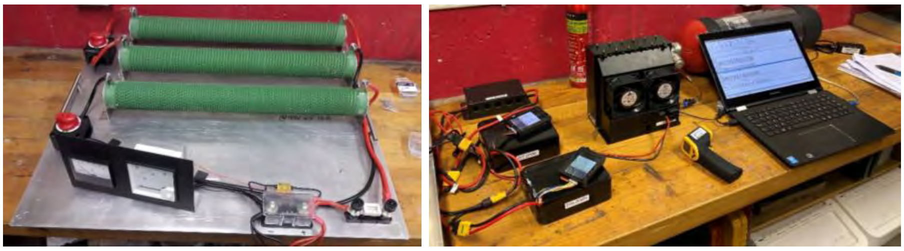

Fig. 4: Test setup for initial fuel cell testing and maintenance conditioning.

To facilitate fuel cell maintenance conditioning and initial system testing, a simple electric load was designed (Fig. 4). It has three resistors rated for 2.5 kW in a configuration that provides two load steps with a current draw of 10 A and 20 A, which is 440 W and 860 W at the relevant voltage levels. The prototype systems' hybrid batteries (11-cell, 16 Ah) and 7.2 L pressure vessel was used in this setup, which gave some limitations in the maximum test duration as the hydrogen supply was limited.

For hydrogen refueling, a gas reservoir was set up at the University of Stavanger. To comply with transport and gas handling regulations, gas safety and transport of dangerous goods (ADR) training courses were taken. The fuel cell supplier provided training in setup and use of the fuel cell system.

2.6 Laboratory Experiments

For Paper IV, the laboratory facilities were upgraded to allow more advanced experiments (Fig. 5). The fuel cells were connected to a DC bus in parallel with a 7.2 kW programmable electronic load and two power supplies capable of providing 44 A, equal to about 2 kW of power at relevant voltages. The power supplies represent the hybrid battery during testing and provide the initial power to start the fuel cells, maintain continuous power through the purge cycles, and provide the

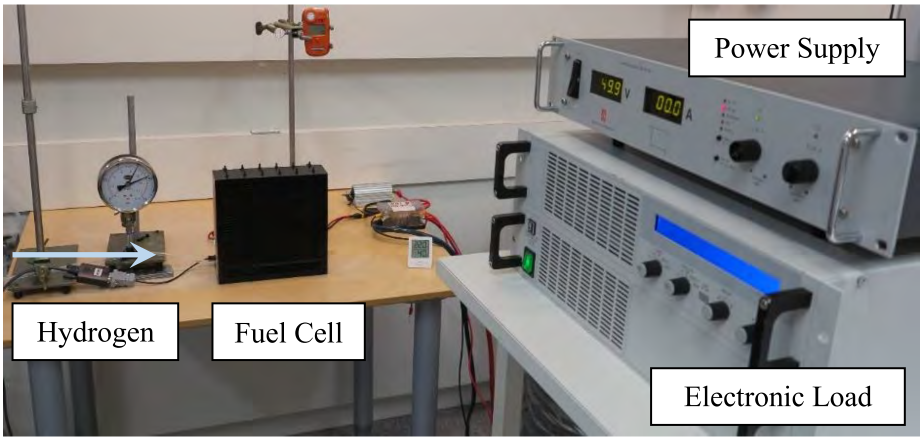

Fig. 5: Laboratory setup for fuel cell testing using a power supply as the secondary power source and a programmable electronic load for accurate load simulation.

power difference between fuel cell power and power demand. The power supply voltage was set to represent different battery state-of-charge levels to prompt realistic load sharing between the fuel cell and power supply. Fuel cell diagnostics were monitored and logged on a laptop at a 1 Hz data rate. The purpose of purging and its relation to membrane hydration is explained in Paper IV.

Hydrogen was supplied from a 50 L cylinder at a supply pressure of about 0.8 barg. The laboratory had an ATEX-certified ventilation area and gas detectors that would cut the hydrogen supply and activate an alarm if dangerous gas concentrations were detected. Portable gas detectors were used to identify leaks. The environmental conditions during testing were typically 20°C and 30% - 45% relative humidity.

With this setup, experiments were carried out to characterize the fuel cell performance and hybrid power management strategy. The system was also exposed to relevant load cycles to obtain useful information on system response and verify that it would handle the conditions of a full-scale flight.

2.7 Flight Testing

Fig. 6: The fuel cell-powered drone airborne during a test flight.

In contrast to laboratory experiments with a controlled environment, a full-scale outdoor test introduces many variables and increases the overall system complexity. Thus, such outdoor tests help establish an impression about technology readiness and identify the most critical challenges. The test flight was carried out in December 2020, on a clear day with a temperature of 5.6°C and relative humidity of 71%. The full details about the test flight are given in Paper IV.

As the propulsion system is a critical system and hydrogen is associated with some risk, obtaining a test flight approval from the national civil aviation authorities was paramount. In that process, a proposed test program was submitted where all relevant factors concerning airworthiness and test execution were described. As hydrogen-based propulsion systems in aviation are novel, there was limited precedent for assessing such permits. A flight permit could potentially have been omitted by flying indoors, but the process gave valuable insights to key concerns from a regulatory and aviation perspective, which must be addressed at some point to receive a permanent flight approval. The process took five months, and the permit was received in November 2020.

To mitigate test flight risks, efforts were made to 1) limit the probability of an unplanned high-energy landing and 2) limit the consequence of such an event. Another principle applied in the test program was to start with a very limited flight envelope to build trust in system performance. As this was established, the flight envelope could be expanded according to defined steps.

3 Results

The key findings and results from the papers are organized according to the research questions and presented in this section. The methods presented in the previous section were used to arrive at the following findings, and the full context and details are presented in Papers I-IV.

3.1 Performance Threshold

The results from the case study in Paper II are presented in Table 2. This answers how a specific fuel cell hybrid system compares to the standard battery option for the relevant drone. Note that the momentum theory model from Eq. 4 was used to estimate the propulsion power.

Table 2: Case results for a fuel cell hybrid system w/7.2 L hydrogen at 300 bar. The battery reference is a pouch cell Li-Ion battery, with 12-cells and 32 Ah capacity.

Ref.	Results	Sym.	Battery ref.	FCHS (7.2 L @300 bar)	Diff %
S1	Effective energy	E	1136 Wh	2954 Wh	+160%
S2	Mass energy system	m_E	7.5 kg	12.2 kg	+63%
S2	Take-off mass	m_{TOM}	16.0 kg	20.7 kg	+30%
S3	Specific energy	ε_S	144 Wh kg^{-1}	242 Wh kg^{-1}	+68%
S4	Propulsion power	P_{TOM}	1215 W	1791 W	+65%
S5	Endurance	t_e	56.1 min	98.9 min	+76%

In Fig. 7, a gross endurance plot illustrating the performance of the fuel cell hybrid system with a range of cylinder configurations is presented. Four specific energy curves are added as reference, and it can be seen that as the cylinder volume becomes larger, the specific energy of the fuel cell hybrid system increases. The first version of the plot was presented in Paper II. The plot was further developed in Paper III, as shown in Fig. 7, and the empirical propulsion power model was used to improve its validity.

Typical Lithium-Ion batteries for drone applications have a specific energy of 144 Wh/kg, assuming an 80% depth of discharge. Comparing FCHS performance with an equivalent battery mass, a performance threshold can be found at 7.4 kg. Thus, the 3 L fuel cell hybrid system should provide better endurance than the equivalent-mass battery option. This assumes that the take-off mass and propulsion power model is accurate. It should be noted that for batteries, there is a minimum size cut-off limit given by the maximum battery power output and the power required for take-off.

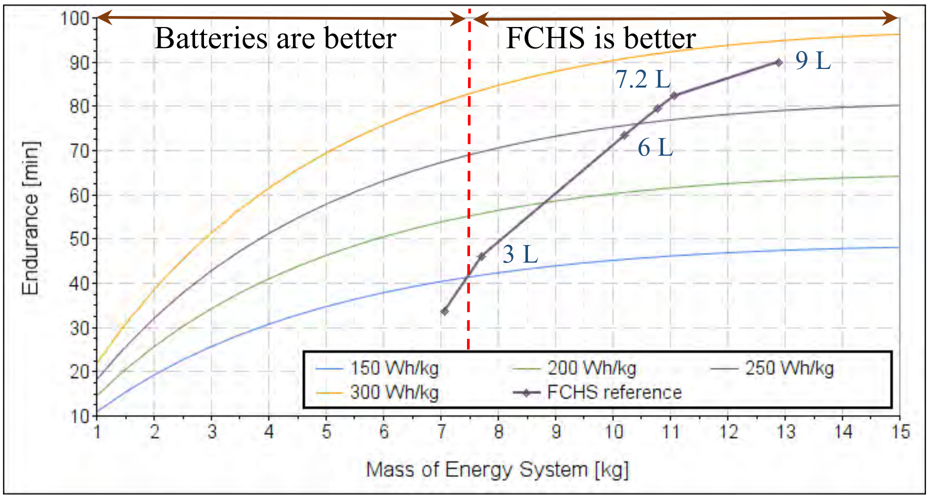

Fig. 7: Gross endurance plot for the reference fuel cell hybrid system and multirotor drone with a range of cylinder options and reference curves for different specific energies. The cylinders used are 2 L, 3 L, 6 L, 6.8 L, 7.2 L, and 9 L with hydrogen at 300 bar.

3.2 Characterization and Flight Performance

To answer RQ2, experiments have been carried out to identify the prototype performance in laboratory and full-scale flight conditions, as presented in Paper IV. Throughout the project, the total runtime for the two fuel cells is 22 and 24 hours.

3.2.1 Polarization Curves

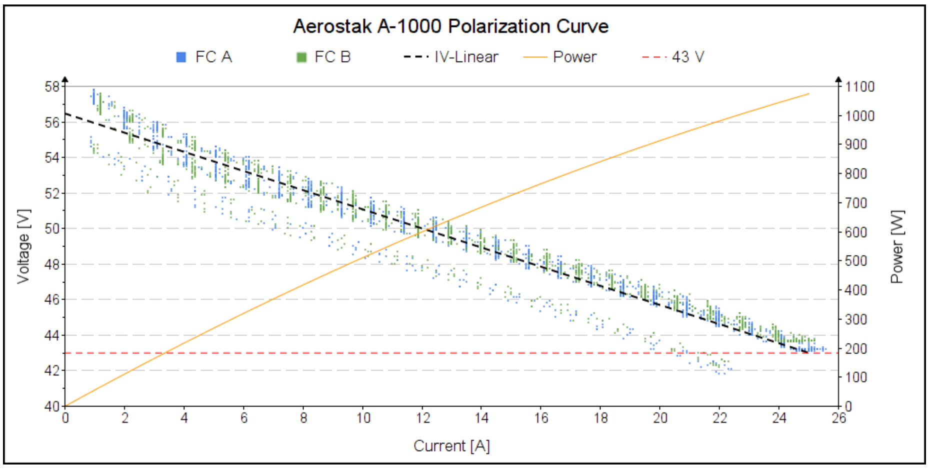

Fig. 8: Polarization curve showing the current-voltage characteristics (i-V) for the two Aerostak fuel cells.

The highest overall performance measured throughout testing was 27.2 A and 25.9 A at 1176 W and 1133 W for FC A and FC B, respectively. By running a polarization-curve test and plotting the current I and voltage V values, a polarization plot for the two Aerostak fuel cells was obtained (Fig. 8). This serves as a practical reference for the nominal performance. A simple linear expression (R^2 = 0.95) for the fuel cell voltage V_{FC} as a function of current I_{FC} is given in Eq. 7.

$$V_{FC} = 56.445 - 0.5386 \cdot I_{FC} \tag{7}$$

In this test, the fuel cells top out at about 25 A and a voltage of 43 V, giving an average cell voltage of 0.66 V. The power supply voltage was set to 43 V during testing, and this forms a fuel cell output limit and defines when the secondary power source steps in to supply further power. By multiplying voltage and current, the electric power output is obtained. A curve for the power output using the linear expression is included in Fig. 8.

3.2.2 Load Cycle Testing

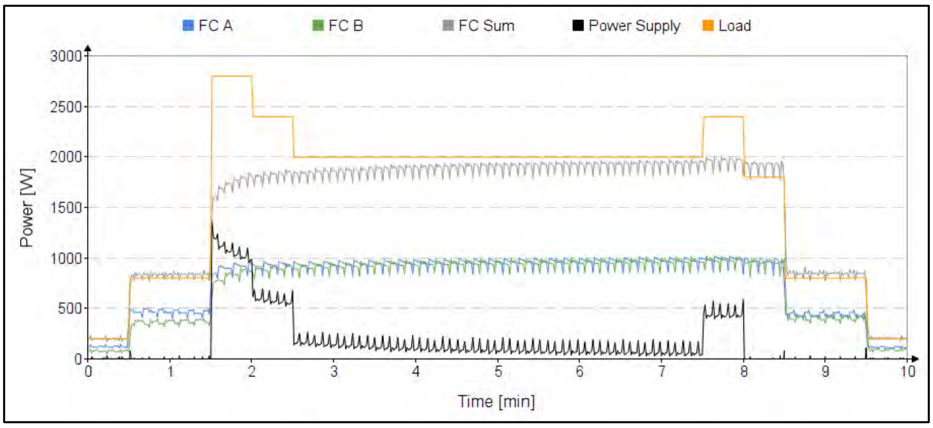

Fig. 9: Test data from a load cycle with both fuel cells and a constant power supply voltage of 45.1 V.

When exposed to a load cycle with a 2.8 kW take-off phase (Fig. 9), the fuel cells jumped to provide a combined output of 1565 W, which is 78% of the rated nominal performance. At 30 seconds after take-off, the fuel cells reached 90% of nominal output. The output further climbed towards full power throughout the cruise phase.

The secondary power source served its purpose and provided a power buffer at take-off as the fuel cells ramped up. The peak hybrid power was 1351 W and a current of 32.5 A. For a 16 Ah battery, that would give a peak discharge rate of 2 C. Spikes in power supply contribution compensates for dips in fuel cell power as purging occurs. The offset between stack A and B purging is consistent throughout the test. The fuel cells reported 261 Wh of energy, making the secondary power source energy contribution 14 Wh, which is 5% of the load profile total energy.

In Fig. 10, the total fuel cell power at six different power supply voltage levels are presented. This demonstrates how the voltage of the secondary power source, representing different battery state-of-charge levels, influences the fuel cell power contribution throughout the load profile. This is a key concept utilized in passive hybrid management systems, and from Eq. 7 it can be found that the fuel cell output will vary by 25% as the hybrid battery state-of-charge is reduced by 3.5 V.

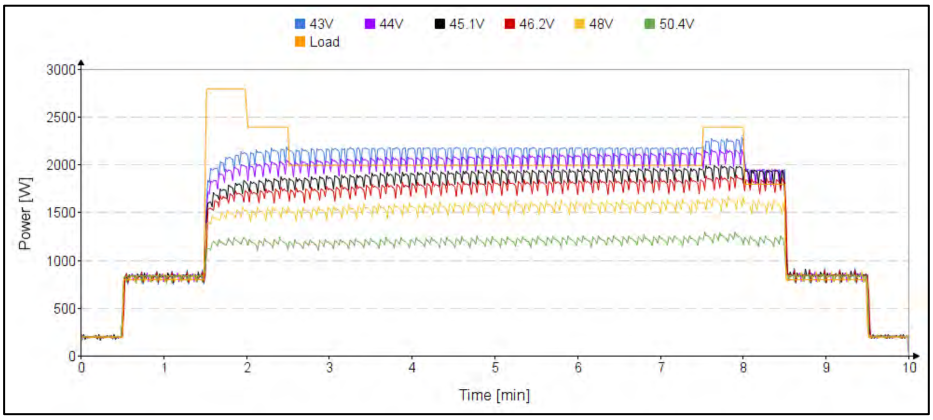

Fig. 10: Combined fuel cell power for a load profile at different power supply voltages. The different voltage levels represent different state-of-charge for 11-cell and 12-cell Li-Ion batteries.

At the highest voltage level, 50.4 V, the total fuel cell power is limited to 1200 W and an individual fuel cell contribution of 600 W. The total energy provided throughout the load profile is then 64% of the complete load cycle. When the voltage is lowered to 45.1 V, the fuel cell provides 95% of the energy. Thus, with a passive hybrid strategy, the fuel cell contribution is somewhat limited when the battery state-of-charge is 100% and will increase as the battery discharge. The fuel cell dynamic response is better when the voltage is high, and the fuel cell loading is lower.

3.2.3 Test Flight Performance

The full-scale test flight phases were: standby, conditioning, take-off, hover, temporary landing with spinning propellers, free flight, and landing. The fuel cells' performance from the flight is plotted in Fig. 11. The maximum power reported by FC A and FC B was 995 W and 963 W at 24.3 A and 23.2A, respectively. Water drops were found in both fuel cell purge tubes after the flight, indicating adequate hydration levels at landing.

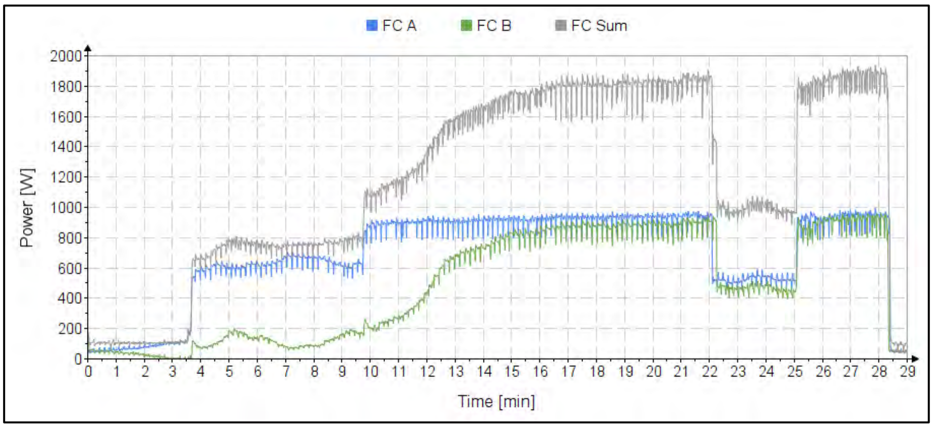

Fig. 11: Fuel cell performance from the test flight with the fuel cell-powered Staaker BG200.

In standby, the relative contribution of FC B drops to zero while FC A takes over and provides all power. As the propellers are started in the conditioning phase, the contribution of FC B increases, but it is not until after take-off that FC B accelerates its power contribution and reaches full output after 5-6 minutes. After the temporary landing, both fuel cells have equal response to the dynamic load at take-off and immediately reach full power. FC A has nominal performance throughout the flight.

The cause of the uneven performance is that FC A had better initial performance and higher voltage. This trapped FC B in a negative loop where FC A continued to improve hydration and performance, further increasing its load share and making it difficult for FC B to catch up. While there are mitigation strategies, this demonstrates a challenge with system architectures using multiple fuel cells. Individual fuel cell performance is highly dependent on membrane status and will vary as they degrade. A consequence of uneven load distribution is a higher use of the secondary power source, which can lower the energy margins.

During the second half of the hovering phase, it appears that the purging sequence is synchronized between the fuel cells. Since there are slight variations in the purging sequence at low and high power outputs, a purge synchronization can occur when the fuel cells operate at different power outputs. This is unfortunate because the hybrid battery discharge loading doubles when it has to compensate for both fuel cells, increasing the discharge peak currents from 25 A to 50 A. This may impact the overall battery capacity, power stability and flight behavior.

3.3 Prospects of Further Adoption

To explore the prospects of further adoption of fuel cell-based propulsion systems for multirotor drones, some key barriers for adoption are identified in Paper I and supplemented with findings from Paper IV.

3.3.1 Regulations

Regulatory permission to fly is critical to the overall viability of fuel cell-based propulsion systems. A basic premise for further adoption is that such drones will be legal to operate where they need to be operated. The technical development of unmanned aircraft systems (UAS) and fuel cell-based propulsion systems has been moving more rapidly than relevant operational and technical regulations, and the regulatory requirements are still not fully settled.

EU has adopted a proportional risk approach to the regulatory requirements and defined three operational classes: open, specific, and certified [47, 48]. Fuel cell-powered drones cannot be used in the 'open' class, as only purely electric drones can be used with a well-understood risk and under strict operational limitations. To be operated in the 'specific' class, the operational concept must be described in a CONOPS (concept of operations), and the risk must be assessed in a SORA (specific operation risk assessment). This considers the ground and air risk of the defined operation and must be within acceptable levels. For the lower risk levels in specific class, product certification (CE) and various mitigation strategies can be sufficient. For medium-risk operations, still in the specific class, a design verification report must be issued by EASA [49]. A special condition for light UAS [50] can then be used as certification basis.

Operations that involve transport of people, dangerous goods, or is carried out over assemblies of people is defined as high risk and falls within the 'certified' class. In principle, compressed hydrogen gas is classified as dangerous goods and belongs in the certified class. However, because the hydrogen pressure vessel is an integrated part of the propulsion system, this is not necessarily the case. The most attractive use-cases related to high-value data or services will typically involve beyond visual line-of-sight (BVLOS) flying or operations above urban and populated areas. Thus, further clarifications about the operational class for the most relevant use-cases are needed.

The risk and damage potential associated with hydrogen is a driving factor for the overall risk associated with the operation. To develop CONOPS and SORA for fuel cell-powered drone operations and learn about the operational possibilities and associated airworthiness requirements, accurate knowledge about the damage potential for a worst-case scenario and the likelihood of such a scenario happening should be known and well documented. Relevant aspects regarding hydrogen risk and mitigation strategies are discussed in Paper IV.

The current test program aims to demonstrate performance and build data on reliability, durability, and identify improvements. This data can be used as a basis for further development and obtaining a more general flight permit. A flight permit could potentially have been omitted by flying indoors. However, the process gave valuable insights to key concerns from a regulatory and aviation perspective, which must be addressed at some point to obtain a permanent flight approval.

The required certification level of the drone and power plant is expected to have a large impact on cost and on how the market develops. Further research should address certification aspects and clarify the relevant requirements and impact for fuel cell-powered multirotor drones.

3.3.2 Technical

Through the literature and technology review in Paper I and experiences presented in Paper IV, an impression about the current technical status are established. The viability and performance of fuel cell-based propulsion systems are demonstrated, and a few systems are found to be commercially available. However, it appears that no systems are well proven in operational environments over time and that further development is needed to reach the technical readiness level required for large-scale adoption.

When certification and airworthiness requirements are settled, the systems must be developed and demonstrated to comply. As each drone integration is unique, certification must be done on an overall system level. That is to ensure a proper match between drone, power plant, and flight envelope. In addition, there will be requirements towards redundancy, energy management, battery safety, mechanical integration, and ground control station performance monitoring. A plan for continued airworthiness where maintenance and durability data are specified must also be in place to ensure that the drone will remain airworthy throughout the defined lifetime, Testing demonstrated challenges with hydration management, passive hybrid power management, and power balancing between the two fuel cell modules. This can lead to challenges with the overall energy management and system reliability and should be addressed in further work. Short-term prototype improvements are related to the radio link and ground control station performance monitoring, hybrid management system, and improved integration of fuel cell and pressure vessel.

The current status is that the technology is not ready to be scaled up and mass-produced. As the complete requirements become clear, from a technical standpoint, it appears to be a question of further investments into research and development to get the technology ready.

3.3.3 Operational

While regulatory and technical aspects address the practical viability, the operational and commercial viability must also be considered. In essence, any additional cost and complexity must be justified. The principal value proposition for fuel cell-powered drones is improved endurance. This can improve mission range, enable BVLOS operations, and provide more efficient operations with less downtime and more coverage per flight. One approach to further increase utility is to ensure a dual-use capability where the fuel cell can charge ground equipment. The fuel cell power plant could also be modular so it can be used on a standard drone as a 'high endurance' module.

In Paper II, a cost analysis of a fuel cell hybrid system and batteries are carried out. It found that for a typical FCHS at the current time, the fixed system cost is € 40 per hour, and the variable cost related to hydrogen consumption is € 11 per hour, giving a direct cost of € 51 per hour. In comparison, battery cost can be as low as € 4.30 per hour. Thus, the cost of FCHS is about 12 times that of the battery option. The cost will be influenced by order volume, degree of customization, technology developments, and certification requirements. Fuel cell and hydrogen-related infrastructure are not considered in this comparison, and there is some uncertainty related to the actual fuel cell durability.

The research found some limitations with storage and use in sub-zero temperatures and polluted environments, which can limit the operational envelope. Hydrogen inevitably introduces some risk in storage, transport, and operations that must be managed. Involved personnel will also need additional training. This imposes some challenges and complexity on logistics and mobility and can reduce operational flexibility.

Based on the current state, it is assumed that some of the first full-scale commercial operations will be of a character that is enabled by using fuel cells. It will probably also be from a fixed location where a limited flight permit can be obtained, and the required infrastructure can be established. Later operational concepts must consider logistics, refueling, hybrid battery management for sustained operations, and more general flight permits.

More data and experience from actual operations in relevant environments should be obtained to move beyond demonstrations and achieve further adoption of fuel cell-powered multirotor drones. Operational requirements will help drive further improvements and will aid the understanding of how operational and logistical concepts can align to form compelling use-cases that give the best operational and financial rewards. Use-cases that best align with value creation will pave the way for further adoption.

3.4 Advancing the State-of-Technology

By addressing the above barriers, advances will be made to ensure regulatory compliance and that technical and operational requirements are met. To answer how the performance of fuel cell-powered drones can be further improved, Paper I explore technology options for three critical sub-systems: fuel cell stack type, cooling strategy, and hydrogen storage. Paper III investigates how central design parameters influence performance and can be used to target future optimization efforts.

3.4.1 Sub-system Improvements

The three most relevant fuel cell types are proton exchange membrane fuel cells (PEMFC), direct methanol fuel cells (DMFC), and solid oxide fuel cells (SOFC). The different options are based on the same basic electrochemical principles, but they operate in different temperature regimes, use different materials, and have different performance characteristics and fuel tolerance. Compared to PEMFC, the alternatives have higher start-up times, poor load adjusting characteristics, and lower power density, which will increase stack mass. This makes them less attractive for multirotor applications. Nevertheless, they might be viable options for fixed-wing UAVs, which operate at lower power levels and more continuous loads. The advantage of more simple fuel storage is compelling, but with the current state of fuel cell technology, PEM fuel cells appear to be the best option.

The cathode type and cooling strategy have a significant impact on the performance of fuel cell systems. Closed cathode fuel cells with liquid cooling can operate in a wider range of environmental conditions, have a lower risk of membrane dehydration, and offers more reliable performance. However, this comes at the cost of a higher power plant mass that will limit endurance and payload capacity. In the short term, air-cooled open cathode fuel cells will provide the best performance. However, their environmental limitations can limit long-term adoption. If future advances manage to reduce the mass of closed cathode fuel cell systems, they might be the preferred option and bring the best promise for large-scale adoption.

While PEM fuel cells are the most promising stack type for multirotor applications, the hydrogen fuel introduces some challenges. It poses a safety risk, and available storage solutions have a certain mass and volumetric impact and can be challenging to integrate. While liquid hydrogen can provide extreme performance under ideal conditions, the viability for use on multirotor drones in actual operations is low due to storage volume and challenges with dynamic consumption. The benefits of chemical storage solutions can be safe low-pressure storage, easy to handle and transport, and low volumetric density. However, some general challenges are low gravimetric density, slow reaction kinetics, low gas supply, high cost, and not all are reusable. Thus, compressed hydrogen gas is currently the best option.

3.4.2 Optimization

To target optimization and improvement efforts, the sensitivity study in Paper III explores several central system parameters. In general, performance improvements can be targeted towards increasing the system energy, improving the propulsion efficiency, or reducing mass.

It is found that there is a 20% - 30% propulsion efficiency loss associated with the coaxial configuration, and a single plane octocopter (S8) could have a 27% improvement in gross endurance from the X8 configuration. With a fuel cell specific power of 738 W/kg, the 700 W power difference between the S8 and X8 configuration at 25 kg thrust can give an 0.95 kg additional mass saving, further improving the endurance. However, other factors like airframe size and mass must be considered. The S8 multicopter would have to be 2.2 m in diameter, compared to the 1.2 m of the X8 version. A higher number of arms will also increase airframe mass.

The propulsion efficiency for the relevant drone is about 9 g/W at 21 kg take-off mass. Thus, a 1 kg mass reduction will give a 111 W power reduction, and about 1 min flight endurance can be gained from a 165 g mass reduction. A mass saving on the drone will benefit all energy systems, while if related to the energy system, it will improve the specific energy of that system and improve the relative performance.

The peak endurance is reached at a 0.67 energy system weight fraction, giving an energy system of 17 kg. Beyond this point, the effective endurance is reduced as energy system mass is increased. A 0.67 weight fraction is relatively high, and will in many cases not be practical.

Battery performance is evolving, and the specific energy is likely to improve in the next years. As this happens, batteries will become more competitive at high energy levels. However, it is important to note that fuel cell hybrid systems also will benefit from improved battery performance. The performance threshold between batteries and FCHS is moved from 7.4 kg with 180 Wh/kg batteries to 8.5 kg with 350 Wh/kg batteries, so the impact on the threshold is somewhat limited.

Lightweight cylinder options store the same energy as standard cylinders but give mass savings that benefit endurance. Thus, the advantage is highest for the larger cylinders, and for a 9 L cylinder, a 7-minute endurance gain can be achieved. The 450 bar cylinders have thicker walls and will be heavier, but they can also store more energy. A 6 L cylinder at 450 bar will give a similar endurance as a 9 L cylinder at 300 bar. The 700 bar cylinders store twice the energy of a 300 bar cylinder, and a 3 L cylinder at 700 bar will give the same endurance as the 6 L cylinder at 300 bar.

Regarding the degree of hybridization (Eq. 3), it is found that for small cylinder FCHS configurations with low specific energy, a high degree of hybridization is beneficial. As the cylinder volume and FCHS energy increase so that the specific energy becomes higher than that of batteries, it is beneficial to limit the degree of hybridization.

