

# CONCEPTUAL DESIGN AND VALIDATION OF A HYDROGEN TRAINING AIRPLANE

Sebastian Piotr Kuk  0000-0002-4502-6867

Institute of Aviation and Applied Mechanics, Warsaw University of Technology,  
24 Nowowiejska St., 00-665 Warsaw, Poland

## ABSTRACT

This study presents the conceptual design and stability assessment of an ultralight hydrogen-electric training aircraft. Building on a Minimum Viable Product (MVP) approach, the analysis first examines design requirements and trends in existing two-seat trainers. A conceptual design process is then applied, with adaptations for the integration of a hydrogen propulsion system comprising a fuel cell stack, electric motor, battery, and high-pressure hydrogen storage. Four alternative configurations for propulsion system placement were proposed and compared; the integrated nose-mounted layout was identified as the most promising. Stability and controllability analyses demonstrated that, despite relatively high moments of inertia and sensitivity in control forces, the aircraft remains stable and controllable across the flight envelope. The results confirm the technical feasibility of hydrogen propulsion integration in the ultralight training segment, while also highlighting the need for further aerodynamic validation, prototype testing, and regulatory development to support the future certification of hydrogen-powered aircraft.

## Keywords

conceptual design, hydrogen aviation, hydrogen propulsion, electric propulsion.

## 1. INTRODUCTION

The aviation sector is an increasing contributor to environmental emissions, including oxides of carbon, nitrogen, and sulfur, as well as water vapor. Although smaller in share than other industries, aviation's impact is amplified by rapid traffic growth and the high climate sensitivity of emissions released at cruising altitudes. This has intensified the search for sustainable propulsion systems.

Hydrogen is widely seen as a promising candidate: it can be produced from renewable sources, produces only water vapor in fuel cells, and offers high energy per unit mass. Yet storage, integration, and certification challenges have limited its adoption beyond experimental projects.

---

\* Corresponding Author. Email address: sebastian1kuk@gmail.com  
Received 07.08.2025 • Revised 23.08.2025 • Accepted 23.09.2025  
© 2025 Author[s]. Article category: research article



To address this gap, the concept of a hydrogen-powered Minimum Viable Product (MVP) aircraft has been proposed [1]. Training aircraft are an ideal starting point due to their small size, modest performance requirements, and high turnover in flight schools.

The aim of this study is to develop and evaluate a conceptual design for a hydrogen-electric training aircraft and to assess its stability, controllability, and feasibility as an MVP for hydrogen aviation.

## **2. HYDROGEN AVIATION TO DATE**

The idea of using hydrogen as a primary aviation fuel is not new – two landmark studies by Lockheed Martin [2] and Airbus [3] outlined possible pathways for hydrogen-powered airplanes more than two decades ago. The first manned hydrogen-combustion aircraft flew as early as 1957 in the United States (Martin B-57B) and 1988 in the Soviet Union (Tu-155). More recently, projects such as ENFICA-FC and HY4 have demonstrated that manned hydrogen flight is feasible. However, all these initiatives were purely research-oriented and did not lead to commercialization. This has generally been the pattern with hydrogen in aviation: while multiple studies review the state of the technology [4]-[6] and document examples of recently developed UAVs [7][8], motor gliders [9], and airplanes [10][11] using PEM fuel cells supplied by hydrogen in flight, none have transitioned to large-scale application. The pipeline of research remains rich, with promising future directions for both UAVs [12]-[14] and airplanes [15]-[17].

The greatest challenge faced by these projects has been the design of propulsion systems, particularly energy storage. While many studies address the challenges of electrical energy storage in general [18]-[23] and hydrogen storage in particular – both in gaseous [24][25] and liquid form [26][27] – no project to date has resulted in a proposal for a commercially competitive hydrogen-powered airplane. This study aims to identify possible directions for the development and commercialization of hydrogen propulsion in aviation.

## **3. TREND ANALYSIS FOR TRAINING AIRPLANES**

The first step in the conceptual design process is an analysis of existing training airplanes as a group, with the goal of identifying key characteristics relevant to the proposed design. Training airplanes are, in most cases, classified as Light or Ultralight General Aviation aircraft and serve primarily to train commercial, sport, or recreational pilots. These aircraft require a minimum of two seats, typically arranged side by side. Although this configuration increases fuselage cross-section and aerodynamic drag, it is generally considered optimal for training purposes, as it allows

for better communication between instructor and student. They are also equipped with dual flight controls, enabling operation from either seat.

The trend analysis was carried out exclusively on two-seat airplanes with a maximum takeoff weight of 1000 kg. The time range was limited to 1991–2018, based on the availability of technical data. Aircraft with insufficient publicly available data (primarily those certified in China and the Russian Federation) were excluded. After applying these criteria, 131 aircraft were included in the dataset (a complete list is provided in Appendix A). Table 1 presents average, minimum, and maximum values of key parameters, along with standard deviations and their relative percentages.

Table 1. Results of training airplane trend analysis

| Parameter            | Unit              | Average | Min   | Max    | Standard deviation | Standard deviation as % of average |
|----------------------|-------------------|---------|-------|--------|--------------------|------------------------------------|
| Length               | m                 | 6.49    | 5.50  | 7.50   | 0.45               | 7%                                 |
| Height               | m                 | 2.30    | 1.70  | 2.96   | 0.26               | 11%                                |
| Wingspan             | m                 | 9.20    | 7.55  | 13.00  | 0.96               | 10%                                |
| Wing chord           | m                 | 1.28    | 0.88  | 1.65   | 0.19               | 15%                                |
| Aspect ratio         | -                 | 7.45    | 5.00  | 14.10  | 1.62               | 22%                                |
| Wing area            | m <sup>2</sup>    | 11.71   | 8.04  | 17.09  | 2.04               | 17%                                |
| Empty weight         | kg                | 343.3   | 200.0 | 658.0  | 91.1               | 27%                                |
| MTOW weight          | kg                | 580.2   | 431.0 | 1043.0 | 140.7              | 24%                                |
| Max wing loading     | kg/m <sup>2</sup> | 55.75   | 36.00 | 95.90  | 11.31              | 20%                                |
| Max power loading    | kg/kW             | 7.93    | 4.46  | 10.99  | 1.30               | 16%                                |
| Max rate of climb    | m/min             | 336.3   | 137.0 | 640.0  | 95.5               | 28%                                |
| Max level speed      | km/h              | 231.4   | 169.0 | 375.0  | 40.0               | 17%                                |
| Cruise speed         | km/h              | 204.0   | 120.0 | 332.0  | 37.4               | 18%                                |
| Stall speed          | km/h              | 75.8    | 52.0  | 130.0  | 12.3               | 16%                                |
| Range                | km                | 1054    | 424   | 2055   | 359                | 34%                                |
| Endurance            | h                 | 5.68    | 3.00  | 14.00  | 2.06               | 36%                                |
| Power                | kW                | 81.11   | 44.69 | 156.57 | 26.92              | 33%                                |
| $W_{empty}/W_{MTOW}$ | -                 | 0.592   | 0.437 | 0.747  | 0.058              | 10%                                |

As the data above show, most parameters vary significantly. Size- and weight-related properties scale with maximum take-off weight (MTOW), while performance characteristics are primarily determined by the aircraft's power-to-weight ratio. The smallest variation is observed in basic geometric dimensions (length, height, wingspan) and in the ratio of empty weight to MTOW. These parameters, when applied in design, are more likely to yield realistic and viable results consistent with existing training aircraft.

