Life Cycle Analysis of Urban Air Mobility Aircraft using Batteries and Fuel Cells

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Abstract

The substantial growth of cars in recent years has led not only to an increase of pollutant emissions but also to an increase of road traffic in large urban centers. Urban air mobility is a possible solution, which is analyzed in this work, where three different electric Vertical Take-Off and Landing (eVTOL) aircraft are considered: *Lift + Cruise* (L+C), *Tilt -Rotor* (TR) e *Tilt -Wing* (TW). Even though the propulsion systems of these eVTOL aircraft are electric, the energy source is not entirely clean. Thus, a study comparing two energy sources, batteries lithium and fuel cells running on hydrogen (green and blue hydrogen), is performed. The three aircraft and their respective versions are designed and sized for a given urban mission. From the conceptual design, the TR configuration is observed to require the least amount of energy to accomplish the design mission. The use of green hydrogen produced via water electrolysis has shown to have a lower environmental impact relatively to the blue hydrogen produced by natural gas reform, due to the use of fewer resources in its production. When comparing the production of batteries with the production of fuel cells, the latter ones present a higher impact regarding human health, due to the use of platinum. However, the aircraft running on hydrogen require less energy to accomplish the same mission. Thus, green hydrogen could be an interesting solution for eVTOL aircraft.

Keywords: urban air mobilty, aircraft design, fuel cells, Li-based batteries, hydrogen, life cycle assessment

1. Introduction

Pollutant and noise emissions are two of the main concerns regarding the introduction of Urban Air Mobility (UAM) aircraft [1].

Climate change and the need for decarbonizing current means of transportation are on the top of the concerns of governmental institutions. There are many challenges and issues related to these problems that need to be overcome, although the best start is to stop making things worse.

Current urban road traffic is expanding with the increase in the number of cars which is not accompanied by the road ways expansion, thus causing not only an increase of time spent on the roads but also environmental waste of fossil fuel and air pollution [2] a, besides being prejudicial to human health (causing for instance tiredness and stress). An alternative to current transport solutions within large urban centres is the use of electric aircraft with vertical take-off and landing capability (eVTOL), where despite much progress has already been done there are still several challenges to surpass [3, 4]. This solution promises to be cleaner from the point of view of local emissions, more silent due to the use of electric motors and safer given the use of distributed electric propulsion and multiple energy sources [5]. An eVTOL aircraft has the potential to be sustainable if the electricity that is used to recharge the batteries or to produce hydrogen via water electrolysis comes from a renewable energy source.

The main disadvantage of electric aircraft is the low energy density of current lithium-ion batteries, which leads to a reduced in range and/or payload [4]. In order to overcome this inconvenience one of the objective of this work is to examine the use of fuel cells. Low-temperature proton exchange membrane (PEM) fuel cells that use hydrogen as a fuel can provide specific energy greater than batteries without producing harmful emissions during operation. The specific energy of lithium-ion batteries has a maximum of 250 Wh/kg [6], unlike batteries, the specific energy of hydrogen is 33.3 kWh/kg , which is even higher than the specific energy density of gasoline, 13.13 kWh/kg [6]. However, hydrogen storage and platinum use in fuel cells are some drawbacks of using fuel cells.

In section 2 these alternatives will be addressed in order to know the state of the art. In this work, a methodology is presented , in section 3, for the initial sizing of three eVTOL aircraft proposed for UAM: *Lift + cruise*, *Tilt-Rotor* and *Tilt-Wing*. This initial design consists of the determination of the maximum take-off weight (MTOW) for a prescribed mission. For each aircraft configuration two versions are designed, one using only batteries and the other using batteries and fuel cells. These aircraft are subsequently preliminarily designed to refine the results (section 4) obtained in the initial design. The main objective of this study is to compare the two versions proposed for each aircraft in terms not only of performance, but also environmental sustainability point of view. In this study only the impact of the production of batteries and fuel cells and their use are considered.