3.4.3 Prototype Improvements

In addition to the aspects outlined in 3.3.2, there are a few improvements that can be made to the prototype. The current fuel cell hybrid system weighs 12.5 kg and is not optimized for maximum endurance. Even though it can provide superior endurance, it weighs 4 kg more than the battery alternative. As more data is gained on actual energy and power requirements for various mission profiles, efforts can be focused on system optimization and establishing a flight envelope. This will show if the hybrid battery can be reduced. Upgrades should also improve space for payload integration and account for this in the flight envelope.

For current testing, a maximum pressure of 200 bar is used due to practical and safety reasons. To reach a 300 bar pressure, the refueling infrastructure and flight permit must be upgraded. With the current prototype and 7.2 L cylinder with 300 bar hydrogen, using the empirical propulsion power model, the gross endurance in hover conditions is calculated to be 76 minutes. That is an 87% improvement over the comparable 40 minutes endurance achieved with the standard battery-powered configuration (32 Ah, 12-cell). By upgrading the pressure vessel to 9 L or 13 L, a gross endurance of 84 minutes and 100 minutes, a 107% and 147% improvement to battery endurance, can be achieved.

4 Discussion

4.1 Scope

The selected scope has produced research results that explore different aspects of fuel cell-powered drones. The research papers complement each other, and together they make up a complete body of research that helps to advance the overall objective of understanding how fuel cells can be used to extend multirotor endurance.

The scope and research questions built on the strengths and benefits of being associated with a drone operator and maximized the possible research outcome for the relevant project boundary conditions. It gave access to operational experience, operator license, pilots, and in-house design and manufacturing. Thus, developing a prototype and performing a full-scale flight was made possible. This again improved the relevance of the research and served to align and prioritize the research topics.

4.2 Limitations

4.2.1 Applied Focus

As the research focuses on a certain drone and fuel cell system, it is somewhat specific and can have limited applicability. However, since the research is carried out in the framework of an industrial PhD program, focusing on specific challenges and solutions is an inherent characteristic of applied research. Efforts have still been made to investigate technology options and generalize the findings where possible.

As the associated drone operator had a specific drone design available for customization, focusing on this made both practical and commercial sense. There were no off-the-shelf fuel cell systems available, and the selected system had to be customized. However, it made sense to take basis in what was available for the project and look at how improvements or variations would impact performance. Focusing on a particular system and drone also made it easier to establish a coherent body of research.

Another fuel cell system option became available mid-project that would have been interesting to explore. However, the investment choice for the current system was made, and the timeline and funding did not allow for further investments.

4.2.2 System-Level Approach

The overall research topic is highly multidisciplinary and involves a range of sub-systems and associated research fields, which made it necessary to limit the scope. Each of the associated research fields is large, and providing relevant research contributions would be challenging to combine with advancing the overall objective. Thus, the focus has been on how these sub-systems interact and the most relevant aspects of multirotor drone integration and use.

To reach more relevant research contributions, it was desirable to focus on the strengths of the project. Being associated with a drone operator and manufacturer gave some unique opportunities and perspectives on the topic. Thus, staying on an overall system-level would benefit the most from this. The research could have focused on more advanced modeling and pursued theoretical system and component designs, but it was preferred that the research supported prototype development and experimental work.

Overall, the research seems to have found a good balance between advancing the overall objective and exploring the most relevant aspects of involved sub-systems.

4.2.3 Limited Experimental Work

More experimental work could have strengthened the research. However, laboratory facilities for advanced experiments and testing were not available early in the project. When the FFI research stay was organized in the second half of 2020, that opportunity was used to carry out much of the experimental work for Paper IV. Getting the prototype drone ready for experiments and test flights and obtaining a flight permit was an elaborate process, and all things considered, the achieved outcome is considered successful.

It would be valuable to have more power consumption data from the relevant drone at an earlier stage. This data could have been used for more advanced hybrid system design and modeling. However, the drone power consumption module had poor accuracy and could not be used. Also, due to limited fuel cell options, more data would not have had any practical impact on the final prototype. But in future work, having accurate power consumption data will be essential to match particular system designs with flight envelopes.

4.3 Contributions and Impact

One of few independent third-party multirotor drone integrations of a fuel cell-based propulsion system is presented. Based on experimental data from laboratory testing and a full-scale flight in a realistic operating environment, a unique overview of associated challenges and further work is provided. Experiences from design, preparations, and execution of the test flight are analyzed to present useful findings. As there is little published research on this topic, the work should be helpful for the research community, as well as drone operators and technology providers.

Throughout the project, the general relevance of the research topic has increased as industrial adoption of drones is further accelerating, and the focus on hydrogen and fuel cells as enabling components for a more sustainable future is becoming more widespread. This specific contribution helps advance the field of high endurance alternatives for multirotor drones and tackles one of the main limitations for further adoption of such systems.

By being the first hydrogen and fuel cell-powered flight approved by the Norwegian aviation authorities, the project also provides a contribution towards sustainable aviation. For the general public, a fuel cell-powered drone is an excellent application and demonstration of environmentally friendly technology.

The project has established a basis for both commercial and research-based paths forward. It has created interest from technology providers and potential customers that can be relevant for further research and development efforts.

4.4 Further Work

Specific prototype improvements are outlined in 3.3.2 and 3.4.3. They entail improvements in radio link and fuel cell monitoring, improved integration of the fuel cell and pressure vessel, payload compatibility, and mass reduction. More general improvements relate to the power plant architecture and hybrid management, environmental robustness, and system optimization for various mission profiles.

Closed cathode, liquid-cooled PEM fuel cells are found to offer some advantages towards environmental robustness and hydration management, which can improve the prospects of long-term adoption. Further research could be carried out to develop lightweight systems and assess the viability for application in multirotor drones.

Further work should clarify relevant certification requirements. The first step will be to develop a CONOPS and SORA for a pilot operation to better understand the operational freedom and associated risk profile. Research should also be carried out to have more accurate data on the risk and damage potential associated with fuel cell-powered drones. As standards and relevant certification basis are established, fuel cell hybrid systems and overall drone integrations must be developed and demonstrated to comply

More research can be done to ensure an optimal match between drones, power plants, and flight envelopes. Data on power consumption characteristics for various mission profiles can be used to optimize system sizing, and models can be developed to support detailed design and more accurate flight envelope estimates. To generalize, the work can be expanded to cover a range of drone sizes and configurations.

To improve the technology readiness level and move beyond demonstrations, fuel cell-powered drones must be proven in operational environments over time. This will drive further technology improvements, improve operational concepts, and establish more knowledge about the overall viability. This is essential to evaluate if the associated cost and complexity are justified by operational benefits.

5 Conclusions

RQ1: A model for assessing the performance threshold for when a fuel cell-based propulsion system will give a higher endurance than a battery-powered alternative is developed and presented. For a specific system, the threshold is found to be at 7.4 kg power plant system mass.

RQ2: The performance of a fuel cell-powered prototype in laboratory and full-scale flight conditions are presented. The fuel cell polarization curves are established, and the system is subjected to relevant load cycles. Different aspects of the relevant systems' architecture and hybrid management strategy, and their impact on overall performance are emphasized.

RQ3: The prospects of further adoption are explored, and it is found that the exact certification requirements remain to be fully settled. There are short- and long-term technical improvements needed, and some further research to be carried out. While the current technical status is not in a state where the technology can be scaled up, the viability of powering multirotor drones with fuel cells is confirmed. As more full-scale operational experience is gained, use-cases and operational concepts that best align with value creation will demonstrate the commercial viability and pave the way for further adoption.

RQ4: To find how the performance can be improved, technology options for fuel cell stack, cooling strategy, and hydrogen storage are investigated. While the current PEM fuel cells with open-cathode and compressed gas fuel storage appear to be the best short-term option, the challenges and potential of the alternatives are highlighted. From prototype testing, several specific improvements are proposed. Further optimization can target increasing system energy, improving propulsion efficiency, or reducing mass. A sensitivity study explored how several central system parameters influence performance and provide detailed guidance for further optimization.

The research has addressed at what conditions fuel cells will give superior endurance, mapped the performance of an actual prototype, investigated the prospects of further adoption, and analyzed how the performance can be improved. Altogether, the research provides unique insights into the use of fuel cells to extend multirotor drone endurance.

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Papers I - IV

Paper I

State-of-Technology and Barriers for Adoption of Fuel Cell Powered Multirotor Drones

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State-of-Technology and Barriers for Adoption of Fuel Cell Powered Multirotor Drones

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***Abstract*— Industrial use of multirotor drones is gaining traction, and fuel cell based power sources have been identified as a way of improving the flight endurance from what is possible to achieve with current lithium-based battery options. The state-of-technology and barriers for further adoption are presented. It is found that there are lightweight options commercially available and that the viability of powering multirotor drones for long-range and high endurance missions is demonstrated. The barriers mainly relate to the future required level of certification, technical improvements, and operational aspects. For advancing the state-of-technology, liquid-cooled fuel cells are identified as an attractive alternative that can expand the environmental flight envelope. However, a high system mass of these fuel cells remains a constraint. Hydrogen storage is a central challenge, and storage alternatives are investigated. To further improve the adoption of fuel cell based power sources for multirotor drones, operational and financial rewards must be well proven for realistic operations and relevant operating conditions.**

I. Introduction

There is an increase in industrial use of unmanned aircraft systems (UAS) and interest in how they can create value through more cost-efficient, time-saving, and higher quality inspections and services. Multirotor drones have the advantage of a small take-off and landing footprint, good positioning control, being able to hover in the same geographical location, and being able to carry payloads at both low and high velocities. These multirotor drones can typically have a take-off mass of up towards 25 kg and a payload capacity of 5 kg. To improve performance and achieve higher mission endurance and range, research efforts have been focused on the power source.

The current state-of-the-art lithium-polymer batteries have a specific energy of 130-200 Wh/kg [1]. Above a certain threshold, adding more batteries will not increase the endurance because of the increased power consumption from the added mass. Thus, the specific energy of the power source must be improved. More energy must be added without adding more mass. Fuel cell hybrid systems have been found to be capable of providing a specific energy of 250-540 Wh/kg [2] on a power system level.

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An alternative approach could be to use a small combustion engine, as done by the 'Perimeter 8' from Skyfront [3]. The main disadvantages compared to Fuel Cell (FC) based systems is the noise level, high maintenance, heat and exhaust management, and vibration challenges that can influence internal and payload sensors.

Previous research has focused mostly on fuel cell systems for fixed-wing unmanned aerial vehicles (UAVs), and more than 20 systems have been demonstrated [4]. A good overview and comparisons of projects and technologies are provided in [5, 6]. Multirotor drones generally have a higher power demand and a more dynamic load profile than fixed-wing UAVs, which introduce some additional challenges.

The scope of this paper is to present the current state-of-technology and investigate what is needed for large scale adoption. First, commercially available fuel cell systems, multirotor drones, and demonstration projects are presented. Then, regulatory, technical, and operational barriers for adoption are investigated. Finally, different approaches to advancing the state-of-technology are presented and discussed.

II. Fuel Cell Hybrid Systems

The most technologically mature and commercially available lightweight fuel cell systems for UAV applications are Proton Exchange Membrane (PEM) fuel cells that run on compressed hydrogen. In a fuel cell hybrid system (FCHS), the fuel cell is the primary power source and the battery is the secondary power source. Ideally, the fuel cell provides a continuous power, and the battery gives the system a better response to dynamic loads, provides redundancy and serves as an energy buffer for emergency landings. The sub-systems of a hybrid fuel cell system are; (1) Fuel Cell Stack, (2) Balance of Plant (BoP), (3) Hybrid Battery, and (4) Hydrogen Storage. BoP includes control electronics, thermal and humidity management systems, etc. The fuel cell stack configuration determines the nominal power. The system has a certain empty-weight, and it is the hydrogen storage and the hybrid battery that determines the amount of energy in the system. When comparing system performance to battery alternatives, it is important that the mass of the complete power-system is considered.

A significant difference between a hybrid fuel cell system for fixed-wing UAVs and multirotor drones are the relative power contribution from the fuel cell and the battery, or degree of hybridization. In general, fixed-wing UAVs have a relatively low and constant power demand in cruise. The fuel cell can then be sized to match that power consumption, reducing the role of the hybrid battery to primarily provide power for climb and maneuvering. Thus, the fuel cell can

Fig. 1: A range of PEM fuel cells. From left: 2.4 kW from Intelligent Energy, Aerostak A-1000 from HES, and Protium-2000 from Spectronik [2, 7, 8].

operate under much more ideal conditions and have a smaller and lighter hybrid battery.

The power demand for multirotor drones are generally higher than for fixed-wing UAVs, and the load profile is more dynamic [9]. Thus, the fuel cells must have a higher nominal power, and have a more active hybrid management system with a larger battery component. This increases the mass of the power system and introduces some additional challenges.

III. State of Technology

A. Fuel Cell Suppliers

Commercially available fuel cell systems from some of the most relevant actors in the market are listed in Table I, and a selection is shown in Fig. 1. These fuel cells are found in most commercially available fuel cell powered UAVs and demonstrator projects. Only fuel cells above 500 W are included. With a hover efficiency of 11 g/W, that corresponds to a take-off mass of 5.5 kg. Multirotor drones and the standard batteries must be of a certain mass before fuel cell based powerplants become a competitive option. Further research could be carried out to identify those threshold values.

When comparing fuel cell systems, it must be noted that they may operate at different voltages, and different hybrid system configurations provide different dynamic load performance. Other factors such as demonstrated flight record, certification level, durability, robustness, and reliability, etc. are also important to consider.

TABLE I. Fuel Cell Systems [2, 7, 8, 10-12].

Vendor	System	Power [W]	Weight [g]	Specific Power [W/kg]	Cooling
HES	A-1000 (HV)	1000	1800	556	Air
	A-1500	1500	2800	536	Air
	A-2000	2000	4380	457	Air
Intelligent Energy	650 FCPM	650	810	802	Air
	800 FCPM	800	930	860	Air
	2.4 FCPM	2400	3250	738	Air
Ballard	FCair 600	600	1800	333	Liquid
	FCair 1200	1200	4000	300	Liquid
MMC	H1	1000	1700	588	Air
Doosan	DP30	2600	3400	764	Air
Spectronik	Protium-1000	1000	5755	174	Liquid
	Protium-2000	2000	7585	264	Liquid
	Protium-2500	2500	9020	277	Liquid

B. Fuel Cell Powered Multicopters and Demonstrators

The Hycopter from HES (Fig. 2a) is powered by a 1500 W fuel cell and has a maximum take-off mass of 15 kg [7]. It is stated to be capable of a 3.5 hours endurance and reaching a 700 Wh/kg system-level specific energy. It has been reported to be used for inspection of Brazilian dams [13], and the Dubai police have expressed interest in using the Hycopter for intelligence, surveillance, and reconnaissance missions [14]. In 2019, a Hycopter was provided to the U.S. Navy for a project for assessing the feasibility of using fuel cell systems on-board naval platforms [15].

Intelligent Energy is primarily targeting third party integrators (Fig. 2b). With the power path module, they can achieve a range of nominal power levels [16, 17]. Together with strategic partners, they have integrated their power modules on different multirotor drones and demonstrated relevant use-cases and performance benchmarks. The 800 W fuel cell power module was integrated with the e-Drone Zero from Skycorp and the SENSUS drone from ISS Aerospace [2]. In project RACHEL, a 70 minutes flight endurance with a 5 kg payload was demonstrated [18]. The maximum take-off mass was below 20 kg, and the previous usable flight time for that drone was 12 minutes. They used a 6 L vessel with compressed hydrogen at 30 MPa. Together with MetaVista, a liquid hydrogen company, an endurance of 10 hours and 50 minutes was demonstrated [18]. A 650 W fuel cell was used, and the cryogenic hydrogen storage contained 390 g hydrogen. In April 2019 it was reported that the record was further improved to 12 hours, 7 minutes and 22 seconds, using an 800 W fuel cell, which at that time was a new Guinness World Record [19].

The FCAir 1200 fuel cell from Ballard has been integrated into the H2-6 from BFD Systems [11]. The drone weighs 12 kg, has a 2 kg payload capacity, and a 90 minute endurance. One unique feature of this drone is that the radiator is located on the arms for efficient cooling, as it is a liquid-cooled fuel cell. Ballard has been active in educating the industry about fuel cell powered drones and has published several useful white papers [5, 20-22].

The Staaker BG-200 (Fig. 2d) from Nordic Unmanned has a maximum take-off weight of 25 kg, a payload capacity of 8 kg, and a maximum endurance of 60 minutes. The fuel cell powered version is expected to have an endurance of about two hours.

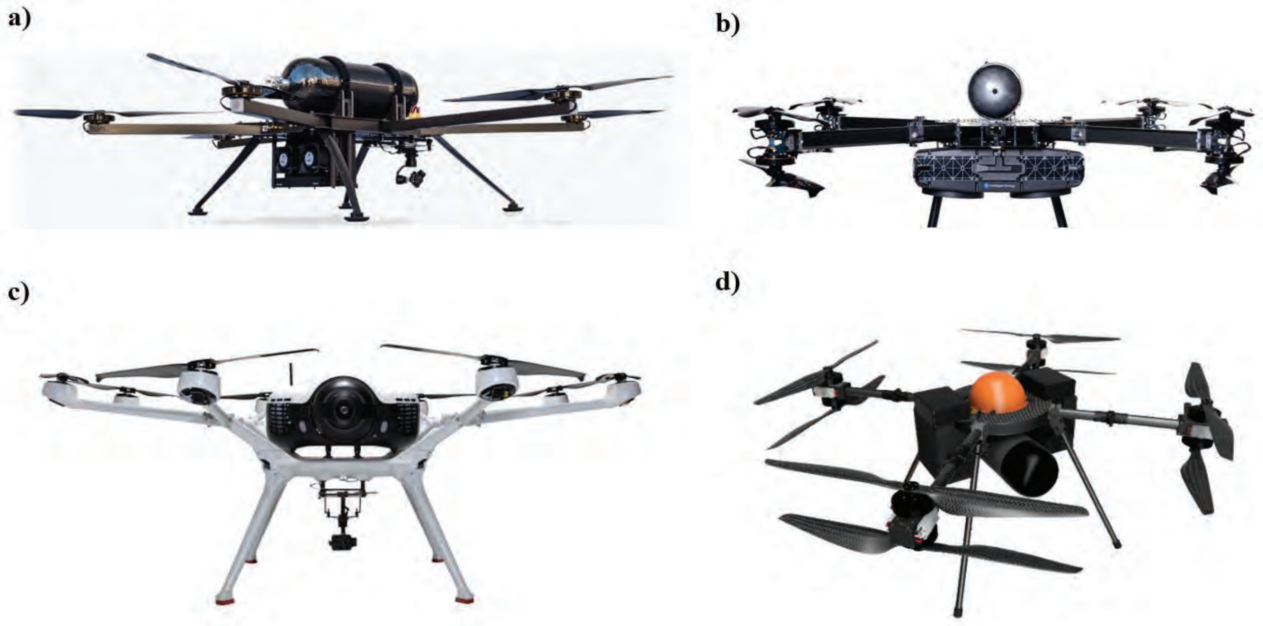

Fig. 2: Some large fuel cell powered multicopters: a) Hycopter from HES, b) 2.4 kW fuel cell from Intelligent Energy on a third party airframe, c) DS30 from Doosan, d) Staaker BG-200 FC from Nordic Unmanned.

A fuel cell from MMC powers the Narwhal drones from BSHARK. They have an endurance of up to 1.5 hours and a payload capacity of 1 kg. The China Southern Power Grid Company has reportedly used the Narwhal 2 drones for power grid inspections [23].

In 2017, EnergyOr supplied the H2QUAD 1000 multirotor drones to the French air force [24]. It is powered by a 1500 W fuel cell, can fly for 2 hours, and carry a 1 kg payload. They also have an H2QUAD 400, which is powered by a 1000 W fuel cell and is capable of a 2 hours endurance [25].

Doosan Mobility Innovation has developed the DP30 Powerpack [12], which is an integrated fuel cell power module that includes all the associated components and can be fitted on any suitable airframe. They also provide the DS30, an octocopter where the power module is integrated (Fig. 2c). It has a payload capacity of 5 kg and a maximum take-off weight of 24.9 kg. In 2019, the DS30 demonstrated a 69 km medical drone delivery, beyond visual line of sight [26]. Doosan has also initiated a project with Skyfire Consulting to establish emergency response and routine inspection routines for a major U.S. gas pipeline [27]. During CES 2020 (Consumer Electronics Show), their fuel cell solutions won two awards; "Best of Innovation" in the Drones and Unmanned Systems category, and an "Honoree" award in the sustainability, Eco-design & Smart Energy Category [28].

C. *Remarks on the State of Technology*

Much of the current activities in the fuel cell market is about demonstrating performance, which is the key value proposition, and relevant use-cases where the improved endurance provides more efficient operations or inspections. The two awards received by Doosan at CES 2020 confirms that the technology is relevant and innovative, and the medical delivery demonstration is a good use-case where the strength of the technology is well exemplified.

According to technology readiness levels (TRL), as defined by the EU [29], the current state-of-technology is that system prototypes are demonstrated in operational environments (TRL 7), and that some systems are complete and qualified (TRL 8). Still, according to publicly available data, it does not appear that any fuel cell powered multirotor drones are well proven in operational environments over time (TRL 9). For potential fuel cell integrators and users, it will be important to have operational and financial rewards well documented and proven. Operational requirements and experience will also further help to advance the state-of-technology.

IV. Barriers for Adoption

A. *Regulatory*

The technical development of unmanned aircraft systems (UAS) has been moving more rapidly than relevant operational and technical regulations. 1st of January, 2022, a new set of relevant EU regulations [30, 31] will come into effect. The European Union Aviation Safety Agency (EASA) is also working on developing certification specifications (CS) for UAVs that have to be certified according to aviation standards [32]. Because the fuel cell hybrid system is a critical part of the propulsion system, it is central for the overall airworthiness of the drone. Thus, it will be important to understand the level of certification and associated technical requirements that will be required for fuel cell powered drones.

According to EU regulations [30, 31], there are three categories of operations: OPEN, SPECIFIC, and CERTIFIED. The requirements are proportionate to the UAS performance, complexity, and type of operation. Operations carried out in remote areas with a low risk profile, away from buildings and people, are classified as OPEN. Beyond visual line of sight (BVLOS) operations will be SPECIFIC or

CERTIFIED. If the operation involves transport of people, dangerous goods, or is carried out over assemblies of people, it is categorized as CERTIFIED. Operations with a risk profile between OPEN and CERTIFIED, are categorized as SPECIFIC and will require adequate risk mitigations. If adequate mitigations are not possible, the UAV will have to be certified according to aviation standards.

OPEN category is regulated by product safety rules, and CE-certification of the drone is required. Requirements are related to failsafe functionality, sound levels, unique serial numbering, remote identification, and that the drone is accompanied by a user's manual. It is also required that the pilot can monitor the remaining energy level, giving the pilot sufficient time to return and land. The manufacturer must also have detailed technical documentation, from which it should be possible to assess whether the system complies with the requirements.

CERTIFIED category is regulated by aviation-specific rules, as defined by EASA. This category will have similar safety and documentation standards as traditional aviation, and catastrophic failure conditions must be extremely improbable ($<10^{-6}$). Initial airworthiness requirements concern design, and continued airworthiness concern maintenance, ensuring that unmanned aircraft vehicle will be airworthy throughout the entire lifetime.

Unmanned aircraft systems will have to be certified according to the EASA certification standard CS-UAS [32] and receive a type certificate (TC). This was released in September 2019. One of the most relevant sections, "UAS power supply, generation, storage, and distribution (CS-UAS.2525)" states:

The on-board generation, storage, distribution and supply of power to each system must be designed and installed to:

1) *Supply the power required for operation of connected loads during all approved operating conditions;*
2) *Ensure no single failure or malfunction will prevent the system from supplying essential loads required for continued safe flight and landing or emergency recovery; and*
3) *Have enough capacity, if the primary source fails, to supply essential loads. Including non-continuous essential loads for the time needed to complete the function, required for safe flight and landing or emergency recovery.*

It is also specified that the propulsion system must be type certified as a part of the UAS or hold an independent type certificate. Other relevant sections in CS-UAS concerns safe filling or recharging of the system (CS-UAS.2430c), energy level information to support energy management (SC-UAS.2445f), and that hazardous accumulation of gas must be safely contained or discharged (CS-UAS.2400d). The powerplant installation must also be designed to handle all likely operating conditions, vibrations, and fatigue (CS-UAS.2400c). In the guidance material, it is specified that power and hydrogen supply lines are to be considered to be a part of the energy distribution system and are also covered by the regulations.

A basic premise for further adoption of fuel cell powered drones is that they will be legal to operate where they are needed to be operated. The question is if a fuel cell based powerplant must be CE-certified or certified according to aviation standards and receive a type certificate (TC). The main factors affecting and driving the level of certification are (1) will the compressed hydrogen fuel storage classify as dangerous goods? and (2) will the most relevant use-cases fall within the CERTIFIED category?

The formulations in the EU-regulations [30, 31] on dangerous goods for the CERTIFIED category are: "involves the carriage of dangerous goods", "designed to transport dangerous goods", "designed for the purpose of transporting dangerous goods", and "carrying as its payload". Because the hydrogen fuel is not 'payload' but a part of the powerplant, it can be interpreted that carrying hydrogen as fuel will not lead to a type certification requirement, even though the compressed hydrogen in principle is 'dangerous goods'. Regarding use-cases, it will remain to be seen if the most relevant use-cases will include beyond visual line-of-sight and operations close to urban or populated areas, which often is related to high-value data, and what the relevant operational classifications will be.

If CE-certification of the fuel cell hybrid system is sufficient, fuel cell powered drones can carry out operations in the OPEN and SPECIFIC categories. The requirements in CS-UAS may still be used as a template in the design for ensuring the airworthiness, but the documentation and testing requirements will then be less comprehensive. If a type certificate is needed, it will have a large impact on the design, testing, and documentation, that again it will have a large impact on the price and on how the market develops. Further research should clarify the required certification level for fuel cell powered multirotor drones.

B. Technical

In a comprehensive review by Sharif and Orhan [4], the status and research potential for PEM fuel cells are detailed. Gong and Verstraete [33] focus on the status and research needs for fixed-wing UAV-specific fuel cell systems. Their recommendations on relevant research topics are; improvements in hydrogen storage, operational robustness, hydration management, and hybridization and power management strategies. The technical barriers for multirotor drones can be condensed into the three topics below.

In general, collecting data on actual performance and reliability will be increasingly important to increase adoption. To become proven technology, flight hours and key performance parameters must be tracked and logged.

1) Airworthiness

To comply with regulations and airworthiness requirements, technical features like energy level monitoring, robust failsafe functionality, and dedicated battery energy buffer for emergency landings are needed.

2) Robustness

As the focus on low weight can compromise the structural integrity, continued efforts should ensure that the systems are robust and can handle relevant physical loads. Proper hydration management and handling wide environmental operating conditions are key to achieving the durability and operational freedom that is needed.

3) Hybridization

The power management system and hybrid batteries have a large impact on the overall system performance and mass. As the load profile is more dynamic than for fixed-wing UAVs, this is even more important for multirotors. There is a potential to optimize and improve hybridization, e.g. by using ultracapacitors [34-36].

C. Operational

1) Value Proposition

The main value proposition of fuel cell powered multirotor drones is improved endurance. This can improve mission range, enable BVLOS operations, and provide more efficient operations with less downtime and more coverage per flight. If an improved endurance cannot be achieved in actual operations and actual use-cases, there is a much weaker case for replacing the traditional batteries. Thus, data is needed to verify the value proposition.

2) Environmental

Current open cathode fuel cells have some environmental restrictions which can be a barrier for further adoption and make fuel cells a less attractive option than batteries. Because of the large airflow needed for cooling, they can be sensitive to pollution. Also, due to the risk of freezing, which can cause damages to the membrane, the minimum operating temperature is typically $-5°C$, and they should not be stored in sub-zero temperatures. If fuel cells could be used in arctic environments, the advantage over batteries would be strengthened and further improve the value proposition.

3) Safety

Hydrogen is a highly flammable gas with a low ignition energy. If escaped gas is allowed to accumulate, it can easily ignite and result in a catastrophic event. Hydrogen only weighs 7 % of air and is very buoyant if released, so if not trapped it will disperse rapidly upwards and disappear [37]. Also, there are safety risks with any type of fuel, so by careful design and proper procedures and training for safe hydrogen management, the risk can be significantly reduced. Nevertheless, the UAS community should be aware that public opinion is important for the larger adoption of UAS in general, and taking safety seriously is critical for gaining public acceptance.

4) Logistics

Supply-chain and logistical requirements will have an effect on the mobility and complexity of the operation and can be a barrier. Thus, the operational concept and use-case must align with good logistical solutions. For refueling, there are two main approaches: refueling from high pressure and large volume hydrogen reservoir or replacing the hydrogen vessel on the drone. Several vessels can be refilled at the base and brought info field for replacement. For on-site refueling, more hydrogen has to be transported, and a compressor should be used to utilize the reservoir better and improve the fill pressure. Sisco, Harrington, and Robinson [22] provides a good overview of hydrogen refueling techniques and challenges.

5) Training

To ensure safe and proper hydrogen handling, fuel cell installation, and operations, the relevant personnel must be trained. Pilots must know how to monitor and respond to critical parameters, and how failsafe routines are affected. This can be included as an advanced topic in traditional training, or dedicated personnel can be trained.

6) Cost

Integrating and using a fuel cell hybrid system have some initial hardware, infrastructure, and training costs. Considering those cost factors, one study found that the cost per hour of flight for a fuel cell powered multirotor drone was 1.37 EUR, compared to 0.69 EUR for a battery-powered drone [38]. Fuel cell cost might drop as the market evolve, but more strict airworthiness requirements can increase the cost levels.

Justifying additional cost and complexity by achieving a return-on-investment is critical for operators. It is expected that as more data on actual operations are gathered, the use-cases that best align with value creation will pave the way for further adoption. However, fuel cell powered multirotors are not expected to replace all battery-powered drones and will probably not be viable for all operations.