The trend analysis also provided the following configuration insights, which were subsequently incorporated into the conceptual design process:

- **Landing Gear:** 104 aircraft (almost 80%) use fixed landing gear.
- **Wing Configuration:** 74 aircraft (56%) have high wings, while 57 (44%) have low wings. However, low-wing designs have become increasingly common closer to 2018.
- **Dihedral Angle:** Almost all aircraft feature a visible dihedral angle, with an average of approximately  $4^\circ$ .
- **Tail Design:** Nearly all aircraft use a conventional tail configuration, as opposed to T-tails or alternative designs

#### 4. HYDROGEN TRAINER CONCEPTUAL DESIGN

Based on the requirements and assumptions established in the previous section, the conceptual design phase was carried out using systems engineering methodology [28]-[30].

The design process initially followed conventional steps, starting with a classical combustion engine layout. Once sufficient baseline data had been obtained, the combustion propulsion system – comprising the internal combustion engine and fuel tanks – was removed and replaced with a hydrogen-electric propulsion system consisting of a hydrogen storage tank, fuel cell stack, battery, and electric motor. A schematic comparison of the two systems is presented in Figure 1 below.

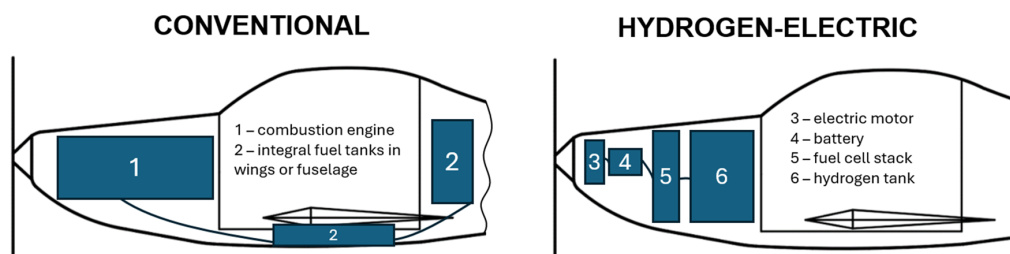


Fig. 1. Hydrogen-electric airplane propulsion system compared to conventional.

The basic characteristics of the proposed aircraft were defined as follows: a side-by-side two-seater within the Light or Ultralight category. According to CS-VLA regulations [31], which were previously applied to most airplanes in this class, the

maximum allowable MTOW is 750 kg. Outside the EU, however, the earlier classification system is still in use, setting the Ultralight limit at 600 kg. To ensure broader applicability, 600 kg was selected as the target MTOW.

Key performance requirements used in the conceptual design process were:

- stall speed: max. 70 km/h (vs. max. 83 km/s required by CS-VLA)
- minimum rate of climb: 5 m/s (300 m/min)
- maximum take-off run: 250 m to fly over a 50 ft (15.24 m) obstacle

Based on these requirements, it is possible to calculate limiting values of wing loading and power loading, which can then be used to determine wing area and required power. Figure 2 below shows the available design space and the chosen design point.

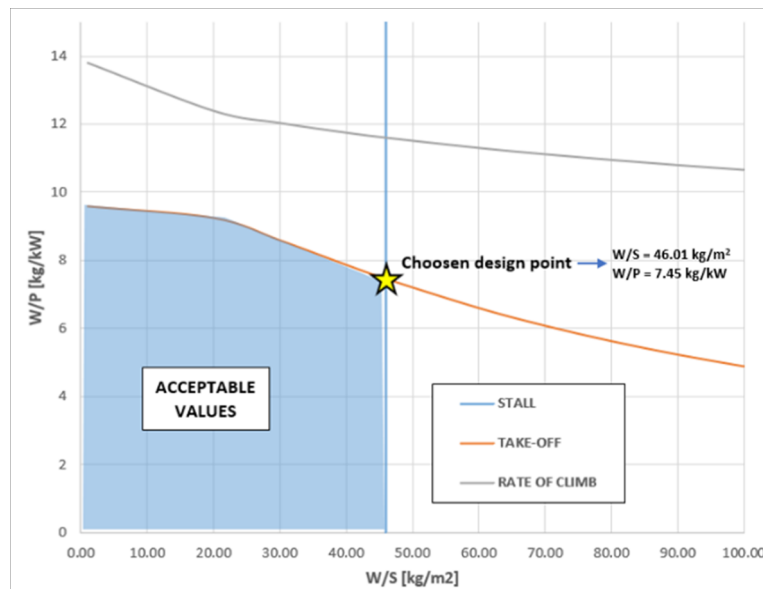


Fig. 2. Depiction of power loading vs wing loading.

In the chart above, the available design space lies in the bottom-left corner. By selecting the intersection point near the middle as the design point, wing loading and power loading are maximized, while wing area and required power are minimized. This approach yields a wing area of 13 m<sup>2</sup> (slightly above average but still within the standard deviation) and a required power of 80.5 kW (very close to the average value).

With the engine power defined, the next step was to size the hydrogen-electric propulsion system. This was carried out through a three-step process:

1. sizing up a conventional combustion propulsion system for comparison (using the same MTOW and power rating),
2. “removing” the conventional propulsion components from the weight budget,

3. sizing a hydrogen-electric system to provide equivalent power using the freed mass.

Based on the power requirement of 80.5 kW, the results of the trend analysis, weight estimation literature [28, 32, 33], and specifications of currently available parts, the component weights were estimated, as shown in Table 2.

Table 2. Fuel system weight estimation

| MTOW = 600 KG      |            |                                     |         |                 |               |          |
|--------------------|------------|-------------------------------------|---------|-----------------|---------------|----------|
| Airplane structure | Two pilots | Classical propulsion system         |         |                 |               |          |
|                    |            | Combustion engine                   |         | Fuel system     |               | Fuel     |
|                    |            | 62.23 kg                            |         | 12.92 kg        |               | 100 kg   |
| 261.55 kg          | 163.3 kg   | Hydrogen-electric propulsion system |         |                 |               |          |
|                    |            | Electric motor                      | Battery | Fuel cell stack | Hydrogen tank | Hydrogen |
|                    |            | 9.66 kg                             | 10.6 kg | 50.3 kg         | 98.3 kg       | 6.275 kg |

For both the electric motor and the fuel cell stack, a total power output of 80.5 kW was assumed. The battery was sized to provide 15 minutes of full-power operation – a standard safety margin. The hydrogen tank was designed according to a typical mass ratio, with hydrogen assumed to constitute 6% of the total tank mass – a value commonly observed for 600-bar composite or steel tanks.