2. Background

2.1. UAM - Urban Air Mobility

According to the articles [7, 8] the first two commercial UAM operations took place in the United States in the 1940s and both used helicopters as a means of transport, one in Los Angeles and another in New York Both ceased because of accidents [9, 10]. Currently several aviation-related companies are striving to boost urban air mobility using flying taxi services, an air transport concept that is expected to be launched in the coming years [11, 3]. In addition to Uber, which estimates the launch of its air taxis in 2023, other companies such as Zephyr Airworks and Airbus [12] are also currently testing their electric air taxis, namely Cora and Airbus-Vahana, respectively [3, 13]. In order to integrate safely and efficiently the UAM operations it is necessary to overcome several barriers, such as community acceptance (where many studies have already been done to better understand see the articles [8]), quality of travel, certification process, safety mainly in its integration into airspace in terms of accidents and material damage, energy efficiency, life cycle emissions and sound footprint [7, 2].

2.1.1 Aircraft configurations for UAM

VTOL aircraft do not require runways for vertical take-off and landing. An helicopter, is able to take off and land vertically, and be efficient at low speeds unlike a fixed-wing aircraft, however it is noisier and less efficient on cruise than the latter. Therefore, the ideal design for VTOL is to try to combine the advantages of vertical flight of a rotary wing aircraft with those of cruising flight of a fixed-wing [2] aircraft. According to *Vertical Flight Society* [14] more than 430 eVTOL concepts have been proposed. For the articles [15, 13], an extensive worldwide survey was conducted to examine the different configurations of existing VTOL aircraft. To choose the most adequate configurations, their behavior should be known, especially in what concerns its performance parameters, such as cruise speed and altitude, range, payload and environmental footprint [16, 13]. The current eVTOL aircraft can be divided or classified depending on the propulsion method [2], but in this section only the configurations used in this work will be discussed.

Lif + Cruise

The lift + cruise VTOLs use two different propulsion systems for vertical and forward flight, using fixed vertical rotors to generate lift for vertical flight and propellers to provide thrust in cruise flight [16, 2, 13]. The wings provide support in the cruising phase, which means a less significant energy consumption compared to helicopters or multi-helicopters [17, 16].

Tilt-Wing

In a Tilt-Wing configuration, the wing together with the propulsive system rotate on an axis to direct the thrust [16]. Turning the wing as a whole reduces the impact of this in the hovering flight and as such reduces the propulsive force required to sustain the aircraft relative [16] a tilt-rotor configuration.

According to Lee et al. [2] Tilt-Wing have a good efficiency in cruise flight, which reduces fuel consumption, making a good choice for long range operations.

Tilt-Rotor

In a tilt-rotor design, its rotors can rotate independently of the wing in order to modify the direction of the impulse [13].

According to Lee et al. [2], despite both tilt-rotor and tilt-wing designs have instability problems when changing from vertical to forward flight, their cruise efficiency is high

In this work, it will be used an all-electric propulsion system using batteries and another using batteries and fuel cells. The architectures of these two electrical systems are illustrated in Figure 1.

2.2. Batteries

Batteries are electrochemical devices that produce electricity in spontaneous reactions when their electrodes are connected through a charge and in contact with a electrolyte[19]. Batteries are composed by two electrodes, a positive cathode (+) and a negative anode (-) [6].

According to Sundén, the most common rechargeable batteries, also classified as secondary batteries, are lithium-ion (Li-ion), lithium-metal (Li-M), nickel-cadmium (Ni - Cd), nickel-metalhydride (Nimh) and zinc-air (Zn-ar) [6].

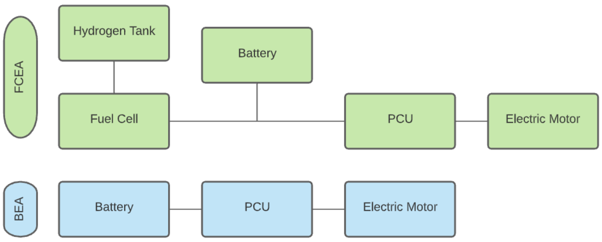


Figure 1: Electric aircraft propulsion systems using fuel cells (FCEA) and electric aircraft using batteries (BEA), adapted from [18]. PCU is the acronym for Power Control Unit.

Currently, the most promising batteries for electric airplanes are lithium-based, which is the lightest metal, due to its low atomic mass [19], and will likely lead to higher specific energy (stored energy per unit mass) [20, 4].

For a small aircraft, current battery state of the art allows its electrification, but for a reduced range and payload [4].

