COBEM 2021
26th International Congress of Mechanical Engineering
ABCM
Associação Brasileira de Engenharia e Ciências Mecânicas
November 22-26, 2021, Virtual Congress, Brazil

COBEM2021-1435
PRELIMINARY SIZING METHOD FOR HYBRID-ELECTRIC POWERTRAIN/PROPULSION SYSTEMS OF eVTOL AIRCRAFTS

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Abstract. *A new class of vehicles is emerging, that could turn the dream of "flying cars" into reality. These are electric or hybrid aircrafts that allow vertical take-off and landing that have been proving to have the potential to revolutionize the future of freight and passenger transportation. Growing interest has brought out the urgency of implementing improvements in the still unresolved technological issues. Indeed, while the onboard technology is in an advanced state, the production and management of the energy required to operate the so called eVTOL (electric vertical take-off and landing vehicles), including power battery, remains a limiting factor. The paper proposes a preliminary sizing method of a hybrid electric powertrain/propulsion system of an eVTOL vehicle for application in the urban aerial mobility (UAM) market. The hybrid propulsion system consists of a combustion engine connected to an electric generator. The purpose of this system is to generate electrical energy to recharge the eVTOL batteries during the flight, thus increasing its range and endurance of operation. The proposed method results from the synergy of two different approaches. The first one is analytical and proposes a numerical model to estimate the energy values (such as power and specific consumption) required by the hybrid propulsion system to operate. The second one is experimental and offers a base of experimental data obtained with bench tests performed on the same system, to validate the results obtained by the numerical model. The iterative mathematical model uses as input data, the maximum takeoff weight (MTOW) of aerial vehicles, the electric motor, and combustion engine performance data obtained from literature, and outputs an estimate of the required energy that the hybrid powertrain must provide for the aircraft to take off and accomplish the mission. This work is aimed at assessing the feasibility of the use of a hybrid powertrain applied to an eVTOL vehicle for the UAM market, seeking to contribute to the solution of issues that are affecting the "big players" of the aerospace industry and research around the world through a method of evaluation consisting of a numerical model fed by historical data and validated by experimental data.*

Keywords: *Hybrid-Electric Powertrain, Hybrid Propulsion, eVTOL, UAM, Extended Range*

1. INTRODUCTION

1.1 CONTEXTUALIZATION

Transport as it is known with cars, trains, trucks, planes, and ships is responsible for taking people and products from point A to point B. However, transport is more present than we imagine, a long time ago we didn't have paved streets. It is more than historically proven that transport transforms the global society. For every evolution of society, new demands are high, and with an increasing world population, demanding a faster pace, a transformation in the transportation field would be no different. The world dreamed about "flying cars" in the future and now with a global movement, we have a new race of nations for evolution in transport, that's where the new Urban Air Mobility (UAM) market enters the scene.

The UAM market is in the process of expansion and is close to becoming a reality (Grandl *et al.* (2018)). Since 2010, the concept of Electric Vertical Takeoff and Landing aircraft (eVTOL) has become a research and development target for several companies around the world, like the tailsitter aircraft presented by Mark Moore to the Administration National Aeronautics and Space (NASA) (Moore (2010)).

The eVTOL is a type of aircraft that uses electrical energy to hover, take off and land vertically, without the need for runways at the airports. This technology has been made possible by advances in avionics, electrical engineering, communication, navigation and surveillance technologies, autonomy, and artificial intelligence. Companies like AgustaWestland with the Project Zero vehicle (AgustaWestland (2013)), Volocopter with its VC1 project (Volocopter (2011)), and Opener with the BlackFly vehicle (Opener (2011)) were one of the pioneer companies in the eVTOL field.

In 2014, the term eVTOL became officially used by the American Helicopter Society (AHS). In 2015, in the United

States of America (USA), there was the 2nd Workshop called Transformative Vertical Flight Concepts: Enabling New Flight Concepts Through New Propulsions and Energy Architectures, in which institutions/organizations such as NASA and the American Institute of Aeronautics and Astronautics (AIAA) consolidated the use of the term eVTOL (Duffy *et al.* (2015)).