A more complex design challenge concerns the distribution of hydrogen propulsion system components within the aircraft structure. In a conventional airplane of this size, both the propeller and combustion engine are mounted in the front, while fuel lines and tanks are distributed within the fuselage and wings. In a hydrogen-electric propulsion system, the motor and propeller can likewise remain in the front, but the remaining components – batteries, fuel cells, and hydrogen tanks – may be arranged in several different configurations. As these elements are relatively heavy and have fixed dimensions, their placement has a decisive influence on the aircraft's center of gravity and, consequently, on its behavior in flight.

As a general rule, all elements of the propulsion system should be placed as close to each other as possible in order to reduce excess weight arising from longer hydrogen fuel lines and electrical wiring. The electric motor is expected to be much smaller and lighter than a combustion engine of the same power – for example, the proposed electric motor [34] is only 21 cm wide with a diameter of 27 cm.

Immediately following the electric motor is the intermittent battery pack, necessary to cover transient power surges. It is likely to be relatively small and straightforward to accommodate, as battery systems can be divided into smaller packs, but adequate cooling must be ensured. For the sake of simplicity in this analysis, it was assumed that the battery system would always be located close to the electric motor and would remain small in both size and mass compared to other components.

The next component – the fuel cell stack – presents a different challenge. It has considerable mass and size, determined by the required voltage and current. Its shape is generally close to a thin cuboid, with the chosen example [35] measuring  $60 \times 40 \times 12$  cm. The fuel cell stack also requires air and hydrogen supply, while water vapor, heat, and electrical energy must be properly discharged. In these respects, the fuel cell stack resembles a conventional combustion engine much more than an electric motor.

Finally, for the high-pressure hydrogen tank of cylindrical shape, a location near the fuel cell stack is preferred – this minimizes the length and weight of fuel lines and also reduces hydrogen leakage. The challenge, however, lies in its mass and volume. With a weight exceeding 100 kg and, in one example [36], dimensions of 50 cm in diameter and 100 cm in length (a 2:1 ratio that is quite common), the tank has the potential to significantly shift the aircraft's center of gravity. For comparison, the estimated empty structural weight of the aircraft is only about 261.55 kg. Since the center of gravity must be appropriately positioned relative to the aerodynamic center, the placement of both the tank and the fuel cell stack is of crucial importance for the aircraft's stability and controllability.

After the initial analysis, four main configurations were identified as potentially viable:

- 1) Hydrogen tank behind the pilot, fuel cells stack in front – the legacy approach (ENFICA FC),
- 2) All elements in the front – the integrated approach,
- 3) Fuel cells stack behind the pilot, hydrogen tank in the front,
- 4) Fuel cells stack in the front, two hydrogen tanks under the wings.

#### **4.1. Legacy configuration - hydrogen tank behind pilot**

The first configuration considered followed the example of the ENRICA-FC project, with high-pressure gaseous hydrogen tanks placed directly behind the pilot. That project used an experimental two-seater converted from the RAPID 200 sports airplane – an aircraft similar in size and weight to the design analyzed here – which makes the comparison both reliable and convincing. This configuration was largely dictated by the fact that the ENFICA-FC project relied on an existing airframe, which limited the available options for propulsion system integration. It offers two main advantages:

1. Splitting the propulsion system makes it possible to maintain the center of gravity in approximately the same location as in the original design – an absolute prerequisite for flight stability and controllability.
2. The unused fuselage space can be employed to accommodate hydrogen tanks.

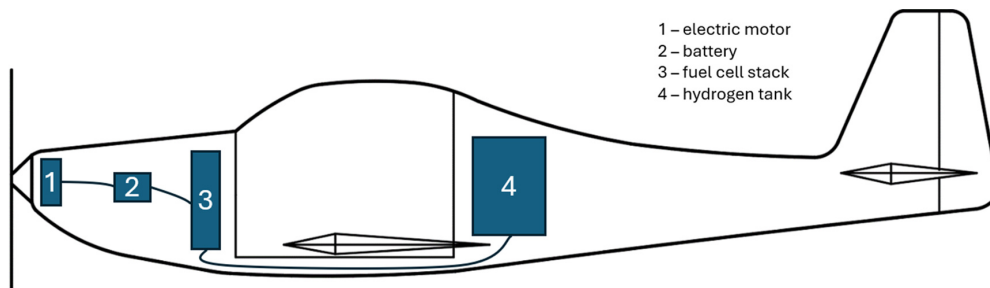


Fig. 3. Schematic of airplane configuration #1.

However, this layout also presents several significant disadvantages:

1. Splitting the propulsion system increases overall weight due to longer hydrogen piping.
2. The risk of hydrogen leakage rises with the length and complexity of the piping. In addition, leaks can occur anywhere between the tank and the fuel cell – effectively surrounding the pilots' cabin. Although hydrogen disperses quickly, in the event of fire or explosion the pilots would not be protected by a firewall.
3. As demonstrated earlier, hydrogen tanks have substantial mass. When located directly behind the pilots, this mass poses a hazard during an emergency landing, necessitating reinforcement of the rear cabin wall – which further increases cabin weight.

#### 4.2. Integrated configuration - all elements up front

The second configuration analyzed was a fully integrated layout, with all propulsion system components placed in the front of the aircraft.

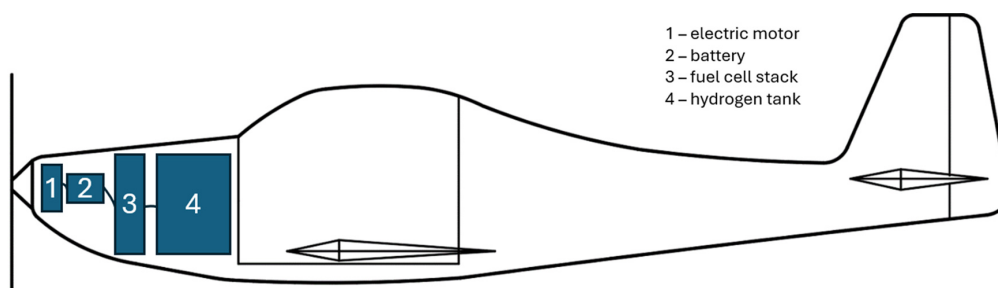


Fig. 4. Schematic of airplane configuration #2.

This arrangement alleviates the major drawbacks of the previous configuration – piping and cabling are reduced to a minimum, the pilot remains protected behind the firewall, and no heavy tank is positioned directly behind the cockpit. However, these benefits come at a cost, as both key advantages of the legacy layout are lost. The center of gravity shifts substantially forward, requiring significant design modifications to compensate, such as:

- increasing the size of the aircraft nose,
- moving the wing forward (which reduces the pilot's downward visibility – an important factor for navigation exercises during training flights),
- increasing either the tail length or the vertical stabilizer area in order to satisfy longitudinal stability and controllability requirements.