According to Dever et al. [20] lithium ion batteries in 2030 can reach 400 Wh/kg and 450 Wh/kg for 2045 years, depending on new According to Sundén, the most common rechargeable batteries, also classified as secondary batteries, are, namely in the selection of materials for cathode, anode and electrolyte. Taking into account the challenges and the current technological development, several organizations conduct research and development so that there can be batteries with energy capacities closer to those of fossil fuel in the future. The most promising lithium-based battery technologies are lithium-air/oxygen (Li-air/O_2), lithium-metal, solid lithium and lithium-sulfur (Li-S) batteries; while the most promising nonlithium-based batteries are aluminium-air (Al-air), magnesium-air (Mg-air) Zinc-air (Zn-air), sodium ions (Na-ion) and flow batteries. All these batteries present potential for aviation and aerospace applications [19, 21, 6]. In this work will be used the batteries of Li-S.

The state of the art of Li-S batteries has a specific energy exceeding 350 Wh/kg [4, 21]. According to NASA [20] the continuous development of electrolytes, anodes and cathodes may lead to specific energies at the cell level of 500 Wh/kg in 2030 and 800 Wh/kg in 2045.

However, for different authors the theoretical potential of Li-S batteries is 2500 Wh/kg according to [22, 21] and more than 3800 Wh/kg for [19], which can be achieved by replacing the graphite electrode for the lithium metal oxide cathode with a more suitable sulfur electrode [22]. Wieczorek [22] says that optimising the electrolyte is one of the most crucial objectives for improving the Li-S battery in terms of performance, especially in terms of cell capacity, rate capacity, safety and service life.

However, according to Petrovic Li-S batteries are not available because of numerous problems as Li dendrite growth, low electronic conductivity, low S mass load and dissolution of polysulfide [19].

According to Smruti Sahoo et al. [4] current Li-S batteries reach 500 Wh/kg of specific energy and 1500 cycles in laboratory environment.

2.3. Hydrogen

Currently in a society where the environmental future of our planet is much debated, hydrogen (H) is considered the fuel of the future, since it stands out for its high energy content and high potential for climate impact reduction [6, 18].

Hydrogen is a colorless, diatomic, odourless, flammable gas [6], which is the most abundant element on Earth, represents more than 70% of everything that is located on the Earth's surface. However, hydrogen is not abundant in its gas form, it is rather usually found in combination with other chemical elements such as water or organic compounds [23].

According to Sunden et al. [6] there are basically three main processes to produce hydrogen by steam reform, gasification and electrolysis. In this section some processes for hydrogen production will be described. Hydrogen is called according to the energy source used in its production process [24, 25]. The two types of hydrogen used in this are green and blue.

Blue hydrogen is achieved from natural gas that is divided into hydrogen and carbon dioxide (CO_2) by Steam Methane Reforming, but considering that the CO_2 emitted in the process is captured and stored by means of the. Carbon Capture Usage and Storage (CCUS) process [24, 25].

Green hydrogen is produced by means of water electrolysis if the electric energy used to power it is from a renewable source [24, 25]. However, this process is still considered expensive [6, 23, 24].

2.4. Fuel cell

Fuel cells are electrochemical devices that transform the stored chemical energy into electrical energy, through combination of hydrogen with oxygen, producing water as sub-product [6, 26].

According to Sahoo et al. [4] when a fuel cell is powered by H_2, it does not emit CO_2 or other harmful pollutants, but contrails may be form under certain conditions.

Of the various technology-based fuel cells, polymer electrolyte membrane fuel cells (PEMFC) and solid oxide fuel cells (SOFC) are the two most common and exploited for aviation applications[4, 26, 6, 27]. In this work, PEMFC will be used.

The PEM is a FC that operates only with hydrogen as a fuel, operates at a relatively low temperature, manufactured by the incorporation of polymeric electrolyte membranes as proton conductor and electrochemical catalyst to withstand the redox reaction [6].

This FC allows faster start-up, low temperature operation, high efficiency and portable applications. However, it presents some disadvantages including the requirement of expensive platinum catalyst, high-cost membrane and cell components, low tolerance to poisoning and water management problems [28].

For Misra [26] and Sahoo et al. [4] the state of the art of specific energy for PEMFC is in the range between 600-800 Wh/kg, attractive for aerospace applications.

The state of the art of PEMFC power density is approximately 0.5 kW/kg at the system level [26].

Therefore, in this work will be used a PEMFC used in the Toyota Mirai 2021, with a maximum output power of 128 kW, a specific output power of 5.4 kW/kg , a weight of 32 kg and 330 cells [29]. It was also considered an efficiency of 50% and a life cycle of 5000 hours for this fuel cell.

