Development and Flight Testing of a Hydrogen Fuel Cell Powered Helicopter UAV

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ABSTRACT

This paper presents the design, development, integration, and flight testing of a hydrogen fuel cell-powered hybrid propulsion system for the AREA UAV, a battery-electric powered unmanned helicopter with intermeshing rotors, developed at the Technical University of Munich. To extend the flight endurance beyond the 20-minute limitation of battery-only operation, a hybrid energy system combining proton-exchange membrane (PEM) fuel cells with lithium-polymer batteries was developed. The system was initially sized using NDARC simulations and refined based on component availability and safety considerations. Ground-based testing validated subsystem performance, including fuel cell characterization, hybrid battery evaluation, and dynamic load testing of the full powertrain. A calibrated fuel cell model was derived from test data to assess system efficiency, with measured hydrogen consumption yielding an overall mission efficiency of 46.1%. Following successful integration, flight tests were conducted in hover-out-of-ground-effect conditions, demonstrating sustained power output exceeding manufacturer specifications and confirming the feasibility of longer than one-hour missions with the installed 380 g hydrogen capacity. The results demonstrate the viability of hydrogen-electric propulsion for small VTOL UAVs and provide valuable insights for future development of sustainable rotorcraft systems.

INTRODUCTION

To meet the climate change targets set out in the EU's Flightpath 2050 plan, the aviation industry must drastically reduce its carbon emissions [1]. One promising avenue toward decarbonizing aviation is the development of electric vertical take-off and landing (eVTOL) aircraft. Over the past decade, both start-ups and established aerospace companies have made significant progress in electric VTOL technology. The first all-electric helicopter flight was demonstrated in 2009 [2], and recent advances in battery technology and distributed electric propulsion have enabled the testing of various eVTOL demonstrators for urban air mobility. In 2021, Joby Aviation completed a battery-powered flight of over 150 miles [3]. However, for longer-range missions, the increasing weight of batteries remains a major limitation.

As an alternative energy carrier, hydrogen offers higher gravimetric energy density and rapid refueling capabilities, making it particularly attractive for aviation applications, including eVTOL aircraft. While hydrogen-powered systems have been demonstrated in fixed-wing aviation—such as Boeing's manned test flights in 2008 [4] and H2Fly's ongoing HY4 campaign [5]—the use of hydrogen in VTOL aircraft has so far been largely limited to small unmanned aerial vehicles (UAVs). Examples include the *NederDrone* by TUDelft [6] and UAV fuel cell systems by companies such as Intelligent Energy, H3Dynamics, and Doosan Mobility. Efforts toward

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manned hydrogen VTOL aircraft are still in early stages, with Piasecki's planned hydrogen-powered version of the CoAx 600 helicopter being a notable development [7].

In previous work at the Institute for Rotorcraft and Vertical Flight (formerly, Institute of Helicopter Technology), a hydrogen hybrid propulsion system designed for the electric research UAV, AREA [8], shown in Fig. 1 was presented. AREA is a battery-powered intermeshing rotor helicopter that uses a single electric motor for lift and control. To extend its flight time from approximately 20 minutes to over one hour, the aircraft's battery pack was replaced with a hybrid system combining fuel cells and batteries. The system was sized and analyzed using NDARC [9], presented in [10].

Figure 1: Battery-powered AREA UAV in flight [8]

This paper builds on that work and describes the subsequent integration and experimental validation of the hydrogen hybrid power system. First, the system was implemented on a ground-based test bench to verify its performance and operational safety. The paper details the test setup, methodology, and results. Following successful ground tests, the system was integrated into the AREA platform and subjected to flight testing. The outcomes of the flight campaign, including performance data and lessons learned, are presented and discussed here. These results form the basis for future improvements in hybrid hydrogen-electric propulsion systems for UAVs and VTOL aircraft.

FUEL CELL SYSTEM DESIGN

The UAV and the components of the fuel cell system were modeled parametrically in the preliminary design software NDARC. This model was then used to size the fuel cell system. The design mission was a flight consisting of mainly cruise at best endurance speed to keep speed low for tests and to demonstrate the maximum achievable flight time. Fig. 2 shows the weight of the fuel cell system and its components compared to a purely battery based system at different cruise durations. The total weight of the system is shown in blue. It shows that the point at which the fuel cell system becomes advantageous is at approximately one hour. Table 1 shows the specifications of the initially sized fuel cell system for one hour cruise duration together with those of the components that were finally elected and integrated into the UAV.