Since then, companies and associations have been looking for the best solutions for the UAM market. A joint effort between universities and researchers makes the market an increasingly recent reality. The performance of regulatory agencies, popular acceptance, infrastructure, and high investments in research and development of new technologies are considered the pillars to boost the UAM market (Grandl *et al.* (2018)).

Some renowned companies in the aerospace field started to invest in this market. Airbus with the Vahana project (Airbus (2017)); Boeing with the PAV vehicle (Boeing (2018)), and Bell with the Nexus (Bell (2019)). Beyond that, there are several companies with ongoing studies to produce eVTOLs with various applications on the market. Most of these companies have not produced real prototypes with controlled flight capability yet.

Beyond the challenges found in any aeronautical project, it is possible to point out two difficulties found in an eVTOL project today: the lack of specific certification and approval for eVTOL vehicles and the low specific energy (Wh/kg) of the batteries used by the vehicles. The first difficulty is also linked to the lack of a safe and efficient management system that will control the movement of these vehicles in urban air spaces. The second difficulty, however, has a significant impact on the development of the project, since it is directly linked to the increase in the eVTOL's mass, reducing the vehicle's autonomy and reach for a minimally viable operation.

1.2 JUSTIFICATION

The urban mobility market has been growing more and more in recent years and several companies around the world are bringing new technologies to the field. Few companies have presented hybrid propulsion system solutions. Currently, Lithium Polymer batteries, widely used in eVTOL vehicles, cannot achieve the idea of a light vehicle that has a long range due to their low specific energy. That's the reason why studying new technologies is needed.

A power generation system that uses a combustion engine consuming fuel to recharge batteries during flight is one way to reduce the weight of batteries that will be used in the vehicle. This happens because burning fossil fuel results in more energy released by mass than the energy released by the mass of a battery, as can be seen in the work presented by Zhu *et al.* (2016).

The big challenge is to find a solution for the generation system which is capable of producing the amount of energy necessary to feed the motors used to lift the eVTOL and at the same time is light, so it doesn't compromise the vehicle's development. Thus, an efficient and applicable solution for eVTOLs with application in the UAM market is sought.

1.3 EVTOL TECHNOLOGIES

There is a movement that has always been present in the aviation community. Since the great wars, man has imagined the fusion of two great creations of the last century, the idea of a hybrid vehicle that would get together the utilities of a car with the functions of an airplane. With this idea of a "Flying car", many engineers and designers began to create prototypes that were the forerunners of the eVTOL vehicles we have today, which came intending to serve a future air mobility market.

Before eVTOL emerged, several VTOL prototypes took shape, the advantage of having the range of a fixed-wing aircraft with the convenience of a helicopter that doesn't need long runways at prepared airports was an advantage that attracted several sectors, including the military. Among these prototypes, it's important to observe the interest of the Convair company, developing the Convair XFY Pogo in 1954, the Avrocar from the manufacturer Avro Canada in 1958, the prototype X22 from the Bell Helicopters company introduced in 1966, and the famous V22 Osprey, produced by Bell and by Boeing with more than 200 units produced and the first flight taking place in 1989 (Bridgewater (2016)).

This movement was greatly influenced by the Canadian Engineer Dr. Paul Moller, who has more than 50 years in the VTOL vehicle business, creator of models such as the M200X Volantor and also the M400 SkyCar. In 1998, Moller International, a company owned by Paul Moller, launches an article in the AIAA with the name "Airborne personalized travel using powered lift aircraft".

In this article, Paul Moller pioneered one of the models that later came to be called UAM. He argued already in 1998 that automobiles, were present in our society to stay. And he argued that a suitable alternative was needed for many inconvenient journeys made by automobiles.