### 4.3. Fuel cells stack behind pilot

The main difference between configurations #1 and #2 was the location of the aircraft's center of gravity – shifted far to the rear in configuration #1 and far to the front in configuration #2. A possible middle ground could be achieved by placing the fuel cell stack behind the pilot while positioning all other components in the front.

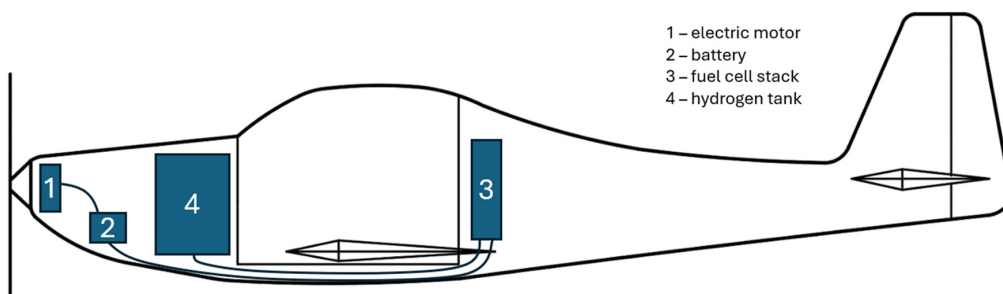


Fig. 5. Schematic of airplane configuration #3.

This arrangement, however, introduces a different set of challenges:

- Overall system weight and complexity remain high due to the long hydrogen lines and electrical wiring.
- Crash safety is somewhat improved (the fuel cell stack is considerably lighter than the hydrogen tank), but fire risk increases because hydrogen piping and electrical wiring run in close proximity over a significant distance.
- Hydrogen leaks outside the firewall are still possible.
- Long electrical wiring results in increased resistance and energy losses.

#### 4.4. Hydrogen tanks under wings

The final configuration considered placed the hydrogen tanks outside the fuselage. The most logical location was beneath the wings, taking advantage of the same effects as conventional fuel tanks integrated within the wings – namely, reduced wing bending loads (by offsetting lift force with tank weight) and improved safety (by separating the fuel reservoirs from the pilots). For reasons of directional stability, hydrogen was assumed to be stored in two tanks rather than one.

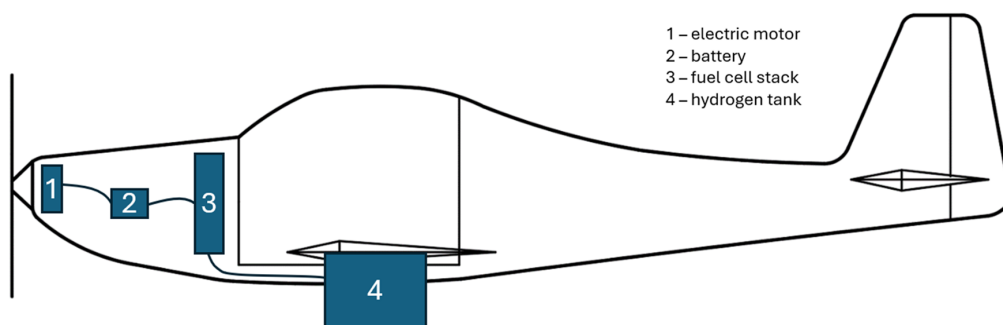


Fig. 6. Schematic of airplane configuration #3.

This configuration offered several advantages over those previously described:

- Crash landing risk minimized.
- Hydrogen leakage more likely due to longer fuel lines – but most of it would occur far from the pilot.
- Reduction in wing structural loads.
- Easier adjustment of the center of gravity (as the tanks move with the wing).

At the same time, important trade-offs were identified:

- Increased weight of hydrogen lines, tank mounts, and nacelles.
- Higher risk of tank damage during landing.
- Increased aircraft drag and pitching moment due to tank-induced aerodynamic resistance.

The last point is particularly impactful, since the tanks have a significant cross-section and cannot be shaped freely. As a result, this configuration would likely lead to a noticeable deterioration in overall aircraft performance.

#### 4.5. Determining final airplane and propulsion system configuration

The final airplane configuration was selected based on the individual score of each design, evaluated on a 1–5 scale (with 5 being the highest). Three categories were considered – safety, performance, and “conventionality” in terms of appearance

and handling. The last criterion was included to reflect an MVP approach to the design – a technology as novel as hydrogen propulsion is more likely to gain acceptance if the product looks and behaves as similarly as possible to what clients are already accustomed to.

The weights assigned to each criterion, together with the scores of the evaluated configurations, are presented in Table 3 below.

Table 3. Airplane configuration scorecard

|                                     | Weight | Config. #1 | Config. #2 | Config. #3 | Config. #4 |
|-------------------------------------|--------|------------|------------|------------|------------|
| <b>Safety</b>                       | 0.5    | 3          | 3.5        | 2          | 4          |
| <b>Performance</b>                  | 0.3    | 4          | 4.5        | 4          | 3          |
| <b>Appearance &amp; handling</b>    | 0.2    | 4.5        | 3.5        | 4.5        | 2          |
| <b>TOTAL WEIGHTED AVERAGE SCORE</b> |        | 3.6        | 3.8        | 3.1        | 3.3        |

As shown, configuration #2 achieved the highest score – though not by a wide margin. Compared with configuration #1, it offered better integration and overall performance, albeit at the cost of a less conventional airplane layout.

Using the parameters and configuration established above, the conceptual design process resulted in relatively high values for tail length (4.22 m) and tail moment arm (3.54 m). These values were driven by the forward position of the wing, itself necessitated by the predicted forward shift of the center of gravity. Final geometric parameters for the wing and stabilizers are summarized in Table 4.

Table 4. Wing and stabilizer parameters

| Component             | Area [m <sup>2</sup> ] | MAC [m] | Span [m] | Profile        | Taper ratio | Sweep angle [°] | Incidence angle [°] | Dihedral angle [°] | Volume coefficient |
|-----------------------|------------------------|---------|----------|----------------|-------------|-----------------|---------------------|--------------------|--------------------|
| Wing                  | 13.04                  | 1.32    | 9.85     | NACA 63(2)-415 | 1           | 0               | 1                   | 4                  | -                  |
| Horizontal stabilizer | 3.11                   | 0.91    | 3.42     | NACA 0012      | 1           | 0               | 0                   | 0                  | 0.65               |
| Vertical stabilizer   | 1.42                   | 1.04    | 1.46     | FX-71-L-150/30 | 0.413       | 0               | 0                   | 0                  | 0.04               |

The resulting values of the static longitudinal and directional stability derivatives (defined as the change in pitching or yawing moments with small changes in angle

of attack or sideslip angle) were  $-1.078$  (longitudinally statically stable) and  $0.00157$  (directionally statically stable), respectively. The control surfaces were sized as follows: ailerons spanning from 70% to 95% of the wingspan, with a chord equal to 20% of the wing chord; elevator and rudder spanning the full length of their respective stabilizers, with a chord equal to 40% of the stabilizer chord.

