

Mass–energy relationships in multirotor unmanned aerial vehicles powered by proton exchange membrane fuel cells: An indicator-based approach

Maciej Mrozowski^{1*}, Jarosław Sęp², Piotr Antoni Wygonik¹

¹ Department of Aerospace Engineering, Faculty of Mechanical Engineering and Aeronautics, Rzeszow University of Technology, Rzeszow, Poland

² Department of Manufacturing Technology and Production Engineering, Faculty of Mechanical Engineering and Aeronautics, Rzeszow University of Technology, Rzeszow, Poland

* Corresponding author's e-mail: m.mrozowski@prz.edu.pl

ABSTRACT

The dynamic development of hydrogen-powered unmanned aerial vehicles (UAVs) has increased the need for consistent methods to assess their mass–energy characteristics, particularly in multirotor platforms, which are characterised by high and continuous power demand during hover-dominated operation. This study aims to identify mass–energy relationships in multirotor UAVs powered by proton exchange membrane fuel cells using an indicator-based comparative framework. The analysis was based on technical data obtained from manufacturer datasheets, technical reports, catalogues, and scientific publications, including maximum take-off weight, empty weight, payload, declared flight endurance, PEMFC rated power, hydrogen tank capacity, and storage pressure. A set of normalised indicators referenced to maximum take-off weight was used, including payload fraction, structural mass fraction, specific endurance, and PEMFC power-to-weight ratio. Pearson correlation analysis, simple linear regression, confidence intervals, and bootstrap resampling were applied to support the graphical interpretation of mass-dependent trends. The results show that most analysed platforms are characterised by structural mass fractions of 75–90% of MTOW, while payload fractions are typically within 10–25% of MTOW. Specific endurance generally falls within the range of 4–10 min/kg and shows a strong negative relationship with MTOW ($r=-0.75$, $R^2=0.56$), indicating that endurance efficiency per unit mass decreases as platform mass increases. In contrast, payload fraction and structural mass fraction showed weak or negligible linear dependence on MTOW, while the power-to-weight ratio exhibited greater dispersion, reflecting manufacturer-specific PEMFC sizing strategies. In addition, a power consistency ratio was introduced to compare estimated average power demand with PEMFC rated power and to assess the internal consistency of manufacturer-declared performance data. The proposed framework provides a first-order comparative tool for identifying mass–energy trade-offs, design constraints, and potential inconsistencies in commercial hydrogen-powered multirotor UAV platforms, rather than an experimentally validated predictive model.

Keywords: energy efficiency, hydrogen drones, mass–energy scaling, multirotor UAV, flight endurance.

INTRODUCTION

In recent years, an increasing emphasis has been placed on alternative energy sources and novel propulsion systems in aviation, driven by the need to reduce fossil fuel consumption and pollutant emissions [1]. Electric propulsion

systems and fuel cells are considered among the most promising directions of development, which is particularly evident in the rapidly growing sector of unmanned aerial vehicles (UAVs). According to market reports, by 2030, the global market value of commercial UAVs is expected to exceed USD 41 billion, with an estimated average annual

growth rate of approximately 19.5%. This technology is increasingly applied in a wide range of demanding applications. UAV platforms are used in infrastructure inspection, monitoring, remote sensing, rescue operations, agriculture, logistics, as well as in observation and surveillance systems [2]. New challenges relating to key operational parameters include extending flight time, increasing payload capacity, increasing operational range, and enhancing the system's level of autonomy, particularly in the case of long-duration monitoring missions, inspections of extensive infrastructure networks, and operations carried out in hard-to-reach areas.

Despite the rapid development of UAV technology, the performance of many platforms remains fundamentally constrained by the characteristics of their power sources. Electric UAVs powered by lithium-ion batteries constitute a representative example. In aviation applications, the energy density of on-board energy storage systems is a critical parameter, as the mass of the energy system directly influences flight endurance, payload capacity, range, and overall operational capabilities [3].

Power limitations are particularly pronounced in multirotor platforms, which, unlike fixed-wing aircraft, require continuous thrust to maintain hover. Consequently, their propulsion systems must deliver high power, resulting in increased energy consumption. Increasing battery capacity does not resolve this issue, as additional mass raises the maximum take-off weight (MTOW), thereby increasing the energy required for sustained flight [4].

To overcome these limitations, a wide range of new propulsion system architectures for UAVs is being developed. The most widely adopted solution is battery-powered electric propulsion, due to its simple design, ease of control, wide component availability, and low noise levels. However, its applicability in long-endurance missions is limited by the low energy density of batteries, long charging times, and performance degradation during repeated charge and discharge cycles [5].

An alternative to electric propulsion systems is internal combustion engine propulsion. Owing to the high energy density of conventional fuels, such systems can provide longer flight endurance for unmanned aerial vehicles. However, their application is associated with several significant drawbacks, including exhaust emissions, increased noise levels, and mechanical vibrations resulting from engine operation [6].

In recent years, increasing attention has been devoted to hydrogen fuel cell-based propulsion systems, particularly proton exchange membrane (PEM) fuel cells. Previous research indicated that hydrogen fuel cells represent a promising alternative to conventional propulsion systems based on internal combustion engines, whilst emphasising that hydrogen storage technologies and energy conversion efficiency remain key challenges limiting their practical application [7]. Hydrogen technology offers significantly higher specific energy density compared to battery systems, which enables extended flight endurance in UAV applications while maintaining low noise levels and zero local emissions. Typically, PEM fuel cell systems can achieve an energy density of 1000–2000 Wh/kg, compared to 150–250 Wh/kg for lithium-ion batteries, which can significantly enhance the flight endurance of unmanned platforms [8]. Hydrogen propulsion systems are particularly attractive for missions requiring long flight durations and high operational reliability. However, a number of technical challenges must be taken into account, relating to the weight of the hydrogen storage system, the weight of the fuel cell stack, the complexity of integrating the power system, and the requirements for the safe transport of hydrogen.

Among the various configurations of unmanned aerial vehicles, multirotor UAVs are of particular interest [9]. These platforms remain airborne due to rotor-generated thrust; therefore, during hover, the entire weight of the aircraft is supported by the propulsion system, resulting in high power demand. Studies indicate that power requirements during forward flight can be up to 64% lower than in hovering conditions, as part of the lift is generated by the aircraft's lifting surfaces [10]. Consequently, the propulsion systems of multirotor platforms operate under conditions of constant and relatively high energy demand. In the case of hydrogen-powered multirotor platforms, design criteria defining the relationships between maximum take-off weight (MTOW), payload, fuel cell power, and hydrogen storage capacity become particularly important.

Despite the growing number of hydrogen-powered UAVs, available technical data are often scattered across manufacturers' data sheets, reports, and scientific publications, while manufacturers usually provide only selected parameters. Similar observations have been made in review papers on hydrogen-powered UAV

systems, which highlight the fragmentation of available research and the lack of comprehensive comparative analyses concerning the architecture of propulsion systems and their operational parameters [11].

The literature still lacks comprehensive analyses and generalised models that would enable the identification of relationships between platform mass, propulsion system parameters, and flight performance in the case of multirotor UAVs powered by hydrogen. An analysis of the relationship between platform mass, propulsion system power, and available energy identifies key design criteria that significantly influence the operational characteristics of this class of systems.