Suggesting that an aircraft that had a logistics system that could also affect the lifestyle in and around cities, as it could change the relationship with which people study/work and where they live. If living 160 kilometers away is only a 20-minute drive, the next demographics and the relationship within cities are likely to change substantially (Moller (1998)).

Given that, Moller (1998) argues that someone could sell his/her high-value apartment in San Francisco, use the income to buy a VTOL and a mountainside property, and still keep a substantial amount of cash and time to enjoy with his/her family and loved ones. The author also suggests an automated airway network, having the human out of flight control, in a highly controlled airspace region. In the year of the study, Moller concludes that a large part of the 40,000 annual road deaths could be eliminated.

In the year of 2018, Professor Anubhav Datta of the University of Maryland reported the status of eVTOL technology in the UAM market. Since August 2014, AHS has led a series of workshops with the help of NASA, AIAA, and SAE (Society of Automotive Engineering) in what it called Transformative Vertical Flight (TVF) to explore the potential and follow the development of more new electric and hybrid-electric propulsion technologies that could enable and drive new forms of air transport in the future.

Air transport can be defined broadly, with manned and unmanned actions ranging from civil to military operations. The spotlight was focused on the potential for on-demand air taxi operations capable of configurations compatible with vertiports. However, the initiative also includes, with equal emphasis, the capability to deliver commercial packages and the delivery of strategic military resources. The interest of the initiative is not in small drones (Unmanned Aerial Systems), but in manned and optionally manned aircraft, with payloads of at least 45-220 kg and Maximum Take-Off Weight of 450 to 2200 kg or more (Datta *et al.* (2018)).

Pure electric vehicles can be defined as those that only use electricity as propulsion. Hybrids are those that have a form of propulsion other than electric, as the case proposed in this work. Because hybrid and conventional vehicles generally have greater range than purely electric ones. (Goyal *et al.* (2018)).

1.4 CATEGORIES

The ability to distribute thrust across the fuselage, without mechanical complexity, and with an independent propulsion system, becomes a new degree of freedom for aircraft designers (Fredericks *et al.* (2013)). With this ease, some categories emerged that soon began to group together. They are:Vectored Thrust; Lift + Cruise; Wingless/Multirotor; HoverBike/HoverDevice; Electric Rotorcraft.

1.4.1 VECTORED THRUST

The Vectored Thrust category includes all aircraft that can be designated as TILT-X (Tilt-Rotor, Tilt-Wing). These aircraft have a wing to allow efficient cruise flight and use the same propulsion system to hover and to fly in cruise mode. The predominant difference within this eVTOL category is due to the use of propellers or Electric Ducted Fans (EDF) as forms of propulsion (Bacchini and Cestino (2019)).

1.4.2 LIFT + CRUISE

The Lift + Cruise category includes aircraft with fully independent cruise and lift thrusters. This category has wings for efficient cruise flight, like the Vectored Thrust category, however, the propulsive system that performs VTOL is different from the propulsive system that performs cruise flight (Bacchini and Cestino (2019)).

1.4.3 WINGLESS/MULTIROTOR

Aircrafts called Wingless are also called Multirotor. This category has large propellers or a lot of propellers. This makes the multirotors efficient in hovering flight, but it also makes them inefficient in cruise flight precisely because they don't have wings. Within the category, there are aircrafts that are suitables for short-range operations in cities that need to solve adversities caused by traffic jams (Bacchini and Cestino (2019)).

Workhorse Group, a small American company invested in the development of a hybrid multirotor vehicle as a solution for the eVTOL market, called SureFly. In 2020, the Moog company acquired the technology for US$5 million.

Figure 1. SureFly Aircraft.
Source: Moog (2021).

1.4.4 HOVERBIKES/HOVERDEVICES

Hoverbikes/Hoverdevices are smaller aircraft. Also called PAV (Personal Aerial Vehicle). Hoverbikes are generally multirotors that can be ridden like a motorcycle (Bacchini and Cestino (2019)).