With all major components defined, the next step was weight estimation and calculation of the center of gravity location. Due to the low weight and structural sensitivity of Ultralight-category aircraft, standard weight estimation methods often yield inconsistent or imprecise results. To improve accuracy, four different estimation methods [28, 32, 33] were employed, and the results averaged to obtain more reliable component weight estimates. A detailed breakdown is provided in Table 5.

Table 5. Weight estimation summary.

| COMPONENT               | Weight [kg]          |                     |                                |                              | AVERAGE |
|-------------------------|----------------------|---------------------|--------------------------------|------------------------------|---------|
| Electric motor          | 9.54                 |                     |                                |                              | 9.54    |
| Fuel cell stack         | 50.31                |                     |                                |                              | 50.31   |
| Hydrogen tank with fuel | 104.71               |                     |                                |                              | 104.71  |
| Battery packs           | 10.59                |                     |                                |                              | 10.59   |
| Propeller               | 11.34                |                     |                                |                              | 11.34   |
|                         |                      |                     |                                |                              |         |
| ALL POWERPLANT          | 186.50               |                     |                                |                              | 186.50  |
|                         |                      |                     |                                |                              |         |
|                         | Method #1<br>Sadraey | Method #2<br>Raymer | Method #3<br>Roskam/<br>Cessna | Method #4<br>Roskam/<br>USAF |         |
| Wing                    | 54.6                 | 85.27               | 138.16                         | 72.17                        | 87.55   |
| Horizontal stabilizer   | 65.5                 | 15.51               | 10.92                          | 20.65                        | 28.15   |
| Vertical stabilizer     | 13.5                 | 4.85                | 4.42                           | 5.56                         | 7.08    |
| Fuselage                | 99.6                 | 43.81               | 31.39                          | 60.61                        | 58.86   |
| Main landing gear       | 34.5                 | 23.97               | 29.78                          | 15.65                        | 25.98   |
| Nose landing gear       | 8.6                  | 4.25                | 15.50                          | 5.02                         | 8.35    |
|                         |                      |                     |                                |                              |         |
| ALL STRUCTURE           | 276.39               | 177.66              | 230.17                         | 179.66                       | 215.97  |
|                         |                      |                     |                                |                              |         |

|                                            |               |               |               |               |               |
|--------------------------------------------|---------------|---------------|---------------|---------------|---------------|
| Flight control system                      |               | 7.61          | 10.08         | 43.50         | 20.40         |
| Hydraulic and pneumatic systems            | 0.73          | 0.60          |               |               | 0.67          |
| Electrical system                          | 10.04         | 42.77         | 16.08         | 33.63         | 25.63         |
| Avionics                                   | 1.71          | 10.68         | 1.81          | 1.81          | 4.01          |
| Air conditioning and AI                    | 0.98          | 12.14         |               | 8.98          | 7.37          |
| Cabin (seats and furnishings)              | 24.25         | 5.44          | 13.89         | 24.25         | 16.96         |
|                                            |               |               |               |               |               |
| <b>ALL EQUIPEMENT</b>                      | <b>37.72</b>  | <b>79.24</b>  | <b>41.86</b>  | <b>112.17</b> | <b>67.75</b>  |
| <b>STRUCTURE + EQUIPEMENT</b>              | <b>314.11</b> | <b>256.89</b> | <b>272.03</b> | <b>291.83</b> | <b>283.72</b> |
| <b>STRUCTURE + EQUIPEMENT + POWERPLANT</b> | <b>500.61</b> | <b>443.39</b> | <b>458.53</b> | <b>478.33</b> | <b>470.21</b> |

In general, all four estimation methods exhibit certain inaccuracies or imbalances when applied to component weights. Method #1 predicts the horizontal stabilizer to be heavier than the wing; Method #2, by contrast, estimates the wing to be almost six times heavier than the horizontal stabilizer; Method #3 goes even further, with the wing thirteen times heavier; while Method #4 significantly overestimates the total weight of onboard equipment. By averaging the results from all four methods, a more balanced and credible outcome was obtained. These averaged values were then used for subsequent mass distribution, center of gravity (CG) analysis, and moment of inertia calculations. Two extreme pilot load configurations were considered – the most forward CG (a single pilot weighing 55 kg) and the most aft CG (two pilots weighing 110 kg each). The results are summarized in Table 6.

Table 6. Airplane center of gravity and moments of inertia.

| <b>CG position</b> | <b>Config.</b>          | $X_{cg}$<br>[m] | $Y_{cg}$<br>[m] | $Z_{cg}$<br>[m] | $I_{xx}$<br>[kg·m <sup>2</sup> ] | $I_{yy}$<br>[kg·m <sup>2</sup> ] | $I_{zz}$<br>[kg·m <sup>2</sup> ] | $I_{xy}$ | $I_{xz}$ | $I_{yz}$ |
|--------------------|-------------------------|-----------------|-----------------|-----------------|----------------------------------|----------------------------------|----------------------------------|----------|----------|----------|
| Most forward       | One pilot, 55 kg        | 2.01            | -0.11           | 0.03            | 604.6                            | 739.6                            | 1288.4                           | 9.53     | 7.49     | 0.93     |
| Most aft           | Two pilots, 110 kg each | 2.102           | -0.1            | 0               | 599.2                            | 788.4                            | 1331.1                           | 0.00     | 12.23    | 0.00     |

As shown in the table, the resulting moments of inertia are relatively high – particularly  $I_{zz}$ , which is most affected by the forward placement of heavy fuel system components and the large stabilizers at the end of the tail. This becomes especially evident when compared with similar aircraft in the same class. For example, the Cessna 150 [37] and DA20 Katana [38] are both larger and heavier, yet they exhibit lower moments of inertia. Table 7 summarizes the moments of inertia for all three aircraft, while Figure 7 presents a shape comparison – where the elongated nose of the hydrogen trainer is immediately apparent.