An analysis of the mass–energy distribution enables the assessment of the proportion of maximum take-off weight (MTOW) allocated to payload, the structural mass fraction, and the variation of flight efficiency with mass distribution. This approach is consistent with the methods used in the analysis of aircraft propulsion systems, where the relationship between power demand and available power is a key factor [12]. Analysis of these indicators enables the identification of characteristic scaling relationships between propulsion system power and platform mass, as well as the determination of key design and structural constraints for hydrogen-powered UAV platforms. The analysis is based on a set of indicators, including the payload to maximum take-off weight ratio, structural mass fraction, specific endurance, and the power to mass ratio of the propulsion system.

The novelty of this study does not lie in presenting the individual indicators as entirely new engineering measures, as some of them are already known and used in the assessment of the performance of aircraft and unmanned aerial vehicles. The scientific contribution, however, lies in integrating these indicators into a unified comparative framework, developed specifically for multi-rotor UAVs powered by hydrogen fuel cells. Unlike previous studies, which focused mainly on the analysis of individual UAV platforms, the optimisation of propulsion systems, flight time modelling or energy management technologies, this study integrated mass parameters, payload capacity, the rated power of a PEM fuel cell, hydrogen storage capacity, hydrogen storage pressure and flight time into a unified set of standardised indicators. The research published to date has focused primarily on selected aspects of the design and

operation of hydrogen-powered unmanned aerial vehicles, such as energy management, propulsion system selection, hydrogen storage and flight time optimisation. However, there is still no standardised methodology enabling a comprehensive comparison of commercial multirotor platforms using standardised mass-energy metrics [13]. As opposed to previous studies, the approach proposed in this paper enables a systematic comparison of commercially available multi-rotor hydrogen-powered UAVs and provides an integrated analysis of the distribution of mass, hydrogen storage capacity, the selection of PEM fuel cell power, and the declared flight endurance.

The aim of this study was to identify mass-energy relationships in multirotor unmanned aerial vehicles powered by hydrogen fuel cells, based on a comparative analysis of available UAV platforms. The analysis is based on the technical parameters obtained from available manufacturer documentation and technical reports, including maximum take-off weight, platform empty mass, payload, flight time, fuel cell rated power, hydrogen tank capacity, storage pressure, and type of hydrogen storage system.

The scope of the study was limited to multirotor UAV platforms powered by hydrogen fuel cells. Fixed-wing platforms and hybrid VTOL platforms, which combine the characteristics of fixed-wing and multirotor aircraft, were excluded from the analysis due to their different aerodynamic and energy characteristics. The platforms analysed belong to similar weight classes, which enables a comparative analysis of technical parameters and selected indicators.

The results are presented in the form of tables and comparative graphs, enabling a clearer identification of the relationships between mass parameters, power system parameters and the predicted flight time. The study also utilised a graph showing the relationships between selected operational parameters to highlight characteristic value ranges and potential design constraints within the analysed class of UAV systems.

RESEARCH METHODOLOGY

The research methodology adopted in this study was divided into several successive stages. In the first stage, the available technical sources were identified, including manufacturers' catalogues, technical reports, and scientific

publications. A preliminary dataset on hydrogen-powered unmanned aerial vehicles was then compiled. In the third stage, the data set was filtered in accordance with the agreed criteria, with particular emphasis on fuel-cell propulsion and multirotor configurations.

In the next stage, the collected data was organised, and missing values were marked as “n/a”, without any attempt being made to estimate them further. Standardised indices were then calculated to enable a comparison of UAV platforms of different sizes and configurations. In the final stage, graphical, statistical, and engineering analyses were carried out to identify mass-energy relationships, characteristic trends, outliers, and the limitations of the platforms under analysis. A general outline of the research procedure is shown in Figure 1.

Criteria for selecting unmanned aerial vehicle platforms

The analysis focused exclusively on unmanned aerial vehicles equipped with fuel cell propulsion systems. The article concentrated on the platforms using hydrogen technology as an energy source, given its high potential for application in UAV power systems.

An additional selection criterion concerned the structural configuration of the platforms. Only multirotor UAVs were included in the analysis, in particular quadcopter, hexacopter, and octocopter configurations. These platforms are characterised by stable hovering capability, high manoeuvrability, and the ability to perform precise operations in confined spaces [12]. Fixed-wing platforms and hybrid VTOL (Vertical Take-Off and Landing)

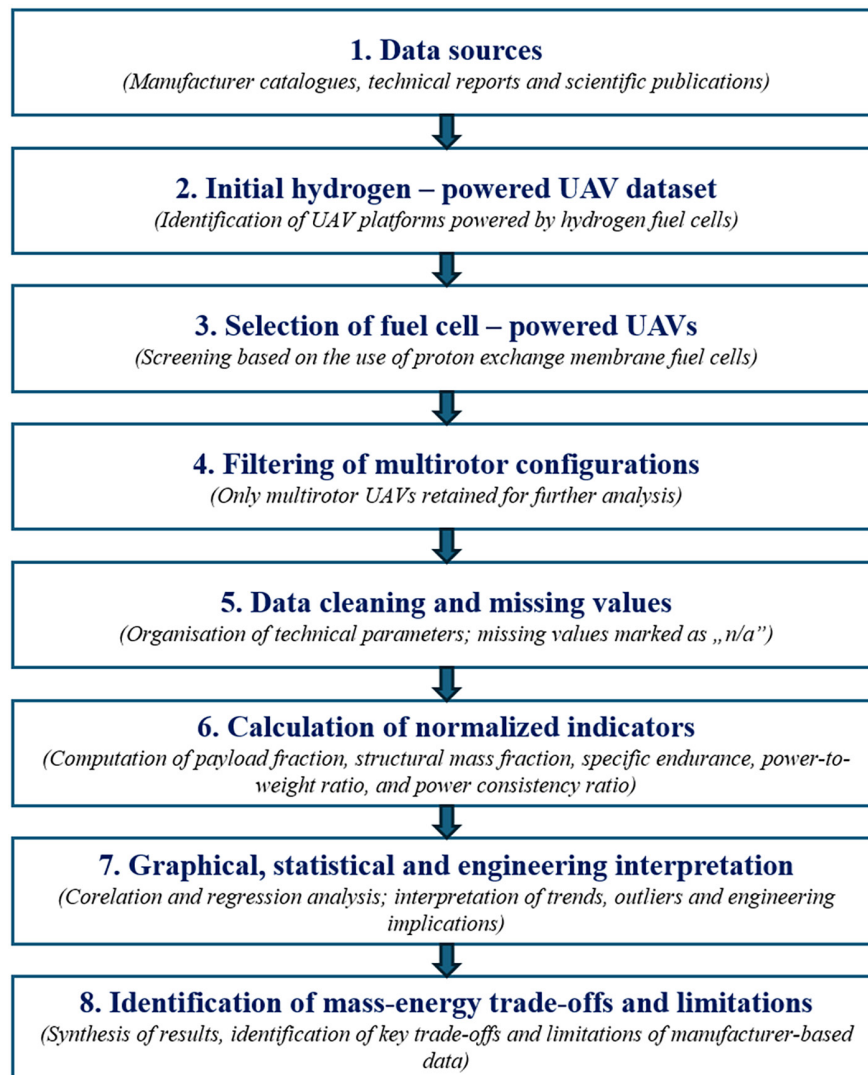


Figure 1. Flowchart of the research procedure used for data collection, platform selection, indicator calculation, and interpretation of mass–energy relationships in hydrogen-powered multirotor UAVs

configurations were not included in the analysis due to fundamental differences in lift generation mechanisms, aerodynamic characteristics, and energetic properties of these systems. These differences directly affect power demand models. For example, in multirotor platforms, induced and profile power components are considered, whereas in fixed-wing configurations, energy consumption is primarily determined by wing aerodynamic characteristics and flight speed [14], (Figure 2).