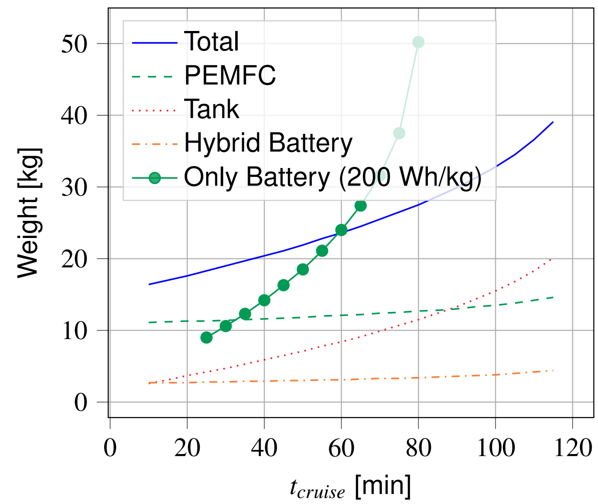

Figure 2: Sized weight of hydrogen systems components at different cruise times [10].

component		init. design	final
FC	2x IE Soar 2.4 kW		
	power	4.8 kW	4.8 kW
	weight	9.3 kg	9.8 kg
Tanks	2x Luxfer L88C 300bar (1 reg. each)		
	volume	11.7 L	18 L
	weight	6.0 kg	9.0 kg
	regulator	0.5 kg	0.7 kg
	H_2	240 g	370 g
Battery	2x14S (2x7S) SLS XTRON 4.4Ah 50C		
	energy	283 Wh	455 Wh
	max. power	8 kW	20 kW
	weight	2.1 kg	3.2 kg
Structure + Cables	weight	5.4 kg	2.5 kg
H_2-system	weight	23.5 kg	25.2 kg
UAV w/o H_2-system	weight	24.3 kg	28.8 kg
TOW	weight	48.4kg	54.0 kg

Table 1: Hydrogen system component weights sized for a cruise duration of 60 min compared to final component selection.

The selected fuel cell system consists of two Intelligent Energy IE Soar 2.4 kW modules connected in parallel. The rated power matches that of the initial design. Additionally, no additional power electronics are needed for either the parallel fuel cell operation or for the connection with the hybrid batteries. The fuel cells include

Figure 3: CAD model of AREA UAV with integrated hydrogen system

volateg regulation which allow configuration of the battery voltage level between 12S and 16S. To match the motor setup of the AREA, 14S batteries where selected. These were selected to be larger than initially designed for an additional safety margin. Finally, the tanks were selected to achieve a higher flight time than 60 min. The tanks are type 3 tanks consisting of a carbon-fibre load-bearing shell and a metallic liner that seals the pressure vessel to the small hydrogen molecules at 300 bar. Higher pressure tanks were also evaluated but not selected, as they tend to have slightly worse gravimetric density and cost, and availability of both tanks and regulators at the time favored the 300bar tanks. Fuel cells tanks and batteries were mounted to a plate milled from high-strength aluminum and integrated into the landing gear. The tanks are held by three tension straps and the batteries are held in sheet-metal holders since neither have any attachment points. The design of the integrated hydrogen system can be seen in Fig. 3. The difference in weight of the UAV itself stems from upgrades to the motor and motor controller and the addition of a landing gear extension for improved visual flying by the pilot.

COMPONENT TESTING & MODELING

To validate the hydrogen-electric propulsion system developed for the AREA UAV, a dedicated test bench was designed, constructed, and operated under controlled laboratory conditions. The primary goal was to characterize the performance of the individual subsystems—fuel cells and hybrid batteries—as well as the complete integrated powertrain under realistic and dynamic load conditions representative of flight missions.

Fig. 5 displays the components of the testbench and how they are connected. The hydrogen used in the experiments was stored in 300 bar industrial gas cylinders and regulated down to the operational pressure of the fuel cell stacks using a pressure regulator. For safety, a normally closed emergency shutoff valve was installed immediately downstream, triggered by power loss or manual emergency stop. The low pressure hydrogen

Figure 4: Mobile Hydrogen Fuel Cell and Battery Testbench with capacity up to 9.6kW and hydrogen pressure regulator

line was instrumented with flow, temperature, and pressure sensors close to the fuel cell inlet to enable precise hydrogen consumption monitoring. Power output was controlled and logged using a programmable electronic load. To separate and monitor the contributions of fuel cells and batteries, additional current sensors were integrated, with data acquisition handled by a microcontroller and a connected PC for visualization and logging. All electrical subsystems were linked to a central emergency stop system to ensure safe shutdown in case of malfunction or gas leakage.