Table 7. Comparison of moments of inertia.

| Aircraft                   | MTOW[kg] | $I_{xx}$<br>[kg·m <sup>2</sup> ] | $I_{yy}$<br>[kg·m <sup>2</sup> ] | $I_{zz}$<br>[kg·m <sup>2</sup> ] | $I_{xx} /$<br>MTOW | $I_{yy} /$<br>MTOW | $I_{zz} /$<br>MTOW |
|----------------------------|----------|----------------------------------|----------------------------------|----------------------------------|--------------------|--------------------|--------------------|
| Cessna 150                 | 757.0    | 825.0                            | 850.0                            | 950.0                            | 1.09               | 1.12               | 1.26               |
| DA20 Katana                | 780.0    | 325.0                            | 900.0                            | 1100.0                           | 0.42               | 1.15               | 1.41               |
| One pilot, 55 kg           | 518.6    | 604.6                            | 739.6                            | 1288.4                           | 1.17               | 1.43               | 2.48               |
| Two pilots,<br>110 kg each | 683.6    | 599.2                            | 788.4                            | 1331.1                           | 0.88               | 1.15               | 1.95               |

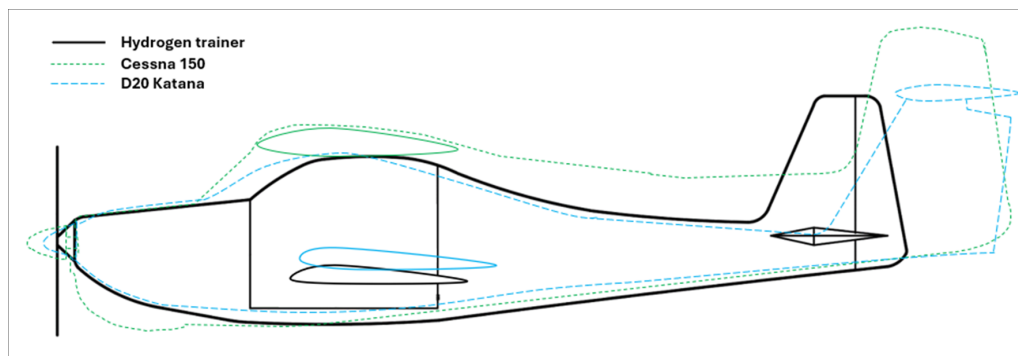


Fig. 7. Shape comparison of the hydrogen trainer, Cessna 150, and DA20 Katana.

Although the calculated moments of inertia are relatively high, they remain within a reasonable range. Using the computed CG limits together with the aerodynamic derivatives, stability and controllability margins were evaluated. As a rule, both stability margins ( $Hn$ ) and controllability margins ( $Hm$ ) should remain positive for any loading configuration across the entire flight envelope. The resulting margins for both take-off weight configurations are presented below as a function of flight speed, for both the maximum and minimum take-off weights of the aircraft.

As shown, all margins remain positive across the entire design speed range, with the exception of a small negative controllability margin at minimum speed for the minimum take-off weight. However, the magnitude and extent of this negative

margin fall within the uncertainty of the calculations – therefore, no additional design changes were introduced at this stage.

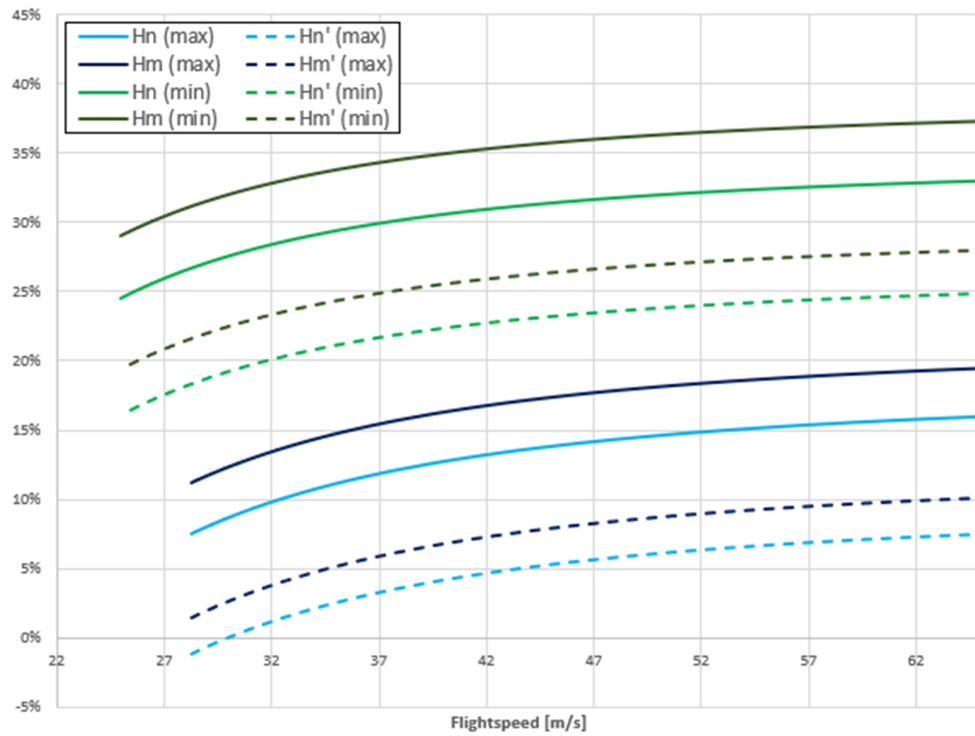


Fig. 8. Stability and controllability margins as functions of airspeed for maximum and minimum take-off weights.

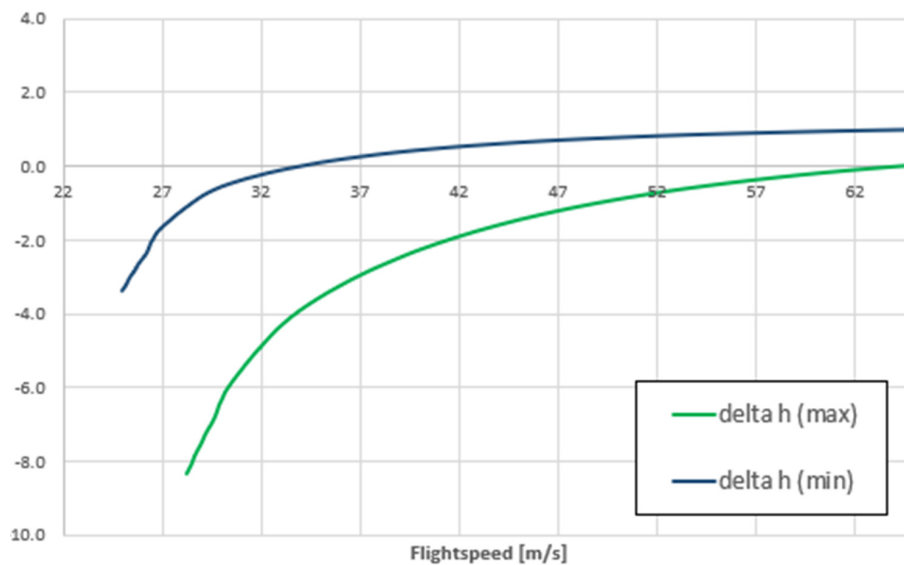


Fig. 9. Elevator deflection for longitudinal trim for maximum and minimum take-off weights.

Another important parameter is the elevator deflection required for stable flight. Since every control surface has a limited deflection range, the deflection required for longitudinal trim at the design cruise speed and weight should ideally be close to zero. This value (expressed in degrees) was calculated separately for both maximum and minimum take-off weights and is presented as a function of airspeed.