V. Advancing the State-of-Technology

By addressing the above barriers, advances will be made to ensure regulatory compliance and that technical and operational requirements are met. Through optimization, the performance can be further enhanced. The power consumption can be reduced by improving the energy efficiency of the multicopter or reducing the mass of the FCHS or the airframe. Mission characteristics like trajectory and velocities can also be optimized. To identify viable options for further advancing the state-of-technology, the following sections investigate the fuel cell type, cooling strategy, and energy storage solution.

A. Fuel Cell Type

PEM fuel cells are the most frequent used type in UAVs, but there are a few options [39, 40]. It is interesting to investigate the most relevant alternatives to better understand how they potentially can yield advantages or disadvantages. The different options are all based on the same basic electrochemical principles, but they operate in different temperature regimes, use different materials, and they have different performance characteristics and fuel tolerance. The most relevant fuel cell types for mobile applications are listed in Table II.

TABLE II. Comparison of Fuel Cell Types [4, 33, 39, 41].

Type	**PEM**	**DMFC**	**SOFC**
Fuel	Hydrogen	Methanol (& water)	Methane/ propane
Charge carrier	H^+	H^+	O^{2-}
Electrolyte	Polymer	Polymer	Ceramic
El. Efficiency	40-50 %	20-30 %	50-60 %
Temperature (°C)	60-80	20-110	800-1000
Stack specific power (W/kg)	>500	>70	>800
System specific power (W/kg)	>150	>50	>100

Proton exchange membrane, or polymer electrolyte fuel cells (PEMFC), is very simple and is the most used type for FC powered UAVs. The electrolyte is a polymer membrane that protons can move through, and a platinum catalyst is used to achieve sufficient reaction rates at low temperatures. They have a relatively high power density, have a short start-up time, adjust relatively simple to load changes, and have a high technical maturity. They do require a high hydrogen purity (99.999 %) and can be contaminated by carbon monoxide (CO) and hydrogen sulfide (H_2S).

Direct methanol fuel cells (DMFC) are similar to PEM fuel cells and also operate at low temperatures. The term direct is used because the hydrogen is not extracted, but the fuel is used in its liquid form. The main advantage is simple fuel management, but they have a very low power density. Thus, they are best for applications with low and steady power consumption for long durations.

Solid oxide fuel cells (SOFC) operate at very high temperatures. Because of this, they have a high reaction rate without any expensive catalyst, and they can run on natural gases such as propane and methane, which are readily available and simple to store. However, thermal management can be complex, they adapt slowly to load fluctuations, and it does take some time to achieve operational temperature. They can have high efficiency, but due to thermal losses, small fuel cells are not that efficient. The ceramic materials used are difficult to handle and expensive to manufacture, and they experience high thermal stresses. Additional sub-systems to pre-heat the air and fuel are needed. In 2011, tests were carried out with the Stalker UAV by Lockheed Martin, using a SOFC that ran on propane. It was reported to have a fuel cell efficiency of 18.8 % and a start-up time of 20 minutes. In addition, the fuel cell was reported to only last for a limited number of flights. The Stalker XE was commercialized with an endurance of 13 hours in 2013.

The disadvantage of low power density, which will make the stacks much heavier than PEM stacks, slow start-up time, and slow load adjusting characteristics does not make SOFC and DMFC attractive options for multirotor applications. They might be attractive options for fixed-wing UAVs, which operate at lower power levels and more continuous loads. The advantage of a more simple fuel storage is compelling, but with the current state of fuel cell technology, PEMFCs appear to be the best option.

B. Cooling Strategy

The fuel cell stack can be cooled by air or by a liquid. The cooling strategy can have an impact on many of the factors that are identified in the barriers for adoption. Air-cooled, open cathode fuel cells that are self-humidified are the most widely used cooling strategy for lightweight fuel cell systems. The air is then used for both cooling and for the chemical reaction. They are simple, efficient, and lightweight. The challenge with this approach, however, is that it is challenging to balance the cell cooling, reactant supply, and membrane hydration. Especially when operating with a highly dynamic load profile under a range of environmental conditions. This can lead to poor cooling and thermal gradients within the fuel cell. The membrane can become over- or underhydrated, which can result in low performance and slow transient load response. It can also enhance degradation mechanisms, leading to a reduced lifetime. If not used regularly, open cathode fuel cells must be conditioned to keep the membrane hydrated. This typically has to be done every month and must be considered in the maintenance program [33, 39].

Liquid-cooled, closed cathode fuel cells can be more compact than open cathode fuel cells, but they require a liquid coolant circuit with a radiator and a pump. This makes the balance of plant (BoP) more complex, which affects the overall system weight, size, and parasitic loads. Thus, the system efficiency is affected, and they offer a lower system specific power and energy than what open cathode fuel cells can offer. However, because only air for the chemical reaction is needed, less than 1/15 of the air consumed by an air-cooled fuel cell is needed. This offers the advantages of a more accurate hydration control, the possibility of filtering the air for use in dusty and sandy environments, and reducing the impact of changes in air pressure and humidity. By using an anti-freeze coolant, operations in sub-zero environments might be enabled [5].

It is clear that the cooling strategy has a large impact on the performance of the fuel cell system. Closed cathode fuel cells can operate in a wider range of environmental conditions, reduce the risk of membrane dehydration, and offer a more reliable performance. However, that currently comes at the cost of higher system mass that will impact the endurance and the payload capacity. Open cathode fuel cells are the most simple option that will give the best performance. In the short term, they will possibly be the best option for demonstrating the potential that lies in fuel cell powered multirotor drones and accelerating the adoption rate. But they have some limitations that can limit long term adoption. If future advances manage to reduce the mass of liquid-cooled fuel cell systems, they will probably be the preferred option and bring the best promise for large scale adoption.

C. Comparison of Hydrogen Storage

PEM fuel cells appear to be the best technical option, but the hydrogen fuel introduces some challenges. It poses a safety risk, and available storage solutions have a certain mass and volumetric impact and can be challenging to integrate. Thus, hydrogen storage is an important barrier for fuel cell powered UAVs [33].

Hydrogen can be stored as a compressed gas (CGH_2), as a liquid (LH_2) at cryogenic temperatures (20-30 K), or in chemical hydrogen storage such as hydrides or high-surface materials [42]. The main requirements of fuel storage are that it can provide a sufficient fuel flow rate at the correct pressure, it has a limited mass and volume, and it should be possible to refill. For PEM fuel cells, there is also a high hydrogen purity required (99.999 %).

Hydrogen has a specific energy of 142 MJ/kg, compared to 46.4 MJ/kg of Gasoline. Thus, the energy content per mass unit is very high. The challenge is related to density, which at room temperature is 0.089 g/L. At 30 and 70 MPa, the density is 20.8 g/L and 41.3 g/L respectively [43]. In a liquid state, when cooled to 20 K at atmospheric pressure, the density is 70.8 g/L [39]. The energy density of liquid hydrogen is 10 MJ/L, compared to 34.2 MJ/L of gasoline, or 26 MJ/L of propane. Thus, gasoline is more than 3 times as energy-dense in terms of volume, even when the hydrogen is cooled to cryogenic temperatures.

TABLE III. COMPARISON OF DIRECT HYDROGEN STORAGE SYSTEMS [a] [39].

Storage System	Mass Storage Efficiency	Storage Density	Specific Energy	Energy Density
	$\% \frac{H_2 \text{ mass}}{\text{storage mass}}$	$\frac{H_2 \text{ mass } [g]}{\text{Storage vol. } [L]}$	$\frac{Wh}{kg}$	$\frac{Wh}{L}$
Compressed H_2 @30 MPa	3.10	14	1200	550
Compressed H_2 @70 MPa	4.80	33	1900	1300
Liquid H_2, Cryogenic	14.20	43	5570	1680
Liquid H_2, Cryo-compressed	7.38	45	2460	1510
Metal Hydride, Conservative	0.65	28	260	1120
Metal Hydride, Optimistic	2.00	85	800	3400

a. Note that the mass and volume of the entire storage system (pressure vessel, valve, tubing, and regulator) are taken into account in these data

Different direct hydrogen storage options are compared in Table III. Metal hydrides can be volume efficient, but they perform poorly in terms of mass. Liquid hydrogen has the best energy to volume and mass characteristics. Compressed hydrogen performs better in terms of mass efficiency than volumetric density.

D. *Liquid Hydrogen Storage*

The potential of using liquid hydrogen to power a fixed-wing UAV was demonstrated in 2013. The Ion Tiger from the Naval Research Laboratory demonstrated a 48 hours continuous flight, which was ~85 % longer than prior flights with gaseous hydrogen [44]. MetaVista and Intelligent Energy have also demonstrated a multirotor powered by liquid hydrogen, reaching 12 hours and 7 minutes endurance [19].

The Ion Tiger team did, however, report some challenges. The cryogenic vessel took 4 hours to reach thermal equilibrium [33]. To achieve maximum hydrogen utilization, the evaporation rate must be carefully managed to match the fuel consumption. Any excess hydrogen must be ventilated to prevent a pressure build-up, and an undersupply will affect the performance. In the Ion Tiger record flight, 39 % of the hydrogen was vented, and only 61 % was consumed for flight due to unintentional boil-off. The dynamic load pattern and dynamic fuel consumption of a multirotor drone will further complicate the chance of reaching a high fuel utilization. Practical challenges include ensuring sufficient insulation to minimize unintentional heat transfer, achieving a low storage system volume for physical integration, and fuel level monitoring. The logistics of resupplying and transporting liquid hydrogen is also a factor that complicates operative use.

From the above, it appears that even though liquid hydrogen can provide extreme performance under ideal conditions, the viability for use on multirotor drones in actual operations is low.

E. *Chemical Hydrogen Storage*

Hydrogen can be stored in metal hydrides or be chemically bound in liquids, and be discharged in reversible or irreversible reactions. To illustrate the potential, there is more hydrogen in a given volume of water (111 g/L) or gasoline (84 g/L), than in pure liquid hydrogen (71 g/L).

There is little data on lightweight hydride solutions for high power UAVs. Some research has been carried out on fuel cell systems in the range of 50 – 300 W. Sodium borohydride ($NaBH_4$) in one of the most researched chemical storage solution for UAVs [33], and it is used by HES in their Aeropak-L capsule and in the EnergyOR EPOD system [25]. They are demonstrated with PEM fuel cells, but several practical and operational limitations have been identified. If too much hydrogen is consumed and the pressure drops below a threshold, not all hydrogen can be extracted, and it will shut down. To avoid over pressurizing the container, a certain power consumption is required at all times. In addition, the tank must be cleaned and catalyst must be replaced after each flight [33]. The Ion Tiger team considered to use sodium borohydride, but discarded it due to low hydrogen weight fraction [45]. HES also provide the Aeropak-S, which is a solid hydride storage that can store 1500 Wh of energy, and is stated to have a 14 % hydrogen weight ratio. The systems from HES is configured for a hydrogen flow that corresponds to a fuel cell power output of 250 W [7].

The benefits of chemical storage solutions can be safe low-pressure storage, low risk of explosion, easy to handle and transport, and low volumetric density. Some general challenges can be low gravimetric density, slow reaction kinetics, low gas supply, high cost, and not all are reusable [46]. More research is needed to overcome those challenges and identify chemical hydrogen storage solutions that satisfy practical and operational requirements.

F. *Compressed Gas*

From the above, it is clear that at the current time, compressed hydrogen is the most straight forward and simple hydrogen storage to use on UAVs. It is quick to refill (3 - 5 min), provides a predictable and reliable hydrogen supply, and can have an unlimited life. The main disadvantage is the shape factor and limited volumetric density, making it challenging to integrate structurally on a multirotor drone.

The most common vessel types are Class III and Class IV. Class III has a metallic liner and a carbon fiber overwrap. The liner prevents permeation and the composite layer provides mechanical strength and stability. Type IV vessels are similar but use a polymer liner. Class IV has a 20 % lower mass at the same volumetric storage density than class III vessels, and have better properties in terms of fatigue and durability [43]. The typical storage efficiency of Class IV vessels is about 5 wt %. Intelligent Energy has collected a range of commercially available pressure vessels for UAVs in a brochure [2].

A paper by Barthelemy et al. [47] provides useful insights into various hydrogen storage solutions and research potential. Typical research on pressure vessels concerns novel fiber and resin concepts, cost-efficient manufacturing, new liner materials, and liner-less concepts [43]. A paper by Alcantar et al. [48, 49] presents and demonstrates how Type IV vessels can be optimized.

A cylinder is only the second best vessel shape. The ideal pressure vessel shape is a sphere, as it distributes the stress better than a cylinder [43]. Thus, it can store more hydrogen at a lower weight. Spherical pressure vessels are however challenging to manufacture, challenging to integrate into an airframe, and there are few commercially available options.

Typical storage pressure is 30 – 35 MPa. The maximum reasonable compression pressure of hydrogen is 70 MPa, because the hydrogen mass density does not increase much beyond that pressure [43]. By increasing from 30 to 70 MPa, the energy amount is doubled. If hydrogen is compressed to 80 MPa, it reaches the volumetric density of liquid hydrogen, but only a gravimetric density of 36 g/L, which is half that of liquid hydrogen, 70.8 g/L. At higher pressures, the mass of the vessel, regulator, and hose is larger, and compression and refueling can be more complex.

Pressure vessels are typically certified according to EN12245, ISO11119-2, DOT, or JP standards, which typically dictate a safety factor of ~1.5 and a non-limited life. It is possible to obtain custom made and limited-life vessels with lower safety factors for maximum endurance applications where the additional cost and higher risk is acceptable.

There is also research into liner-less vessels, referred to as Class V vessels [50]. The Ion Tiger team considered that option, but they had challenges with hydrogen leakage and went for another solution [45].

One emerging technology is 'hybrid storage', where high-pressure technology is combined with conventional hydrides [43]. Thus, it is estimated that perhaps the volumetric storage density of a 70 MPa CGH2 could be achieved with a 35 MPa pressure vessel. In practice, there will be some complexity and additional mass related to thermal management and in integrating a heat exchanger, but H_2GO Power [51] has some patents and is working on commercializing similar technology.

VI. Concluding Remarks

Several demonstrations have verified the performance and confirmed the viability of powering multirotor drones with fuel cells. The technology does however not appear to have been fully proven in operational environments (TRL 9). In terms of regulatory barriers, the minimum requirement is that the fuel cell hybrid systems are CE-certified. Because the hydrogen fuel could be categorized as dangerous goods, a full type certificate according to aviation standards might be required. If that is the case, it is expected to have a large impact on the future development of this technology. This should be clarified in future research.

The main technical barriers concern airworthiness, robustness, and hybridization. Several potential operational barriers are identified and discussed. Further research is recommended to identify the threshold for when using a fuel cell based powerplant is more beneficial than traditional batteries.

Open cathode PEM fuel cells are confirmed to be the best option for multirotor applications in the short term, but some limitations and challenges are outlined. Closed cathode fuel cells can offer some solutions like wider environmental operating conditions, but the mass of these systems remains a challenge. Compressed hydrogen is confirmed to be the best storage method, but there might be some potential in a hybrid storage solution that combines hydrides and a pressure vessel.

To achieve further adoption of fuel cell powered multirotor drones, more data and experience from actual operations in relevant environments should be obtained. Operational needs and requirements will help drive further improvements, and it will aid the understanding of how operational and logistical concepts can align to form compelling use-cases that give the best operational and financial rewards.

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Paper II

Suitability Analysis of Implementing a Fuel Cell on a Multirotor Drone

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Suitability Analysis of Implementing a Fuel Cell on a Multirotor Drone

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ABSTRACT: Increased flight time of multirotor drones is a key enabler for further adoption and industrial use of drones. A model for analyzing the performance of a fuel cell hybrid system for a multirotor drone is presented and applied for a case with an X8 multirotor drone with a maximum take-off mass of 25 kg. Endurance is the main performance parameter, and the model can be used to quantify the relative performance between different power sources. The model aims to determine if a specific hybrid fuel cell system is a viable option for a given multirotor drone and if it will provide better endurance than when powered by batteries. The model can also be used in system optimization and sensitivity analysis. In a case study, a fuel cell hybrid system with a 7.2 L cylinder with hydrogen at 300 bar is found to increase the flight time by 43 minutes (+76%) from the currently used LiPo-batteries. A plot identifies the energy system mass threshold for when the fuel cell hybrid system gives better endurance than batteries to be 7.3 kg. Based on current technology status, the cost of a fuel cell hybrid system is about 12 times that of LiPo-batteries.

KEYWORDS: PEM fuel cell; Hybrid system; Multirotor drone; Endurance model

INTRODUCTION

There is an increasing use of unmanned aircraft systems for industrial applications as cost-efficient, safe, and time-saving alternatives to traditional methods. One of the main restrictions for further adoption of multirotor drones is the limited endurance. The typical flight time of a multirotor drone powered by LiPo-batteries is 20–50 minutes. With operational safety margins, the effective mission time is generally low, which limits the operational range and possible area coverage.

Fuel Cell Hybrid Systems (FCHS) have emerged as one viable option to extend endurance on multirotor drones. They consist of a fuel cell that provides a continuous power and a hybrid battery to handle transient loads and power peaks. Such systems can provide a higher specific energy than batteries. Compared to internal combustion engines, fuel cells offer less maintenance, no vibrations, and more silent operation.

Early research efforts have mainly focused on fixed-wing Unmanned Aerial Vehicles (UAV). Bradley *et al.* (2009b) presents the fundamentals of fuel cell powerplant design considerations for small UAVs. One of the first demonstrator projects was in 2003, with more than ten projects in the following years (Bradley *et al.*, 2009a). Gong and Verstraete (2017) presents some of the later developments for fuel cell powered UAVs.

Multirotor drones have more power-intensive propulsion systems than fixed-wing UAVs and a more dynamic power profile. As the dynamic response of fuel cells is quite poor, hybrid batteries are essential for the maneuverability. Poor hybrid management

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can lead to membrane dehydration and fuel starvation (Verstraete *et al.*, 2014; Nishizawa *et al.*, 2013). Boukoberine *et al.* (2019) provides an overview of various power sources and energy management systems for multirotor drones.

There are some commercially available fuel cell systems and fuel cell powered drones. Intelligent Energy provides 650 W and 800 W fuel cell modules that can be integrated on multirotor drones (Barrett, 2018b), and in 2019 they announced a more powerful 2.4 kW fuel cell module (Barrett, 2019b). HES provides a range of lightweight fuel cells and the Hycopter, a fuel cell powered drone which has prompted interest from the Dubai Police (Barrett, 2018a; Barrett, 2019a). In 2017, the French Air Force purchased H2QUAD 1000 drones from EnergyOR, capable of carrying a 1 kg payload for 2 hours (Barrett, 2017). The performance of fuel cell powered drones is continuously improved, and in 2019 project Rachel achieved an endurance of 70 minutes with 5 kg payload and a take-off mass of 20 kg. A project by Metavista used a 650 W Intelligent Energy FC to carry out a 10 hours and 50 minutes flight using liquid hydrogen storage (Barrett, 2019c).

Due to the high power requirements and the need for larger batteries, fuel cell hybrid systems for multirotor drones are more massive than for fixed-wing UAVs. Thus, FCHS is not a viable option for all multirotor drones. This paper presents a model for assessing whether a fuel cell hybrid system is a viable option as a power source on a multirotor drone, and if it will provide a better performance than when powered by batteries as the primary power source.

The model uses endurance as the primary performance parameter, and the intention is that it can be used as a tool in the early stages of concept development and preliminary design to identify the best power source for a specific multirotor drone. By quantifying the performance of various system configurations, the model can also be used in optimization and sensitivity analysis.

The model assumes an open cathode proton exchange membrane (PEM) fuel cell with compressed hydrogen as fuel. This is one of the most developed and commercially available lightweight fuel cell types available. The model assumes that the system is designed with adequate margins to compensate for degradation mechanisms and environmental effects when operated within the defined operational envelope, and is not considered numerically.

First, the endurance model and the sub-models for calculation of energy, mass, and propulsion power consumption are presented. A case study of a fuel cell hybrid system on a multirotor drone with a maximum take-off mass of 25 kg is carried out, and the validity, potential improvements, and further research are outlined.

ANALYTIC MODELS

ENDURANCE

The basic equation for flight endurance is:

$$t_e = \frac{E}{P} \tag{1}$$

where E is the available energy, P is the power consumption, and t_e is the endurance. Using this equation, the performance of different energy systems can be compared. By using endurance as the basis for comparison, the total mass of the energy system and its effect on the power consumption is considered. As it is a theoretical comparison using all the available energy for propulsion and assuming static hovering, no transient effects from maneuvering and dynamic effects on the efficiency are considered. However, the relative gross endurance is considered to give a reasonable indication of the relative performance of a multirotor drone with different power sources. The sub-models for estimating the energy, mass, and power consumption related to battery- and fuel cell based power sources are provided below.

SPECIFIC ENERGY

The specific energy ε_S of a power source is a gravimetric performance indicator, specifying the amount of energy E stored per unit of mass m:

$$\varepsilon_S = \frac{E}{m} \quad (2)$$

This is an important parameter when comparing different power sources for multirotor drones, because the power consumption can be quite weight sensitive. Thus, the aim is to store as much energy possible, for as low weight possible. In general, a power source with a higher specific energy will give a better endurance. However, if there is a difference in the total mass of the power source, the endurance should be used as basis for comparison to capture and quantify the impact on the propulsion power.

SUB-MODELS FOR ENERGY AND ASSOCIATED MASS

BATTERY

The battery capacity E_{batt} and weight m_{batt} can be adapted from the battery specifications, or it can be calculated from Eq. (3) using the specific energy ε_S:

$$E_{batt} = \varepsilon_S \cdot m_{batt} \cdot \eta_{DOD} \quad (3)$$

The specific energy relates to the battery chemistry. The most common battery type for multirotor drones are LiPo-batteries, which typically have a specific energy of 180 $Wh \cdot kg^{-1}$. The depth of discharge η_{DOD} of the battery affects the cycle life, as investigated by Dogger *et al.* (2011). A η_{DOD} of 80% is considered a deep discharge (Mi and Masrur, 2018a) and by exceeding this, the batteries can experience permanent damage and limited cycle life. This aspect is important to consider when comparing power sources, so that they are compared by the amount of effective energy that can be used.

Batteries are simple in use, but they do have some inherent disadvantages such as performance degradation over time, reduction of capacity in cold weather, and that the capacity depends on the discharge rate (Dell *et al.*, 2001). These factors can be considered numerically but are not included in this model.

FUEL CELL HYBRID SYSTEM

The hybrid system is characterized by the degree of hybridization β_{batt}, as calculated by Eq. (4). This is the relative average power distribution between the fuel cell and the battery. It is a design parameter that is used in system sizing and is related to system energy through the design endurance, efficiency, utilization factors, and safety margins. The range is from 0 to 1, where 0 is only fuel cell power, and 1 is only battery power (Mi and Masrur, 2018b).

$$\beta_{Batt} = \frac{P_{batt}}{P_{FC} + P_{batt}} \quad (4)$$

The total energy of a fuel cell hybrid system E_{FCHS} is the sum of the effective energy available from the FC system and hybrid battery:

$$E_{FCHS} = E_{FC} + E_{h.batt} \quad (5)$$

The mass of the fuel cell hybrid system m_{FCHS} includes the mass of the fuel cell stack with plant balancing control electronics m_{FC}, the hydrogen cylinder with regulator and hose m_{H_2}, and the hybrid battery $m_{h.batt}$. The mass of hydrogen is only about 5% of the pressure vessel mass, and is neglected:

$$m_{FCHS} = m_{FC} + m_{H_2} + m_{h.batt} \quad (6)$$

When comparing power sources, it is important that all mass contributions associated with the systems are included to get a realistic comparison. The mass and power specifications of a fuel cell system is governed by what is commercially available.

HYDROGEN ENERGY

The effective electric energy from a fuel cell system E_{FC} depends on the amount of hydrogen that is stored and the efficiency of the fuel cell. As a function of pressure and cylinder volume, it is:

$$E_{FC}(p,V_{cyl}) = \rho_{H_2}(p)\cdot V_{cyl}\cdot h_{H_2}\cdot \eta_{FC}\cdot \eta_{\mathrm{H2}} \tag{7}$$

where the density of hydrogen ρ_{H_2} and the cylinder volume V_{cyl} gives the hydrogen mass. The density of hydrogen as a function of pressure can be calculated according to the equation presented in (Lemmon *et al.*, 2008), or be extracted from relevant tables. The specific enthalpy of hydrogen at the Lower Heating Value (LHV) is $h_{H_2} = 33.6 Wh\cdot g^{-1}$. By multiplying this with the hydrogen mass, the theoretical energy stored in the system is obtained. The fuel cell efficiency η_{FC} is related to the cell voltage and can be assumed to be 50% (Larminie and Dicks, 2003). The last factor is the fuel utilization factor η_{H2}, representing the fact that not all hydrogen is used in the chemical reaction. This can be assumed to be 0.95 (Larminie and Dicks, 2003).

The cylinder volume and associated mass is given by commercially available options. A range of Class IV cylinders, carbon fiber wound vessels with a polymer liner, rated for 300 bar are listed in Table 1. The specifications may vary between different manufacturers, and more lightweight cylinders are available. These might, however, have lower safety factors and a limited number of fill cycles.

Table 1. Properties for a series of lightweight Class IV cylinders from CTS. They are certified to store 300 bar hydrogen according to EN 12245 (CEN, 2002). A fuel cell efficiency of 50% is assumed for the energy estimates.

Volume [L]	Cylinder Mass [kg]	H_2 mass [gram]	Storage eff. [%]	Energy [Wh]	Specific Energy [$Wh\cdot kg^{-1}$]
2	1.2	41.7	3.5	700	584
3	1.4	62.5	4.5	1050	750
6	2.5	125.0	5.0	2101	840
6.8	2.7	141.7	5.2	2381	882
7.2	2.8	150.0	5.4	2521	900
9	3.8	187.6	4.9	3151	829

CTS – Composite Technical Systems

HYBRID BATTERY

The energy capacity of the hybrid battery as a function of the primary power source, the fuel cell system energy, can be calculated according to Eq. (8):

$$E_{h.batt}(E_{FC}) = \frac{\beta_{batt}}{1-\beta_{batt}}\cdot E_{FC} + (t_{emc}\cdot P_{FCHS}) \tag{8}$$

where emergency power backup is calculated from the average power consumption P_{FCHS} and the time required for an emergency landing t_{emc}. By modifying Eq. (3), the mass of the hybrid battery $m_{h.batt}$ can be calculated according to Eq. (9):

$$m_{h.batt} = \frac{E_{h.batt}}{\varepsilon_S\cdot \eta_{DOD}} \tag{9}$$

The allowed depth of discharge must be considered to ensure that the required energy is available. Also, the calculated energy and mass are minimum values. In practice, a commercially available option that can provide the required energy and power (discharge rate) must be selected. Eq. (10) can be used to convert to the much used mAh battery definition. U_{nom} is the nominal battery voltage:

$$C_{mAh} = \frac{E_{h.batt}}{\eta_{DOD} \cdot U_{nom}} \cdot 10^3 \tag{10}$$

SUB-MODEL FOR POWER CONSUMPTION

The relation between mass and propulsion power for the relevant multirotor drone must be established to capture the effect of changes in mass on the endurance. A simple approach to estimating this is presented below.

MASS MODEL

The take-off mass of a multirotor drone is:

$$m_{TOM} = m_{EW} + m_E + m_{PL} \tag{11}$$

where the empty weight m_{EW} includes the airframe, electronics and the propulsion system. The mass of the energy system m_E must include all components associated with the power source. For a fuel cell hybrid system, this mass is calculated according to Eq. (6). If relevant, the payload mass m_{PL} can also be added. m_{TOM} must be below the regulatory or design Maximum Take-off Mass (MTOM).

PROPULSION POWER

The propulsion power model for a single and coaxial rotor is based on one-dimensional momentum theory. The power required for a single isolated propeller in stationary hovering is provided in Eq. (12), as outlined by Leishman and Ananthan (2006):

$$P_{hover} = \frac{T^{3/2}}{\sqrt{2 \cdot \rho_{air} \cdot A_{prop}}} \tag{12}$$

where A_{prop} is the propeller disc area, T is the thrust in newtons, and ρ_{air} is the density of air. For two propellers in a coaxial configuration, the required power is:

$$P_{coax} = \kappa_{\text{int}} \frac{(2T)^{3/2}}{\sqrt{2 \cdot \rho_{air} \cdot A_{prop}}} \tag{13}$$

Because the lower propeller is affected by the wake of the upper propeller, a coaxial configuration is not 100 % efficient. This is considered by the factor κ_{int}, which is presented in Table 2 for various boundary conditions. Most coaxial propeller configurations have an inefficiency somewhere in the range of 22 - 28 %. The actual efficiency will depend on many factors and can be identified by empirical data.

Table 2. Inefficiency factor κ_{int} for coaxial propeller configurations (Leishman and Ananthan, 2006)

κ_{int}	Boundary condition
$\sqrt{2} = 1.41$	The coaxial rotors operate in the same plane, at the same thrust and/or torque.
1.281	The rotors operate at the same thrust. Lower rotor does not affect the wake contraction of the upper rotor, but half the area operates in the slipstream velocity induced by the upper propeller.
1.219	The rotors operate at the same torque/power. Lower rotor does not affect the wake contraction of the upper rotor, but half the area operates in the slipstream velocity induced by the upper propeller.
1	Assumed to have ideal performance with no inefficiency.