The technical data for the UAV platforms analysed were taken from manufacturers' available data sheets, technical documentation provided by manufacturers, technical reports, and scientific publications on UAV systems and fuel cell-based propulsion systems. Due to the lack of standardised reporting standards for technical parameters in the case of commercial UAV platforms, the availability of data varied.

Scope of the collected data

For the purpose of this study, a set of technical parameters was compiled to describe the mass and energy characteristics of hydrogen fuel cell-powered multirotor UAVs. The selected parameters enable detailed mass–energy analysis and comparative evaluation of different UAV platforms. This approach is consistent with the previous studies, in which UAV models simultaneously accounted for mass, energy, and operational parameters to analyse flight endurance and propulsion system efficiency [16]. The collected dataset includes the following parameters:

- UAV platform name,
- manufacturer,
- structural configuration,
- maximum take-off weight,
- empty weight,
- maximum payload,
- flight endurance,
- fuel cell rated power,
- hydrogen tank capacity,
- hydrogen storage pressure.

The summary of the collected data is presented in Table 1, which serves as the basis for subsequent comparative analysis and for determining the mass-to-energy ratios discussed in the following chapters of this paper. In the event of discrepancies, the values provided by the manufacturer were taken as the most representative for the platforms under analysis.

During the development of the dataset, difficulties were encountered in obtaining technical information due to the limited availability of data provided by manufacturers and available in technical documentation. To ensure the consistency of the analysis, missing values were marked as “n/a” (not available). To maintain the reliability of the results, no attempt was made to estimate the missing values based on analogies with other platforms. The main limitation of the dataset under analysis is its reliance on the publicly available data from manufacturers, which is not reported in accordance with a uniform standard. In many cases, the information regarding the actual mission profiles, average power requirements, the mass of

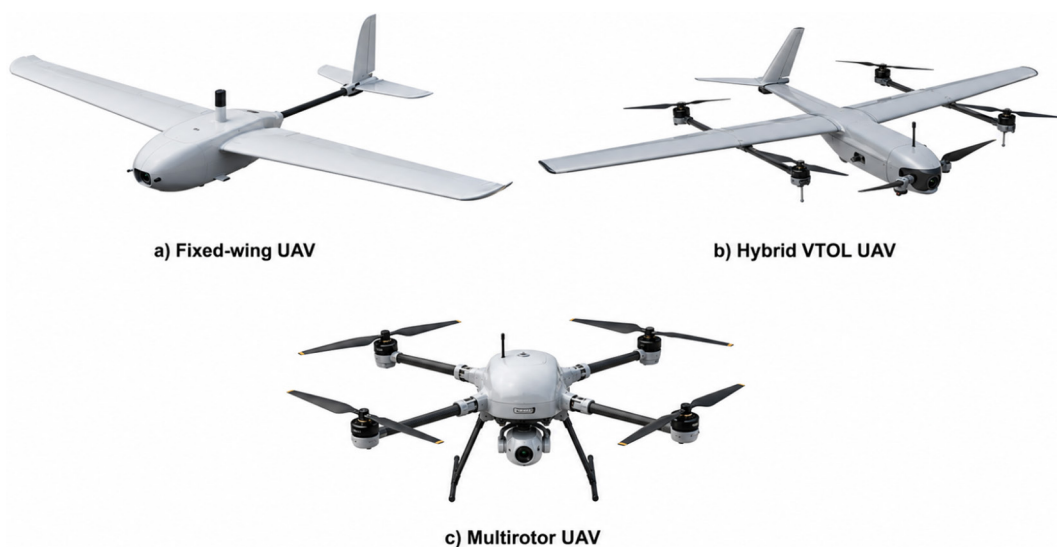


Figure 2. Basic UAV configurations: a) Fixed-wing, b) VTOL hybrid design, c) Multirotor [15]

Table 1. Summary of technical specifications for multirotor UAVs powered by fuel cells

UAV Model	Manufacturer	Configuration	MTOW [kg]	E_w [kg]	M_p [kg]	t_E [min]	R_{PEMFC} [kW]	V_{cyl} [L]	P_{tank} [bar]	Refs.
HyDrone 1550	MMC	Hexacopter	22.0	16.5	5.0	150.0	n/a	9.0	350.0	[17,18]
HyDrone 1800	MMC	Hexacopter	25.0	20.0	5.0	240.0	1.8	14.0	300.0	[19,20]
DS035CCD	DOOSAN	Quadcopter	21.7	18.7	3.0	120.0	3.0	10.8	350.0	[21]
DS30W	DOOSAN	Octocopter	24.9	21.9	3.0	120.0	2.7	10.8	350.0	[22]
DT30X	DOOSAN	Hexacopter	24.9	21.0	5.0	150.0	2.6	10.8	350.0	[23,24]
Anna	Hylium	Quadcopter	11.0	6.6	4.4	n/a	2.0	n/a	n/a	[25,26]
Dodeca	Hylium	Hexacopter	24.0	21.0	2.0	240.0	2.4	12.0	n/a	[26,27]
Hexa	Hylium	Hexacopter	20.0	17.0	3.0	300.0	2.0	12.0	n/a	[26,28]
H2D55	HEVEN	Octocopter	29.5	25.0	4.5	120.0	n/a	n/a	n/a	[29]
Phoenix H25	Atlas (SHHITS)	Quadcopter	33.0	26.0	7.0	90.0	3.6	12.0	350.0	[30]
H6H2	HARRIS AERIAL	Hexacopter	25.0	20.0	5.0	180.0	2.4	10.8	350.0	[31,32]
H2-6	CELLEN	Hexacopter	25.0	20.0	5.0	150.0	2.4	12.0	350.0	[33,34]
Staaker BG200	NORDIC UNNAMED	Octocopter	25.0	16.0	9.0	99.0	2.0	7.2	300.0	[35]
Phoenix	Spectronik	Hexacopter	21.0	19.0	2.0	90.0	2.0	9.0	300.0	[36]
SKYLLE 1550H	YTK	Hexacopter	19.0	14.0	5.0	170.0	1–1.8	9.0	350.0	[37]
NOTUZI H100	YTK	Quadcopter	8.3	7.3	1.0	110.0	1–1.8	n/a	350.0	[37]
Hycopter1	HUS	Quadcopter	6.7	5.2	1.5	n/a	n/a	3.0	300.0	[11,38]
Sensus M4-H2	AEROSPACE	Quadcopter	8.0	6.5	1.5	90.0	0.8	3.0	300–350	[39]
UAV model	Manufacturer	Configuration	MTOW [kg]	E_w [kg]	M_p [kg]	t_E [min]	R_{PEMFC} [kW]	V_{cyl} [L]	P_{tank} [bar]	Refs.
Sensus L4-H2	AEROSPACE	Quadcopter	25.0	16.5	6.0	180.0	2.4	n/a	300–350	[39]
X4-1900H	FPVDRONE	Quadcopter	29.0	14.5	n/a	120.0	3.0	12.0	350.0	[40]
HYCOPTER	H3Dynamics	Hexacopter	16.5	14.0	2.5	180.0	1.5	12.0	n/a	[41]
Gryphon	Skycutter	Hexacopter	25.0	18.0	6.0	120.0	n/a	10.8	n/a	[42]
HydroCopter mini	Hydrogen Craft	Quadcopter	10.5	9.0	1.5	120.0	1.3	5.0	350.0	[43]
HydroCopter 4	Hydrogen Craft	Hexacopter	25.0	19.0	6.0	180.0	3.4	n/a	n/a	[44]
Ranger	Zhongyu	Hexacopter	n/a	12.7	n/a	210.0	1.2	9.0	300.0	[11]
Jupiter H2	FlightWave	Octocopter	n/a	n/a	1.3	120.0	0.7	3.0	n/a	[11,45]