The maximum elevator deflection is approximately  $-8^\circ$ , which represents a reasonable and achievable value.

The final parameter to be verified is the control force required from the pilot to achieve this deflection. This force should be neither too high nor too low, in order to ensure optimal controllability even for inexperienced pilots. The control force (expressed in newtons) was calculated for both take-off weight configurations and is presented below as a function of airspeed.

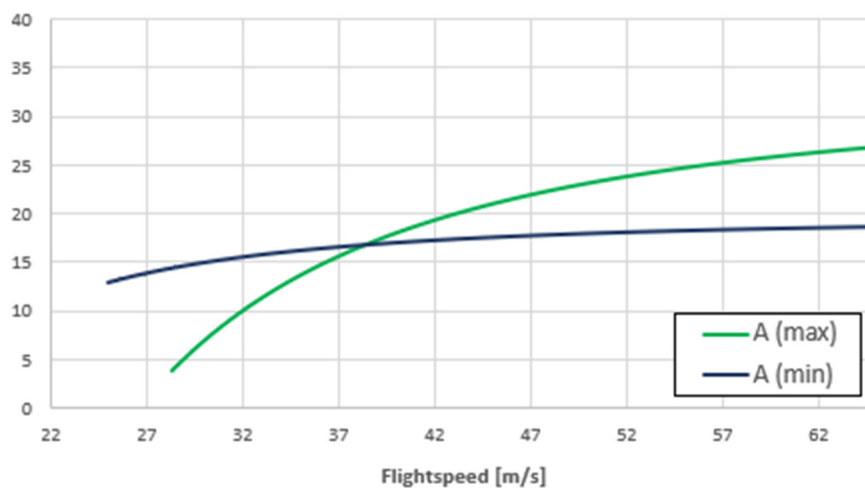


Fig. 10. Pilot force on control stick for maximum and minimum take-off weights.

As shown in the figure, the required forces are relatively small – less than 30 N across the entire range. This is much lower than generally accepted values and indicates that the aircraft would be very sensitive to control stick movements, which is highly undesirable for a training airplane. At this stage, no design changes were introduced, as there are several practical modifications to the control system itself that could alleviate this issue – for example, adding a spring mechanism to the control chain to increase the required pilot input forces.

## 5. SUMMARY AND CONCLUSION

This study has presented the conceptual design and stability/controllability evaluation of an ultralight hydrogen-electric training aircraft. The analysis demonstrated that a purpose-built hydrogen-powered trainer can remain stable and

controllable in flight despite the novel propulsion system and unconventional configuration. Key findings include:

- Feasibility of hydrogen propulsion integration – The conceptual design confirmed that hydrogen-electric propulsion (fuel cell + motor + high-pressure gas storage) can be integrated into a side-by-side, two-seat trainer within the 600 kg MTOW limit, provided that mass is carefully managed and structural adaptations are implemented.
- Optimal configuration – Of the four different propulsion system distribution approaches analyzed, the integrated nose-mounted system was favored for its safety and structural integrity.
- Structural and CG feasibility – Mass distribution and CG range were shown to remain controllable across different pilot loadings, with positive stability and controllability margins throughout the flight envelope.

This work represents a Minimum Viable Product (MVP)-level validation of hydrogen propulsion in the ultralight training segment. While further detailing, testing, and certification would be necessary for full-scale development, the present study demonstrates that hydrogen propulsion is not only theoretically feasible but also potentially flightworthy in a light, two-seat airplane.

At the same time, several limitations of the applied methods should be acknowledged. Aerodynamic behavior should be validated through advanced software simulations and/or wind tunnel testing, followed by a flight test campaign with a dynamically representative prototype. Additional research is also required to establish the limits and requirements for integrating hydrogen propulsion systems with aircraft structures, with particular attention to safety. At present, no certification or airworthiness regulations exist for hydrogen-powered aircraft – such frameworks should be discussed and developed with regulators. This is especially critical given the number of ongoing hydrogen aviation projects, many of which are scheduled for flight testing within the next decade [39]–[42].

## REFERENCES

- [1] Kuk S. Hydrogen-powered ultralight training aircraft – a systems engineering approach. *Transactions on Aerospace Research*, 2025;279(2): 1–17. <https://doi.org/10.2478/tar-2025-0006>.
- [2] Brewer GD, Morris RE, Lange RH, Moore JW. Volume I: Summary report: Study of the application of hydrogen fuel to long-range subsonic transport aircraft. NASA CR-132558. 1975.
- [3] Airbus Deutschland GmbH. Liquid hydrogen fuelled aircraft – system analysis. Final technical report (publishable version). 2004.
- [4] Yusaf T, Mahamude ASF, Kadirgama K, Ramasamy D, Farhana K, Dhahad HA, Abu Talib AR. Sustainable hydrogen energy in aviation – a narrative review. *Int J Hydrogen Energy*. 2024;52(Part C):1026–1045. <https://doi.org/10.1016/j.ijhydene.2023.02.086>