1.4.5 ELECTRIC ROTORCRAFT

Electric Rotorcrafts, also known as eHelos, are aircraft similar to conventional helicopters, but they fly using electrical energy from batteries (Bacchini and Cestino (2019)).

2. POWER GENERATION SYSTEM

Vehicle configuration and propulsion system architecture are two key points for vehicle performance attributes. Vehicle configuration is a factor that constrains the design of the propulsion architecture. The aim of the hybrid-electric propulsion system is to explore the inherent advantages of different propulsion technologies to achieve high power/weight ratios in the flight (Avera and Singh (2019)).

The main difference between a hybrid-electric and a purely electric propulsion system can be seen in the figures 2 and 3:

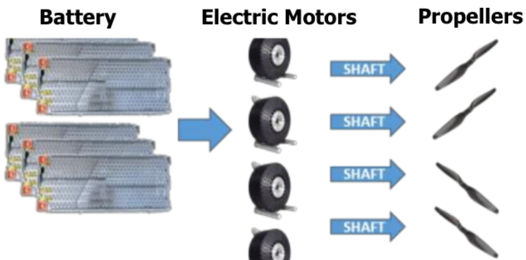

Figure 2. Pure electric propulsion system.
Source: Zhu *et al.* (2016).

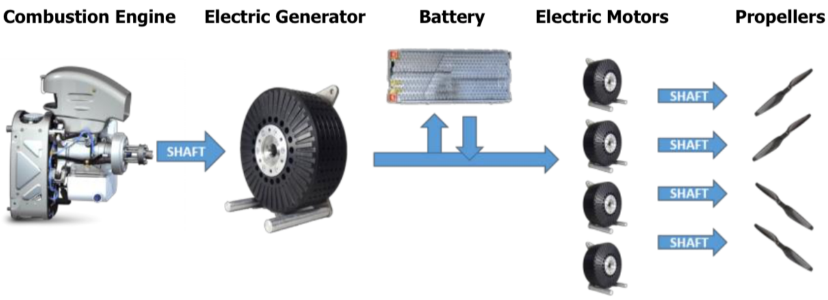

Figure 3. Hybrid-electric propulsion system.
Source: Zhu *et al.* (2016).

In the purely electrical system, the vehicle's engines are powered exclusively by batteries, so the in-flight performance criteria are determined by the energy density characteristics and capacity of the energy storage system. In the hybrid-electric system, the generation system composed by the generator and combustion engine is responsible for feeding the vehicle's batteries. These batteries are then used to power the motors responsible for the lift of the aircraft . The purpose of this work will be to study the hybrid configuration.

The vehicle having the hybrid propulsion configuration is expected to have a significantly longer range than battery powered designs due to the higher energy density of fuel compared to batteries. While a vehicle of this type is expected to be required to have a backup battery, such a battery is only used in emergency situations and is not intended to be used to increase the vehicle's performance capability (Avera and Singh (2019)).

The figure 4 represents the differences between the energy densities of storage systems and gasoline:

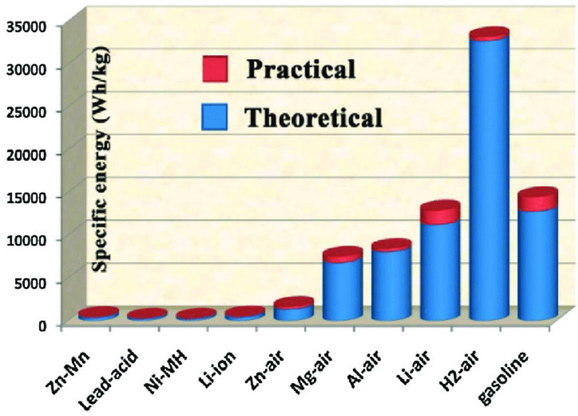

Figure 4. Comparison of energy density of some models of rechargeable batteries, hydrogen fuel cell and gasoline.
Source: Zhu *et al.* (2016).