The combined thrust $2T$ of one coaxial pair should equal the take-off mass of the drone divided by the number of arms n_{arm}, as expressed in Eq. (14):

$$2T = \frac{m_{TOM} \cdot g}{n_{arm}} \tag{14}$$

Substituting Eq. (14) into Eq. (13), the generic equation for power consumption as a function of the take-off mass is:

$$P_{TOM}\left(m_{TOM}\right) = n_{arm} \cdot \kappa_{\text{int}} \frac{\left(\frac{m_{TOM} \cdot g}{n_{arm}}\right)^{3/2}}{\sqrt{2 \cdot \rho_{air} \cdot A_{prop}}} \tag{15}$$

By simplifying it for the case of a X8 configuration with four arms, the propulsion power as a function of the take-off mass becomes:

$$P_{TOM}\left(m_{TOM}\right) = \kappa_{\text{int}} \frac{\left(m_{TOM} \cdot g\right)^{3/2}}{2\sqrt{2 \cdot \rho_{air} \cdot A_{prop}}} \tag{16}$$

Parasitic loads from the on-board electronics are assumed to be considered by the propulsion power. The model can be calibrated and validated by experiments using the exact propeller configuration. For relative comparisons, it is assumed to provide relevant results.

ANALYSIS STEPS

Six analysis steps are detailed using the above models. By following this approach, it should be clear if a fuel cell hybrid system is a viable option and improves endurance. It is assumed that a FC system and degree of hybridization is selected based on an expected average and peak power profile.

S0: DEFINE BASIC PARAMETERS AND CALCULATE BATTERY BENCHMARK

Collect the parameters listed in Table 3. From the battery specifications, the battery benchmark performance can be calculated:

I. The energy of the reference battery E_{batt} can be identified from the battery specifications. The depth of discharge η_{DOD} must be considered, as in Eq. (3). Use Eq. (10) to convert between mAh and Wh.

II. Calculate take-off mass using $m_E = m_{batt}$ in Eq. (11).

III. Calculate the propulsion power P_{TOM} using Eq. (15) or Eq. (16).

IV. Calculate the battery reference endurance using Eq. (1).

S1: ENERGY IN FC-SYSTEM

By knowing the cylinder volume and pressure, the available energy of the fuel cell system E_{FC} is calculated from Eq. (7).

S2: HYBRID BATTERY PROPERTIES

From the calculated energy of the FC-system, the minimum energy required in the hybrid battery $E_{h.batt}$ and the associated mass $m_{h.batt}$ is calculated using Eq. (8) and Eq. (9).

S3: CALCULATE SPECIFIC ENERGY

All mass and energy components are known at this point, and the total mass m_{FCHS} and energy of the fuel cell hybrid system E_{FCHS} can be calculated according to Eq. (5) and Eq. (6). As an early indicator of the relative performance, the specific energy of the FCHS can be calculated using Eq. (2).

S4: PROPULSION POWER

The take-off mass m_{TOM}, Eq. (11), is then used to calculate the associated propulsion power P_{TOM} with Eq. (15) or Eq. (16).

S5: ENDURANCE

Knowing the propulsion power P_{TOM} and the total energy E_{FCHS} of the fuel cell hybrid system, the endurance can be calculated using Eq. (1).

S6: ANALYZE THE RESULTS

By analyzing the endurance for various systems, the relative performance is quantified and can be compared. This analysis approach can be followed to assess a) if a fuel cell hybrid system will give better flight time than when powered by batteries, and b) in sensitivity analysis and optimization of the FCHS.

CASE STUDY: FCHS ON A 25 KG X8 MULTIROTOR DRONE

DRONE AND FUEL CELL HYBRID SYSTEM

The endurance model from the previous chapter is applied to an X8 multirotor drone with a maximum take-off mass of 25 kg (Fig. 1). The fuel cell hybrid system consists of two A1000 Aerostak fuel cells, which combined can provide 2 kW of nominal power and a hybrid battery that is connected through a power management unit. 7.2 L hydrogen is stored in a Class IV composite cylinder at 300 bar. The case parameters are listed in Table 3, and a cost analysis is included at the end of the case study.

Fig. 1: Staaker BG200 multirotor drone from Nordic Unmanned and an Aerostak fuel cell from HES

CASE RESULTS

By going through the analysis steps from S0 to S6 using the defined case parameters (Table 3), it is found that the fuel cell powered drone will achieve a flight time of 99 minutes. That is an improvement of 43 minutes compared to when it is powered by the original 7.5 kg LiPo-batteries. The FCHS is heavier than the original batteries, but even a similar mass off LiPo-batteries (12.2 kg) will only give an endurance of 59 minutes. That is only 3 minutes more than with the original batteries. The key results from the analysis are listed in Table 4.

It should be noted that the higher take-off mass will reduce the payload capacity when trying to stay below a maximum take-off mass of 25 kg, and that a higher take-off mass can affect maneuverability.

Table 3. Case parameters for the Staaker BG200 from Nordic Unmanned AS.

Parameter	Symbol	Values
	Multirotor drone	
Propeller diameter	d_{prop}	28 in
Empty weight	m_{EW}	8.5 kg
LiPo-battery mass	m_{batt}	7.5 kg
LiPo-battery capacity	E_{batt}	1136 Wh (32Ah @44.4V, η_{DOD} = 80%)
	Hybrid Fuel Cell System	
Fuel cell power	P_{FC}	2000 W
Hybrid battery power	$P_{h.batt}$	400 W
Degree of hybridization	β_{batt}	0.17
Energy buffer for emergency landing	t_{emc}	2 min (@2.4 kW)
Mass of FC system	m_{FC}	4.4 kg
Mass of 7.2 L H_2 cylinder	m_{H_2}	4.0 kg

Table 4. Results from the case with a fuel cell hybrid system w/7.2 L Hydrogen at 300 bar

Ref.	Results	Sym.	LiPo ref.	FCHS (7.2 L @300 bar)	Diff.	%
S1	Effective energy	E	1136 Wh	2954 Wh	+1817 Wh	+160 %
S2	Mass energy system	m_E	7.5 kg	12.2 kg	+4.7 kg	+62.6 %
S2	Take-off mass	m_{TOM}	16 kg	20.7 kg	+4.7 kg	+29.5%
S3	Specific energy	ε_S	144 Wh·kg^{-1}	242 Wh·kg^{-1}	+98 Wh·kg^{-1}	+68 %
S4	Propulsion power	P_{TOM}	1215 W	1791 W	+575.8 W	+64.6 %
S5	Endurance	t_e	56.1 min	98.9 min	+42.8 min	+76.3 %

ENDURANCE PLOT AND ANALYSIS

By using the endurance model , a plot can be established that simplifies performance comparison between various power systems and system configurations. In Fig. 2, the FCHS performance with the cylinders in Table 1 is presented together with a LiPo-battery reference curve. The threshold for where a FCHS will give better performance than LiPo-batteries is at 7.3 kg. Above that mass, a FCHS will give a better endurance.

From the battery graph, it can be seen that the endurance increases rapidly with battery size until the threshold of 7.3 kg. Above this, the performance is only marginally improved with increasing battery size, and it tends to converge towards 60 minutes. The specific energy of batteries remains constant, and therefore does not scale well above this threshold. In that region the power consumption increases with the added mass so most of the added energy is consumed. To increase the endurance, more energy must be added without adding much more mass. This is where fuel cell hybrid systems have an advantage.

A fuel cell hybrid system has a high self-weight before any hydrogen storage is added (which contains most of the energy). But from that point, all increase in mass is related to increase in energy storage, and the specific energy of the energy system increases rapidly. Thus, a small increase in mass will give a large increase in stored energy, and even a 3 L hydrogen cylinder would give a higher endurance than LiPo-batteries.

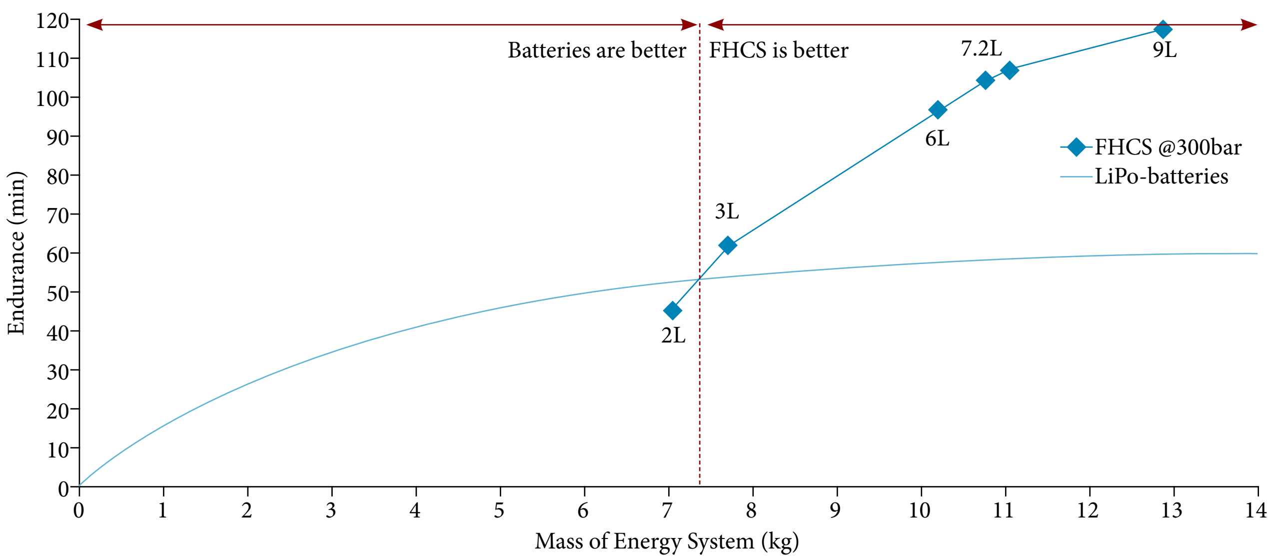

Fig. 2: Endurance plot for various power sources as a function of system mass. Note that a minimum battery mass is required to provide sufficient power to take off.

The threshold and relative performance will vary depending on the characteristics of the specific drone in question. The main factors is the power requirement of the drone, the weight sensitivity of the propulsion system, and the mass of a suitable fuel cell hybrid system. Because of the low power density of fuel cells, batteries are generally the only viable option for small multirotor drones. However, when multirotor drones and their energy source reaches a certain size and mass, fuel cell hybrid systems can become an attractive alternative. Further research could analyze the threshold for various drone sizes and FCHS characteristics.

COST ANALYSIS

Taking basis in the above case, this analysis considers the direct cost factors related to each of the energy systems. It is assumed that all required infrastructure is available and the cost of electricity is neglected.

As FCHS are not off-the-shelf components, the cost is highly affected by order volumes, degree of customization, technology developments, certification requirements, and commercial strategies. Because prices are provided on a case-to-case basis, they are also confidential. The experience of the authors is, however, that the cost of a typical FCHS that is similar to the system defined in the case study can be in the range of € 30–50000. The warranty guaranteed durability can be from 500 to 1000 hours, even though the design-durability for some systems is 3000 hours. Based on this, a reasonable estimate is a fixed system cost of € 40 per hour.

The variable cost is related to the hydrogen consumption. One 7.2 L tank at 300 bar contains 150 g of hydrogen, which has a cost of about € 18 when supplied by an industrial gas supplier in Norway. For an endurance of 99 minutes, that gives € 11 per hour. Thus, the direct cost of a fuel cell hybrid system is € 51 per hour.

For reference, the cost of the LiPo-batteries from the case is about € 2000. At a depth-of-discharge of 80%, a typical cycle life of 500 cycles can be assumed (Dogger *et al.*, 2011). With the estimated 56 minutes endurance, that gives 467 flight hours and a cost of € 4.30 per hour.

Thus, the cost of using a fuel cell hybrid system is about 12 times that of using traditional LiPo-batteries. This is considered to be a conservative estimate and the numbers are expected to improve when they become off-the-shelf components, and the availability and price of hydrogen improves. A complete return-on-investment analysis will have to include all costs related to the multirotor drone, infrastructure, training, logistics, maintenance – and quantify the operational advantage. For some cases, the added endurance from using a FCHS might enable certain operations where endurance and range is critical, significantly improving the value proposition.

It should be noted that the durability and cycle life of both energy systems depends greatly on how they are used and stored. There is also a time limit of one year for some fuel cells, where the warranty will expire and they need to be serviced. If they are not frequently used, open-cathode fuel cells need to be conditioned by being operated at about 60-70% power for 1-2 hours every month to maintain membrane hydration. That requires man-hours, hydrogen, and some additional infrastructure that must be considered.

DISCUSSION

VALIDITY OF THE MODEL

Efforts have been made to make a simple model that is easy to apply, while still capturing the parameters that have the largest effect on the endurance. It assumes stationary hovering and an average power consumption. The intention of the model is to provide a relative performance comparison between system configurations and to indicate if a fuel cell hybrid system will provide better endurance than with batteries for a specific multirotor drone. For this intended purpose, the validity is considered to be adequate.

If the objective, however, is detailed system optimization or accurate endurance estimates, the model should be further improved. More advanced models can be based on actual mission profiles and simulate various dynamic effects that influence power consumption and the overall system efficiency. These models will include more parameters, which might not be known in the early phases of system design, and they can introduce some uncertainty. Thus, the design stage and scope of the analysis will determine the most appropriate model and level of detail to be used.

MODEL IMPROVEMENTS

For fixed-wing UAVs, it is common to use the range and endurance models outlined by Traub (2011). Hovenburg *et al.* (2017) carry out a sensitivity analysis to quantify the impact of system mass, altitude, and speed on the endurance and range. Donateo *et al.* (2017) simulated the H_2 consumption and state of charge along a pre-defined mission profile and found that the net endurance from a detailed model was lower than what the simpler gross endurance estimate suggested, demonstrating the value of more detailed models for accurate estimates.

There are different approaches to modeling the power consumption of multirotor drones. They can be based on basic dynamics (Powers *et al.*, 2015) and energy calculations, empirical models, or theoretical models. If the exact propulsion system is known, experimental data can be used to establish an accurate relation between the thrust and propulsion power consumption. A model by Hwang *et al.* (2018) considers system mass, efficiency, battery discharge, and drag for steady-level flight and hovering to predict the endurance for a flight path with defined distances, flight speeds, and hovering time. Liu *et al.* (2017) presents a theoretical power consumption model, estimates the parameters, and validates the model through test flights. Two additional models are presented by Abdilla *et al.* (2015) and Gatti and Giulietti (2013). External environmental factors are also of interest to model. Scicluna *et al.* (2019) investigated the impact of wind in hovering and found that it actually can improve the endurance. The above models for multirotor drones assume batteries as the power source. Future research can combine their approaches with FCHS models to achieve a higher accuracy than the model presented in this paper.

Ustolin and Taccani (2018) present an alternative approach to identify the best power source. They calculate the energy required for a multirotor drone with a defined take-off mass to complete a particular mission profile. In their case, they found that 1089 Wh was needed for a 7 kg drone to complete a 120 minutes flight profile. A 500 W fuel cell hybrid system would weigh 4.4 kg, which was 30% less than batteries would. Thus, they concluded that the fuel cell hybrid system was the best option.

This approach will identify the most lightweight system, but that is not necessarily the same as having the best endurance. A fuel cell hybrid system with a higher specific energy than batteries can give a better endurance even though the take-off mass is higher, as demonstrated in this paper. Their approach does not capture this because the take-off mass and endurance are assumed up-front, and changes in the take-off mass and their effect on the actual endurance are not calculated.

SYSTEM OPTIMIZATION AND TECHNICAL IMPROVEMENTS

Currently, there are not many high-power lightweight fuel cells for multirotor drones on the market, and there is still room for improvement to make such systems even more competitive to batteries. To optimize the performance of a fuel cell powered multirotor drone in general, the power consumption must be reduced, and the available energy must be increased. The power consumption can be minimized by improving the efficiency of the propulsion system and by reducing mass. The self-weight of the fuel cell hybrid system is especially important and should be as low as possible. The available energy can be increased by improving the fuel cell efficiency and increasing the amount of stored hydrogen through optimizing the hydrogen storage. A breakdown of component weight and power loss could be a useful tool for targeting optimization efforts, as presented in one paper for a fixed-wing UAV (Bradley *et al.*, 2007).

The model presented in this paper can be used in optimization to quantify the impact of various system parameters. An improved version of this model can be used to optimize the fuel cell hybrid system for specific mission profiles and to identify operational limitations.

More technical improvements related to fuel cells for UAVs were identified in a paper by Gong and Verstraete (2017), outlining the status and research needs. They recommend further research into hydrogen storage and on-site refueling, the impact of altitude on the performance of the fuel cell, water management for non-humidified operation, operational robustness, and hybridization. The latter is especially important for multirotor drones because it has a large impact on the system mass and the dynamic response. One promising approach to improve hybrid systems is to use a supercapacitor, as demonstrated by Gong *et al.* (2018).

USE OF FC POWERED DRONE IN OPERATIONS

Moving from an initial assessment of the feasibility for using a fuel cell hybrid system to practical application, there are a few aspects to consider. In terms of structural integration, any impact on the center of gravity will affect the stability and maneuverability (Lapeña-Rey *et al.*, 2017). They also outline thermal management as a challenge. Considering evaporation at the cathode, the net heat generated by a 2 kW PEM fuel cell is about 1.6 kW (Larminie and Dicks, 2003). The operating temperature of such fuel cells is about 80 °C (O'Hayre *et al.*, 2016), and the thermal management system must maintain this temperature throughout the flight envelope. Failure to do so can cause membrane de-hydration and performance degradation. Environmental conditions such as ambient air temperature and humidity have a large impact, and a typical acceptable operating temperature range is 5 - 40 °C. This is a topic that is relevant for further research because it has an important impact on the durability and the operating envelope.

Looking beyond endurance, cost and lifecycle performance will also be important to consider (Belmonte *et al.*, 2018). The inherent safety challenges associated with hydrogen must be addressed, and suitable regulations for safe integration and operation of such systems must be developed (Sisco and Robinson, 2019). The latter is especially important for more wide scale adoption of fuel cell powered drones.

CONCLUSION

A model for analyzing and quantifying the potential of using a hybrid fuel cell system on a multirotor drone is presented. The model can be used to identify if a fuel cell hybrid system will give a better endurance than when powered by LiPo-batteries. The model is applied to a case and to create an endurance plot, demonstrating the value of the model. A fuel cell hybrid system will not always be a viable option for multirotor drones, but for certain sizes of multirotor drones, they can provide a performance advantage. Further analysis of the threshold for various drone sizes and FCHS characteristics is recommended.

In the case of an X8 multirotor drone with MTOM of 25 kg, a FCHS with a 7.2 L hydrogen cylinder at 300 bar will give a 43 minutes improvement of the endurance, a 76 % increase compared to the reference batteries. A cost analysis estimates the cost of a fuel cell hybrid system to be about 12 that of LiPo-batteries, assuming the current state of technology.

Future research could improve the validity of the propulsion-power model. By improving the model to account for the dynamic effects from a specific mission profile, more advanced system design and optimization can be carried out. The models should be verified with experimental data. For operations, it will be important to know the maneuvering freedom like maximum range, and optimal cruise and maneuvering velocities. The impact of environmental conditions on fuel cell performance, degradation mechanisms and durability is a highly relevant topic. Finally, identifying potential barriers for further adoption of FC-powered multirotor drones, how the technology can be improved and optimized, and how the return-on-investment figures can be improved will also be of interest to the research community and the industry.

AUTHOR'S CONTRIBUTION

Conceptualization: Apeland J, Pavlou D and Hemmingsen T; Methodology: Apeland J; Investigation: Apeland J; Writing - Original Draft: Apeland J; Writing - Review & Editing: Apeland J, Pavlou D and Hemmingsen T; Supervision: Pavlou D, Hemmingsen T and Fagertun O.

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Paper III

Sensitivity Study of Design Parameters for a Fuel Cell Powered Multirotor Drone

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REGULAR PAPER

Sensitivity Study of Design Parameters for a Fuel Cell Powered Multirotor Drone

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Abstract
The use of multirotor drones for industrial applications is accelerating, and fuel cell based propulsion systems are highlighted as a promising approach to improve endurance – one of the current main limitations. Due to multirotor drones' unique requirements, careful system design is needed to maximize the performance advantage. In this work a sensitivity analysis that quantifies the impact of central system parameters for an X8 multirotor drone with a 2 kW fuel cell hybrid system is presented and discussed. Thrust stand measurements identified a 20–30% efficiency loss from the coaxial configuration, and a 'single' configuration can reduce power consumption by 700 W at 25 kg take-off mass. Thus, a smaller fuel cell system can be used, giving an additional 1 kg mass saving and 75–140 W power reduction. Peak endurance is found at a 0.67 energy system weight fraction, and if batteries are improved from 180 Wh/kg to 350 Wh/kg, the energy system mass threshold from where fuel cells are superior rises from 7.4 kg to 8.5 kg. At 700 bar, a 3 L hydrogen cylinder can replace a 6 L at 300 bar, provide a 72-min endurance, and is the preferred option to reach minimum system volume. This work provides guidance in early conceptual stages and insights on how fuel cell based powerplants for multirotors can be improved and optimized to increase their value proposition. Further research can expand the work to cover other system variations and do experimental testing of system performance.

Keywords Fuel cell · Hybrid power · Multirotor drone · Performance threshold · Sensitivity analysis

Abbreviations

BEMT	Blade Element Momentum Theory
BoP	Balance of Plant
CONOPS	Concept of Operations
DC	Direct Current
DMFC	Direct Methanol Fuel Cell
EASA	European Aviation Safety Agency
FC	Fuel Cell
FCHS	Fuel Cell Hybrid System
LHV	Lower Heating Value
LiPo	Lithium-Polymer (battery)
PEM	Proton Exchange Membrane
SOFC	Solid Oxide Fuel Cell
SORA	Specific Operation Risk Assessment
UAV	Unmanned Aircraft Vehicle

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1 Introduction[1]

There is an increase in the industrial use of unmanned aircraft systems and interest in how they can create value through more cost-efficient, time-saving, and higher quality inspections and services. Multirotor drones have the advantage of a small take-off and landing footprint, reasonable positioning control, can hover in the same geographical location, and carry payloads at both low and high velocities. These multirotor drones can typically have a take-off mass of up to 25 kg and a payload capacity of 5 kg. To improve performance and

[1] Parts of this paper was presented and published in the Proceedings of the 2020 International Conference on Unmanned Aircraft Systems, Athens, Greece [5].

achieve a higher mission endurance and range, research efforts have been focused on the power plant.

The most common energy source used is pouch cell lithium-ion batteries, often referred to as LiPo batteries, with a specific energy of 130–200 Wh/kg [1]. However, above a certain threshold, adding more batteries will not increase the endurance due to the increased power consumption from the added mass. To further improve the endurance, the power plant's specific energy must be improved - more energy must be added without adding more mass. Fuel cell hybrid systems can provide a specific energy of 250–540 Wh/kg [2] on a power plant level and can give a better endurance than batteries.

Early research has focused on fixed-wing UAVs [3, 4]. As multirotor drones have more power-intensive and dynamic load profiles, the fuel cell hybrid systems require a higher nominal stack power and a higher degree of hybridization than fixed-wings. Integration and use on multirotor drones are now becoming a highly relevant research field due to two main factors: 1) lightweight fuel cell systems with high enough performance are now becoming commercially available, creating supply, and 2) multirotor drones with an adequate energy system capacity is now emerging and becoming more popular for industrial use, creating a demand.

There is limited research exploring fuel cell hybrid system design and optimization for multirotor drones in the 25 kg take-off mass and power range. This research should be valuable for the fuel cell drone community as it provides useful insights into central parameters and performance thresholds that can guide system optimization and improvements. This is essential for unlocking the full potential of the technology and for ensuring further technology adoption.

This sensitivity analysis investigates the impact on drone performance from several relevant system parameters. Experimental data for a relevant propulsion system is presented and used to develop an empirical power consumption model, which is then used in a sensitivity study to ensure a high validity. Factors like propulsion system configuration and efficiency, take-off mass and energy system mass fraction and energy perspectives concerning improved battery and hydrogen storage performance are investigated. For context, the current state-of-technology and some broader perspectives on fuel cell adoption are also presented and discussed.

2 State-of-Technology

2.1 Fuel Cell Hybrid Systems

Lightweight proton exchange membrane (PEM) fuel cells that run on compressed hydrogen are the most technologically mature and most frequently used type for UAV applications, but there are a few options like DMFC (direct methanol fuel cells) and SOFC (solid oxide fuel cells). The different options are based on the same basic electrochemical principles, but they operate in different temperature regimes, use different materials, and have different performance characteristics and fuel tolerance [5–7].

In PEM fuel cells, the electrolyte is a polymer membrane that protons can move through, and a platinum catalyst is used to achieve sufficient reaction rates at low temperatures. They have a relatively high power density, have a short start-up time, a relatively good transient load response, and have a high technical maturity. They require a high hydrogen purity (99.999%) and can be contaminated by carbon monoxide (CO) and hydrogen sulfide (H_2S).

The power demand for multirotor drones are generally higher than for fixed-wing UAVs, and the load profile is more dynamic [8]. Thus, the fuel cells must have higher nominal power and have a more active hybrid management system with a larger battery component. This increases the mass of the power system and introduces some additional challenges.

In a fuel cell hybrid system (FCHS), the fuel cell is the primary power source, and a 'hybrid' battery is the secondary power source (Fig. 1). Ideally, the fuel cell provides continuous power, and the battery gives the system a better response to dynamic loads, handle peak loads, provides redundancy, and serves as an energy buffer for emergency landings. The sub-systems of a hybrid fuel cell system are (1) Fuel Cell Stack, (2) Balance of Plant (BoP), (3) Hybrid Battery, and (4) Hydrogen Storage. BoP includes control electronics, power management, and thermal and humidity management

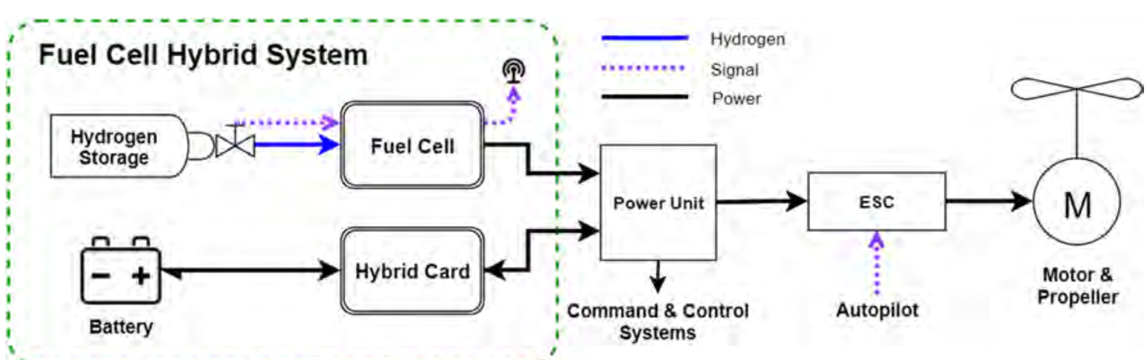

Fig. 1 Simplified layout of a fuel cell hybrid system based multirotor propulsion system

Table 1 Fuel cell systems [2, 9–13]

Vendor	System	Power [W]	Mass [g]	Specific Power [W/kg]	Cooling
HES	A-1000 (HV)	1000	1800	556	Air
	A-1500	1500	2800	536	Air
	A-2000	2000	4380	457	Air
Intelligent Energy	650 FCPM	650	810	802	Air
	800 FCPM	800	930	860	Air
	2.4 FCPM	2400	3250	738	Air
Ballard	FCair 600	600	1800	333	Liquid
	FCair 1200	1200	4000	300	Liquid
MMC	H1	1000	1700	588	Air
Doosan	DP30	2600	3400	764	Air
Spectronik	Protium-1000	1000	5755	174	Liquid
	Protium-2000	2000	7585	264	Liquid
	Protium-2500	2500	9020	277	Liquid

systems. The fuel cell stack configuration determines the nominal power. The system has a certain empty mass, and it is the hydrogen storage and the hybrid battery that determines the amount of energy in the system. When comparing system performance to battery alternatives, it is essential that the mass of the complete power-system is considered.

Commercially available fuel cells from some of the most relevant actors in the market are listed in Table 1. These fuel cells are found in most commercially available fuel cell powered UAVs and demonstrator projects. When comparing fuel cell systems, it must be noted that they may operate at different voltages, and different hybrid system configurations provide different dynamic load performance.

2.2 Fuel Cell Powered Multicopters and Demonstrators

The Hycopter from HES is powered by a 1500 W fuel cell and has a maximum take-off mass of 15 kg [9]. It is stated to be capable of a 3.5 h endurance and reaching a 700 Wh/kg system-level specific energy. In 2019, a Hycopter was provided to the U.S. Navy to assess the feasibility of using fuel cell systems onboard naval platforms [14].

Intelligent Energy is primarily targeting third party integrators. With the power path module, they can achieve a range of nominal power levels [15, 16]. Together with strategic partners, they have integrated their power modules on different multirotor drones and demonstrated relevant use-cases and performance benchmarks. The 800 W fuel cell power module was integrated with the e-Drone Zero from Skycorp and the SENSUS drone from ISS Aerospace [2]. In project RACHEL, a 70 min flight endurance with a 5 kg payload was demonstrated [17]. The maximum take-off mass was below 20 kg, and the original usable flight time for that drone was 12 min. They used a 6 L vessel with compressed hydrogen at 30 MPa. Together with MetaVista, a liquid hydrogen company, an endurance of 10 h and 50 min was demonstrated [17]. A 650 W fuel cell was used, and the cryogenic hydrogen storage contained 390 g hydrogen. In April 2019, it was reported that the record was further improved to 12 h, 7 min, and 22 s, using an 800 W fuel cell, which at that time was a new Guinness World Record [18].

The FCAir 1200 fuel cell from Ballard has been integrated into the H2–6 from BFD Systems [11]. The drone weighs 12 kg, has a 2 kg payload capacity, and a 90-min endurance. One unique feature of this drone is that the radiator is located on the arms for efficient cooling, as it is a liquid-cooled fuel cell. Ballard has been active in educating the industry about fuel cell powered drones and has published several useful white papers [19–22].