The physical structure of the test bench was designed to be mobile and fit through standard laboratory doors, allowing outdoor operation under a covered area adjacent to the lab, as can be seen in Fig. 4. This configuration provided both weather protection and sufficient ventilation for safe hydrogen use, without the need for a dedicated exhaust system.

Three classes of tests were conducted:

1. Fuel Cell Characterization: The individual fuel cell modules (2.4 kW) were subjected to a series of transient step current loads as well as longer steady-state loads up to 65 A. These tests enabled extraction of polarization curves and dynamic response characteristics. Initial load transitions showed a growing contribution from the hybrid battery due to the slower transient response of the fuel cells.
2. Battery Testing: Hybrid battery modules were evaluated under various C-rate discharge profiles. Transient load interruptions were also applied to calibrate electrochemical models for time-varying behavior.
3. Integrated System Testing: The full system (fuel cells and batteries) was operated using a programmable load profile based on a representative AREA UAV flight mission. The profile included seg-

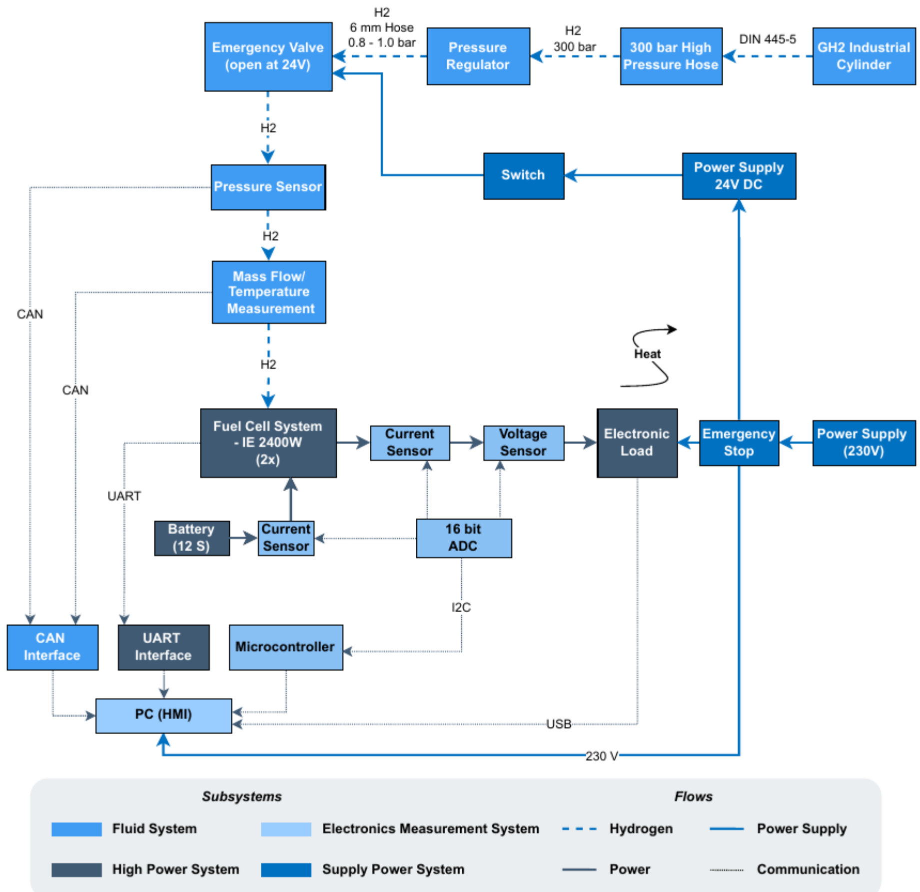

Figure 5: Schematic of testbench used to test fuel cells and batteries of the UAV system.

ments such as idling, hover, transition, high and low cruise, and load spikes simulating gusts or maneuvers.

To characterize the steady-state behavior of the hydrogen fuel cell system, a polarization curve model was implemented and calibrated using the aforementioned tests. The modeled relation of current density and cell voltage can be seen in Fig. 6. The model, in the form of Eq. 1, incorporates activation, ohmic, and concentration losses, while anode activation losses were neglected due to their relatively small impact and to avoid parameter ambiguity during optimization. The voltage-current relationship was fitted using the logarithmic form of the Tafel equation for cathode activation, a linear ohmic term, and a concentration loss term based on limiting current density.

$$v(i) = a_C + b_C \ln(j - j_{\text{leak}}) + j \cdot \text{ASR}_\Omega + c \cdot \ln\left(\frac{j_L}{j_L - (j + j_{\text{leak}})}\right) \tag{1}$$

Here, j is the current density, j_{leak} is the leakage current density, j_L is the limiting current density, and ASR_Ω is the area-specific resistance. The activation loss parameters a_C and b_C are derived from the cathodic transfer coefficient α_C and the exchange current density j_{0C} via:

$$a_C = -\frac{RT}{\alpha_C n_C F} \ln(j_{0C}) \tag{2}$$

$$b_C = \frac{RT}{\alpha_C n_C F} \tag{3}$$

The resulting polarization curve matched the test data closely. The model shows good agreement with literature values from Ng and Datta [11], though concentration losses remain underrepresented due to the absence of high current density data in the available test range.