3. Implementation

3.1. Conceptual design

In order to determine some basic and general parameters of the aircraft the follow-up of the conceptual design was based on the books [27, 30, 31] and the article [1].

In order to analyze the effectiveness of VTOL principles for UAM, a methodology was used to estimate power, mass, energy, aircraft dimensions, stability, gliding ratio, noise emissions and life cycle assessment. And these are determined using analytic and semi-empirical equations associated with a set of mission and configuration related parameters. It should be noted that this work uses an iterative process to estimate the maximum take-off mass (MTOM), using the principles used for conventional aircraft [1, 31, 27]. The estimation of MTOM is of utmost importance in the conceptual design of an aircraft, since the initial estimation of all parameters of the aircraft depends on it.

3.2. Life Cycle assessment

Life cycle assessment (LCA) is a tool used to assess the effects and environmental impact of a product or service. This evaluation includes the phases that go from the extraction of the raw material to the end of the product or service's life. The application of this methodology is mainly governed by the ISO 14040 (2006) [32] and ISO 14044 (2006) [33] standards. Its application aims at the development and improvement of a product or service, strategic planning, formulation of public policies, marketing and others.

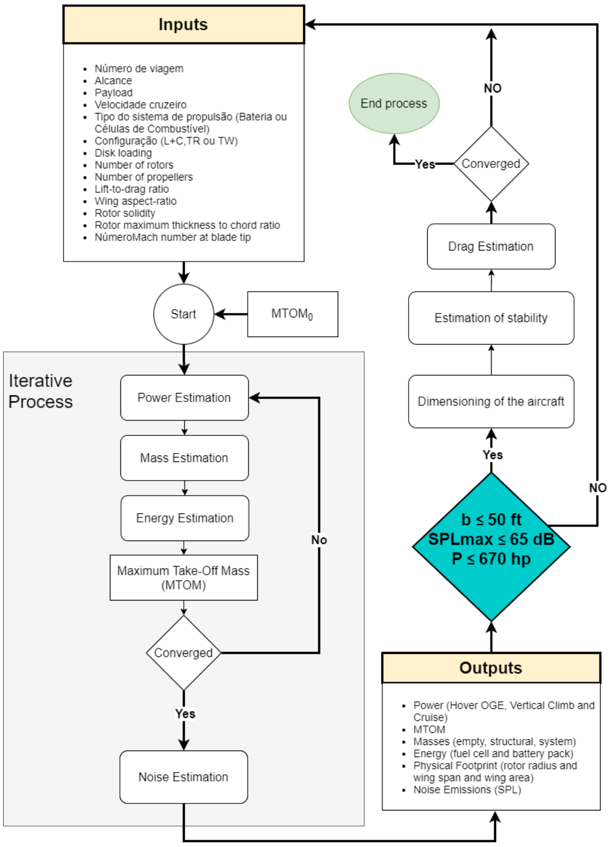


Figure 2: Methodology for the design of an aircraft. For the estimation of mass, power, energy and noise the article was the reference [1], for aerodynamic resistance [2, 16, 27], for stability and sizing parameters [30, 31].

Life cycle assessment is divided into 4 phases [ISO 14040 (2006)] [32]:

- definition of objective and scope;
- analysis of inventories;
- impact assessment;
- interpretation.

3.2.1 Goal and scope definition

The application of the life cycle assessment tool aims to study environmental impacts and quantify the emissions caused by the production and use of batteries, biofuels, and fossil fuels.

The application will be made taking into account the steps from the cradle to the grave, and also from the cradle to the end of production (cradle to gate).

The functional unit used for this work and in which all calculations are based on the energy required to do a mission for better comparison and uniformity of results, the results obtained from the application of the ACV Energy tool in kWh/ per mission.

3.2.2 Invetory Analysis

The inventory analysis phase is characterized by the collection and calculation of relevant data regarding the inputs and outputs of each stage, as well as the entire life cycle.

In this phase, the energy and mass spent during the processes are counted, as well as the emissions emitted to air, water and land.