Note: own elaboration based on [11–45]. E_w – empty weight; M_p – maximum payload; t_E – declared endurance; R_{PEMFC} – rated PEMFC power; V_{cyl} – hydrogen tank capacity; P_{tank} – hydrogen storage pressure.

the hydrogen tank, the mass of auxiliary components, the operating point of the fuel cell, and the actual efficiency of the entire system was lacking. Consequently, the results obtained should be interpreted as a first-order comparative analysis, rather than as a direct prediction of flight performance. This approach is consistent with the standard practice in UAV data analysis, where missing data often result from measurement limitations or the unavailability of source information [46]. A further limitation stems from the fact that the flight endurance figures declared by manufacturers may be obtained under various test conditions, including different payload configurations, flight

modes, environmental conditions, wind speeds, ambient temperatures, and hydrogen tank fill levels. Furthermore, the way in which the payload is defined may vary from one manufacturer to another, as some specifications state the maximum payload, whilst others may refer to the recommended operational payload. These differences introduce uncertainty into the comparative assessment and may affect the interpretation of outliers.

Normalised indicators

To perform a comparative analysis of the mass and energy characteristics of the selected

platforms, a set of indicators is defined to normalise key parameters with respect to maximum take-off weight (MTOW). This approach enables direct comparison of platforms with different sizes and configurations. The selection of these indicators is based on the previous research indicating that the flight time and performance of multirotor unmanned aerial vehicles depend primarily on the platform's mass, payload capacity, available on-board energy and the power requirements of the propulsion system [17, 35]. Payload Fraction is defined as:

$$PL_F = \frac{M_P}{MTOW} \cdot 100\% \quad (1)$$

This ratio expresses the proportion of payload mass (M_P) relative to the maximum take-off weight (MTOW) and serves as a measure of how efficiently the platform's mass is utilised for useful load [47]. Payload-related parameters are of great importance, as the mass of the payload directly affects the energy efficiency, stability, and mission capability of multirotor aircraft [48]. Another indicator is the structural mass fraction, defined as the ratio of empty mass (excluding payload) to the maximum take-off weight (MTOW):

$$S_{MASS} = \frac{E_W}{MTOW} \cdot 100\% \quad (2)$$

This ratio represents the structural mass fraction, defined as the ratio of structural mass (E_W) to the maximum take-off weight (MTOW) [6]. This indicator is of particular importance, as the empty weight includes not only the airframe, but also the propulsion system, on-board equipment, the fuel cell assembly, auxiliary components, and the hydrogen storage system [6, 11].

Another indicator is the specific flight endurance, defined as the flight endurance normalized with respect to the maximum take-off weight:

$$t_{UE} = \frac{t_E}{MTOW} \left[\frac{\text{min}}{\text{kg}} \right] \quad (3)$$

This indicator is defined as the ratio of flight endurance (t_E) to the maximum take-off weight (MTOW), enabling the assessment of energy efficiency per unit mass [min/kg] and direct comparison of UAVs with different sizes and configurations. The use of flight endurance normalised by mass is consistent with previous studies, which have demonstrated that flight endurance is primarily governed by available on-board energy,

power demand, vehicle mass, and mission conditions [17,35]. Based on these findings, this study has incorporated this indicator into a comprehensive set of standardised mass-to-energy indicators, enabling the identification of mass-to-energy relationships and an objective comparison of multirotor unmanned aerial vehicles powered by hydrogen.

The final indicator is defined as the ratio of available propulsion power (R_{PEMFC}) to the maximum take-off weight (MTOW):

$$PTW_R = \frac{R_{PEMFC}}{MTOW} \left[\frac{W}{kg} \right] \quad (4)$$

This indicator was taken into account because the performance of the propulsion system has a direct impact on the manoeuvrability of the unmanned aerial vehicle, its payload capacity, and flight duration [49]. In the case of UAVs powered by PEM fuel cells, the rated power of the cell should be regarded as a comparative parameter reflecting the available power of the propulsion system, rather than as the actual average power requirement during flight [6].

The indicators presented in this sub-section form the basis for the analysis of mass-energy relationships set out in the following sections of the article. Taken together, these indicators describe the fundamental design trade-offs between payload capacity, the proportion of mass accounted for by the airframe and power system, the available power of the propulsion system, and flight time. Consequently, the proposed indicator-based approach enables a consistent comparison of multirotor hydrogen-powered unmanned aerial vehicles using heterogeneous data declared by manufacturers.

Statistical approach

To complement the graphical interpretation, statistical analyses were performed to quantify the relationships between maximum take-off weight (MTOW) and the proposed normalised indicators: PL_F , S_{MASS} , t_{UE} and PTW_R . Pearson's correlation coefficients were calculated to determine the direction and strength of the linear relationships. Subsequently, separate simple linear regression models were fitted for each indicator, with MTOW used as the independent variable [50]. For each model, the regression slope, coefficient of determination (R^2), p-value, and 95% confidence interval for the slope were determined.

To assess the statistical uncertainty of the estimated relationships, non-parametric bootstrap resampling with 10,000 repetitions was applied. Bootstrap 95% confidence intervals were calculated for the Pearson correlation coefficient.

Only the platforms with complete numerical data for the variables included in a given analysis were considered, whereas the observations with missing values marked as “n/a” were excluded. For the SKYLLE 1550H and NOTUZI H100 platforms, for which the rated PEMFC power was reported as a range of 1.0–1.8 kW, the arithmetic mean value of 1.4 kW was adopted for the calculation of the power-to-weight ratio.

A set of criteria for evaluating UAV performance

To analyse mass–energy relationships, a simplified analytical model based on the literature was applied to hydrogen fuel cell-powered multirotor UAVs. These criteria enable the identification of relationships between mass, energy parameters, power requirements, and platform flight endurance. Flight endurance, as described in, was adopted as the primary evaluation parameter [35]:

$$t_e = \frac{E}{P_{AVG}} \quad (5)$$

where: t_e – flight endurance, E – available onboard energy, P_{AVG} – average power demand.

It is assumed that flight endurance depends not only on the available on-board energy, but also on the total platform mass, which influences the propulsion system power demand. In the adopted model, the take-off weight is expressed as [35]:

$$m_{TOW} = m_{EW} + m_E + m_{PL} \quad (6)$$

where: m_{TOW} – maximum take-off weight, m_{EW} – empty mass (excluding payload), m_E – energy system mass, m_{PL} – payload mass.

In fuel cell-based systems, the available energy is determined by the amount of stored hydrogen and the system efficiency, and can be expressed as [35]:

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

where: $\rho_{H_2}(p)$ – hydrogen density at a given pressure, V_{cyl} – hydrogen tank capacity, h_{H_2} – lower heating value of hydrogen, η_{FC} – fuel cell efficiency, η_{H_2} – hydrogen utilisation factor.

The selected criterion ($E_{FC}(p, V_{cyl})$) indicates that increasing the volume or pressure of hydrogen storage leads to an increase in available energy. However, the mass of the system, which affects power requirements, must be taken into account. In this study, the set of criteria was not used to directly predict the flight time of individual platforms, but rather as an interpretative tool to aid in the analysis of the results.

The inclusion of these criteria enables improved interpretation of the results and the identification of key physical relationships between mass, available energy, propulsion system power, and flight endurance.