3. METHODOLOGY

3.1 PRELIMINARY CHARACTERISTICS OF THE EVTOL VEHICLE

The aircraft design development methodology presented by Daniel Raymer (Raymer (2018)) is a good starting point for the development of this work. It is very important to define the basic/preliminary requirements before actually starting the project. Therefore, a survey of the main existing and under development projects was made and a parametric analysis was done with the main requirements.

3.1.1 CATEGORY

There are several factors in choosing an eVTOL vehicle category, such as mission type, payload, range, and maximum takeoff weight. It is important to take into account the type of certification that the product will be subjected to. Since each certification process implies different costs, deadlines, and requirements until reaching to a final product.

Research developed by Porsche Consulting (Grandl *et al.* (2018)) shows that the fastest model to receive certification and enter the market is the multirotor platform. Since that in this category, no extra systems are needed to differentiate the aircraft in hover flight mode and cruise flight mode, as is the case with the Lift + Cruise and Vectored Thrust configurations. For this reason, this type of configuration has simpler manufacturing subsystems.

As one of the objectives of this work is to present an engineering solution as an alternative to reduce the weight of batteries used in the field of eVTOL vehicles, the time factor in the market is essential. The development of lighter batteries with greater load capacity and energy density is directly related to the range and autonomy of these vehicles. So, the category defined for this work is the multirotor category.

3.1.2 MISSION PARAMETERS

For the development of a conceptual project, one of the main points to be met is the market expectation, since the product will have the user as its final point. Another important factor to be considered is to analyze what the main companies in the field are developing in terms of technology.

Given the research achieved, the proposal is to work with a vehicle with a maximum take-off weight (MTOW) of 1000 kg capable of carrying a payload of 250 kg, which corresponds to 2 passengers + extra load. The expectation is that the vehicle with the hybrid-electric propulsion system will have a minimum range of 100 km.

So, the parameters to be used for the design are presented in the table 1:

Table 1. Parameters used for the design of the hybrid-electric propulsion system.

Category	Multirotor
MTOW	1000 kg
Payload	250 kg
Range	Minimum of 100 km
Endurance	Minimum of 1 hour

3.2 DETERMINING THE POWER OF VTOL MOTORS IN HOVER FLIGHT

Considering companies that develop electric motors, it is possible to have access to technical performance information provided by the manufacturers themselves. The main reference companies researched in this work are T-MOTOR and EMRAX. The first one develops electric motors with radial flow and the second one with axial flow.

In small unmanned aerial vehicles (UAVs) it is common to attribute the MTOW to thrust ratio equal to or less than 70 %. In this work, as it is a manned vehicle, the safety requirements are more demanding, so the value to be considered must be less than 60 %.

From the value of MTOW and consulting technical information of the electric motors, it is possible to estimate the power consumed by the hovering vehicle by the motors responsible for the lift of the aircraft. The number of rotors to be used depends on the maximum thrust of the system over the maximum thrust that each motor can provide.

Linked to this, there is a parameter to be taken into account to determine the vehicle's lift propulsive system. It's the configuration of coaxial or non-coaxial motors. The first configuration allows a reduction in motor installation points, which implies an aircraft with fewer arms and, consequently, lighter vehicles. On the other hand, the coaxial configuration has a loss of real thrust efficiency, as the lower motor receives an already accelerated airflow from the upper motor (Coleman *et al.* (1997)).

Furthermore, electric motors are not 100 % efficient machines, there are always system losses (Guedes (1994)). So, in this work, a thrust efficiency of 90% will be considered for the calculations. Another important parameter that is related to the characteristics of electric motors is the efficiency that relates thrust mass and power (g/W). As the sizing will be done generically, values between 7.0 and 10.0 g/W will be used.