Doosan Mobility Innovation has developed the DP30 Powerpack [12], an integrated fuel cell power module that includes all the associated components and can be fitted on any suitable airframe. They also provide the DS30, an octocopter where the power module is integrated. It has a payload capacity of 5 kg and a maximum take-off mass of 24.9 kg. In 2019, the DS30 demonstrated a 69 km medical drone delivery beyond visual line of sight [23]. Doosan has also initiated a project with Skyfire Consulting to establish emergency response and routine inspection routines for a major U.S. gas pipeline [24]. During CES 2020 (Consumer Electronics Show), their fuel cell solutions won two awards; "Best of Innovation" in the Drones and Unmanned Systems category, and an "Honoree" award in the sustainability, Eco-design & Smart Energy Category [25].

3 Reference System and Performance

3.1 Fuel Cell Hybrid System and Multicopter

The Staaker BG-200 FC multirotor drone (Fig. 2) is used as a reference platform [26]. It has an X8-configuration with 28″

Fig. 2 Staaker BG-200 FC from Nordic Unmanned with the reference fuel cell hybrid system installed

propellers and is designed for a 25 kg maximum take-off mass. The empty mass is 8.5 kg, including the airframe and all fixed components, but not the power plant or payload. The standard battery alternative weighs 8 kg and has a specific energy of about 180 Wh/kg.

The reference fuel cell hybrid system (FCHS) used in the sensitivity analysis consists of two 65 cell fuel cell stacks that can provide a nominal power of 2 kW combined, an 11S LiPo hybrid battery (16 Ah), and a 7.2 L hydrogen cylinder [27]. The Class IV carbon fiber cylinder can store 150 g hydrogen at 300 bar and weighs 2.8 kg. The total mass of this fuel cell hybrid system is 12.2 kg, and the specific energy is 242 Wh/kg. A range of Class IV cylinders from *Composite Technical Systems SpA* is used to present alternative system configurations in the sensitivity analysis [28].

Aerostak A-1000 fuel cells from HES is used in a passive parallel hybrid configuration, where the power split between the fuel cells and battery is controlled by the DC-bus voltage. The fuel cell voltage is initially higher than the battery voltage. As the power demand increase, the fuel cell voltage will drop to a certain threshold voltage at max power, which is matched with the battery voltage. From that point, the battery will provide all additional power supply, and the fuel cell will operate at a constant output, as illustrated in Fig. 3. That is as long as the battery capacity and discharge characteristics can manage the additional load. In low power demand situations, the fuel cell can charge the battery. This is controlled by the 'hybrid card' (Fig. 1), which has a DC-DC converter and diodes that limits charging voltage and current. Similar hybrid systems are investigated in [29, 30].

3.2 Gross Endurance

Gross endurance is effective for assessing the relative performance of various energy system options [31]. As presented in [27], the flight endurance is found by dividing the effective energy E on the power consumption P. By assuming a constant fuel cell efficiency and using the average power consumption, the model represents static hovering conditions and gives the gross endurance. The effective energy is the actual energy that can be utilized for propulsion, considering a relevant battery depth of discharge and hydrogen usage. The power consumption is a function of the take-off mass and accounts for the energy system mass. Even though the specific energy [Wh/kg] can be used in a basic comparison of energy systems, the gross endurance gives a better representation of the impact different energy systems have on both energy and mass through the power consumption. In contrast to gross endurance, net endurance considers more dynamic conditions and can provide more accurate range and endurance estimates for specific mission profiles. This is more useful in detailed system design and in establishing an operational envelope.

3.3 Performance Threshold between FCHS and Batteries

Figure 4 is established in [27] and applies to the reference drone and reference fuel cell hybrid system (FCHS). It has

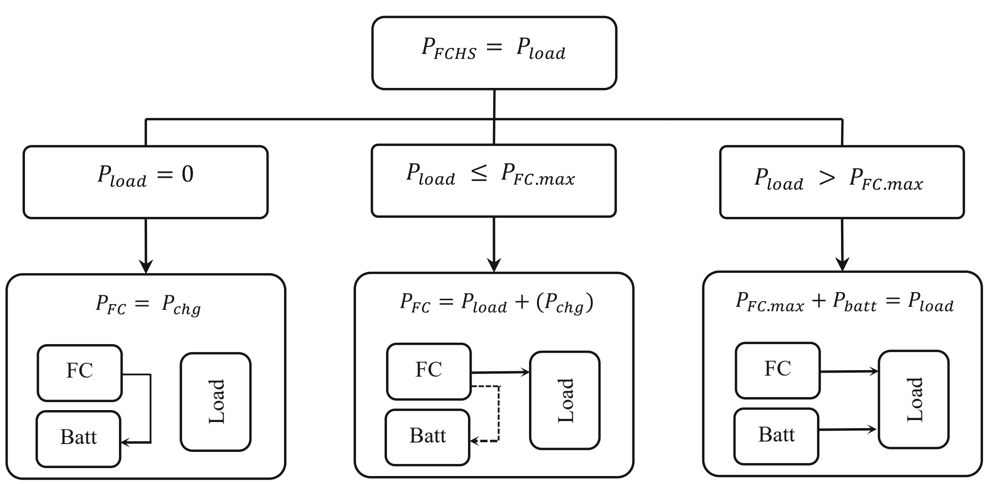

Fig. 3 The three main states of the hybrid system, where the fuel cell is 1) charging the battery, 2) providing power to a load and potentially charging, and 3) the fuel cell is operating at max power, and the battery is providing the remaining power

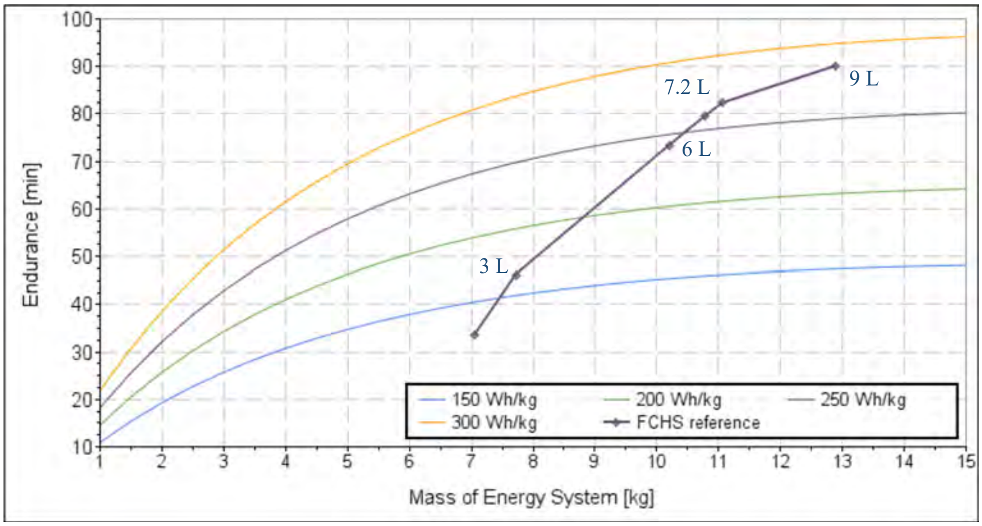

Fig. 4 Gross endurance plot for the reference fuel cell hybrid system and multirotor drone with a range of cylinder options and reference curves for different specific energies. The cylinders used are 2 L, 3 L, 6 L, 6.8 L, 7.2 L, and 9 L with hydrogen at 300 bar. Note that in practice, there is a lower cut-off limit given by the power required for take-off

been expanded to include curves for a range of constant specific energies, which serve as useful references. The graphs show how gross endurance is affected by the specific energy and total energy system mass. A range of FCHS system configurations is included, making it simple to identify the performance threshold for when the best endurance can be achieved. The 150 Wh/kg curve is close to the effective specific energy for the standard LiPo-batteries, which shows that the FCHS will give a better gross endurance above a threshold mass of about 7.5 kg. This case and underlying models are used as a basis for this sensitivity study to explore how various system parameters affect the relative performance of battery and fuel cell systems, and identify the impact on the performance threshold.

It can be seen that the endurance improves rapidly at low energy system mass and that this tendency continues longer for the higher specific energy curves. At some point, however, the curves flatten and will start to decrease. The propulsion system load response determines these characteristics. At some point, the energy system's added mass increases the propulsion power so that the added energy does not compensate and give a net endurance gain. This typically happens at high propulsion system utilization, where the propulsion efficiency becomes poor.

The diagram also emphasizes a significant difference between batteries and FC hybrid systems. Batteries have constant specific energy, so the mass and energy scale linearly. The power is coupled with the energy capacity through the discharge rate of the battery. For FCHS, power and energy are decoupled, and the specific energy is not constant. An FCHS with a given power rating has a certain empty weight before any energy is added to the system. Hydrogen storage has a relatively high specific energy of typically 600 to 900 Wh/kg, so the overall energy system specific energy is not constant but improves rapidly as more hydrogen is added. From this, it is clear that FCHS are most competitive when the relevant drone has a certain energy system mass, and a certain amount of hydrogen can be stored. For low mass energy systems, batteries will, in most circumstances, give the best performance.

4 Sensitivity Analysis

A fundamental condition for using a Fuel Cell Hybrid System (FCHS) to power a multirotor drone is that the endurance will be better than when it is powered by batteries. Next, a sensitivity analysis takes the gross endurance threshold analysis one step further by investigating how central system parameters affect the relative performance between batteries and a fuel cell based power plant. A breakdown of several central system parameters is provided in Fig. 5. An empirical power consumption model is developed and used, which improves the validity of the analysis. The sensitivity study can provide valuable input for system designers and for guiding improvements and optimization efforts.

4.1 Propulsion System Modelling

4.1.1 Analytic Model

The propulsion system determines how efficiently the electric power is converted into vertical thrust. It can be useful to have an analytic model that is general and requires as few parameters as possible so that it easily can be used to compare a range of options. One of the most basic models is based on the momentum theory. As derived in [27], the propulsion power for a multirotor drone with X8 configuration is:

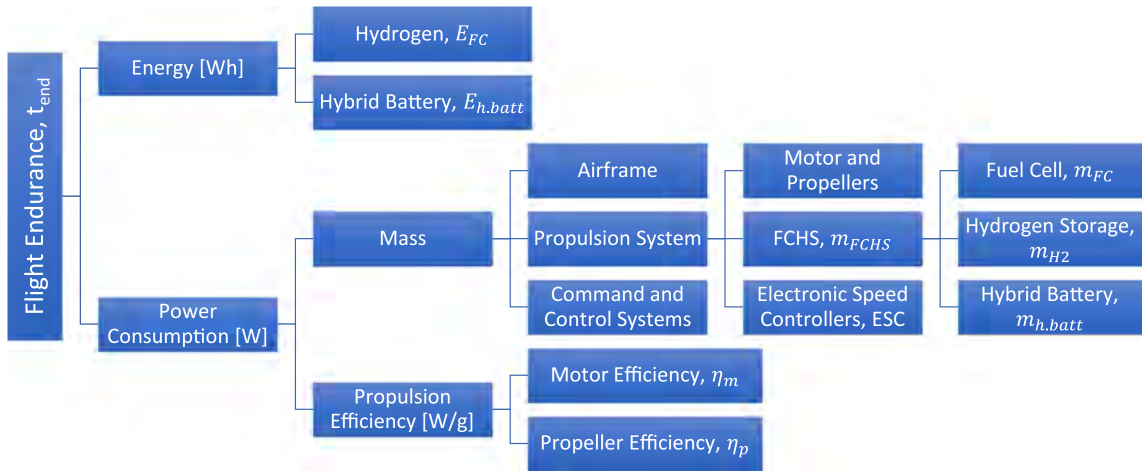

Fig. 5 Breakdown of the most significant system parameters that impact multirotor drone flight endurance

$$P_{TOM}(m_{TOM}) = \kappa_{\text{int}} \frac{(m_{TOM} \cdot g)^{3/2}}{2\sqrt{0.5 \cdot \rho_{air} \cdot \pi \cdot D_{prop}^2}} \quad (1)$$

where D_{prop} is the propeller diameter, ρ_{air} is the density of air, m_{TOM} is the take-off mass, and κ_{int} is the coaxial efficiency factor. This can typically be 1.22, 1.28, or 1.41, depending on the assumptions made [32]. The advantage of this model is that the input parameters are easy to identify. The coaxial propulsion efficiency is somewhat represented, but the accuracy might not be known, so the model should be calibrated and validated.

Blade element momentum theory (BEMT) is another modeling approach [32]. It is based on momentum theory, but it incorporates some propulsion system-specific parameters and can be identified by numerical methods or experiments.

4.1.2 Experimental Data and Empirical Model

The overall propulsion efficiency is determined by the motor efficiency and how well the electric power is converted to mechanical power at the propeller shaft, and propeller efficiency through how well the mechanical power is converted to thrust through the propeller's aerodynamic performance. Assuming a motor efficiency $\eta_m = 85\%$, which is considered to be very good, and a propeller efficiency $\eta_p = 80\%$, a decent overall propulsion system efficiency is 68% [33]. Many factors can influence the efficiency, and they typically have a narrow operating range with optimal performance. The best way to capture the inefficiencies and get accurate performance data is to test and measure the actual propulsion system. This can be done by carrying out test flights and analyzing the power consumption data or by running the propulsion system in a thrust stand.

Experiments were carried out in a thrust stand using a propulsion system similar to the reference drone: U8II KV100 motors and 28″ propellers from T-motor [34]. The measurement accuracy is ± 0.5% on thrust and voltage, and +/ 1% on electric current [35]. Data was collected for a single and coaxial propeller configuration with a face-to-face setup and a 109 mm propeller separation. There is a back-to-back configuration on the drone, but the relative propeller motion is similar to the drone.

The experimental data curves in Fig. 6 are scaled to represent the complete drone propulsion system. The single motor measurements are multiplied by eight, and the coaxial data is multiplied by four. The momentum theory reference curves are calculated with Eq. (1) and use coaxial compensation factors of 1.22 and 1.41.

According to the experimental data, the coaxial inefficiency is 20% at low thrust values and increases to 30% at 25 kg thrust, representing a 700 W power difference. Thus, the momentum theory coaxial compensation factors are close, but they underestimate the actual consumption, as seen in the plot. This can lead to an inaccurate power consumption response to mass changes and affect the sensitivity analysis accuracy.

Through curve fitting for the coaxial experimental curve, an empirical equation for estimating the power consumption of the X8 reference drone as a function of take-off mass is provided in Eq. (2). The power is given in W, and the take-off mass m_{TOM} unit is kg, with a validity interval of 0 to 25 kg.

$$P_{\exp}(m_{TOM}) = 2.3369 {m_{TOM}}^2 + 64.417 m_{TOM} \quad (2)$$

As demonstrated, experimental data can be used to establish empirical performance models or be used to calibrate and validate analytic models. Accurate propulsion power data is vital for achieving high accuracy when determining an operational envelope or in power plant design and sizing. It should be noted that this data represents static hover conditions and that other parasitic power draw that can occur. When in flight, the turbulence can be lower as more fresh air is introduced, improving the propulsion efficiency [36]. Mapping of in-

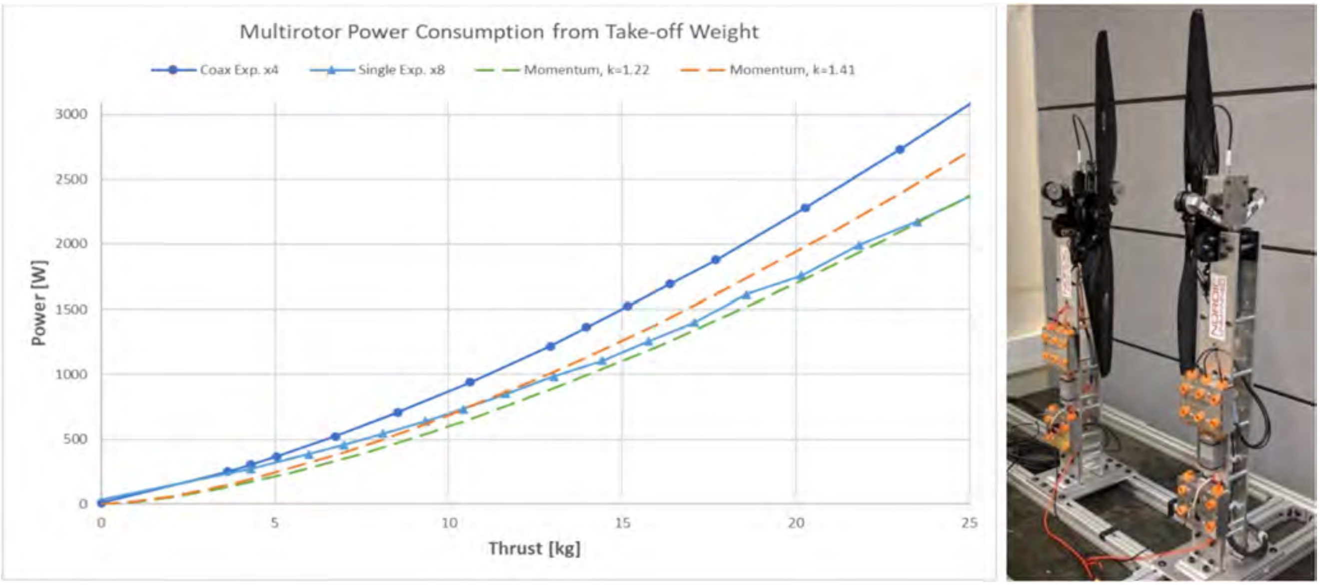

Fig. 6 Experimental and analytic data on the power consumption for an X8 multirotor drone, with 28″ propellers. The experimental data is collected using an RCbenchmark 1780 series thrust stand (right) at the University of Stavanger, using coaxial and single rotor setups. Momentum theory (Eq. 1) is used to establish the analytic curves

flight power consumption for various flight stages will be necessary for detailed design and accurate determination of the operational envelope.

4.2 Impact of Propulsion System Configuration

The propulsion system configuration and optimal matching of motor and propeller for the relevant operating loads have a large impact on the overall propulsion efficiency. In Fig. 7, the impact of having octocopter (S8) and hexacopter (S6) configurations instead of a coaxial X8 configuration is illustrated. The plot was obtained by calculating the reference fuel cell hybrid system's endurance for the different configurations. A constant empty mass, U8II KV100 motors, and 28 "propellers are assumed. The S8 and S6 curves are based on single propeller experimental data, and the X8 curve on the Eq. (2) model.

The S8 configuration will give a 27% improvement in gross endurance from the X8 configuration, which corresponds with the 20–30% propulsion efficiency loss associated with the coaxial configuration. The S6 configuration gives a 15% increase in endurance from the X8.

Based on airframe sizing equations [37], an S8 multicopter with 28″ propellers would have to be 2.2 m in diameter, compared to the 1.2 m of the X8 version. A hexacopter also using the 28″ propellers would have a 1.7 m diameter. If the hexacopter's overall size is limited to that of the X8, the maximum propeller diameter is 20″. Airframe size is an important factor to consider when assessing configurations, as it can have a large impact on the utility.

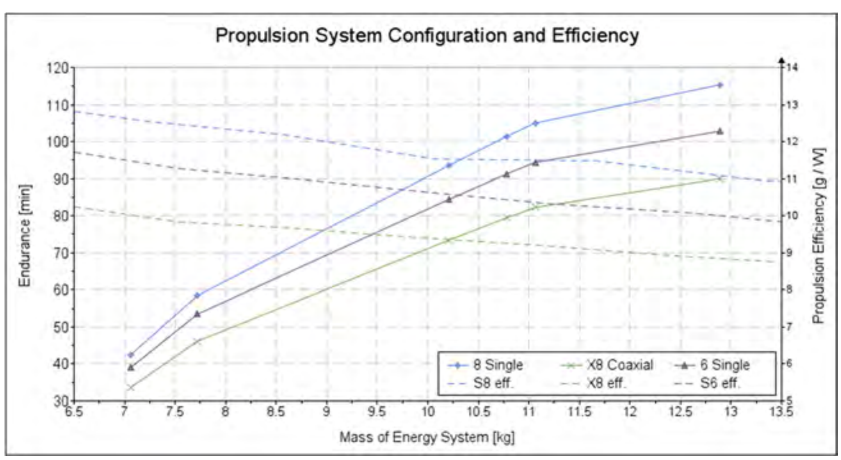

Fig. 7 Gross endurance for the reference FCHS system with different propulsion system configurations. The overall propulsion efficiency (g/W) is established from thrust stand measurements and the required propeller thrust for each of the configurations

At a 25 kg take-off mass, assuming a uniform distribution, each motor must provide 3.125 kg thrust, and the propeller disc-loading is 78.6 N/m^2. The thrust efficiency is then 10.5 g/W for the S8 configuration, and 8 g/W for the X8 configuration. The S6 propellers have to provide 4.1 kg thrust, have a disc loading of 105 N/m^2, and a propulsion efficiency of 9.22 g/W. Due to a 25% lower propeller area, each motor has to work at a higher throttle where the overall efficiency is lower. The 20" S6 configuration would have a disc loading of 209 N/m^2. The propeller area for this configuration is only 50% that of the octo-configurations, and while the propeller area is reduced, the same thrust must be generated from a lower propeller area. To achieve that at an optimal efficiency, another propeller and motor combination will have to be used.

Many factors influence the overall propulsion efficiency. In general, larger propeller diameters give a higher propeller efficiency [33]. The number of motors determines the required thrust, and the disc loading is determined by the propeller size. The propeller pitch and optimal angular velocity are central parameters, and the propeller torque at the relevant thrust level must be matched with the ideal motor operating torque. Other aerodynamic factors that are influenced by the configuration is the efficiency loss due to vertical airflow interaction between coaxial propellers and horizontal separation to avoid overlapping airflows.

The overall propulsion efficiency is especially relevant when a hybrid power plant is used because it impacts the power sizing of the system. If the drone can lift the same load at a lower power level, it might allow for a smaller and lighter fuel cell system and hybrid battery. With a fuel cell specific power of 738 W/kg, the 700 W efficiency loss between an S8 and X8 configuration at 25 kg thrust can give a 0.95 kg mass saving that will further improve endurance.

However, it should be noted that the different configurations have a different number and type of arms and motors, which will affect the drone empty mass and give a secondary endurance or payload capacity impact. The maneuverability and responsiveness are also influenced. Selecting the ideal configuration can be challenging and will depend on the operational requirements. An X8 multicopter has some redundancy and smaller overall size, making it more practical to transport and store at the cost of a less efficient propulsion system. However, this section has shown that regardless of the selected configuration, the propulsion system can be optimized to provide a peak efficiency at the relevant operating loads.

4.3 Mass Sensitivity

The mass sensitivity depends on the efficiency characteristics of the propulsion system. Assuming a constant propulsion efficiency of 11 g/W, a 1 kg change in mass gives a change in power consumption of 90.9 W. That is the propulsion efficiency given for the U8II KV100 from T-motor at 50% throttle [38]. At 40% throttle, it is 13.3 g/W, and at 90% throttle, it is 7.1 g/W, giving a 1 kg mass change a 75 W and 140 W impact, respectively. Thus, the propulsion efficiency and motor utilization degree can significantly impact the mass sensitivity, emphasizing the importance of an accurate propulsion power model.

Figure 8 was established by calculating gross endurance based on the propulsion power associated with a 10% and 20% mass reduction in take-off mass for the reference drone, and with a payload of 5 kg. For the 10% (1.95 kg) and 20% (3.9 kg) mass reduction, the endurance gain was 16% and 36%, respectively, which is 13 min and 30 min for the 7.2 L configuration. About 1 min flight endurance can be gained for a 165 g mass reduction. The 5 kg payload gives a 28% reduction in endurance, which is 23 min for the 7.2 L configuration giving a take-off mass of 24.6 kg, and bringing the power consumption up from 2154 W to 2992 W. This illustrates the importance and impact of mass and mass savings on the performance. Analyzing performance in limit scenarios is important for identifying the operational envelope.

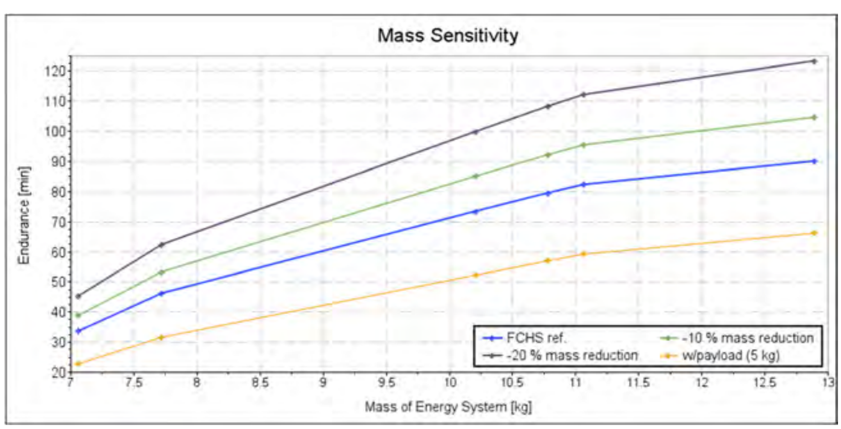

Fig. 8 Mass sensitivity of the reference drone and fuel cell hybrid system. For the 7.2 L cylinder configuration and 11.1 kg energy system, the take-off mass is 19.6 kg

Weight reductions could come from a more lightweight airframe, cables, connectors, motors, electronics, and other improvements of fixed components [39]. However, the design will still have to be robust and handle relevant imposed vibrations with minimum deflections. Mass savings on a fuel cell hybrid system can be related to improved integration of the fuel cell stack and pressure vessel into the airframe, more lightweight pressure vessel, or lower degree of hybridization and smaller hybrid battery. Reduction in power consumption from mass savings can allow for using a fuel cell stack with a lower power rating, saving further mass. There are also interesting approaches where the hybrid system and energy storage also have a structural role, giving further savings. For a small multirotor, it was found that integrating the batteries in the structure could give a theoretical 41% increase in endurance [40]. The location of a mass saving is of importance. A mass saving on the drone will benefit all energy systems, while if related to the energy system, it will improve the specific energy of that system and improve the relative performance.

4.3.1 Ideal Energy System Mass Fraction

When analyzing various energy systems and system configurations, it is interesting to know the ideal energy system mass fraction. This refers to take-off mass, and a weight fraction of 0.5 on a drone with a take-off mass of 17 kg will have an empty mass of 8.5 kg and an energy system of 8.5 kg. Figure 9 is based on Fig. 4, but the energy system mass fraction is used on the x-axis. The peak endurance is reached at a 0.67 weight fraction, giving an energy system of 17 kg. Beyond this point, the effective endurance is reduced. This energy system mass is relatively high and will, in many cases, not be practical to carry. There should also be some payload capacity, reducing the available mass fraction for the energy system to stay within maximum take-off mass limits.

One interesting finding is that even though the different specific energies will give different endurance, the endurance curves' characteristics and peak endurance are similar. The peak endurance and general shape of the curves are determined by the propulsion system response to the mass increase and associated propulsion efficiency. The endurance gain is relatively marginal towards peak endurance, and the curve turning point is probably a better indicator of the ideal energy system mass. Further research could look into how the ideal energy system mass can be identified in general for various multirotor drones and energy system characteristics. Research carried out by L. Traub [41] found the optimal battery weight fraction for fixed-wing UAV maximum range and endurance at cruise conditions to be 2/3 of the total mass. M. Gatti [42] also found similar indications for multirotor drones. Traub states that in most cases, other practical concerns related to take-off mass, payload capacity, maneuverability or operating limitations would dictate the maximum battery size.

4.4 Specific Energy

The gravimetric energy density, specific energy, is an important factor when comparing energy systems. If an energy system has a higher specific energy, the same amount of energy can be carried at a lower mass, giving a secondary endurance or payload capacity benefit. Alternatively, more energy can be carried for the same mass, also increasing endurance. To increase the specific energy, the energy system's mass can be reduced, or the energy amount can be increased. The specific energy of a fuel cell hybrid system is:

$$\varepsilon_{S.FCHS} = \frac{E_{FC} + E_{h.batt}}{m_{FC} + m_{H_2} + m_{h.batt}} \quad (3)$$

where the E_{FC} is fuel cell system energy, $E_{h.\ batt}$ is hybrid battery energy, m_{FC} is the mass of the fuel cell stack and

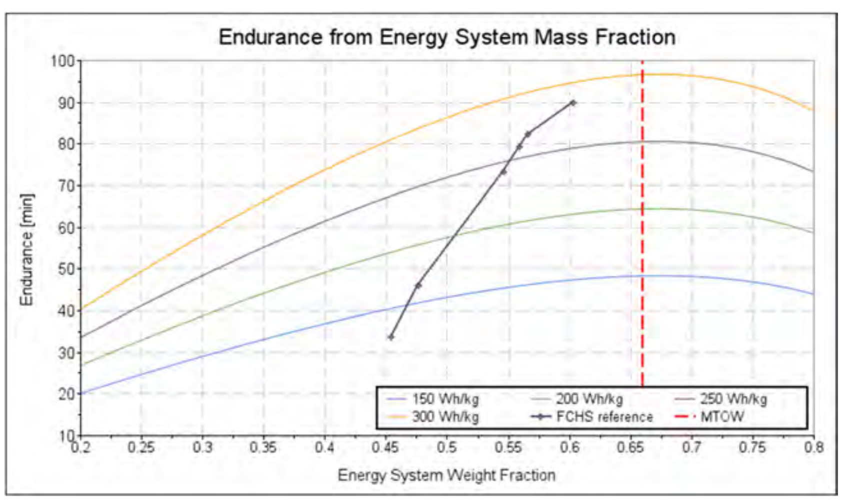

Fig. 9 Gross endurance as a function of energy system mass fraction. The empty mass is 8.5 kg. Peak endurance is reached at a 0.67 weight fraction, with an energy system of 17.2 kg and a take-off mass of 25.7 kg

balance of plant, m_{H2} is hydrogen storage mass and $m_{h.\ batt}$ is hybrid battery mass. The reference FC hybrid system's specific energy ranges from 124 Wh/kg to 284 Wh/kg. The fuel cell system's specific energy can be higher than that of the hybrid battery, so in most cases, it is beneficial for the overall specific energy that the hybrid battery is as small and lightweight as possible. This minimum size is limited by 1) energy buffer for emergency landings, and 2) the design nominal and peak power, which is related to battery discharge rate and the design operational envelope and associated power consumption profile. There has also been some research about hybrid systems using supercapacitors to achieve the required performance at a lower mass of the hybrid component. This can improve load smoothing, fuel cell efficiency, and durability [43–46].