- [5] Gunasekar P, Manigandan S, Praveen Kumar TR. Hydrogen as the futuristic fuel for the aviation and aerospace industry – review. *Aircraft Eng Aerosp Technol*. 2021;93(3):410–416. <https://doi.org/10.1108/AEAT-07-2020-0145>
- [6] Yusaf T, Fernandes L, Abu Talib AR, Altarazi YSM, Alrefae W, Kadrigama K, et al. Sustainable aviation – hydrogen is the future. *Sustainability*. 2022;14(1):548.
- [7] Savvaris A, Xie Y, Malandrakis K, Lopez M, Tsourdos A. Development of a fuel cell hybrid-powered unmanned aerial vehicle. In: 24th Mediterranean Conference on Control and Automation (MED); 2016 Jun 21–24; Athens, Greece. p. 1242–1247. <https://doi.org/10.1109/MED.2016.7536038>
- [8] Desantes JM, Novella R, García-Cuevas LM, Lopez-Juarez M. Feasibility study for a fuel cell-powered unmanned aerial vehicle with a 75 kg payload. *Transactions on Aerospace Research*. 2022;2022(2):13–30. <https://doi.org/10.1109/MED.2016.7536038>
- [9] Czarnocki P, Dudek M, Drabarek K, Frączek W, Iwański G, Miazga T, et al. Electric motor-glider powered by a hydrogen fuel cell stack. *MATEC Web Conf*. 2019;304:03011. <https://doi.org/10.1051/mateconf/201930403011>
- [10] Ghosh D, Willich C, Kallo J. High efficient energy system for electric passenger aircraft propulsion. In: AIAA SciTech 2019 Forum; 2019 Jan; San Diego, CA. AIAA 2019-1672. <https://doi.org/10.2514/6.2019-1672>
- [11] Romeo G, Borello F, Correa G. ENFICA-FC: Design, realization and flight test of all-electric 2-seat aircraft powered by fuel cells. *Proc ICAS*. 2010. See also: Romeo G, Borello F. Design and realisation of a two-seater aircraft powered by fuel cell electric propulsion. *Aeronaut J*. 2010;114(1155):281–297. <https://doi.org/10.1017/S0001924000003730>
- [12] Bradley TH, Moffitt BA, Mavris DN, Parekh DE. Design space exploration of small-scale PEM fuel cell long-endurance aircraft. In: 6th AIAA Aviation Technology, Integration, and Operations Conference (ATIO); 2006 Sep 25–27; Wichita, KS. AIAA 2006-7701. <https://doi.org/10.2514/6.2006-7701>
- [13] Mobariz KN, Youssef AM, Abdel-Rahman M. Long endurance hybrid fuel cell-battery powered UAV. *World J Model Simul*. 2015;11(1):69–80.
- [14] Krawczyk JM, Mazur AM, Sasin T, Stokłosa AW. Fuel cells as alternative power for unmanned aircraft systems – current situation and development trends. *Transactions on Aerospace Research*. 2014;237(4):49–62.
- [15] Rondinelli S, Sabatini R, Gardi A. Challenges and benefits offered by liquid hydrogen fuels in commercial aviation. *Int J Sustainable Aviation*. 2017;3(3):200–216. <https://doi.org/10.1504/IJSA.2017.10007966>
- [16] Thirkell A, Chen R, Harrington I. A fuel cell system sizing tool based on current production aircraft. *SAE Tech Pap*. 2017;2017-01-2135. <https://doi.org/10.4271/2017-01-2135>
- [17] Kadyk T, Winnefeld C, Hanke-Rauschenbach R, Krewer U. Analysis and design of fuel cell systems for aviation. *Energies*. 2018;11(1):204. <https://doi.org/10.3390/en11010204>
- [18] Thomas CE. Fuel cell and battery electric vehicles compared. *Int J Hydrogen Energy*. 2009;34(15):6005–6020. <https://doi.org/10.1016/j.ijhydene.2009.05.025>
- [19] Jain A, Jain A. Battery technology and the future of battery swapping systems for electric vehicles: opportunities and challenges. *Int J Adv Res*. 2022;10(Oct):553–567.

- <https://dx.doi.org/10.21474/IJAR01/15523>
- [20] Kuśmierek A, Galiński C, Stalewski W. Review of hybrid gas-electric aircraft propulsion systems versus alternative systems. *Prog Aerosp Sci.* 2023;141:100925. <https://doi.org/10.1016/j.paerosci.2023.100925>
  - [21] Adler EJ, Martins JRRA. Hydrogen-powered aircraft: Fundamental concepts, key technologies, and environmental impacts. *Prog Aerosp Sci.* 2023;141:100922. <https://doi.org/10.1016/j.paerosci.2023.100922>
  - [22] Abu Salem K, Palaia G, Quarta AA. Review of hybrid-electric aircraft technologies and designs: critical analysis and novel solutions. *Prog Aerosp Sci.* 2023;141:100924. <https://doi.org/10.1016/j.paerosci.2023.100924>
  - [23] Ansell PJ. Review of sustainable energy carriers for aviation: benefits, challenges, and future viability. *Prog Aerosp Sci.* 2023;141:100919. <https://doi.org/10.1016/j.paerosci.2023.100919>
  - [24] Dudek M, Raźniak A, Dudek P, Korkosz M, Wygonik P, Bogusz P, Frączek W. Some aspects of gaseous hydrogen storage and the performance of a 10-kW polymer electrolyte membrane fuel cell stack as part of a hybrid power source. In: 2nd International Conference on the Sustainable Energy and Environmental Development (SEED); 2017 Nov 14–17; Kraków, Poland.
  - [25] Romeo G, Cestino E, Borello F. More/all electric aircraft based on fuel cell energy system: the ENFICA-FC experience. In: 28th International Congress of the Aeronautical Sciences (ICAS 2012); 2012 Sep 23–28; Brisbane, Australia.
  - [26] Winnefeld C, Kadyk T, Bensmann B, Krewer U, Hanke-Rauschenbach R. Modelling and designing cryogenic hydrogen tanks for future aircraft applications. *Energies.* 2018;11(1):105. <https://doi.org/10.3390/en11010105>
  - [27] Rondinelli S, Sabatini R, Gardi A. Challenges and benefits offered by liquid hydrogen fuels in commercial aviation. In: Practical Responses to Climate Change (PRCC 2014); 2014 Nov 27–28; Melbourne, Australia. <https://doi.org/10.3316/informit.042058746545488>
  - [28] Sadraey MH. *Aircraft design: a systems engineering approach*. Chichester: Wiley; 2013.
  - [29] Galiński C. *Wybrane zagadnienia projektowania samolotów*. Warszawa: Wydawnictwa Naukowe Instytutu Lotnictwa; 2016.
  - [30] Galiński C. *Wybrane zagadnienia konstrukcji samolotów*. Warszawa: Oficyna Wydawnicza Politechniki Warszawskiej; 2020.
  - [31] European Aviation Safety Agency. *Certification Specifications for Very Light Aeroplanes (CS-VLA)*. Cologne: EASA; 2009.
  - [32] Raymer DP. *Aircraft design: a conceptual approach*. 6th ed. Reston (VA): American Institute of Aeronautics and Astronautics; 2018.
  - [33] Roskam J. *Airplane design. Part V: Component weight estimation*. 3rd ed. Lawrence (KS): DARcorporation; 2018.
  - [34] MGM Compro. REB 90 electric motor: technical datasheet. Accessed 2024. <https://www.mgm-compro.com/electric-motor/80-kw-electric-motor/>
  - [35] EH Group. EH81 fuel cell stack: technical datasheet. Accessed 2024. <https://hyfindr.com/common/datasheet/product/174/inline/EHGroup-EH81-datasheet-1.pdf>
  - [36] Doosan Mobility Innovation. Ultralight type 4 hydrogen tank: datasheet. Accessed

2024. <https://www.doosanmobility.com/en/products/hydrogen-tank>
- [37] Swann MD, Takahashi TT. A total flight envelope approach to conceptual design stability & control. In: 15th AIAA Aviation Technology, Integration, and Operations Conference (ATIO); 2015 Jun 22–26; Dallas, TX. AIAA 2015-3377. <https://doi.org/10.2514/6.2015-3377>
- [38] JSBSim. Mass properties database: documentation. Accessed 2025. <https://jsbsim.sourceforge.net/MassProps.html>
- [39] ZeroAvia. Hydrogen-electric aviation program overview. Accessed 2025. <https://zeroavia.com/>
- [40] Airbus. ZEROe: towards the world's first zero-emission commercial aircraft. Accessed 2025. <https://www.airbus.com/en/innovation/energy-transition/hydrogen/zeroe-our-hydrogen-powered-aircraft>
- [41] H2FLY. Company and project overview. Accessed 2025. <https://www.h2fly.de/>
- [42] CFM International. RISE program overview. Accessed 2025. <https://www.cfmaeroengines.com/rise/>