RESULTS AND ANALYSIS

This section presents the results of the relationships between mass, energy and operational parameters for hydrogen-powered UAV platforms. The analysis was carried out using indicators and their relationships to maximum take-off weight. The results obtained are presented in the form of scatter plots, which enable the identification of trends and outliers.

Statistical assessment of mass-energy relationships

To provide a consolidated statistical assessment of the relationships presented in Figures 3–6, Pearson correlation and simple linear regression analyses were performed for maximum take-off weight (MTOW) and each of the four normalised indicators: payload fraction (PL_F), structural mass fraction (S_{MASS}), specific flight endurance (t_{UE}), and power-to-weight ratio (PTW_R). The results are summarised in Table 2. In addition to the Pearson correlation coefficient and the coefficient of determination, the analysis included the regression slope, its p-value, and the corresponding 95% confidence interval. Statistical uncertainty was further evaluated using non-parametric bootstrap resampling with 10,000 repetitions.

No statistically significant linear relationship was identified between MTOW and payload fraction. The Pearson coefficient was close to zero ($r = -0.02$, $p = 0.922$), and MTOW explained less than 0.1% of the variability in (PL_F). Both the classical confidence interval for the regression slope and the bootstrap confidence interval for

Table 2. Correlation, regression, and uncertainty analysis of MTOW and selected normalised indicators

Indicator	n	Pearson r	p-value	R ²	Regression slope	95% CI for slope	Bootstrap 95% CI for r	Interpretation
PL_F	23	-0.02	0.922	0.00	-0.023 %/kg	-0.502 to 0.457	-0.411 to 0.413	No linear relationship
S_{MASS}	24	-0.16	0.452	0.03	-0.222 %/kg	-0.823 to 0.379	-0.498 to 0.288	Very weak, non-significant relationship
t_{UE}	22	-0.75	<0.001	0.56	-0.391 min/kg per kg	-0.552 to -0.230	-0.916 to -0.554	Strong negative relationship
PTW_R	20	-0.47	0.038	0.22	-1.933 W/kg per kg	-3.743 to -0.124	-0.765 to 0.130	Moderate but less robust negative relationship

Note: for SKYLLE 1550H and NOTUZI H100, the rated PEMFC power used in the PTW_R calculation was 1.4 kW, corresponding to the arithmetic mean of the reported 1.0–1.8 kW range.

the correlation coefficient included zero. Therefore, the proportion of platform mass allocated to payload cannot be considered a direct function of platform size within the analysed dataset. Instead, it is likely governed by platform-specific design decisions, propulsion architecture, and the mass of the on-board hydrogen system.

A similarly weak relationship was obtained for structural mass fraction. The correlation between MTOW and (S_{MASS}) was negative but small ($r = -0.16$, $p = 0.452$), with $R^2 = 0.03$. The 95% confidence intervals again included zero, providing no evidence of a systematic linear decrease in structural mass fraction with increasing MTOW. This result indicates that larger platforms do not necessarily allocate a smaller proportion of their take-off mass to the airframe, propulsion system, and auxiliary components.

The strongest statistical relationship was observed for specific flight endurance. The correlation between MTOW and (t_{UE}) was strongly negative ($r = -0.75$, $p < 0.001$), and the regression model explained approximately 56% of the observed variability. The estimated slope indicated that an increase in MTOW of 1 kg was associated, on average, with a decrease of approximately 0.39 min/kg in specific flight endurance. Both the classical and bootstrap confidence intervals remained entirely below zero, confirming the stability of the negative trend. This finding supports the physical interpretation that propulsion power demand increases with platform mass, whereas available on-board energy does not necessarily increase proportionally.

For the power-to-weight ratio, a moderate negative correlation was obtained ($r = -0.47$, $p = 0.038$), with MTOW explaining approximately 22% of the variability in (PTW_R). The ordinary least squares slope was negative, and its classical

95% confidence interval marginally excluded zero. However, the bootstrap confidence interval for the correlation coefficient extended across zero, indicating greater uncertainty than in the case of specific flight endurance. Consequently, the relationship between MTOW and (PTW_R) should be interpreted cautiously, as it may be affected by individual platform configurations and by differences in manufacturers' propulsion-system sizing assumptions.

Assessment of the indicator (PL_F)

Weight efficiency in unmanned aerial vehicles is a key factor in assessing their operational capabilities [47]. In the case of multirotor platforms, the distribution of weight between the airframe, the propulsion system, and the mission-critical components is of particular importance [48]. To enable the assessment of these relationships, the payload-to-maximum take-off weight ratio (PL_F) has been introduced.

Figure 3 shows the relationship between the payload fraction and the maximum take-off weight of UAVs. The results indicate that most platforms exhibit a payload fraction in the range of 10–25%, suggesting that the majority of the total mass is attributed to the platform structure and propulsion system. No clear correlation was observed between the payload fraction and MTOW, which may indicate that this parameter is primarily determined by design constraints rather than directly by platform size. This observation is confirmed by the results of the statistical analysis set out in Table 2. The Pearson correlation coefficient was close to zero ($r = -0.02$), indicating no linear relationship between maximum take-off weight (MTOW) and the (PL_F). This result is consistent with the previous studies indicating that the payload capacity of

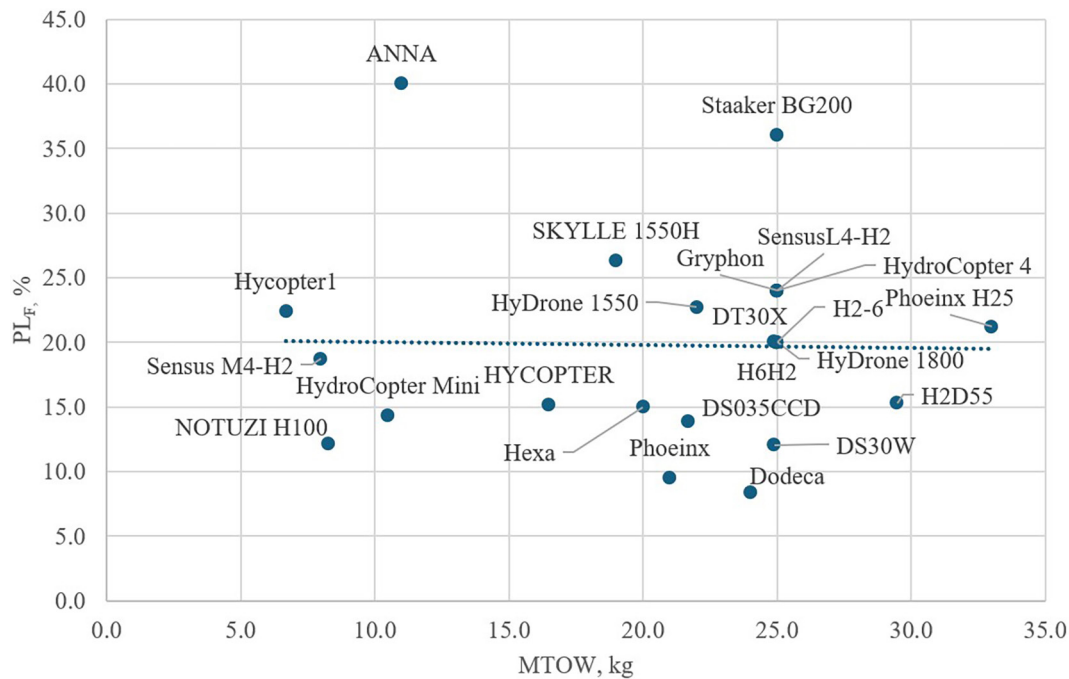


Figure 3. Relationship between payload fraction (PL_F) and MTOW for the analysed hydrogen fuel cell-powered multirotor UAVs

multi-rotor UAVs is determined not only by the size of the platform, but also by the configuration of the propulsion system and the mass of the power supply system. In the case of the platforms powered by PEM fuel cells, the mass of the fuel cell stack, BoP components and the hydrogen storage system limits the available payload [6,11].