The system responded reliably throughout all segments of the mission profile. During high-power demands exceeding fuel cell capacity, the batteries compensated for the deficit. Conversely, during low-load phases, the fuel cells recharged the batteries, maintaining battery voltage stability.

Hydrogen consumption was monitored continuously. The fuel cells exhibited periodic hydrogen purge events to clear reaction byproducts, leading to transient spikes in consumption. These purges reduced overall system efficiency, particularly for small systems without hydrogen recirculation. Fig. 7 shows the hydrogen flow and calculated efficiency at increasing output power levels.

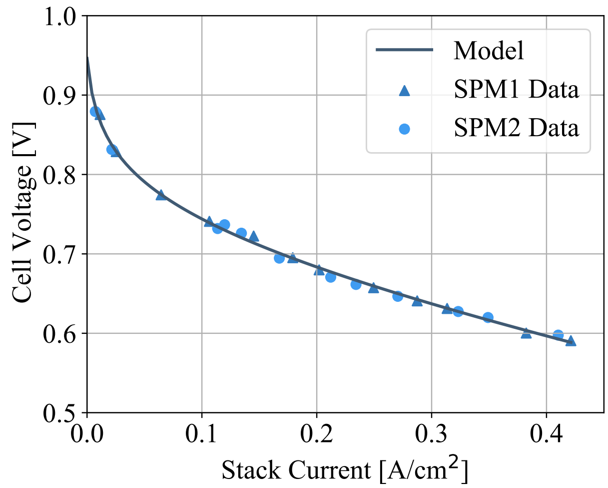

Figure 6: Voltage/Current Density model of the testes fuel cell. Current density was calculated using an estimated cell size of 89 cm^2

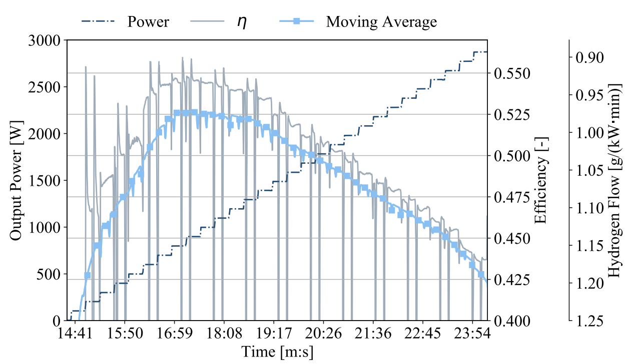

Figure 7: Evaluation of total fuel cell efficiency incl. electric losses, cooling and purging hydrogen losses.

By applying a moving average (blue line) an efficiency curve can be approximated. It also shows that at low output power, the auxiliary systems such as fans and control systems decrease efficiency significantly. Using the lower heating value (LHV) of hydrogen the efficiency can be calculated according to Eq.4.

Over the course of a shortened simulated mission profile, which uses 749 Wh electrical energy, the system consumed 48.8 g of hydrogen, resulting in a net efficiency of 46.1%:

$$\eta_{\text{total}} = \frac{E_{\text{miss.}}}{m_{H_2,\text{miss.}} \cdot \text{LHV}} = \frac{749 \text{ Wh}}{48.8 \text{ g} \cdot 33.3 \text{ kWh/kg}} = 46.1\% \quad (4)$$

These mission-tests confirm that the hybrid hydrogen-electric system is capable of delivering the required power under dynamic conditions and can enable safe UAV operation with significantly extended endurance compared to battery-only configurations.