4.4.1 Improved Batteries

Battery performance is evolving rapidly, and the specific energy is likely to improve in the next years. As this happens, the benefit threshold relative to fuel cell hybrid systems will be affected, and batteries will become more competitive at high energy levels. However, it is important to note that fuel cell hybrid systems also will benefit from improved battery performance, and the exact impact will depend on the hybrid battery energy requirement and associated mass savings. In Fig. 10, the gross endurance plot for the reference FCHS is modified for three improved battery specific energies, assuming a constant degree of hybridization of 17%.

The performance threshold between batteries and FCHS is moved from 7.4 kg with 180 Wh/kg batteries to 8.5 kg with 350 Wh/kg, so the impact on the threshold is not that large. The endurance improvement for the battery-powered system, however, is quite significant. For an 8.5 kg energy system, the endurance is doubled. Instead of performing between the 2 L and 3 L fuel cell system, it approaches the 7.2 L fuel cell system.

Even though the specific energy of new batteries improves, they must provide an adequate discharge rate. Because of the coupling between capacity and power, they can have challenges with providing sufficient power at the relevant energy levels and might not be suitable for high power applications.

4.4.2 Higher H2 Pressure

The effective energy E_{FC} from the fuel cell system as a function of storage pressure p and cylinder volume V_{cyl} can be calculated according to the following equation [27]:

$$E_{FC}(p, V_{cyl}) = \rho_{H_2}(p) \cdot V_{cyl} \cdot h_{H_2} \cdot \eta_{FC} \cdot \eta_{H_2} \tag{4}$$

where $\rho_{H2}(\rho)$ is the hydrogen density as a function of pressure, V_{cyl} is the internal cylinder volume, h_{H2} is the specific enthalpy of hydrogen (LHV), η_{FC} is the fuel cell efficiency, and η_{H2} is the hydrogen utilization. The fuel cell efficiency is typically 50% and can be assumed to be constant. Factors like load dynamics, membrane hydration, and cell temperature have an impact on efficiency. The hydrogen utilization can be assumed to be 98%, but if there are leaks or high amounts of gas is purged, the utilization is lower.

The most common cylinder type used on drones is Class IV, carbon fiber composite cylinders with a polymer liner. They are relatively lightweight and can typically store 300 bar of hydrogen. With EN 12245 certification, they have a safety factor of 1.5, is tested at 450 bar, and have a non-limited life (NLL) from a design perspective. There are also other certification standards like DOT, ISO, TPED, and more. There are also lightweight cylinders with a lower safety factor and limitations to the number of fills and fill frequency. They will not store more hydrogen but can give a mass saving.

The density of hydrogen at 300 bar, 450 bar, and 700 bar is 20.8 g/L, 28.8 g/L, and 39.7 g/L. Even though the density is not linear to the pressure increase, the amount of hydrogen at

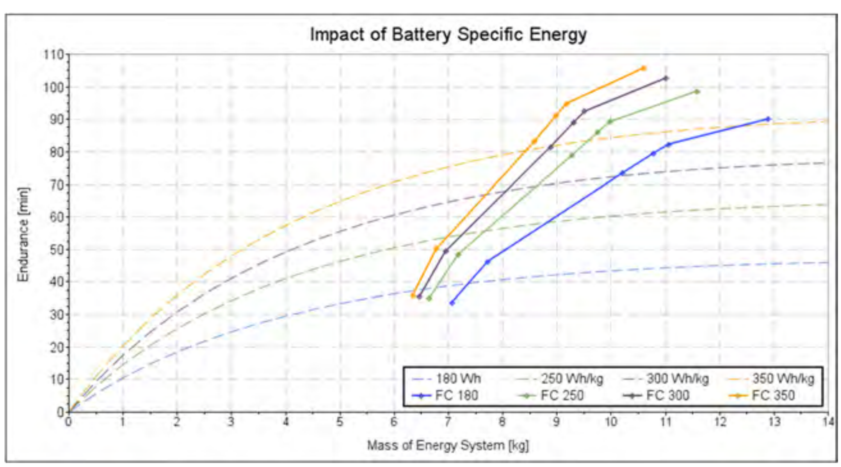

Fig. 10 Impact on gross endurance for the reference FCHS system with specific energies of 180 Wh, 250 Wh, 300 Wh, and 350 Wh compared to the battery-only performance

700 bars is almost double that of 300 bar. However, with higher pressure comes some additional cylinder mass. There are not many cylinders for 450–700 bar pressure commercially available, but they can be custom made from manufacturers like Sinoma. The reduction valve also has to be upgraded so it can reduce the pressure to the 1 bar hydrogen at a sufficient flowrate that is needed for the fuel cell, typically about 15 L/min pr. kW. The higher pressure can also lead to some additional risk in the case of a ground impact.

Using Eq. (4) to calculate effective energy, the CTS cylinders' specific energy is in the range of 554 Wh/kg to 787 Wh/kg, not including the regulator. It should be noted that the smaller cylinders are less efficient, which is in part related to the fixed mass of the cylinder boss, which is similar for all vessels.

The impact on endurance from some different cylinder options and storage pressures is illustrated in Fig. 11. The degree of hybridization is kept at 17%, which scales the hybrid battery with hydrogen energy and have some impact on the response. Due to limitations in commercially available cylinder options, some assumptions regarding cylinder mass are made.

The 300 LW cylinders are slightly lighter, but they contain the same amount of hydrogen. Thus, the endurance of the smaller cylinders is about the same. The mass savings influence the power consumption for the larger cylinders, and an endurance gain of 7 min can be achieved for the 9 L cylinder.

The 450 bar cylinders are heavier, but the energy stored is also higher, giving a higher initial endurance. The 6 L cylinder at 450 bar gives about the same endurance as the 9 L at 300 bar. The 700 bar gives an even higher initial endurance, and the 3 L cylinder option gives the same endurance as the 6 L at 300 bar, 72 min. This can give a considerable advantage in situations where volume for integration is scarce. The endurance jumps between cylinders are quite large, and a superior endurance can be achieved from the 6 L cylinder and up. The mass at this point, however, starts to become relatively high. For the 9 L option at both 450 bar and 700 bar, the added mass catches up, and the endurance gain is minimal.

4.4.3 Degree of Hybridization

The relative contribution of a secondary power source in a hybrid system is defined by the degree of hybridization β [47]. For $\beta = 0$, the fuel cell provides all power. As β increase, the battery contribution become higher. In the reference fuel cell hybrid system, the hybrid degree is $\beta = 0.17$.

The gross endurance for various degrees of hybridization is presented in Fig. 12. A constant specific power of 526.3 W/kg is assumed for the fuel cell stack, which corresponds with 3.8 kg for the 2 kW reference system. As the hybridization degree change, the stack power and mass changes. Commercial off-the-shelf stack power levels are limited, but custom stacks can be requested. The fuel cell hybrid system has 1.1 kg of auxiliary equipment, and the hydrogen cylinder mass ranges from 1.2 kg to 3.8 kg for the relevant cylinders. The hybrid battery energy $E_{h.\ batt}$ is a function of the fuel cell system energy E_{FC}, and can be calculated [27]:

$$E_{h.batt}(E_{FC}) = \frac{\beta}{1-\beta} \cdot E_{FC} + (t_{emc} \cdot P_{FCHS}) \quad (5)$$

The electric energy from the fuel cells and hydrogen storage E_{FC} is calculated from Eq. (4). An energy buffer to handle an emergency landing is also included, where the full power P_{FCHS} can be maintained for $t_{emc} = 2\ min$.

The specific energy of the 3 L fuel cell system with $\beta = 0$ is 152 Wh/kg, which is just above the 144 Wh/kg battery

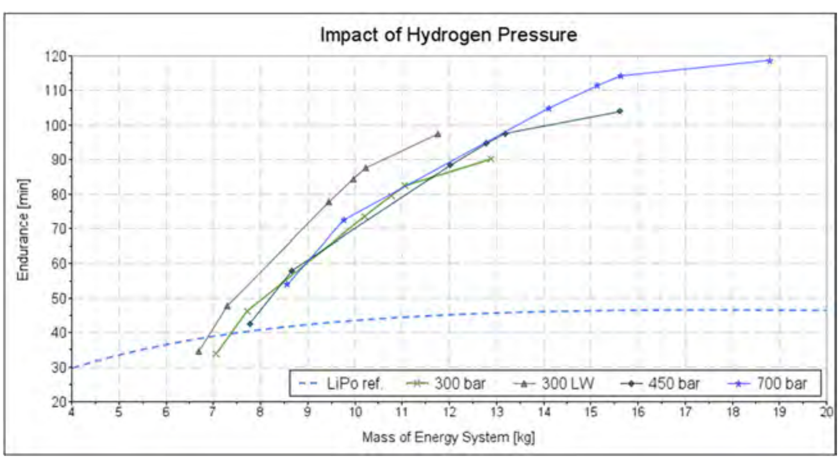

Fig. 11 The impact on the endurance of various storage pressures and associated pressure vessels. The LiPo reference curve is based on a 144 Wh/kg effective specific energy. The 300 bar cylinders are based on the reference cylinders from CTS: 2 L, 3 L, 6 L, 6.8 L, 7.2 L, and 9 L. The 300 LW cylinder is 30% lighter than the certified 300 bar cylinders, and the 450 bar cylinders are 30% heavier. The 700 bar cylinder is based on data from the manufacturer Sinoma [2], having a specific energy of 960 Wh/kg

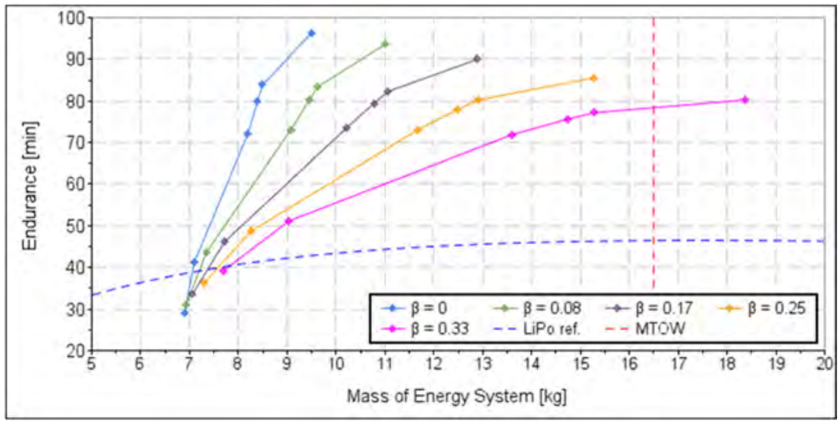

Fig. 12 Fuel cell hybrid system with different degree of hybridization β for the 2 L – 9 L CTS cylinder range

reference value, assuming 80% depth-of-discharge. With the highest hybridization ($\beta = 0.33$), the 3 L system has a specific energy of 191 Wh/kg, and the endurance is improved by 10 min. However, for the 7.2 L system, the specific energy is reduced as hybridization increases. For the $\beta = 0.17$ case, the impact of the hybrid battery is a 2.5 kg mass increase and a 1.6-min reduction in endurance, compared to the $\beta = 0$ case.

Thus, for the small cylinder configurations with limited energy and endurance (<144 Wh/kg), higher degrees of hybridization can improve the endurance. As the cylinder volume and energy increase, higher degrees of hybridization increase the overall system mass and can reduce endurance. Thus, for high-energy fuel cell systems, it can be beneficial to limit hybridization. This relates to the constant specific energy of batteries and variable specific energy of fuel cell systems, and how they contribute to the overall specific energy through mass and energy (Eq. (3)).

However, it must be noted that for the relevant fuel cell type, a hybrid battery must be present to sustain nominal operation through hydration purge cycles and manage peak loads. For small batteries, the power criteria are often the driving criteria. A maximum discharge rate of 5C will give a minimum capacity of 10.8 Ah at the relevant voltage and power levels, while the energy needed for a two-minute emergency landing is only 1.8 Ah.

5 Further Fuel Cell Adoption

While analysis of performance threshold and parameter sensitivity is important, several perspectives need to align to ensure increased industrial adoption of fuel cell powered multirotor drones. The most critical barriers are related to technical, regulatory, and operational aspects [5].

5.1 Technical Readiness

Much of the current activities in the fuel cell market are about demonstrating performance, which is the key value proposition, and relevant use-cases where the improved endurance provides more efficient operations or inspections. Still, according to publicly available data, it does not appear that any fuel cell powered multirotor drones are well proven in operational environments over time, which corresponds to Technology Readiness Level 9. It will be necessary for potential fuel cell integrators and users to have operational and financial rewards well documented and proven. Operational requirements and experience will also further help to advance the state-of-technology.

In terms of technical improvements, the regulatory developments will drive some new requirements and facilitate a closer integration into the multirotor drones. Sharif and Orhan [48] have detailed the status and research potential for PEM fuel cells. Gong and Verstraete [4] focus on the status and research needs for fixed-wing UAV-specific fuel cell systems, and their recommendations on relevant research topics are; improvements in hydrogen storage, operational robustness, hydration management, and hybridization and power management strategies.

5.2 Regulatory Barriers

A basic premise for further adoption is that fuel cell powered drones must be legal to operate where they are needed to be operated. Because the fuel cell hybrid system is a critical part of the propulsion system, it is central to the drone's overall airworthiness. The question is if fuel cell based power plants must be certified according to EASA aviation standards and have a type certificate [49], or if product certification (CE) is sufficient. The main factors driving the level of certification are the level of risk associated with the stored hydrogen and if the most relevant operations and use-cases will fall within the 'Certified' category.

As the hydrogen fuel is an integrated part of the power plant and not a payload, it is, by definition, not 'dangerous goods', which would trigger the need for type certification. However, the risks must be adequately mitigated, and the operation will have to be defined through a CONOPS (concept of operations) and a SORA (specific operation risk assessment). As most relevant use-cases will include beyond visual line-of-sight and operations close to urban or populated areas, a type-certified propulsion system will give the best operational flexibility. But it will also be a significant cost driver as strict technical requirements and proving compliance is a comprehensive undertaking.

5.3 Operational Barriers

Supply-chain and logistical requirements will affect the mobility and complexity of the operation. Thus, the operational concept and use-case must align with reasonable logistical solutions. To ensure safe and proper hydrogen handling, fuel cell installation, and operations, the relevant personnel must be well trained. Integrating and using a fuel cell hybrid system have some initial hardware, infrastructure, and training costs. Considering those cost factors, one study found that the cost per hour of flight for a fuel cell powered multirotor drone was 51 EUR, while battery-powered operations would be 4.30 EUR [27]. The fuel cell cost might drop as the market evolve, but more strict airworthiness requirements may further increase cost levels.

Justifying additional cost and complexity by achieving a return-on-investment is critical for operators. It is expected that as more data on actual operations are gathered, the use-cases that best align with value creation will pave the way for further adoption. However, fuel cell powered multirotors are not expected to replace all battery-powered drones and will probably not be viable for all operations.

6 Summary and Concluding Remarks

A sensitivity analysis is carried out to identify the impact of central system parameters for a multicopter fuel cell hybrid system (FCHS). There is limited research on such lightweight high-power systems for multirotor drone applications of this scale, and this paper contributes with an analysis that is useful for system design, targeting improvements, and optimization. To increase technology adoption, it is essential that knowledge on how to achieve ideal performance is known to the fuel cell drone community.

Thrust stand test data is used to establish an empirical propulsion system model that improves the analysis's validity. Gross endurance is used as the main parameter, and the impact of propulsion system configuration and efficiency, take-off mass, improvements in hydrogen storage, and how improved battery performance impact the FCHS benefit threshold is studied.

There are many aerodynamic and mechanical factors that influence the overall propulsion efficiency. Different configurations will have different number of motors, propeller size, and disk loading. The motor and propeller combination must be matched to provide peak efficiency at the relevant operating loads. Thrust stand data shows a 20–30% loss in propulsion efficiency due to the coaxial propeller configuration. At 25 kg thrust, that amounts to a 700 W power difference between a coaxial and single octocopter propulsion system configuration. Lower propulsion power in nominal flight can also allow for the use of a smaller fuel cell system that will provide additional weight and endurance benefits. There are also other practical considerations concerning overall physical size and redundancy to consider.

In terms of take-off weight, a 10% (1.95 kg) mass reduction will improve the endurance by 16%, which is 13 min for the 7.2 L configuration. With improvements in battery specific energy from 180 Wh/kg to 350 Wh/kg, the performance threshold between batteries and FCHS is moved from 7.4 kg to 8.5 kg. That is not significant, but the analysis demonstrates that it is important to consider that battery improvements also benefit the FCHS. Concerning hydrogen storage, a lightweight cylinder can be beneficial for large cylinder volumes. That is because the energy does not change, but mass savings give an endurance benefit. If a 450 bar cylinder is used, a 6 L cylinder can replace a 9 L one at 300 bar. A 700 bar cylinder will somewhat increase the risk, but if the overall system volume is of the highest importance, even a 3 L cylinder can provide a 72-min endurance.

The state-of-technology is presented, and it is shown that several demonstrations have verified the performance and confirmed the viability of powering multirotor drones with fuel cells. However, the technology does not appear to have been fully proven in operational environments. To achieve further adoption, more data and experience from actual operations in relevant environments should be obtained. Operational requirements will also help drive further improvements, and it will aid the understanding of how operational and logistical concepts can align to form compelling use-cases that give the best operational and financial rewards. In terms of regulations, it will be important to clarify certification requirements, as this can have a significant impact on the fuel cell drone market.

Continued efforts should be targeted towards improving and optimizing fuel cell hybrid systems in terms of mass and performance. Further research could look at specific mission profiles and analyze the impact of FCHS on the operational envelope and provide net endurance estimates.

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Author's Contributions Jørgen Apeland has prepared the material, carried out data analysis, and written the original draft. All authors contributed to research conceptualization, reviews, and final editing. Dimitrios Pavlou and Tor Hemmingsen have supervised the project. All authors have read and approved the final manuscript.

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Data Availability All underlying data and calculations are available upon request.

Declarations

Ethical Approval Not applicable.

Consent to Participate Not applicable.

Consent to Publish The authors and relevant institutions approve publishing this research.

Competing Interests Jørgen Apeland is employed by Nordic Unmanned AS, the main stakeholder of the project. The authors declare no further relevant financial or non-financial interests.

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Tor Hemmingsen has near 40 years experience in research, education and management, related to chemistry, corrosion and oil and gas industry. He has been employed to University of Stavanger and University of Tromsø. Since 2007 he has been a full professor in Corrosion and Electrochemistry, and 2011-15 Prorector at University of Stavanger. He has been Department Heads of Mathematics and Natural Sciences 2000-2008 and Department for Mechanical and Structural Engineering and Materials Science 2016-23. He has been Board member of EuChemMS 2006-10, and President in Norwegian Chemical Society 2005-14. He has authored more than 70 international papers and supervised more than 100 student theses.

Paper IV

Characterization and Flight Test of a 2 kW Fuel Cell Powered Multirotor Drone

J. Apeland, D. Pavlou and T. Hemmingsen

Manuscript

Characterization and Flight Test of a 2 kW Fuel Cell Powered Multirotor Drone

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Abbreviations

CONOPS	Concept of Operations	PEM	Proton Exchange Membrane
EASA	European Aviation Safety Agency	SOC	State-of-Charge (batteries)
FC	Fuel Cell	SORA	Specific Operation Risk Assessment
FCHS	Fuel Cell Hybrid System	UAV	Unmanned Aircraft Vehicle

Abstract

Fuel cell based propulsion systems can improve the endurance of multirotor drones, improving their utility and competitive advantage. A 2 kW fuel cell system is integrated on an X8 multirotor drone with a 21 kg take-off mass. The fuel cells are exposed to load cycles on a laboratory scale and to full-scale conditions. The test flight is carried out in a realistic environment, with approval from the Norwegian civil aviation authorities. At 2.8 kW take-off load, 78 % of nominal fuel cell output is reached immediately, and 90 % is reached after 30 seconds. The maximum hybrid load is 1351 W and 32.5 A. With a passive hybrid strategy, a 3.5 V hybrid battery voltage gives a 25 % increase in fuel cell power output. Unique challenges of multirotor drone integration are addressed, and further research should match flight envelope with system sizing, improve environmental robustness, clarify risk and damage potential, and address regulatory compliance and airworthiness requirements.

1 INTRODUCTION

Multirotor drones are becoming increasingly attractive for industrial applications as they require little space for take-off and landings, are highly maneuverable, and can carry a range of payloads [1]. However, they have more power-intensive propulsion systems than fixed-wing UAVs, which limits endurance and range. One approach to extend endurance is to use a hydrogen fuel cell based power plant.

An overview of the state-of-technology and barriers for adoption of fuel cell powered multirotor drones are presented in [2]. Some central fuel cell providers are Intelligent Energy and HES, but actors like Plug Power and Northwest UAV are also working on relevant systems. The UAV section of Ballard Power Systems, previously Protonex Technology, was recently acquired by Honeywell International to grow business opportunities within urban air mobility and broader aerospace applications [3]. They have previously supplied fuel cell systems to the Boeing ScanEagle UAV program [4].

There are a few commercial fuel cell powered drones available. ISS aerospace have the Sensus 4 and 6 that is powered by 800 W and 2.4 kW fuel cells from Intelligent Energy [5]. HES Energy Systems have the Hycopter [6]. The DS30 drone from Doosan Mobility Innovation has a stated endurance of 2 hours and has carried out several demonstrations [7-9]. One was a 90-minute gas pipeline inspection over 44 km, and another was a 69 km flight between two islands. US-based Harris Aerial has a Carrier H6 Hydrone with a 5 kg payload capacity, powered by a 2.4 kW fuel cell from Intelligent Energy. A UK project called RACHEL demonstrated a 70-minute flight with a 5 kg payload [10]. The technology readiness level and certification status for these systems are unknown.

Hydrogen-powered aviation has recently been gaining momentum as there is a global push towards more sustainable mobility solutions. With large commercial aviation actors like Airbus [11] looking into fuel cell technology, ripple effects are expected to benefit unmanned aviation and drones as the market grows and certification aspects are addressed.

For fuel cell powered unmanned systems, most research has focused on fixed-wing UAVs [12-15]. Fuel cell hybrid systems for multirotor drones need to handle transient loads that are more dynamic and have higher amplitudes. With a minimalistic design and high-performance focus, such systems introduce some unique challenges for hybrid power management and system sizing. There is some research on fuel cell hybrid systems in the range of 50 W to 500 W [16-21], but there is little research published on systems in the kW range for multirotor drone applications. Belmonte, et al. [22] did a conceptual development of a fuel cell powered octocopter, and Arat and Sürer [23] integrated and tested a 30 W fuel cell on a small multirotor drone. They recommended further research into more powerful systems.

In this paper, a 2 kW fuel cell based power plant for a multirotor drone with a 21 kg take-off mass is presented and tested. The performance is characterized in a laboratory environment, and the system is subjected to relevant load profiles where a passive hybrid management strategy and influence of system voltage are investigated. A test flight is described and carried out, and the most relevant aspects of obtaining a flight permit from the national aviation authorities are detailed. Based on the test flight and laboratory testing, several experiences relevant for short-term and long-term improvements together with relevant research topics are highlighted.

This paper presents one of few independent third-party fuel cell drone integrations and provides a unique perspective on the technology readiness and prospects of full-scale implementation. It provides guidance for the research community and relevant stakeholders about the challenges associated with adopting and using a fuel cell powered multirotor drone.

2 FUEL CELL HYBRID SYSTEM

2.1 SYSTEM OVERVIEW

The main components of the fuel cell based propulsion system are detailed in Fig. 1. Two Aerostak A-1000 proton exchange membrane (PEM) fuel cells are used, referred to as FC A and FC B. Each stack has 65 cells and is rated for 1 kW continuous power and 1.3 kW peak power for short durations. The exact performance characteristics of the fuel cells are measured and presented in the next section. Each fuel cell has internal control electronics that manage balance-of-plant components and handle thermal and hydration aspects.

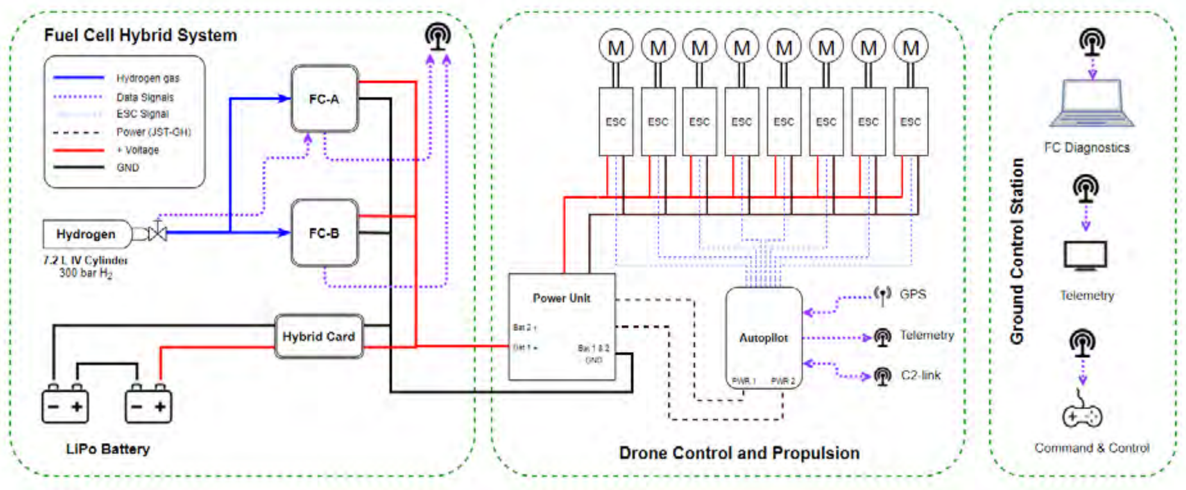

Fig. 1 Layout of the fuel cell hybrid system and drone propulsion system. (2 column, color)

A Lithium-Ion battery (pouch cell), referred to as 'hybrid battery', is connected in parallel with the fuel cells. It provides power for starting the fuel cells, power buffer for rapid load changes and high loads, redundancy for emergency landings, and sustains operation through fuel cell purging. The hybrid card is designed to regulate charge current and voltage into the batteries, and they will be charged if there is excess power from the fuel cells. In standard design, the hybrid card is integrated with the fuel cell module. That configuration is investigated by Verstraete, et al. [19].

The current system architecture (Fig. 1) was customized for this project. The hybrid card was extracted to manage the hybrid battery, and a direct hybridization with a passive power management strategy is used. While this is a simple and to some degree, efficient approach, there are also some challenges and limitations that are further investigated in the following sections.

The electric energy that can be provided by the fuel cells is determined by the chemical energy in the hydrogen gas stored and the electric efficiency of the fuel cell. This is rated to be 50 % at 49 V for the Aerostak fuel cells. In the current system, a 7.2 L pressure vessel stores hydrogen at 300 bar. A regulator reduces the pressure and supplies the fuel cells with gas at 0.6 – 0.8 bar. A pressure sensor reports the remaining hydrogen pressure through one of the fuel cells.

The power demand from motors and motor controllers (ESC) is controlled by the flight controller to achieve the desired maneuvers. Fuel cell data is sent through two radio links (EZ50 radio, 912 Mhz) to a laptop, where status, performance, and remaining hydrogen level can be monitored. The command and control link (C2-link, 2.4 gHz) provides maneuvering commands to the flight controller, and telemetry (433 Mhz) transmits essential flight data at the ground control station.

2.2 Staaker BG200 FC Drone

The fuel cell hybrid system was integrated on a Staaker BG200 multirotor drone [24]. It has an X8 coaxial configuration with 28" propellers, an arm-to-arm width of 1.2 m, and is designed for a maximum take-off mass of 25 kg. The airframe is modified to accommodate the fuel cell hybrid system, as shown in Fig. 2. The hybrid card and fuel cell radio links are attached between the pressure vessel and drone center hub. The fuel cell hybrid system weighs 12.5 kg, and a mass breakdown is provided in Table 1. Using an empirical model for the relevant coaxial propulsion system, the power consumption in static hover at 21 kg take-off mass is found to be 2.4 kW [25].

The standard BG200 drone has a take-off mass of 16.5 kg, where the batteries weigh 8 kg. They have a nominal capacity of 32 Ah at 44.4 V (12 cells), which gives 1152 Wh of energy and a specific energy of 144 Wh/kg, assuming 80 % depth-of-discharge. This gives a typical hover endurance of 40 minutes, and in forward cruise a maximum endurance of about 60 minutes can be achieved.