Consider the following inputs shown in the table 2 to calculate the power required for hovering flight:

Table 2. Inputs to determine the hover power of the electric motors used in the vehicle's lift system.

MTOW	1000 kg
Number of Rotors (N_r)	12 to 16
Coaxial Efficiency (η_c)	80 %
Efficiency of Electric Motors (η_m)	90 %
MTOW/Thrust Ratio (W/T)	60 %
g/W Efficiency($\eta_{g/W}$)	7,0 to 10,0

The maximum available thrust (T_{max}) of electric motors can be given by the following equation:

$$T_{max} = MTOW/(W/T) \quad (1)$$

From this result, it is possible to determine what the maximum thrust of commercially existing electric motors should be ($T_{max.mot}$). This information will be very useful to determine which model can be used in the vehicle's lift propulsion system:

$$T_{max.mot} = T_{max}/(N_r * \eta_c * \eta_m) \quad (2)$$

Then, the thrust for hover flight (T_{hover}) that each engine must have will be determined from the following equation:

$$T_{hover} = MTOW/(N_r * \eta_c * \eta_m) \quad (3)$$

So, the power of the VTOL engines (P_{total}) in hover flight is determined by the following equation:

$$P_{total} = MTOW/(\eta_{g/W} * 1000) \quad (4)$$

3.3 DETERMINING THE MINIMUM POWER THAT THE HYBRID-ELECTRIC PROPULSION SYSTEM SHOULD GENERATE

The power generated by the hybrid-electric system is composed by the combustion engine and the electric generator, which is a brushless electric motor. It is important to consider two important factors. These are the system efficiency losses and the total power. In every system, there are always mechanical, electrical, and thermal losses. For the development of the calculations, generator and rectifier efficiencies will be considered (Soares (2017)). This way, we can achieve:

Table 3. Inputs to determine the minimum power required that the hybrid-electric propulsion system must generate.

Rectifier Efficiency (η_r)	90 %
Generator Efficiency (η_g)	90 %

So, the minimum power required ($P_{required}$) that the system must generate to keep the lift system working in hover flight is calculated by the following equation:

$$P_{required} = P_{total}/(\eta_g * \eta_r) \tag{5}$$

3.4 COMBUSTION ENGINE CONSUMPTION PARAMETERS

The combustion engine is an essential part of the hybrid-electric propulsion system and the consumption and performance parameters of the engine are essential for the sizing method of this work. There are different types of combustion engines in different applications. Part of the goal of this sizing method is to determine a range of values that describes the characteristics of the engine.

From the amount of power required, it is possible to determine which combustion engine can be used in the system. So, the power generated ($P_{generated}$) by the engine must be greater than the power required ($P_{required}$), and the engine performance parameter - specific fuel consumption (SFC) - is important to preliminarily determine the mass of fuel to be used in the vehicle.

3.5 CALCULATIONS OF THE BATTERY MASS OF THE SYSTEM

The batteries used in the eVTOL vehicle are essential for the operation of the motors responsible for the lift system of the vehicle. If the hybrid propulsion system fails during the flight, the batteries are responsible for ensuring that the vehicle lands safely. As known, it is still necessary that there are batteries in the vehicle even knowing that they represent a percentage of the total takeoff weight. But unlike vehicles powered only by batteries, their flight time directly impacts the mass that will compose the system and for this work, the backup battery flight time will be between 5 and 10 min.

The estimate of the mass of batteries that should be used in the system depends on the required power ($P_{required}$), the battery flight time (t_{bat}), the energy density (ρ_{ener}) and the battery use capacity without compromising the life cycle, which is around 80 %. The parameter regarding which type of energy storage system will be used in the vehicle is the energy density and the values used for this sizing method are between a range going from 180 to 250 Wh/kg. So, the mass of batteries can be estimated as the following equation:

$$M_{bat} = (P_{required}/t_{bat})/(80\% * \rho_{ener}) \tag{6}$$

3.6 ENDURANCE

To determine the vehicle's endurance, it is necessary to preliminarily estimate the fuel mass (M_{fuel}) that will be used in the project. In this part of the project development, as the level of detail is still superficial, there is no need for this mass to be 100 % accurate. Therefore, as a first estimate, values representing less than 10 % of the vehicle's total mass will be used. The endurance can be calculated as the following equation:

$$Endurance = (M_{fuel} * \eta_{g/W})/(SFC * MTOW/1000) \tag{7}$$

To achieve the endurance desired, it is necessary to certify that the entire hybrid-electric propulsion system is capable of generating enough energy for the good operation of the electric motors. For this, it is important to attest to an optimal relation between fuel consumption and engine weight. This way it's possible to ensure the accomplishment of the aircraft's mission. The generator must be able to transform chemical energy from the combustion engine into electrical energy, fully certifying the energy needed to lift the aircraft and to charge the batteries.

4. RESULTS AND DISCUSSION

It is necessary to emphasize that the development of the eVTOL market is strictly linked to the last decade. The drone market got highlighted and companies began to develop bigger and more efficient electric motors. However, eVTOL aircraft are large and heavy compared to regular drones. This generates a shortage and a market need that is still far from being developed and masterfully solved.

The radial flow motor of the brand T-MOTOR model U15XXL is capable of providing 102 kg of maximum thrust, presenting a g/W ratio that varies from 4.48 to 11.08 depending on the output power. EMRAX axial flow motors are commonly used as generators and rarely as motors for a vehicle's support system. The technical information provided by the manufacturer does not relate the engine's operation to a propeller. The EMRAX 228 engine is a strong candidate for use as a lift propulsion motor, however, some experimental tests must be accomplished to provide more accurate values of maximum thrust and power to ensure that the vehicle accomplishes its mission.

The central parameter of this methodology refers to the power required to feed the vehicle's electric motors and the parameter with great impact that is directly linked to the results is the efficiency ($\eta_{g/W}$). So, the results presented in table 5 considers variations in the efficiency number, while the table 4 shows the input parameters:

Table 4. Inputs used to generate the results n°1.

MTOW	1000 kg
Payload	250 kg
N_r	12
SFC	6 g/(kW.min)
t_{bat}	5 min
ρ_{ener}	200 Wh/kg
Configuration	Coaxial

Table 5. Results n°1.

$\eta_{g/W}$	7,0	7,5	8,0	8,5	9,0	9,5	10
T_{max} (kg)	1666,67	1666,67	1666,67	1666,67	1666,67	1666,67	1666,67
$T_{max.mot}$ (kg)	192,90	192,90	192,90	192,90	192,90	192,90	192,90
T_{hover} (kg)	115,74	115,74	115,74	115,74	115,74	115,74	115,74
P_{total} (kW)	142,82	133,33	125,00	117,64	111,11	105,52	100
$P_{required}$ (kW)	176,36	164,46	154,43	145,52	137,17	129,95	123,45
$P_{generated}$ (kW)	183,33	173,33	160,00	151,66	143,33	134,16	128,33
M_{bat} (kg)	111,61	104,17	97,66	91,91	86,81	82,24	78,13
M_{fuel} (kg)	48,39	55,83	62,34	68,09	73,19	77,76	81,88
Endurance (h)	0,94	1,16	1,39	1,61	1,83	2,05	2,27

So, if the electric propulsion system gets a lower g/W ratio, the vehicle will have more efficient electric motors, which impacts the entire hybrid-electric propulsion system, including the weight of the aircraft structure.

Another important point refers to the number of motors to be used in the vehicle because the choice directly impacts the vehicle's layout. By dividing the maximum available thrust (T_{max}) by the number of rotors (N_r), a value of maximum thrust needed for each motor is found.

By choosing more rotors (N_r = 16), it is possible to have access to more market options, as the maximum thrust required for each motor is lower. Since a few motors are designed to exclusively meet the maximum thrust lifting needs of the eVTOL market.