3.2.3 Impact category

The main objective of the Life Cycle Impact Assessment (LCIA) is to evaluate and study a product or service system from an environmental perspective, where LCI results are classified within the impact categories, each with a category indicator. The execution of LCIA involves appropriate methods, according to Bueno and Rossignolo [34] today there are more than 50 methods for the application of LCIA. Also according to Bueno e Rossignolo [34] the main methods widely used in the LCIA phase are: textitEco Indicator 99, EDIP 97, EDIP 2003, (Dutch) Handbook on LCA (CML2002), TRACI, EPS 2000, Impact 2002(+), LIME, Swiss Ecoscarcity (Ecopoints 2006), Recipe, Meeup and Impact World +. The impact categories are what differentiate these methods. These impact categories can be expressed at midpoint or endpoint.

Knowing that Recipe is a method that integrates and frames the approaches of midpoint and endpoint, this method will be used in this work for the evaluation of impacts. The midpoint methodology contains a larger number of impact categories in a general and more detailed way, in reference to endpoint that normally consider the three impact categories (human health, ecosystem quality and resource use) [35].

There are three scenarios or perspectives within the ReCiPe method. The first is the individualistic perspective, which is based on short-term interests, approximately 20 years; the second is the hierarchical perspective based on scientific consensus, the evaluation is made considering a period of approximately 100 years, and finally the egalitarian perspective, the interest in the result is over the long term, approximately 1000 years [35].

Here, a hierarchical perspective will be used.

3.2.4 Interpretation

The interpretation is the final stage of the LCA, where the results of the inventory analysis and impact analysis are verified and evaluated, falling within the defined objective and scope, in order to reach certain conclusions, recommendations and model limitations.

4. Results

This section is divided into two parts. The first part (sub-section 4.1) encompasses the results obtained by applying the methodology mentioned in section 3 to conceptually design the aircraft for a given mission profile. The results from the life cycle analysis to the aircraft studied are presented in sub-section 4.2.

4.1. Aircraft Design

A standard and simple mission over four 30 km trips resulting in 120 km covered without replenishment or battery recharge or replacement. This mission is characterized by 1 minute at vertical climb power for each vertical flight operation (i.e. take-off and landing), cruise flight at an altitude of 1km + 0^{o}C, payload of 900 lb (including 1 pilot and 4 passengers with respective luggage) and 20 minutes of battery reserve.

For the design of the aircraft and the propulsion system the following restrictions have been imposed on the MATLAB® code: maximum allowable power of 670 hp, wing span not exceeding 50 ft, noise limit of 65 dB for the aircraft hovering at an altitude of 500 ft. For the aircraft design, the ranges of values indicated in the Table 6[1] were taken into account.

Three different aircraft configurations were studied: L+C, TR and TW. These configurations are illustrated in Figures 3, 4 and 5. For each one of these configurations two versions were considered, one with batteries only and another with fuel cells and batteries. In the latter version, the batteries help fuel cells during power demanding stages, i.e. vertical flight operations.

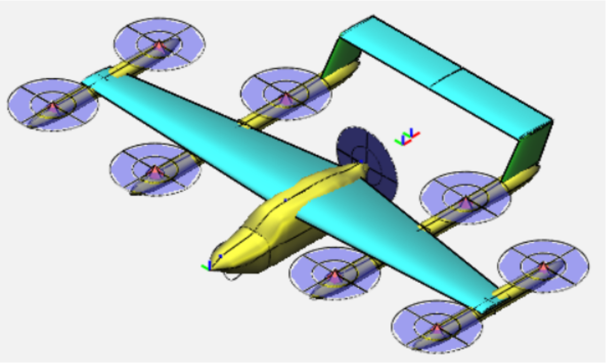


Figure 3: Aircraft type L+C

General characteristics and properties of these aircraft after being conceptually designed are shown in table from Figure 6. The total flight time in minutes considering the take-off, cruise and landing phases. From the Figure 6 you can see that V_{cr} of the L+C configuration in both versions is higher than V_{cr} of the TR and TW configurations, so it has shorter flight time for the same range. It