Particular attention should be paid to individual platforms achieving higher values for the indicator (PL_F), in particular ANNA (40%) and Staaker BG200 (36%). Furthermore, it can be observed that the SKYLLE 1550H platform (26%) falls just outside the dominant range. This may be due to design optimisation aimed at increasing transport capacity or the use of more efficient energy solutions.

Assessment of the indicator (S_{MASS})

The proportion of empty weight in multirotor platforms constitutes a significant portion of the total UAV weight and often represents the primary design constraint. This results from the need to ensure adequate structural strength and the integration of the propulsion system, both of which directly affect operational performance [49]. In order to quantify this phenomenon, a ratio of empty weight to maximum take-off weight (MTOW) has been introduced. Figure 4 shows the relationship between the platform's empty weight and its

maximum take-off weight. The graph shows that most platforms have a specific weight ratio (2) of around 75–90%, indicating that the mass of the platform itself, together with the propulsion system, accounts for the majority of the total mass. The statistical results in Table 2 indicate that the relationship between MTOW and (S_{MASS}) is weak, which confirms that structural mass fraction is mainly influenced by platform-specific design and energy system integration. This means that only a limited portion of the mass can be allocated to payload or additional energy resources. A similar increase in non-payload mass has been observed in fuel-cell-powered platforms, where hydrogen tanks, BoP components, and the hydrogen storage system increase the platform's unladen mass [6,11]. Therefore, the high values of the index obtained in this study should be interpreted as the result of the combined effect of the structure's mass and the integration of the power supply system, rather than the structure's mass alone.

Several models that deviate from the prevailing range are worth noting. These include platforms such as ANNA (60%), Staaker BG200 (64%), Sensus L4-H2 (66%) and X4-1900H (50%). These platforms are characterised by a lower proportion of unladen weight, which may indicate that their design has been optimised to increase the payload.

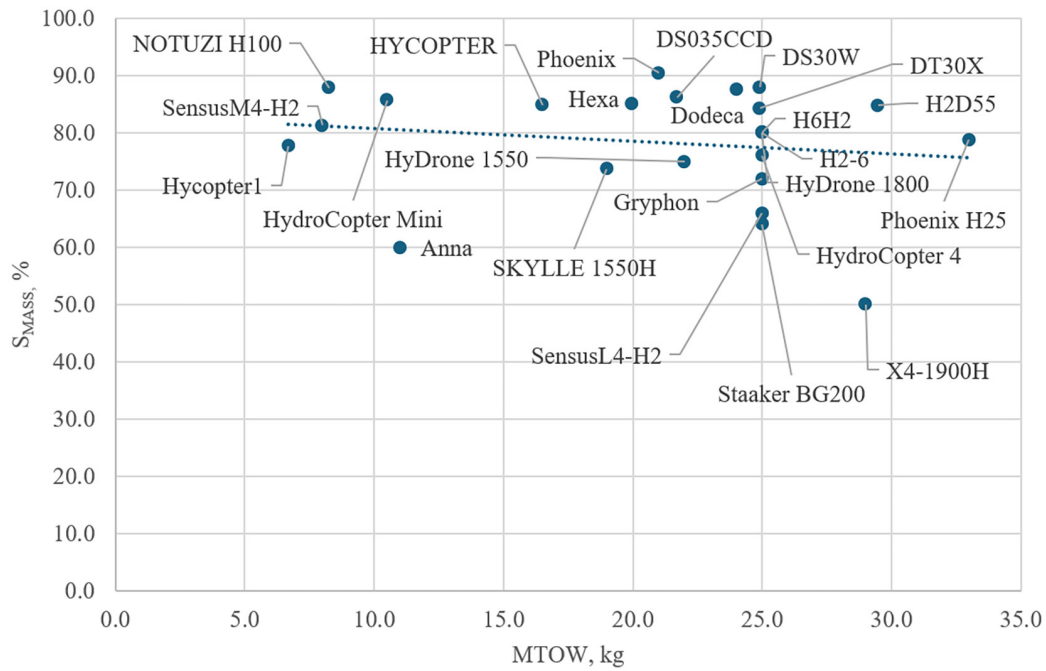


Figure 4. Relationship between structural mass fraction (S_{MASS}) and MTOW for the analysed hydrogen fuel cell-powered multirotor UAVs

Assessment of the indicator (t_{UE})

The indicator (t_{UE}) is used to assess the energy efficiency of UAV platforms per unit mass. It enables direct comparison of different platform designs regardless of their size. Higher values of (t_{UE}) indicate more efficient utilisation of available on-board energy, whereas lower values reflect increased energy losses or higher propulsion power demand associated with specific design characteristics.

Figure 5 illustrates the relationship between the specific flight endurance (t_{UE}) and the maximum take-off weight (MTOW). The results indicate a clear decreasing trend, showing that energy efficiency per unit mass declines as platform mass increases. This relationship is consistent with the analytical model presented in [35]. The results of the statistical analysis presented in Table 2 support the observed downward trend. The Pearson correlation coefficient ($r = -0.75$) indicates a strong negative linear relationship between specific flight endurance (t_{UE}) and maximum take-off weight (MTOW), while the coefficient of determination ($R^2 = 0.56$) shows that approximately 56% of the variability in specific flight endurance can be explained by MTOW within the analysed dataset. The observed trend is consistent with the previous studies indicating that the flight endurance of multirotor UAVs depends primarily on platform mass,

propulsion power demand, and the amount of energy available on board. As platform mass increases, propulsion power demand generally rises, whereas the available on-board energy does not necessarily increase proportionally, resulting in lower specific flight endurance [4,17].

The values of the specific flight endurance (t_{UE}) for most of the analysed platforms fall within the range of 4–10 min/kg, indicating a relatively consistent level of energy efficiency among UAVs. However, several platforms deviate from this range. Higher values are observed for Hexa (15.00 min/kg), NOTUZI H100 (13.33 min/kg), HydroCopter Mini (11.43 min/kg), SensusM4-H2 (11.25 min/kg), and HYCOPTER (10.91 min/kg), which may indicate a favourable mass-to-energy ratio or a highly efficient propulsion system. Conversely, lower values are recorded for platforms such as Phoenix H25 (2.73 min/kg) and Staaker BG200 (3.96 min/kg), as well as near the lower limit for H2D55 (4.07 min/kg) and X4-1900H (4.14 min/kg). These results may reflect higher platform mass, increased propulsion power demand, or lower efficiency in utilising the available on-board energy. The presence of such outliers indicates that, in addition to platform mass, UAV energy efficiency is influenced by factors such as structural configuration, propulsion system efficiency, and hydrogen storage characteristics.