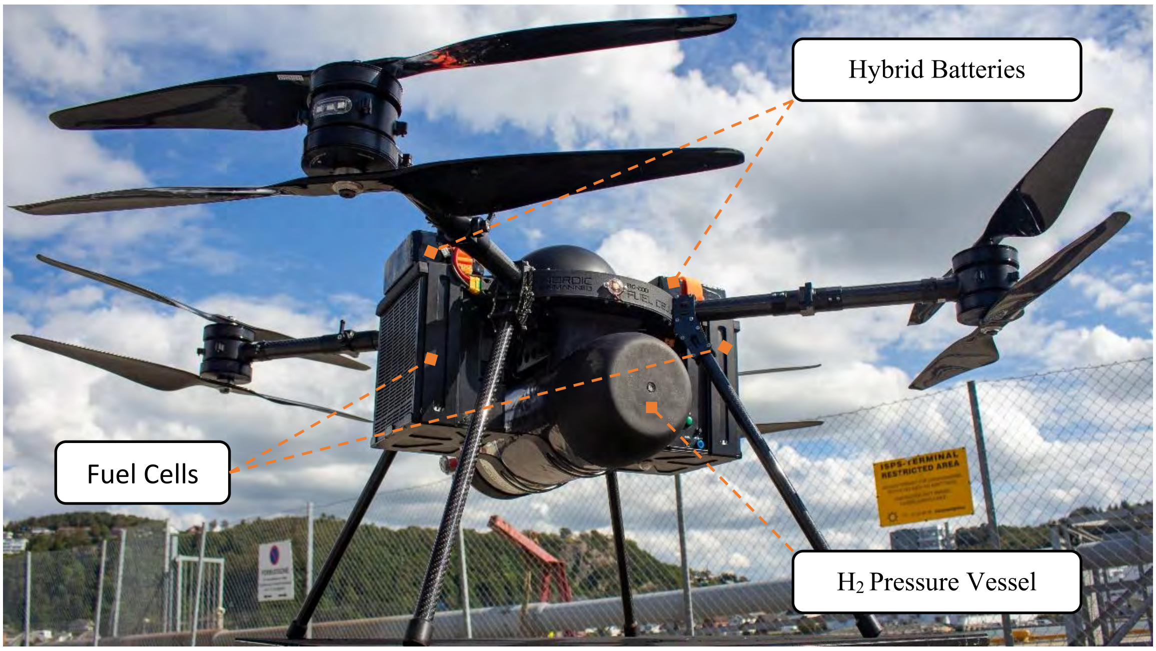

Fig. 2 Staaker BG200 FC prototype with a 2 kW fuel cell system, 7.2 L hydrogen cylinder, and hybrid batteries. (1 column, color)

The hybrid battery used in the FCHS is an 11-cell battery with a total energy capacity of 521 Wh, assuming 80 % depth-of-discharge. This has been tested on the drone to provide a 16-minute flight endurance at a 21 kg take-off mass, which will give redundancy if the fuel cell fails during flight. The hybrid battery is oversized to adds margins and additional redundancy for the test flight phase as there are many unknowns at this stage.

The 7.2 L pressure vessel is a carbon fiber filament wound cylinder with a polymer liner (Class IV). It is designed according to EN 12245 and rated for a nominal pressure of 300 bar. That gives 150 g hydrogen and 2521 Wh of electric energy, assuming a fuel cell efficiency of 50 % [26].

On an FCHS level, the effective energy is 3042 Wh, and the specific energy is 243 Wh/kg. The gross endurance for the current system in hover 76 minutes, a 90 % increase from the comparable endurance of the standard battery option. Gross endurance considers the total energy available for propulsion and the average propulsion power for a flight. Previous research has identified that for a power plant mass above a threshold of 7.3 kg, a fuel cell hybrid system will provide superior performance for this drone [26].

Table 1 Mass breakdown of Staaker BG200 w/fuel cell hybrid system

Drone empty mass	8.5	kg
Fuel cell stacks (2 x 1 kW)	4.4	kg
7.2 L pressure vessel (w/regulator)	4.0	kg
Hybrid battery (11 S / 16 Ah)	4.1	kg
Take-off mass	**21**	**kg**

2.3 Power Management

Power management and hybrid system design are vital aspects of optimizing mass and flight performance. In general, the power consumption of multirotor drones is higher and more dynamic for a given take-off mass, compared to fixed-wing UAVs. Thus, more attention must be made to system design to ensure an adequate flight envelope.

Active power management strategies use DC-DC converters to manipulate the various power sources' voltage to control the power distribution. This does, however, add some mass and introduce efficiency loss to the system, which is not ideal for high-performance, lightweight systems. The relevant fuel cell hybrid system uses a passive strategy, where the fuel cells are the primary power source, and a battery is the secondary power source.

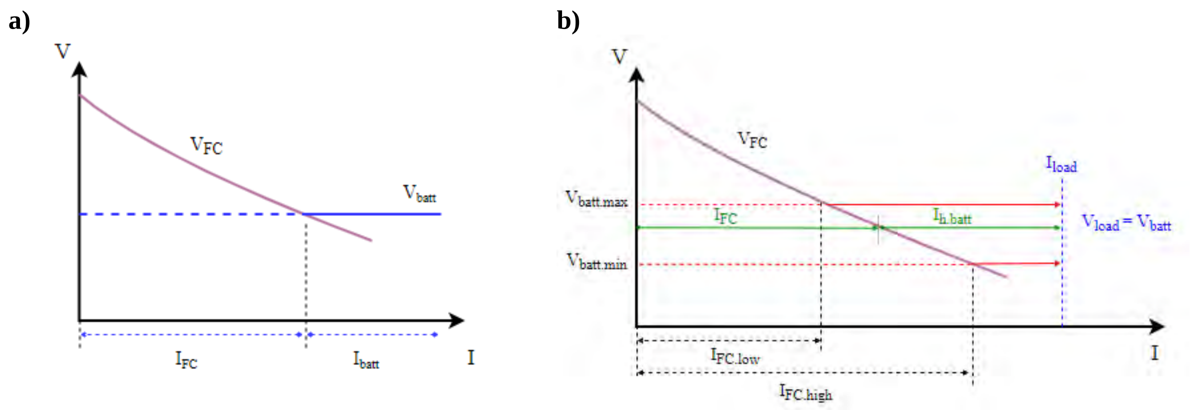

Fig. 3 Relation between voltage and load distribution in a passive hybrid system for a) a fuel cell and a constant voltage secondary power source and b) a fuel cell and battery with varying voltage. (2 column, color)

In a passive system, the power distribution between the primary power source and the secondary power source is determined by the respective voltages and voltage response to the load they are exposed to. Fig. 3a displays the voltage response of a fuel cell connected to a power source with a constant voltage. As the fuel cell is exposed to an increasing load I, the voltage drops. When the load reaches I_{FC}, the voltage matches that of the secondary power source. As the load further increase, the voltage remains constant, and the fuel cell will continue to provide I_{FC} while the secondary power source supplies all further load. By manipulating the voltage, the maximum fuel cell contribution can be controlled.

Using batteries, the voltage will not be constant, as illustrated in Fig. 3b. The maximum battery voltage is achieved at 100 % state-of-charge (SOC). This defines the lower fuel cell limit $I_{FC.low}$, which is where the fuel cell will start to share the load with the battery. As the SOC decrease, the fuel cell contribution will increase. At a constant load, the power distribution will shift, and as the fuel cell load increase, the battery contribution will decrease. The lower voltage limit will be at the maximum continuous fuel cell operating limit $I_{FC.high}$. To protect the fuel cells, the system must be designed to not fall below that voltage limit during flight.

An additional effect to consider is that there can be a certain battery voltage drop ΔV associated with high power discharges. Two important battery parameters to minimize this are the acceptable discharge rate, determined by internal resistance, and the overall battery capacity. The system design must also ensure a sufficient energy buffer to handle an emergency landing at any time throughout the flight envelope. This will define the minimum battery voltage limit for nominal operations. In a fuel cell failure scenario, the battery has to handle supplying the full propulsion power.

2.4 HYDRATION STRATEGY

In traditional fuel cell systems, there are active sub-systems devoted to hydration management to ensure reliable performance and minimize degradation mechanisms. In lightweight high-performance systems for mobile applications, passive hydration strategies are often used. For the Aerostak fuel cells, a stack conditioning event is carried out every 10 seconds, often referred to as 'purge.' During this event, the fuel cell stack is disconnected from the external load, and the stack is electromechanically shorted for a duration of about 100 milliseconds. This generates humidity on the cathode side, which keeps the membrane hydrated, maintaining its ionic conductivity. During purge, a valve is opened that allows excess water to evacuate. To prevent the fuel cell from shutting down and maintain a continuous power supply, the hybrid battery takes over the full power during purge. This will generate a voltage and current drop during purge. The dynamic response of the hybrid battery for the relevant load will determine the amplitude of this interference.

During start-up, the cooling fans ramp, the main hydrogen supply valve is opened, and the purge valve cycle seven times. This sequence takes 15 seconds to complete before the fuel cell system becomes ready to operate. When turned off, a purging sequence is initiated to remove water present at the anode side.

3 LABORATORY TESTING

The fuel cells were tested for 19 and 22 hours prior to the flight test to characterize performance, test load cycle response, and investigate hybrid power management. The longest continuous test was 3 hr and 13 min. This helped validate and build confidence in system performance while maintaining hydration and preparing them for the test flight. It also allowed for testing and verification of sub-systems like fuel cell radio links.

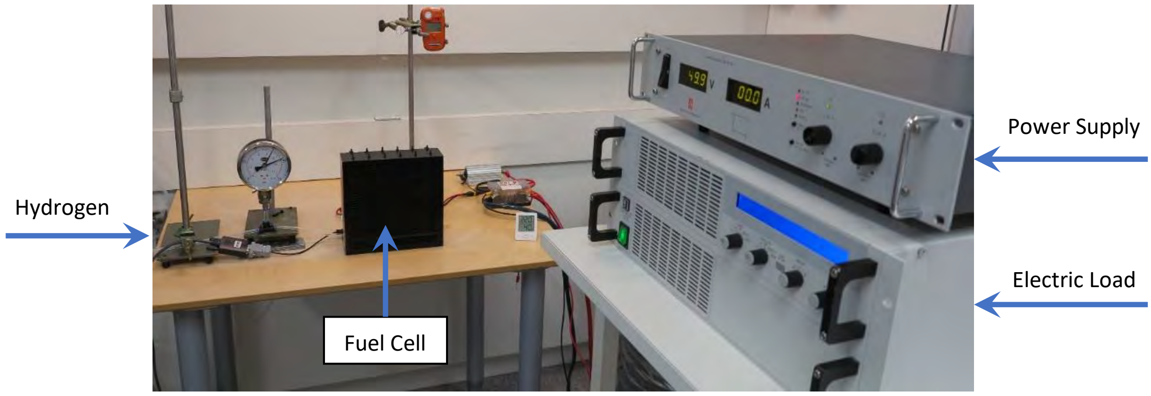

Fig. 4 Laboratory setup with fuel cells as the primary power source and a power supply as a secondary power source, operating at a constant voltage. An electric load is used to simulate various loads. (1 column, color)

In the test setup (Fig. 4), one or two fuel cells could be operated simultaneously. They were connected to a DC bus in parallel with a 7.2 kW programmable electric load and two power supplies capable of providing 44 A, equal to about 2 kW of power at relevant voltages. The power supplies represent the hybrid battery during testing and provide the initial power to start the fuel cells, maintain continuous power through the purge cycles, and provide the power difference between fuel cell power and power demand. The power supply voltage was set to represent different battery state-of-charge levels to prompt realistic load sharing between the fuel cell and power supply. Fuel cell diagnostics were monitored and logged on a laptop at a 1 Hz data rate.

Hydrogen was supplied from a 50 L cylinder at a supply pressure of about 0.8 bar. Testing was carried out in a laboratory with an ATEX-certified ventilation area and gas detectors that would cut the hydrogen supply and activate an alarm if dangerous gas concentrations were detected. Portable gas detectors were used to identify leaks. The environmental conditions during testing were typically 20 °C and 30 – 45 % relative humidity.

3.1 FUEL CELL ACCURACY

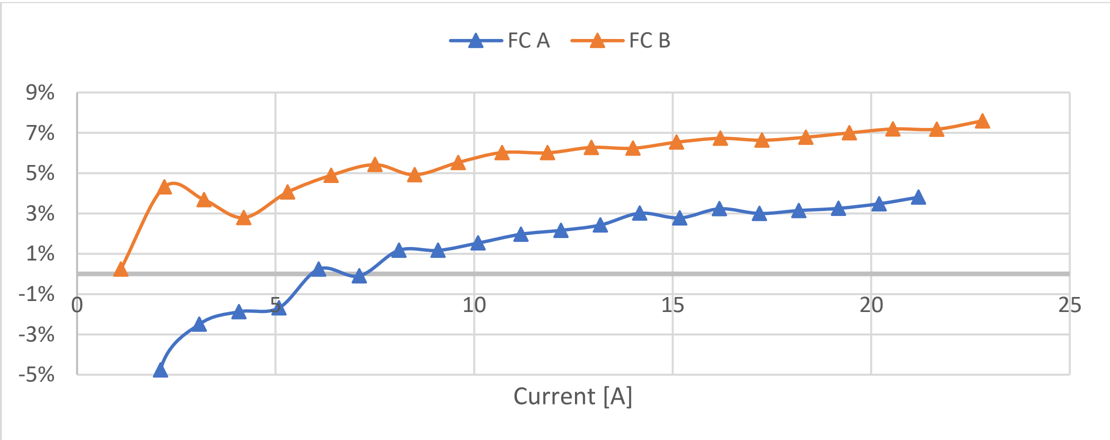

Fig. 5 Accuracy of fuel cell current measured with a 30 A and 60 mV shunt. (1 column, color)

The fuel cells provide stack voltage and current measurements used to present power and energy during operation. A test was carried out to identify the deviation between the reported fuel cell current and actual current (Fig. 5).

At high loads, they overestimate the current and power estimate by 3 – 7 %. FC B has a constant current offset to FC A of about 3-4 %, which is in the range of 0.2 A to 0.8 A. At high loads, a voltage drop of 1 V was identified between the fuel cell and the electric load, which can further overestimate the fuel cell power by 2 %.

3.2 Polarization Curves

To characterize individual fuel cell performance, a test was set up to identify the two Aerostak fuel cells' polarization curves. The load was brought up to 25 A and down again, with 30 seconds at each ampere and 5 seconds at half ampere steps. The electric power, product of measured voltage and current, reported by the fuel cell and load for the test cycle is illustrated in Fig. 6. The power supply voltage was 43 V. Each test took 29 minutes, and three tests were carried out for each fuel cell with a 5-minute pause between. Test results were consistent between the test runs, and it is assumed that steady-state performance was achieved.

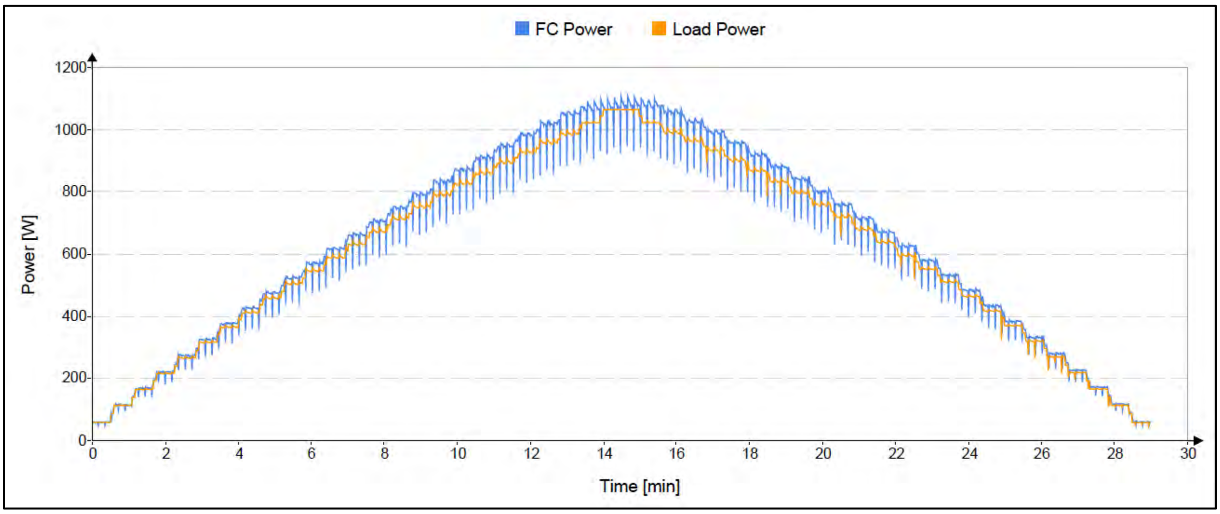

Fig. 6 Plot of electric load and fuel cell power for a polarization curve test of FC A (IV-3). (1 column, color)

From the load and fuel cell power curves in Fig. 6, it can be seen that fuel cell power is higher than the load, and that the difference is most significant at higher loads. This is consistent with the findings in the measurement accuracy analysis. The test topped out at about 1100 W. The highest performance measured during FC A and B testing was 27.2 A and 25.9 A, at 1176 W and 1133 W, respectively.

Dips in fuel cell power can also be observed, which is associated with fuel cell purging. Purge frequency can be seen to be about three purges for each load step. The power drop amplitude is larger at higher loads, which might be related to the fuel cell's dynamic response and recovery to full power after purge. The electric load curve is relatively continuous, demonstrating a good dynamic response from the secondary power source.

Plotting the current I and voltage V values from the load cycle in Fig. 6, a polarization curve for the two Aerostak fuel cells is obtained in Fig. 7. A linear expression ($R^2 = 0.95$) for the fuel cell voltage V_{FC} as a function of current I_{FC} is:

$$V_{FC} = 56.445 - 0.5386 \cdot I_{FC} \tag{1}$$

From this, the fuel cell power P_{FC} as a function of output current can be calculated:

$$P_{FC} = I_{FC}\left(56.445 - 0.5386 \cdot I_{FC}\right) \tag{2}$$

The fuel cell output current is proportional to the amount of fuel consumed, but due to internal losses, the voltage drops as the output increase [27]. The initial drop from activation losses can be seen at low currents, but the plot is dominated by Ohmic losses from internal fuel cell stack resistance, which is linear to the output current. The test does not reach the third characteristic phase, where mass transport losses become prevalent.

There are two parallel datapoint collections. The top one is fuel cell performance, and the lower one is from purge-related power dips. The distance between the two increases at higher output currents. For a given voltage level, fuel cell B data points are shifted to the right of fuel cell A. That is assumed to be related to the measurement accuracy where FC B is found to report a higher output current than FC A.

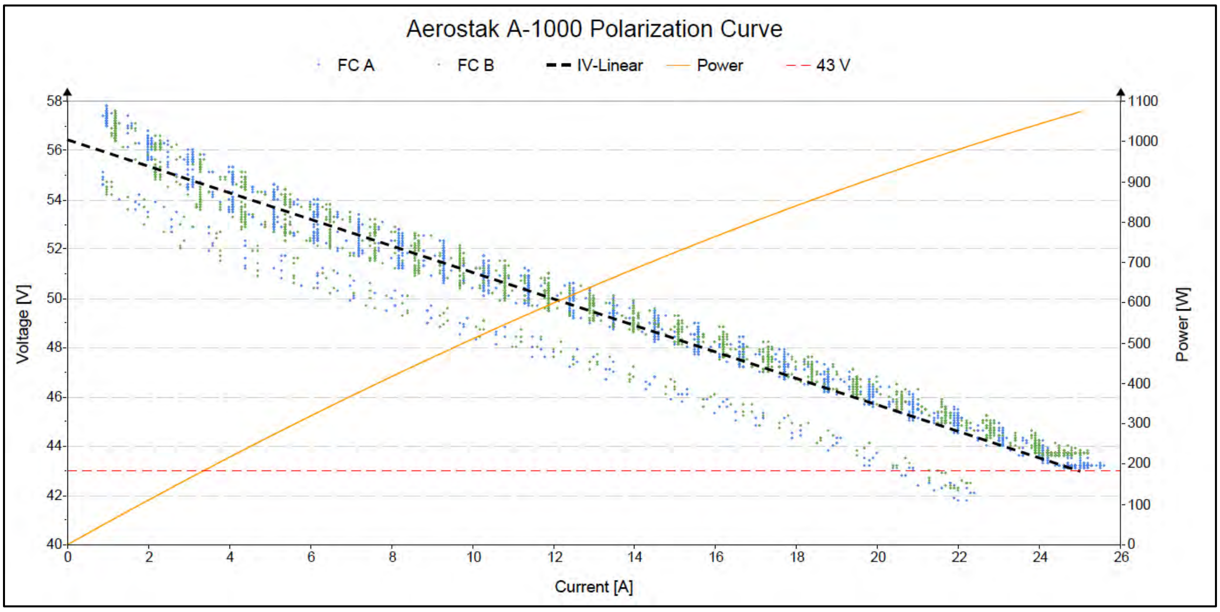

Fig. 7 Polarization curve detailing the current-voltage characteristics (i-V) for the two Aerostak fuel cells. (2 column, color)

The fuel cells top out at about 25 A and a voltage of 43 V, giving an average cell voltage of 0.66 V. The power supply voltage was set to 43 V during testing, and this forms a fuel cell output limit and defines when the secondary power source steps in to supply further power. If the voltage were higher, the fuel cell would be limited at lower output power.

The polarization curve is a useful tool in hybrid system design to match fuel cell and battery characteristics and achieve the desired power distribution. The polarization curve represents static steady-state conditions and can be considered as ideal performance. This is a helpful reference to assess if the fuel cells provide nominal performance during operations and maintenance conditioning and identify degradation throughout the fuel cell lifecycle. When not properly hydrated, the initial fuel cell voltage can be in the range of 45 – 50 V. It must be noted that the performance will be lower under dynamic conditions, as explored by Verstraete, et al. [20].

At the time of testing, the fuel cells were more than one year old. Even though they have been stored in an isolated atmosphere and maintained, the achieved performance might be lower than for new fuel cells due to standard degradation mechanisms. There might also be individual differences between fuel cell models, so this does not represent a general Aerostak A-1000 performance.

3.3 Load Profile

A relevant load profile for a typical mission with nine phases, as seen in Fig. 8, was defined and programmed on the electric load: 1 - standby, 2 - conditioning, 3 - take-off, 4 - hover, 5 - cruise, 6 - hover, 7 - downclimb and landing, 8 - cooling down, 9 - standby. Based on estimates, the power levels are assumed to be representative for the Staaker BG200 FC drone. The profile takes 10 minutes and consumes 275 Wh of energy. The energy associated with a particular mission profile is the sum of power level and time for each phase i:

$$E = \sum P_i \cdot t_i \tag{3}$$

By exposing the fuel cell hybrid system to a relevant load profile, valuable data and experience on system response and performance helped build confidence and validate system performance for flight testing. In the conditioning phase, motors are started and ramped up without taking off. This is an important step to prepare the fuel cells by allowing the stack temperature to rise and improve hydration before they are exposed to full take-off power. This also allows for performance verification before the mission is initiated.

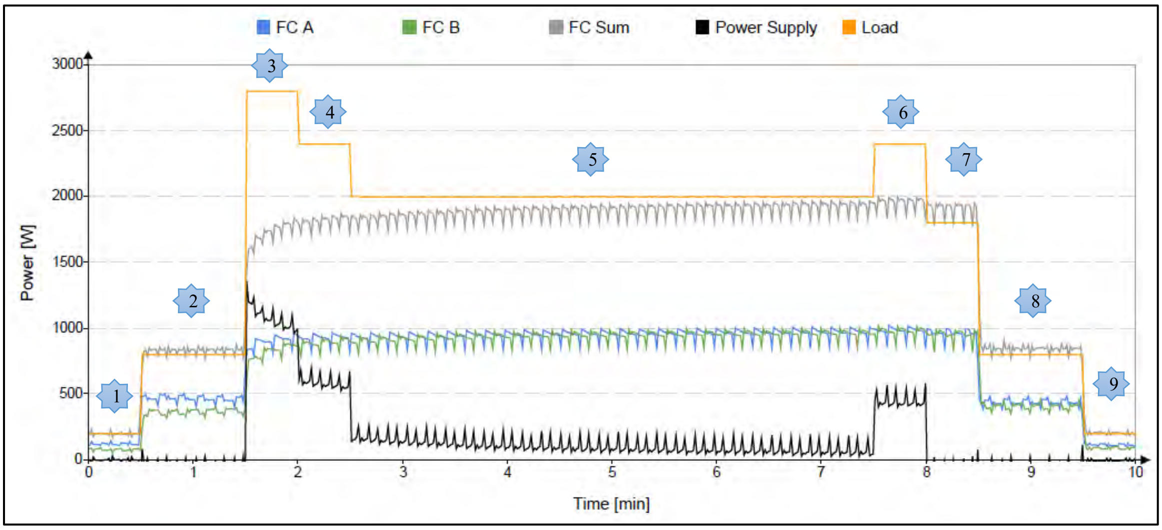

Fig. 8 Test data from a load cycle with both fuel cells and a constant power supply voltage of 45.1 V. (2 column, color)

During phase 2, conditioning, there is an offset between the two fuel cells. The offset appears to disappear at full power, but it is known that fuel cell B over-reports power from the identified measurement accuracy. This was consistent throughout testing and is assumed to originate from individual performance differences between FC A and B.

At take-off, the fuel cells jump to provide a combined output of 1565 W, which is 78 % of the rated nominal performance. At 30 seconds after take-off, the fuel cells reached 90 % of nominal output. The output further climbs towards full power throughout the cruise phase.

The hybrid power source serves its purpose and provides a power buffer at take-off as the fuel cells ramp up. The peak hybrid power was 1351 W, and a current of 32.5 A. For a 16 Ah battery, that would give a 2C peak discharge rate. Spikes in power supply contribution compensate for dips in fuel cell power as purging occurs. The offset between stack A and B purging is consistent throughout the flight. The fuel cells reported 261 Wh of energy, making the hybrid power energy contribution 14 Wh, a 5 % energy contribution of the load profile total energy.

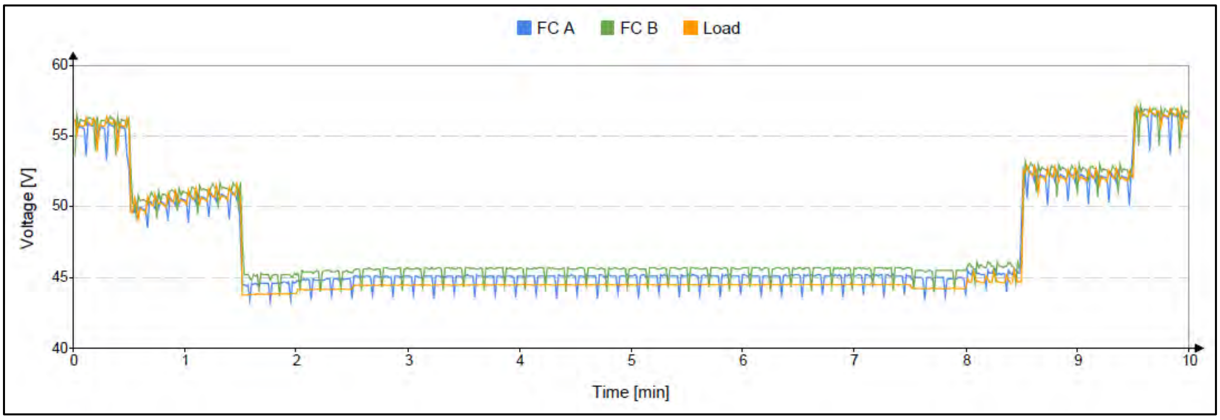

Fig. 9 Voltage plot from a load cycle test with a power supply voltage of 45.1 V. (1 column, color)

The voltage plot in Fig. 9 is from the load profile test in Fig. 8. At standby, the voltage is about 56 V. For the conditioning phase, the voltage drops, as expected from the polarization curve (Fig. 7). The voltage recovers by about 1 V as hydration and temperature improve throughout conditioning, and the performance stabilizes. At take-off, the voltage drops to the hybrid power source voltage level and remains there until landing, and the load is reduced. If a battery were used, the voltage would drop as the state-of-charge decreases or during high discharge peaks.

In Fig. 10, the load profile and total fuel cell power at six different power supply voltage levels are presented. This demonstrates how the voltage of the hybrid power source influences the total fuel cell power contribution throughout a load profile.

At the highest voltage level, 50.4 V, the total fuel cell power is limited to 1200 W and an individual contribution of 600 W. The total energy provided throughout the load profile is 64 % of the complete load cycle. When the voltage is lowered to 45.1 V, the fuel cell provides 95 % of the energy. Thus, the fuel cell contribution is somewhat limited when the battery state-of-charge is 100 % and will increase as the battery discharge. The fuel cell dynamic response is better when the voltage is high, and fuel cell loading is lower.

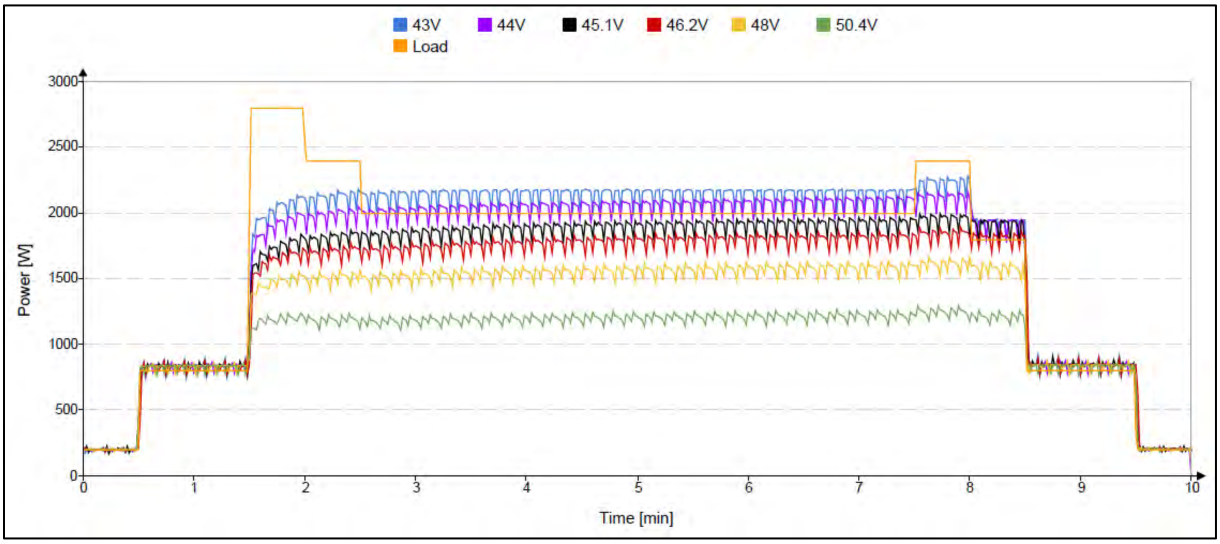

Fig. 10 Total fuel cell power for a load profile at different power supply voltages. The different voltage levels represent different state-of-charge for 11S and 12S Li-Ion batteries. (2 column, color)

4 TEST FLIGHT

In contrast to controlled environment laboratory testing, full-scale outdoor testing introduces many variables and increases the overall system complexity. Thus, such testing is useful for establishing an impression about the technology readiness and identifying the most critical challenges. The test flight was carried out in December 2020 [28], using the Staaker BG200 FC prototype. Test flight approval, regulatory considerations, and performance data from the flight follow. The most relevant experiences from the test flight are presented and elaborated on in the next section.