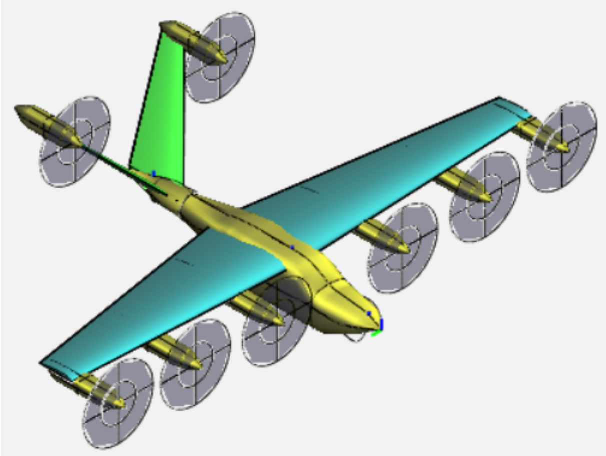


Figure 4: Aircraft type TR

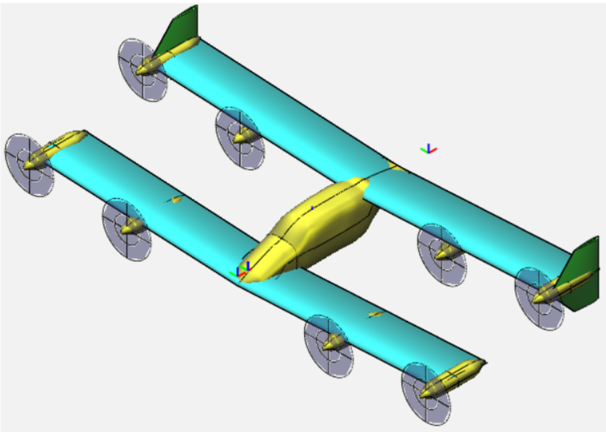
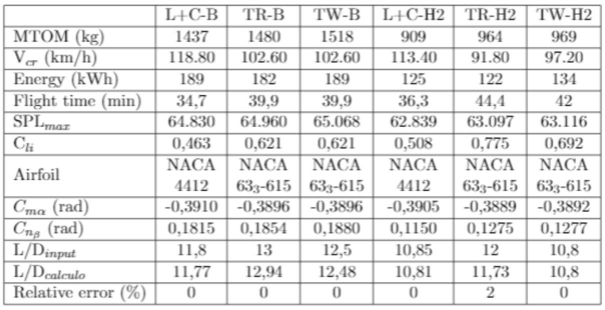


Figure 5: Aircraft type TW



	L+C-B	TR-B	TW-B	L+C-H2	TR-H2	TW-H2
MTOM (kg)	1437	1480	1518	909	964	969
V_{cr} (km/h)	118.80	102.60	102.60	113.40	91.80	97.20
Energy (kWh)	189	182	189	125	122	134
Flight time (min)	34,7	39,9	39,9	36,3	44,4	42
SPL_{max}	64.830	64.960	65.068	62.839	63.097	63.116
C_{li}	0,463	0,621	0,621	0,508	0,775	0,692
Airfoil	NACA 4412	NACA 63_3-615	NACA 63_3-615	NACA 4412	NACA 63_3-615	NACA 63_3-615
$C_{m\alpha}$ (rad)	-0,3910	-0,3896	-0,3896	-0,3905	-0,3889	-0,3892
C_{n_β} (rad)	0,1815	0,1854	0,1880	0,1150	0,1275	0,1277
L/D_{input}	11,8	13	12,5	10,85	12	10,8
$L/D_{calculo}$	11,77	12,94	12,48	10,81	11,73	10,8
Relative error (%)	0	0	0	0	2	0

Figure 6: General characteristics and properties of aircrafts.

should be noted that in both cases the aircraft with TR-B configuration consumes less energy because it has a higher gliding ratio V_{cr}nt. It is also possible to note from Figure 6 that the TW-B aircraft has a value of SPL_{max} slightly higher than 65 dB. It is worth to mention that for a reference pressure P_{ref} = 20 μPa, a SPL = 70 dB is considered a moderate noise, which corresponds to, for example, the noise caused by urban traffic [36].

For the wing design, in accordance with the values of C_{li} [30] the best airfoil is the one whose $(C_l/C_d)_{max}$ is the highest, $C_{m\ min}$ is the lowest, $(t/c)_{max}$ is the lowest, the C_{dmin} is the lowest and C_{lmax} is the highest.

It should be noted that for the calculation of total L/D, the induced aerodynamic drag caused by the vertical stabilizers and the aerodynamic drag caused by the nose of the aircraft was not considered, as it is difficult to obtain at this early design stage.

Knowing this requirements the book of Sadraey[30] and the aircraft Cessna 337 Skymaster were used as reference for the design of the fuselage in this work with the help of *Openvsp*. For this work, the same fuselage was considered for all aircraft models with a seat arrangement in a straight line 1 + 1.