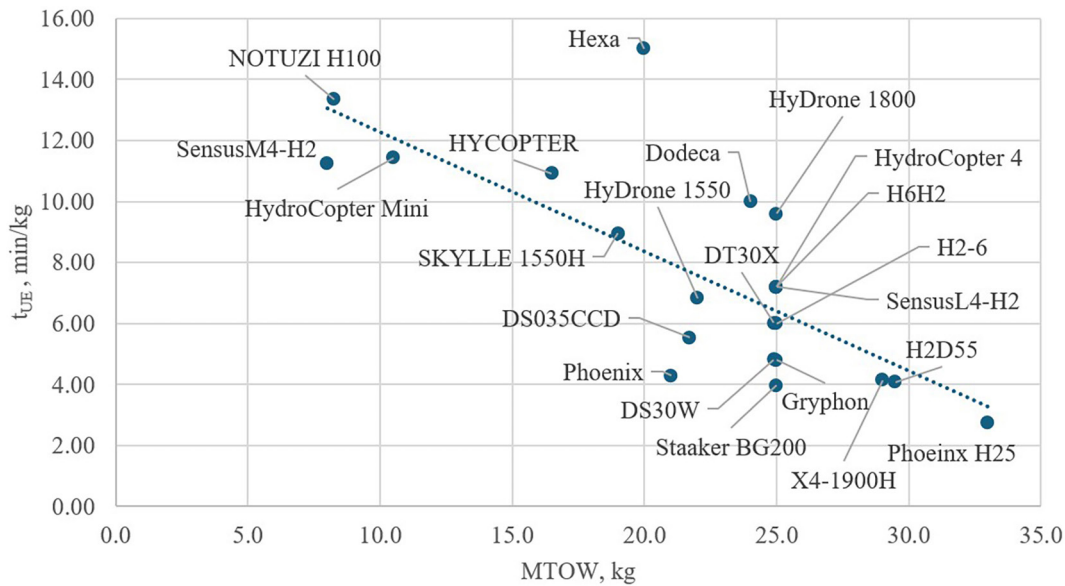


Figure 5. Relationship between specific endurance (t_{UE}) and MTOW, showing a decreasing trend with increasing platform weight

Assessment of the indicator (PTW_R)

The power-to-weight ratio is a parameter that characterises the propulsion performance of unmanned aerial vehicles. It defines the relationship between the available propulsion power and the platform mass, directly influencing flight dynamics and mission capability [49]. To quantitatively describe these properties, a performance indicator (PTW_R), normalised with respect to the maximum take-off weight (MTOW), is defined.

Figure 6 shows the relationship between power-to-weight ratio and maximum take-off weight.

Unlike flight duration, no strong correlation was observed between the analysed variables. The values vary widely and fall within a relatively broad range, indicating the different design approaches used by manufacturers. The variation in the index values observed indicates that the rated power of the propulsion system is not determined solely by the maximum take-off weight (MTOW). It also reflects the manufacturers' assumptions regarding the required manoeuvrability, power reserve, mission profile and flight dynamics requirements [49].

Higher values of the indicator (PTW_R), exceeding approximately 120 W/kg, are observed for

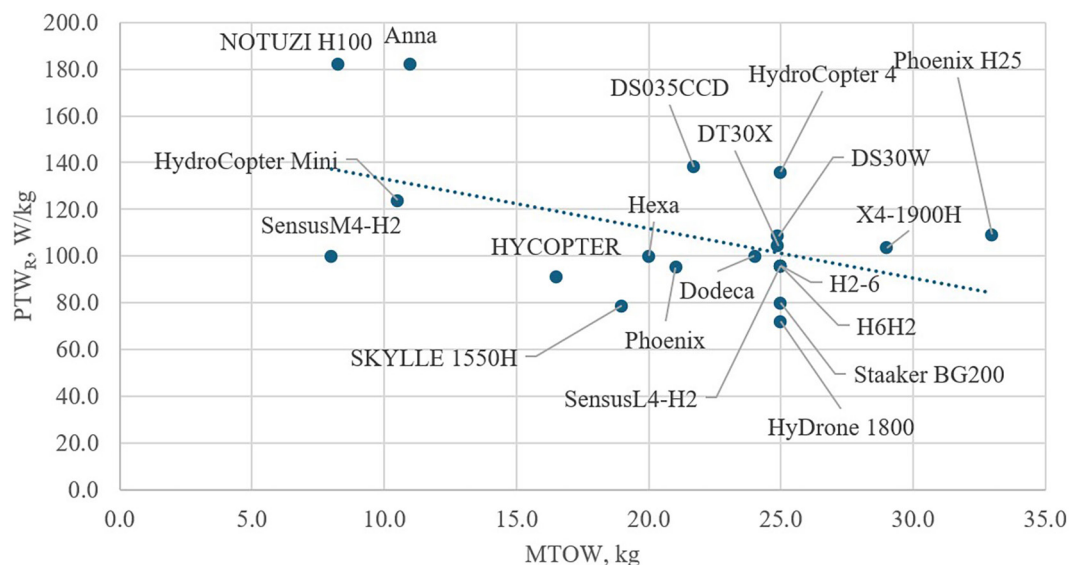


Figure 6. Relationship between power-to-weight ratio (PTW_R) and MTOW, indicating manufacturer-specific propulsion sizing strategies

DS035CCD (138.2 W/kg), HydroCopter 4 (136.0 W/kg), HydroCopter Mini (123.8 W/kg), and particularly Anna (181.8 W/kg) and NOTUZI H100 (181.8 W/kg). These platforms exhibit relatively high power-to-mass ratios, which may indicate that they were designed with high flight dynamics, rapid propulsion system response, and the capability to perform manoeuvres requiring fast thrust variations. It should be noted that the platforms with the highest (PTW_R) values often correspond to designs with lower take-off weight (e.g., Anna, NOTUZI H100, HydroCopter Mini), which further amplifies the indicator values. This suggests that, in these cases, design priorities were focused on maximising dynamic performance at the expense of energy efficiency and flight endurance.

Interpretation of results

To enable physical interpretation of the results, a set of performance evaluation criteria was developed. These criteria allow the analysis of relationships between platform weight, available system energy, power demand, and flight endurance.

According to Equation 5, the flight endurance of an unmanned aerial vehicle is proportional to the available on-board energy and inversely proportional to the propulsion power demand. In practical terms, increasing the volume or pressure of hydrogen storage leads to increased flight endurance; however, this effect is constrained by the corresponding increase in system mass [35].

An increase in platform mass, as shown in Equation 6, results in higher propulsion power demand, particularly under hover conditions characteristic of multirotor platforms. Consequently, an increase in available system energy does not necessarily translate linearly into extended flight endurance. This effect is reflected in the decrease of specific flight endurance with increasing maximum take-off weight. The results shown in Figures 4–6 confirm the relationships described above. The decreasing trend in specific flight endurance (t_{UE}) for larger UAV platforms is particularly significant, as it reflects the increasing contribution of propulsion power demand to the overall energy balance. Despite this trend, no clear correlation is observed between the fuel cell power-to-weight ratio (PTW_R) and maximum take-off weight (MTOW). This suggests that manufacturers adopt diverse strategies for propulsion system selection, depending on mission requirements and platform-specific operational constraints.