4.1 FLIGHT APPROVAL AND PREPARATIONS

As the propulsion system is an essential system on multirotor drones and hydrogen gas is associated with some risk and damage potential, obtaining a test flight approval from the national civil aviation authorities (CAA-N) was paramount. Through this process, a proposed test program was submitted where all relevant factors concerning airworthiness and test execution were described and discussed. Hydrogen-based propulsion systems in aviation are novel, and there is limited precedent for assessing such systems. A flight permit could potentially have been omitted by flying indoor, but the process gave valuable insights to key concerns from a regulatory and aviation perspective, which must be addressed at some point to receive a permanent flight approval.

In principle, compressed hydrogen gas is classified as dangerous goods and would trigger a requirement that the drone and propulsion system is type certified according to EASA regulations [2]. However, because the hydrogen pressure vessel is an integrated part of the propulsion system, the certification requirement is not triggered. However, it cannot be used in the ‘open’ class, as defined by [29], as only purely electric drones can be used here and with a very well-understood risk and strict operational limitations. To be operated in the ‘specific’ class, the operational concept must be well described in a CONOPS (concept of operations), and the risk must be assessed in a SORA (specific operation risk assessment). This considers the ground and air risk of the defined operation and must be within acceptable levels.

To mitigate risk for the test flight, efforts were made to 1) limit the probability of an unplanned high-energy landing and 2) limit the consequence of such an event. The relevant drone was flight-tested and qualified using standard batteries prior to installation of the fuel cell hybrid system. Loss of propulsion is one of the most critical failure modes, and one mitigation was to ensure a sufficient power plant redundancy so that a safe emergency landing could be carried out even if the fuel cells fail. In testing, a 16-minute endurance was demonstrated on the hybrid batteries alone, giving a proper margin to handle unexpected scenarios. The drone has some redundancy in the X8 configuration and coaxial motor setup, in that loss of one motor/propeller is acceptable without leading to a critical situation. The laboratory testing up-front also played an important role in building reliance in FCHS performance and verifying sub-system performance.

To limit the consequence, a maximum altitude limit was defined to limit the potential impact energy. The flight was carried out over soft farmland, and the airframe of the drone protects the fuel cells and hydrogen vessel from direct impacts. Clear procedures for handling an incident were defined, and actions were made to shield personnel from a potential blast and dangerous plumes. The fuel cell and hydrogen operator also had training in handling and transport of dangerous goods.

There was an increased concern about the third-party risk associated with fly-away due to the potentially very high endurance combined with the presence of hydrogen. The hydrogen pressure was limited to a maximum of 200 bar, and the drone had a kill-switch installed to force a landing in case of loss of control.

Another principle applied in the test program was to start with a very limited flight envelope to build trust in system performance and behavior. As this was established, the flight envelope could be expanded according to defined steps.

4.2 Test Flight Data

The test flight was carried out in Sandnes, Norway, in December 2020. It was a clear day with a temperature of 5.6 °C and relative humidity of 71 %. There was a 2.6 m/s wind at take-off and gusts of 5 m/s during the flight. The fuel cell performance is plotted in Fig. 11, and the voltage-current output is plotted in Fig. 12 for comparison with the polarization curve. In phase one, the drone is standby, and the fuel cells provide 100 W of power (Fig. 11). The drone consumption is 25 W (0.5 A), and the remaining 75 W (1.5 A) is used to charge the batteries. In the second phase, the motors are started to condition the fuel cells and prepare them for take-off. This lasted 6 minutes. Take-off was initiated, and the drone hovered 5 m above the ground for 12 minutes in phase three. In phase four, the drone was landed while the propellers were spinning. A short second flight was initiated in phase five to test some maneuvering response. In the sixth phase, the drone was landed and returned to standby.

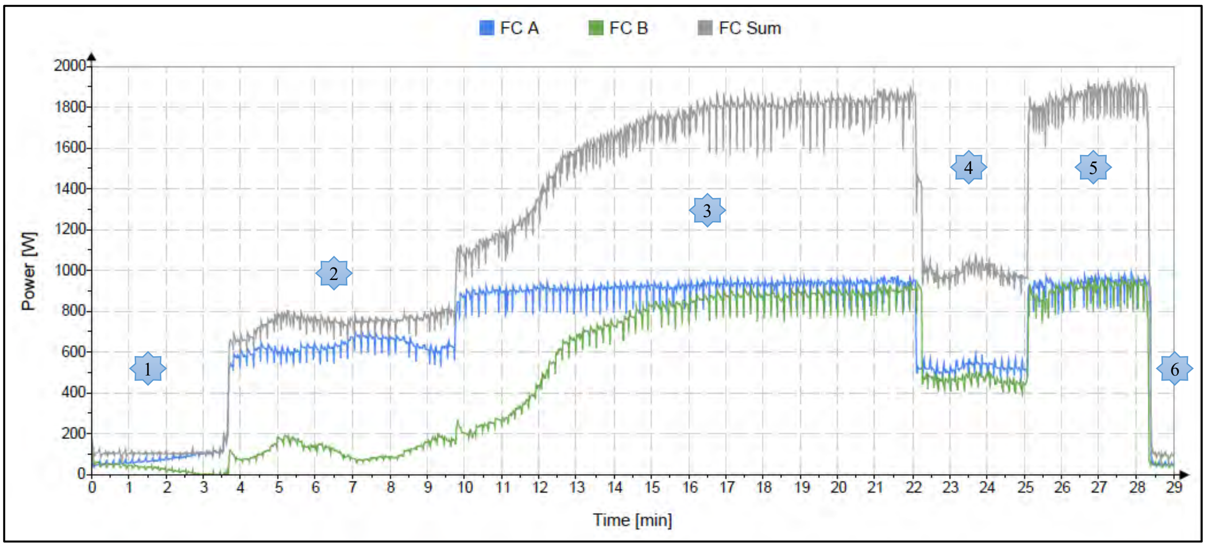

Fig. 11 Fuel cell performance from the test flight with the fuel cell powered Staaker BG200. (2 column, color)

The test consumed 44.7 grams of hydrogen, equal to a pressure drop of 75 bar. The maximum power reported by the FC A and B was 995 W and 963 W at 24.3 A and 23.2A. There were water drops in both fuel cell purge tubes after the flight, indicating adequate hydration levels. The battery was active in phases three and five and provided a buffer between fuel cell performance and drone power consumption. Before and after the flight, the hybrid battery measured 45.1 V (cell: 4.1 V) and 43 V (cell: 3.9 V).

In standby, the relative contribution of FC B drops to almost zero while FC A takes over. As the propellers are started, the contribution of FC B increases, but it is not until after take-off that FC B accelerates the power contribution and reaches full output after 5-6 minutes. After the temporary landing in phase four, both fuel cells have equal response to the dynamic load at take-off and immediately reach full power. FC A has nominal performance throughout the flight.

During the second half of phase three, it appears that the purging sequence between the fuel cells is synchronized. Because there are slight variations in the purging sequence at low and high power output, a purge synchronization can occur when the fuel cells operate at different power outputs. This is unfortunate because the battery loading increases as it must compensate for both fuel cells, increasing the discharge peak currents from 25 A to 50 A. This can impact the overall battery capacity and impact power stability and flight behavior.

Analyzing Fig. 12, while FC A provides a consistent high performance, FC B operates at a lower voltage for much of the flight. The linear polarization curve from Fig. 7 is included and serves as a practical performance reference. As voltage dropped to 43 V after take-off, the current output of FC B improved while operating at that voltage. However, it can be seen that neither FC A or B reach similar performance as achieved during polarization curve testing at high output currents.

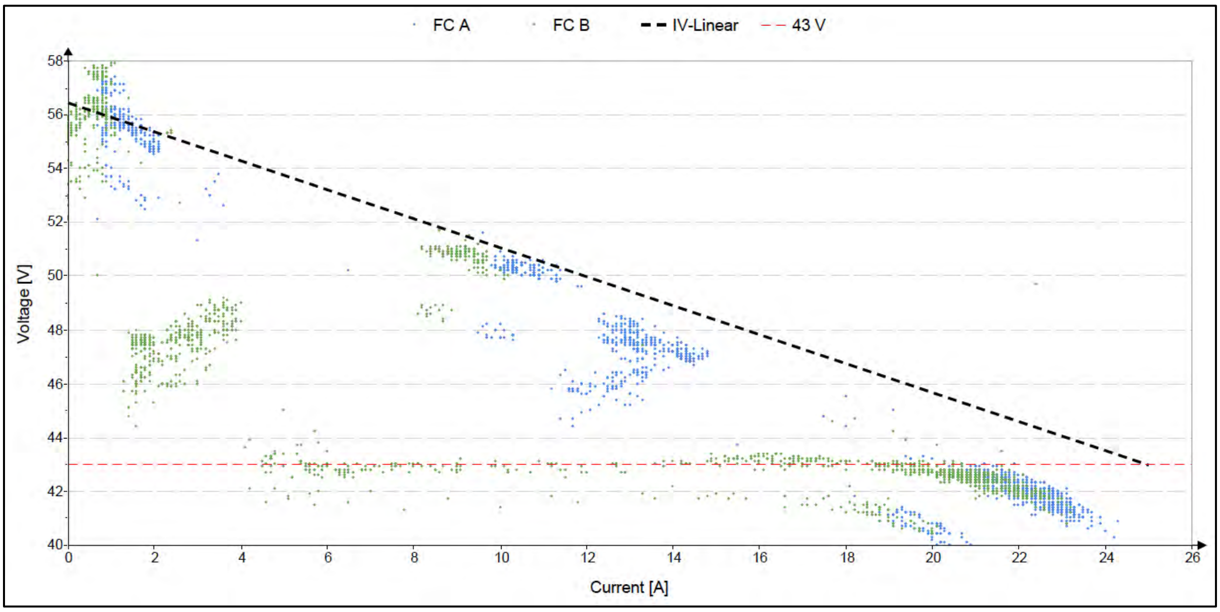

Fig. 12 Plot of fuel cell voltage and current output from the test flight. The battery voltage was between 45.1 V and 43 V. (2 column, color)

5 EXPERIENCES AND FUTURE WORK

Multiple experiences have been made from developing and testing the fuel cell hybrid system and drone integration. Some of the most relevant topics regarding overall viability and further work are presented and discussed next.

5.1 PERFORMANCE OPTIMIZATION

The current fuel cell hybrid system weighs 12.5 kg, and it is not optimized for maximum endurance. As more experience is gained with actual energy and power requirements, efforts can be focused on system optimization.

In general, performance improvements can be targeted towards increasing the system energy, improving the propulsion efficiency, or reducing mass. A sensitivity study that quantifies the impact of various system parameters for the relevant system is presented in [25].

To increase energy, the pressure vessel volume can be increased, higher pressure can be used, or the energy conversion efficiency can be improved. For current testing, a maximum pressure of 200 bar is used due to safety and practical reasons, and to reach a 300 bar pressure, the refueling infrastructure must be upgraded. With the current prototype, the gross endurance in hover conditions is 76 minutes, an 87 % improvement over the battery-powered standard configuration. By upgrading the pressure vessel to 9 L or 13 L, a gross endurance of 84 minutes (+ 107 %) and 100 minutes (+ 147 %) can be reached.

Improving the efficiency, the drone can carry a certain mass at a lower power consumption. That will influence the energy consumption and give an endurance benefit. A secondary effect is that the power stack power can be lower, giving additional mass savings. The propulsion efficiency for the relevant drone is about 9 g/W at 21 kg take-off mass [25]. Thus, a 1 kg mass reduction will give a 111 W power reduction.

A mass breakdown of the current system is provided in Table 1. Even though the endurance is high, the current power plant mass is 4 kg higher than the battery alternative. This influences payload capacity and flight dynamics, in addition to a further endurance improvement potential. As more experience about the exact energy needs is established, the hybrid degree and battery size can potentially be reduced. Improvements in battery technology and specific energy can give mass reduction. By having a tighter integration of the FCHS in the drone airframe and use more lightweight pressure vessels, further improvements can be reached.

5.2 Power Management

5.2.1 Individual Fuel Cell Systems

In the current fuel cell hybrid system, the two fuel cells operate individually without any central control (Fig. 1), and the relative power contribution is managed by the individual fuel cell voltage-current characteristics (Fig. 7). When exposed to a certain load, the voltage drops. If one carries a higher load than the other, it experiences a larger voltage drop, and the load is balanced between the two fuel cells so they operate at the same voltage. The challenge arises if one of the fuel cells is not operating at a nominal performance. This can drain more battery energy than expected and limit flight endurance.

There can be individual differences between fuel cells, and throughout testing, FC B has needed more conditioning than FC A to reach nominal performance. For the test flight, stack hydration is assumed to be the main cause of the uneven power distribution at the start. As FC A had a better initial performance, a secondary effect is that when FC A carries most of the load, it will further condition and improve performance, while FC B is not given a chance to catch up. One mitigation is to increase the overall load further, stressing the best performing fuel cell more and forcing a load distribution to allow both to condition. After both reached nominal performance, the dynamic response and load sharing were good. As the fuel cell stacks start to degrade, individual stack performance and power management can become an increasing challenge.

A challenge related to individual fuel cells was the purge synchronization that occurred during the test flight and that the two fuel cells need to be started individually. Altogether, this highlights the challenge of having individual fuel cell systems operate without a central management system.

5.2.2 Passive Hybrid Strategy

The overall power management strategy between a primary and secondary power source is outlined in 2.3. The hybrid battery voltage difference between fully charged and a lower limit (Fig. 3b) for standard operations can be about 3.5 V. That equals a combined fuel cell output change of 13 A or about 580 W power, using Eq. (1) and (2) . Thus, the fuel cell output power will vary about 25 % as the batteries discharge. That does also mean that when the battery is fully charged, the fuel cell is not operating at nominal power, and the battery is utilized more than it could have been. This highlights the importance of careful design and attention to hybrid strategy for predictable energy management.

In system sizing, the degree of hybridization is an important parameter. If a high degree is targeted, with a large hybrid battery, the fuel cell can be operated at a continuous and efficient output, while the battery handles most dynamic loads and transient response. But to minimize mass, the hybrid battery should be small, and a lower degree of hybridization should be used. The fuel cell can then be exposed to more dynamic loads that make it less efficient and degrade faster. It can also be more challenging for a small battery to handle peak loads.

For more accurate hybrid management, DC-DC converters can give active voltage control and adjust relative contributions to achieve ideal fuel cell operating conditions and predictable hybrid battery use. By adding a supercapacitor, the system can achieve an even better dynamic response when small batteries are used [30].

Howroyd and Chen [31] have proposed a control strategy with a dual diode power-path controller that can improve the hybrid power electronics' efficiency to over 97 %. Nishizawa, et al. [32] also propose a direct hybridization system, where DC-DC converters are replaced diodes for each power source. Passive and active hybrid strategies should be further investigated for multirotor drone applications.

5.2.3 Hybrid Battery State-of-Charge

A challenge with the current hybrid card is that charging performance is limited, and the battery cannot be fully charged on-board [19]. For sustained operations with multiple flights, fuel cells lose some of their competitive advantages with rapid refueling if the battery must be replaced or charged externally. Depending on the hybrid system design, there might not be power available for charging in flight. It should also be noted that if fuel cell power is used for charging, it will consume hydrogen and limit fuel cell endurance. One option can be to let the fuel cell run after landing and use the remaining hydrogen buffer to top-charge the battery. That will give a more self-sustained operation, but the disadvantage is that it will take some time. The battery management system (BMS) must also manage safe charging to 100 % state-of-charge and balance cell voltage. Future BMS should also be implemented to provide accurate state-of-charge estimates that consider discharge rate and battery aging, and not rely on battery voltage.

5.3 Hydration and Performance Degradation

As the current fuel cells are air-cooled and have an open cathode, they are exposed to the environment and woundable to drying. As experienced in the test flight, fuel cell membrane hydration is essential to achieving nominal fuel cell performance. Both fuel cells were used two weeks prior to the flight and demonstrated nominal performance. They were stored in a protected atmosphere and assembled on the drone 3 hours and 30 minutes prior to the flight, so exposure to ambient conditions was similar. However, individual fuel cell performance can vary as they age and degrade, and throughout testing, it has been more challenging to maintain nominal performance for FC B.

The intention was that both fuel cells should reach nominal performance in the conditioning phase prior to take-off. For the test, a mitigating action could be to start and run FC B first for a while, and then start FC A. The hydration challenge could possibly have been avoided if they were conditioned closer to the test flight. Standard maintenance recommendations are that if they are not in use, they must be conditioned at about 50 – 70 % of the nominal load for 1 - 2 hours every month.

It is unknown if the two-week storage or the 3.5-hour exposure prior to flight was the main challenge. But this underlines the need for further research into the relationship between storage and sensitivity of exposure to ambient conditions and how it influences membrane hydration and performance degradation. The scope should be to define guidelines for acceptable exposure and associated conditioning requirements. It could also be interesting to investigate practical approaches to minimize exposure when not in operation between missions.

5.4 Environmental Factors

After the test flight, traces of grass were found in the fuel cell stack. This highlights a key challenge with an open cathode, air-cooled fuel cells: they are woundable to pollution as they consume a high volume of ambient air to cool the stack and supply reactant. The cathode can be contaminated by foreign objects like grass, dust, water, and dirt – or chemical gases like sulfur gas, natural gas, or environments with carbon monoxide. This can damage the fuel cell stack and cause irreversible degradation. Typical durability is stated to be 500 hours or one year, but little data is available about expected durability for such lightweight, high-performance fuel cell systems for multicopters.

The temperature during the test flight was 5.6 °C, which is relatively low, and the humidity was 71 %. This impacts cooling and hydration, as less air is needed to cool the stack, which also reduces drying associated with high airflow, but the exact effect is unknown. Research should be carried out to identify the impact of cold weather and various environmental parameters on system performance and hydration. This will be relevant for establishing environmental limits for the operational envelope.

Current systems can typically be used down to -5°C, but they cannot be started below 0°C. This can pose some operational limitations in some geographical regions, and research should be conducted to improve this. Montaner Ríos, et al. [33] have investigated the cold start of a 4 kW PEM fuel cell in temperatures of -15°C and -30°C. They used a liquid-cooled fuel cell stack and purged the cathode and electrode with 40°C dry air and hydrogen to remove water prior to freezing. With a passive strategy, they achieved a cold start at -15°C in less than 30 seconds. The cathode catalyst layers must be above 0°C to prevent the pores from being plugged by ice, so they ran the stack in potentiostatic mode to heat the stack quickly.

There are also other practical challenges associated with cold weather, like that polymers become stiff and potentially brittle. In the current system, polyethylene tubes and push-connectors are used, and in assembly at the test field, the temperature made them hard to connect. This can increase the risk of leaks, which can pose a safety and performance risk, and must be considered in future system design.

Further work should improve environmental robustness, as it is of high importance from an operational perspective and to improve the prospects of further adoption. Users will need these systems to be used in maritime environments with salty air, in urban environments with exhaust, on construction sites with dust and sand, and in sub-zero temperatures. Liquid-cooled fuel cells might provide some solutions here, but current systems do not have the required performance to power large multirotor drones.

5.5 Hydrogen Refueling

To fill the 7.2 L pressure vessel, a ‘blowdown’ fill strategy from a 200 bar reservoir was used [34]. After filling, a pressure of 190 bar was measured, but at the start of the test flight, a pressure of only 138 bar was reported. Due to a negative Joule-Thompson coefficient of hydrogen, it heats as it expands during filling, and the fill rate determines the final gas temperature. When the gas later cools, the pressure drops. Nevertheless, to explain the complete pressure drop, a temperature difference of 120 degrees would be needed, which is relatively high, and would probably damage the cylinder. A second factor is that the pressure sensor was not calibrated, so the accuracy of that pressure is unknown.

To achieve full endurance, it is essential that the cylinder pressure is correct, so procedures must ensure an adequate fill pressure. Fill strategies can be to use a gas chiller, fill slowly, top fill after steady-state, or overfill by 5 – 10 %. Overfilling is accepted by the pressure vessel if the steady-state pressure is at nominal pressure [35].

5.6 Telemetry and Fuel Cell Monitoring

The current fuel cell monitoring solution with two separate radio links is not ideal. Both fuel cell radio links were functional, but about 6-7 % of the ASCII data was corrupt, much higher than when tested in laboratory conditions. There was no operational risk associated with this, as there still was sufficient data to monitor performance, but the challenge should be addressed. Potential causes can be limited radio line-of-sight, interference, and electromagnetic noise.

Intelligent Energy has recently announced an Ardupilot integration for transmission through the telemetry link [36], that will provide information about fuel cell status, battery data, hydrogen level and allow for automatic failsafe features. This is a substantial improvement as it improves safety and energy management, reduces system complexity and mass, and allows for a more compact ground control station setup.

5.7 Structural Integration

Many considerations go into an ideal structural integration of a fuel cell hybrid system on a multirotor drone. All components must remain attached during all likely operating loads, and the design should contribute to reducing risk. The fuel cells should have unrestricted airflow in and out of the stack, and they should be exposed to minimum vibrations. The introduction of multiple power sources also increases the number of power cables, which can increase electromagnetic noise that can affect sensors and flight systems.

5.7.1 Pressure Vessel Integration

The pressure vessel has a relatively high volume and is one of the most challenging components to integrate. The installation must be safe but also easily accessible and simple to replace. Together with the fuel cell stacks, they can have a high impact on the aerodynamic performance and introduce drag that reduces cruise efficiency and wind resistance. The layout also impacts the center of gravity and can influence flight performance. The BG200 integration (Fig. 2) is symmetric and does not introduce any significant offsets. One challenge with the current layout is payload integration, and future upgrades should include accommodation for relevant payloads.

Working with Royal Netherlands Navy, TU Delft recently demonstrated a novel concept where the pressure vessel is used as a central airframe component. The fixed-wing VTOL (vertical take-off and landing) has a wingspan of 3 m, a distributed propulsion system using 12 electric motors, and an 800 W fuel cell system with a 6.8 L pressure vessel [37-39].

5.7.2 Simple and Modular Installation

With the current integration, fuel cells and the pressure vessel are installed in the workshop before transport to the test field. That introduces a risk of low initial performance as they are exposed to ambient conditions and can lose hydration, as experienced in the test flight. It should be possible to store them in a protected atmosphere and install them before the flight. Ideally, the complete fuel cell hybrid system should be modular so that the basic drone can be used for standard operations, while the 'high endurance' module could be installed and used when needed. This will significantly expand the utility of the drone and dual-use.

5.7.3 Safety by Design

Efforts have been made with the current integration to ensure safety by design. In a scenario with an unplanned high energy landing, the fuel cells and pressure vessel are protected from direct impacts by the structural integration and airframe. Another configuration could be to have a top mount pressure vessel. That can be beneficial for the center of gravity and payload integration, but it will also be more exposed to high-energy impacts. Attention should also be made to the risk of heat and fire from component failure or battery fire to the pressure vessel and hydrogen fuel lines. Thus, the relative positioning and mitigating strategies should be considered.

5.8 Regulatory Compliance

All drones must operate within acceptable risk, and in aviation that is managed by certification. The current test program aims to demonstrate performance and build data on reliability, durability, and identify improvements. This data can be used as a basis for further development and to obtain a more general flight permit.

To move forward, initial airworthiness must be demonstrated based on a certification basis or standards. A challenge for drones in general, and fuel cell powered in specific, is that relevant standards and regulations are currently being made. A special condition for light UAS was released in December 2020 [40], which details airworthiness specifications for unmanned aircraft that operate in specific category under 'medium risk.' Another relevant standard in development targets performance test methods for fuel cell powered unmanned aircraft systems (IEC 62282-4-202).

Each drone integration will be unique, and certification must be done on the overall system level, not only on a sub-system level. That is to ensure a proper match between drone, power plant, and flight envelope. In addition, certification has requirements towards redundancy, energy management, mechanical integration, and ground control station performance monitoring. A plan for 'continued' airworthiness must also be in place to ensure that the drone will remain airworthy throughout the defined lifetime, where maintenance and durability data is specified. As introduced in 4.1, relevant operations must be defined by a CONOPS (concept of operations) and SORA (special operations risk assessment). This must be addressed in future work and is critical for increasing the technology readiness level and improving the prospects of further technology adoption.

5.9 Research on Risk and Hydrogen Safety

The risk and damage potential associated with hydrogen is a driving factor for the overall risk associated with the operation and the restrictions that will have to be imposed. When defining CONOPS and SORA, accurate knowledge about the damage potential of a worst-case scenario, and the likelihood of such a scenario happening, should be known and well documented. A worst-case failure scenario is a drop from a considerable height with a full pressure vessel, battery fire upon impact, and damage to the pressure vessel that causes a full release of hydrogen and a subsequent ignition.

5.9.1 Damage Potential

Olav R. Hansen [41] has found that due to the strong buoyancy of hydrogen, the high stoichiometric concentration and high sonic release velocity, the gas will quickly dilute and reach less reactive concentrations. For a severe leak from a 350 bar pressure vessel, the initial release rate was 5.9 kg/s, but this was reduced to half after 5 – 6 seconds. At this time, 7.5 % of the gas had a concentration above 15 %, which is a typical lower detonation limit. Thus, the highest risk of detonation is within the first 5 – 10 seconds after release, and when outdoors, large release events are needed to pose a significant danger. For reference, the 7.2 L pressure vessel store 150 g hydrogen.

Molkov and Kashkarov [42] have developed a predictive model to estimate pressure effects from the release and combustion of hydrogen from a pressure vessel rupture combined with fire. For a 12 L vessel at 700 bar pressure, they found the no-harm distance for a shock wave to be 35 m. No-harm was defined as temporary loss of hearing can occur, and 13.5 mbar overpressure above 0.01 mbar s impulse. Minor building damage could occur at 18 m, injury distance was 7.5 m, and fatality distance was 1 m.

5.9.2 Likelihood of Damage

The likelihood of a worst-case scenario occurring depends on the likelihood of an unplanned high energy landing occurring, the integrity of the components, and how well these components are integrated and protected. The pressure vessel is the most important single component. The current vessel is designed according to EN 12245, is designed for 900 bar, and is tested to 450 bar ($S_f = 1.5$).

The potential drop altitude is a very central parameter, and in recent tests [37], a 6.8 L pressure vessel with 285 bar hydrogen was tested according to STANG 4575 and dropped from a 12 m tower onto a metal plate. The regulator broke, and the hydrogen evacuated in a few minutes. This kind of testing provides valuable data on component integrity and helps establish an accurate understanding of risk that can help shape reasonable operational constraints and mitigations. That can be the use of airbags (low altitude) or a parachute (high altitude) to reduce impact energy, or to improve overall system redundancy.

While limited flight has been demonstrated, further research is needed to optimize system performance and match power consumption characteristics for the relevant flight envelope with detailed system design. A first step will be to map the power consumption for various mission profiles, velocities, and take-off mass. To estimate the practically achievable maximum range and endurance, the optimal cruising velocity should be identified. Second, detailed system sizing for a target flight envelope should be carried out, tested, and further optimized. Gong, et al. [18] present an interesting analysis of a fuel cell powered fixed-wing UAV where they investigate how system design and mission profiles affect the overall performance. In [43], a mission profile is used to derive performance targets for the system design.

6 Conclusions

A 2 kW fuel cell hybrid system's performance is characterized and exposed to relevant load profiles with a peak load of 2.8 kW. It is then integrated into an X8 multirotor drone with a take-off mass of 21 kg and flight tested. The specific energy on a power plant level was 243 Wh/kg, and the gross endurance for the current system is estimated to be 76 minutes, a 90 % increase from the comparable endurance of the battery-powered alternative. Details on system performance and test flight approval from national aviation authorities are provided. The main results are:

- The two fuel cells reached a maximum power output of 1176 W and 1133 W at 27.2 A and 25.9 A output current. Cell voltage was measured to be 0.66 V at 25 A output. The fuel cells overestimate power at high loads by 3 – 7 %, which equals 0.6 A to 1.4 A at 20 A output current.

- When exposed to a 2.8 kW take-off load in load cycle testing, the fuel cells made an initial jump to 1.56 kW, 78 % of nominal performance, and reached 90 % 30 seconds post-take-off. The secondary power source reached a peak power output of 1351 W and 32.5 A at take-off.

- With a passive hybrid strategy, the fuel cell output will vary by 25% as the hybrid battery state-of-charge is reduced by 3.5 V. Over a 10-minute mission profile, the fuel cell energy contribution was 64 % with a secondary power source voltage of 50.4 V, and 95 % with a voltage of 45.1 V. Thus, fuel cell contribution will increase as the hybrid battery discharge.

- A full scale fuel cell powered drone flight was completed with approval from Norwegian civil aviation authorities. There were some initial challenges with stack hydration and power balancing between the two stacks, highlighting potential challenges of having two independent passive balanced fuel cell systems and sensitivity of exposure to ambient conditions.

One of few multirotor drone integrations of a fuel cell based propulsion system is presented. Based on experimental data from laboratory testing and a full-scale flight in a realistic operating environment, a unique overview of associated challenges and further work is provided. Short-term improvements are related to the radio link and integration of fuel cell monitoring into the ground control station, hybrid management system, and modular and simple integration of fuel cell and pressure vessel.

Further research is needed to optimize system performance and match power consumption characteristics with relevant flight envelope and system design. As standards and relevant certification basis are developed, regulatory compliance must be demonstrated to assure that the fuel cell hybrid system and drone integration is airworthy. Accurate knowledge about hydrogen risk and damage potential is essential to defining future operations according to standard CONOPS and SORA methodology. Research should also be carried out to map performance at various environmental parameters and improve environmental robustness.

Acknowledgment

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