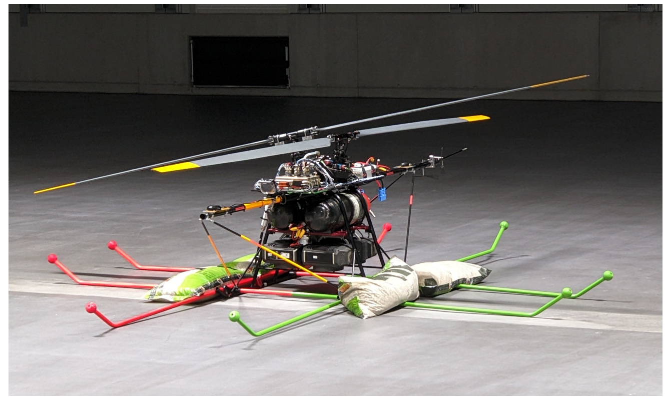

Figure 8: AREA UAV during ground-testing weighed down by sand bags.

FLIGHT TESTING

Following the integration of the hydrogen fuel cell system with the AREA UAV's flight control unit, initial ground runs were conducted to verify safe and stable operation under load. The landing gear was ballasted with sandbags to allow safe high-power system operation while stationary, as can be seen in Fig. 8.

Subsequent flight tests were carried out in April 2025 at the Mengen-Hohentengen airfield. The UAV operated from both designated VTOL pads and a paved apron area east of the runway, as shown in Figure 10. For safety reasons, the planned extended mission flights with forward cruise were deferred. Instead, all flight tests were conducted as controlled hover flights in close proximity to the operator, with the pilot standing behind a protective screen. Although hover flight is not aerodynamically efficient, it represents a higher continuous power demand for the propulsion system than forward flight, thus serving as a conservative stress test of the fuel cell powertrain.

The performance of the hydrogen-electric system during one representative five-minute hover segment is illustrated in Fig. 9. This flight segment was conducted in calm wind conditions and at an altitude of more than 3 m above ground level, placing the rotor well outside the ground effect region and thus representing one of the most power-intensive conditions encountered in typical civil rotorcraft operations. The average propulsion power required was approximately 5600 W. This is significantly higher than the modeled hover power due to the pilot selecting a higher rotor RPM than originally specified, in order to maintain additional control authority for safety during early flight trials.

Despite the elevated power requirement, the fuel cell system successfully supplied a sustained power output of approximately 5400 W. The remaining appr. 200 W were provided by the hybrid battery, as evidenced by the slowly decreasing battery voltage shown in Fig. 9. Notably, this output exceeds the manufacturer's specified end-of-life continuous power rating of 4800 W, indi-

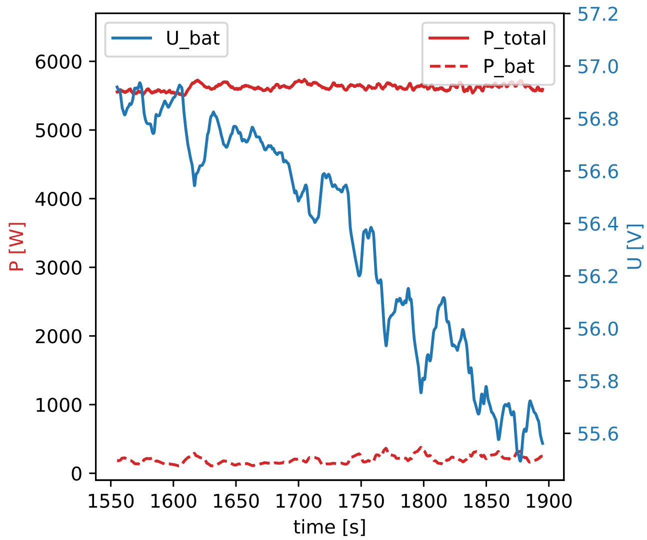

Figure 9: Power (red) and voltage (blue) data from the fuel cell system during hover-out-of-ground-effect operation. The dashed line shows power drawn from the hybrid batteries.

cating that higher performance is achievable on newer systems.

Using previously established system efficiency values from bench testing, the hydrogen consumption rate can be estimated. At 5400 W, the previously measured fuel cell efficiency is 44%. This gives a hydrogen mass flow of 369 g/h. Given the onboard hydrogen mass of 380 g, this corresponds to a maximum hover duration of nearly exactly one hour in out-of-ground-effect conditions.

Further observations during the campaign confirmed that even moderate headwinds reduced the power demand sufficiently for the fuel cell system alone to sustain flight, allowing the batteries to recharge. In forward flight, a substantial reduction in power requirement is expected, further extending the potential mission duration.

In conclusion, the flight tests successfully demonstrated the system's ability to sustain high-load operations in hover using primarily fuel cell power. With minor optimization of rotor speed or onboard mass, and in typical mission profiles including forward flight, the UAV is expected to achieve significantly longer endurance.

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Figure 10: AREA UAV with hydrogen system in flight during testing at airport Mengen-Hohentengen.

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