To illustrate the applicability of the adopted criteria, a case study analysis of selected UAV platforms was conducted. Four models were selected based on the distribution shown in Figure 5 two representing extreme values of specific flight endurance (t_{UE}) (SensusM4-H2 by AEROSPACE and Phoenix H25 by Atlas), and two located along the trend line, considered representative cases (SKYLLE 1550H by YTK and X4-1900H by FPVDRONE). This approach allows for a more reliable evaluation of the model across the full range of analysed data. The analysis was based on manufacturer-provided data summarised in Table 1. The calculations were performed assuming hydrogen density from 300 to 350 bar, a lower heating value of hydrogen of 33.6 Wh/g, a fuel cell efficiency of 50%, and propulsion power demand derived from the relationship between available energy and the declared flight endurance [35]. In order to assess the consistency of manufacturers' data, an additional indicator has been introduced, defined as the ratio of the estimated average power demand to the rated power of the fuel cell (8):

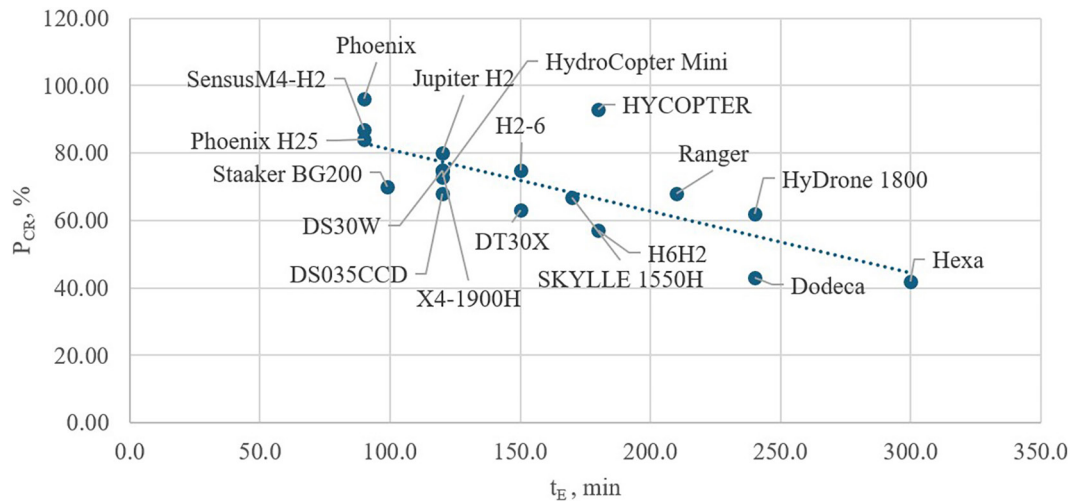
$$P_{CR} = \frac{P_{AVG}}{P_{PEMFC}} \cdot 100\% \quad (8)$$

This indicator allows the degree of utilisation of the available propulsion power to be assessed and serves as a criterion for evaluating the internal consistency of manufacturer-declared performance parameters. Indicator (8) is not directly defined in the literature, but its interpretation follows from classical relationships used in the analysis of propulsion systems, such as the power utilisation factor and power margin [12]. It allows for an assessment of the extent to which the power system is suited to the mission requirements and the identification of potential power oversizing or underestimation.

The results presented in Table 3 allow for a comparison of the selected UAV platforms in terms of hydrogen storage capacity, estimated available energy, average power demand, rated PEMFC power, and the power consistency ratio (P_{CR}). The obtained (P_{CR}) values indicate order-of-magnitude consistency between the estimated average power demand and the rated PEMFC power for the selected platforms. However, these values should not be interpreted as direct validation of manufacturer data, because the calculations are based on simplified assumptions and do not include transient loads, mission profile variability,

Table 3. Calculation results for selected hydrogen-powered UAVs

UAV model	V_{cyl} [L]	P [bar]	ρ_{H_2} [kg/m ³]	m_{H_2} [kg]	E_{FC} [kWh]	t_e [min]	P_{AVG} [kW]	R_{PEMFC} [kW]	P_{CR} [%]	Refs.
SKYLLE 1550H	9.00	350	23.65	0.21	3.40	170.00	1.20	1 – 1.8	67.00	[35,33]
X4-1900H	12.00	350	23.65	0.28	4.53	120.00	2.26	3.00	75.00	[38,33]
SensusM4-H2	3.00	350	23.65	0.07	1.15	90.00	0.76	0.80	95.00	[37,33]
Phoenix H25	12.00	350	23.65	0.28	4.60	90.00	3.06	3.60	85.00	[28,33]


Figure 7. Relationship between power consistency ratio (P_{CR}) and declared flight endurance (t_e) for selected UAV platforms

auxiliary power consumption, or environmental effects. To illustrate the relationship between the power utilisation rate of the propulsion system and the operational performance of UAV platforms more clearly, Figure 7 compares the (P_{CR}) indicator with the declared flight time of the systems under analysis. The results obtained indicate that the estimated average power demand is of the same order of magnitude as the rated power of the PEMFC cell for the selected platforms. However, the criteria adopted are simplified and do not take into account the influence of mission profile, environmental conditions, transient loads, power consumption by auxiliary equipment, or changes in power demand during flight. For this reason, their application in this study is interpretative in nature and serves to help explain the observed trends and design trade-offs between mass, available energy, and propulsion system performance.

CONCLUSIONS

The main scientific contribution of this study is the development of a standardised indicator-based methodology for the comparative assessment of

multi-rotor hydrogen-powered UAVs. Whilst previous studies have focused mainly on flight endurance modelling, propulsion system selection, energy management, mission optimisation or indicators such as the Endurance Gain Index (EGI) [51], the proposed approach integrates payload fraction, structural mass fraction, PEMFC rated power, hydrogen storage parameters, and flight endurance into a unified comparative framework. This makes it possible to identify mass–energy relationships, design trade-offs, and structural limitations that are not immediately apparent from manufacturers’ individual catalogue data. The main conclusions from the analysis are as follows:

- Most of the hydrogen-powered multirotor UAVs analysed are characterised by a high proportion of structural mass, typically in the range of 75–90% of the maximum take-off weight (MTOW). This means that the bulk of the platform’s mass is accounted for by the airframe, the propulsion system, the PEMFC stack, the hydrogen storage system, and auxiliary components.
- The payload ratio for most of the platforms analysed typically falls within the range of 10–25% of MTOW. This confirms that

payload capacity remains severely limited by the weight and integration requirements of the hydrogen propulsion system.

- The specific flight endurance (t_{UE}) most commonly took values in the range of 4–10 min/kg. A strong negative correlation was observed between (t_{UE}) and MTOW, indicating that flight efficiency per unit of mass decreases as the platform's mass increases.
- No clear linear relationship was found between MTOW and either the payload ratio or the structural mass ratio. This means that these ratios depend to a greater extent on the platform architecture, the integration of the propulsion system, and the manufacturer's design specifications than on the size of the UAV itself.
- The power-to-weight ratio of the PEMFCs varied significantly between platforms. This suggests that the rated power of the fuel cell is selected not only on the basis of MTOW, but also taking into account the mission profile, power reserves, manoeuvring requirements, and the powerplant selection strategy.
- An additional (P_{CR}) power consistency indicator enabled a preliminary comparison of the estimated average power requirement with the rated power of the fuel cell. The values obtained indicate consistency of the same order of magnitude for the selected platforms; however, they should not be interpreted as experimental validation of the data declared by the manufacturers.
- From a practical point of view, the results show that simply increasing hydrogen storage capacity is not sufficient to improve the endurance of multirotor UAVs. The power system should be optimised in conjunction with the airframe mass, the mass of auxiliary components, the efficiency of the propulsion system, and the mission profile.

The main limitation of this study is that the analysis is based on the publicly available data from manufacturers, which is not reported in accordance with a uniform research standard. Differences in the procedures for measuring flight duration, definitions of payload, environmental conditions, mission profiles, hydrogen storage configurations, and reporting methods may affect the direct comparability of the platforms under analysis. For this reason, the proposed methodological framework should be regarded as a first-order comparative

assessment method, rather than as an experimentally verified predictive model. Further research should include experimental validation, uncertainty analysis, dynamic energy modelling based on mission profiles, and the optimisation of hybrid propulsion systems under varying environmental conditions and dynamic load profiles.

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