4.2. **Life Cycle assessment**

The results of life cycle evaluations will be presented in this sub-section. These results estimate the emissions caused by fuel cells and batteries using green and blue hydrogen as their energy source. The life cycle assessment shall examine processes from production to use. It should be emphasized that in this analysis the recycling was not considered, as well as the hydrogen storage tank due to lack of data.

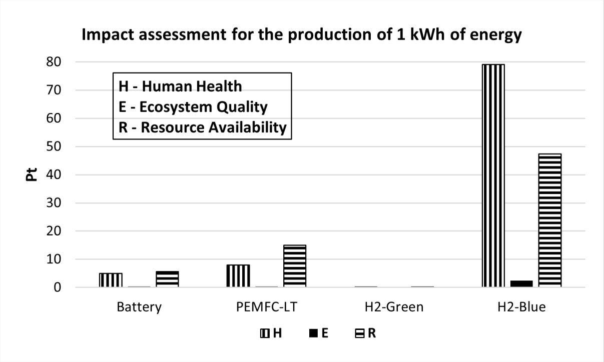


Figure 7: Impact assessment for the production of 1 kWh of energy, between Li-S battery, PEMFC-LT fuel cell, green and blue hydrogen.

Figure 7 presents the results for the generation of 1kWh of energy, using batteries, fuel cells and two H2 production processes and considering the endpoint method. From a cradle to gate approachfuel cells have been found to have higher impact in the human health category (H) and resource scarcity (R), which was already expected as fuel cells use platinum as a catalyst. It is worth to mention that the greater the mass of the platinum, the greater its efficiency.

Regarding the production of hydrogen, observing Figure 7, it is possible to note that the production of blue hydrogen causes a higher impact than green hydrogen, even considering the capture of CO_2, as expected.

Figure 8 presents data to quantify emissions and analyze which of the alternatives are more viable in environmental terms. This analysis was drawn up for the year 2023, for which the introduction of aircraft into the urban network is foreseen [12]. The impacts were estimated by mission.

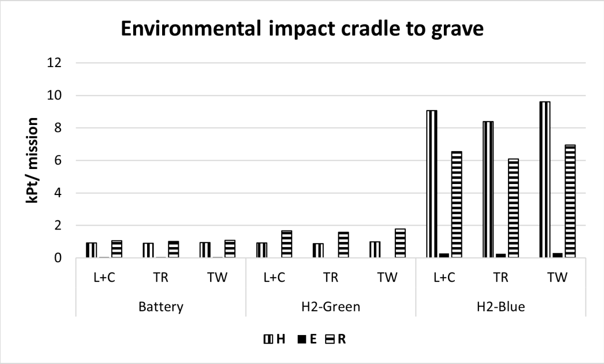


Figure 8: Environmental impact assessment for each aircraft considered, including battery versions and fuel cells powered by green and blue hydrogen.

Analyzing the Figure 8 the battery solution is the most environmentally friendly regardless of the aircraft configuration.

However, given that global warming is one of the as, this is directly related to climate change, and not only affects human health but also the ecosystem. Green hydrogen alternatives have been found to have a lower carbon footprint, mainly for the TR model, as it consumes less energy per mission. Green hydrogen is therefore the most promising solution from the point of view of global warming.

5. Conclusions

The performance of the three main eVTOL aircraft configurations was evaluated in terms of MTOM, energy consumed, flight time and SPL_{max}. The results of the conceptual design demonstrate that fuel cell aircraft consume less energy for the prescribed urban mission because they have a lower MTOM value due to the high energy density of the fuel cells. In the same study it was verified that the aircraft with the TR configuration present the most satisfactory results from the point of view of energy consumption. A life cycle assessment was carried out to evaluate which alternative, batteries or fuel cells, has the lowest environmental impact. Blue hydrogen presented higher environmental impacts, since it derives from fossil fuel and requires large amounts of resources. The same was observed for the production of fuel cells, which need many resources, including platinum. Due to this last point, it was observed that batteries have a lower overall environmental impact than fuel cells. For different aircraft, those using green hydrogen powered fuel cells have slightly lower impacts on human health and ecosystems than those using only batteries. However, the impact on resources is greater than for battery-only solutions due to the use of platinum. This problem can be mitigated if the latter material is recycled.

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