However, when selecting a smaller number of motors (N_r = 12), fewer fixing points are needed for the motors, and consequently less mass is added to the system. If it's not necessary the assembly with coaxial motors, it's possible to eliminate the coaxial efficiency factor (η_c) of the formulation.

Another result to be analyzed is related to the combustion engine performance parameters, since it is an essential component for the energy generation system. The results are shown in the table 7 and the input parameters in the table 6:

Table 6. Inputs used to generate the results n°2.

MTOW	1000 kg
Payload	250 kg
N_r	12
$\eta_{g/W}$	9,0 g/W)
t_{bat}	5 min
ρ_{ener}	200 Wh/kg
Configuration	Coaxial

Table 7. Results n°2.

SFC (g/kW.min)	4,0	4,5	5,0	5,5	6,0	6,5	7,0
T_{hover} (kg)	115,74	115,74	115,74	115,74	115,74	115,74	115,74
$P_{required}$ (kW)	137,17	137,17	137,17	137,17	137,17	137,17	137,17
$P_{generated}$ (kW)	141,25	141,11	146,00	143,63	144,16	141,53	144,28
M_{fuel} (kg)	73,19	73,19	73,19	73,19	73,19	73,19	73,19
Endurance (h)	2,74	2,44	2,20	2,00	1,83	1,69	1,57

It is categorical to state that an engine that consumes less fuel will need a smaller fuel tank to fulfill the needs of the proposed mission. By considering the SFC variation, a relation between specific fuel consumption and endurance can be created. For engines with high SFC, more fuel would be needed to obtain the same range as a low SFC engine.

To verify the advantage that a hybrid system can offer, the endurance of a purely electric vehicle was calculated. For comparison purposes, the same parameters of "Table 4 were used: Inputs used to generate the results n°1.", with the obvious exception of the battery flight time and the SFC. In the purely electrical configuration, the entire energy generation system composed by the combustion engine, generator, and fuel tank was replaced by batteries. So, the input data is presented in the table 8 and the results in the table 9:

Table 8. *Inputs* used to generate the results n°3.

MTOW	1000 kg
Payload	250 kg
N_r	12
ρ_{ener}	200 Wh/kg
Configuration	Coaxial

Table 9. Results n°3.

$\eta_{g/W}$	9,0 (hybrid)	9,0 (electric)
T_{max} (kg)	1666,67	1666,67
$T_{max.mot}$ (kg)	192,90	192,90
T_{hover} (kg)	115,74	115,74
P_{total} (kW)	111,11	111,11
$P_{required}$ (kW)	137,17	111,11
M_{bat} (kg)	86,81	360,24
M_{fuel} (kg)	73,19	0
Endurance (min)	109,8 (1,83h)	20,75

It is possible to notice that there is an increase of about 415 % in the battery mass of the pure electric system compared with the hybrid system. While the endurance was increased by about 530 % in the hybrid-electric system compared with the pure electric system.

5. CONCLUSION

It is primarily necessary to emphasize that the g/W ratio is a key concept in the development of this project. It was possible to observe in a preliminary way that a viable eVTOL vehicle system must present electric motors with efficiency $\eta_{g/W}$ greater than 7.5, thus ensuring endurance greater than 1 hour. In these conditions, the combustion engine must have a nominal power of at least 173.33 kW.

The focus of this work is not to determine the best configuration for electric motors (number of engines and coaxial configuration or not), since the focus is on the energy generation system and not on determining the vehicle's operational characteristics.

An important point in this work is the relation between SFC and the specific power of the combustion engine. It can be observed that when an engine influences the mass of the system more due to its specific power than its SFC, that is, the engine does not have very different fuel consumption from its competitor, but the specific power is lower, there is a heavy engine for the vehicle and not an optimal choice for the project. On the other hand, when the engine does not have a specific power that is very different from its competitor, but has a high SFC, there is an engine that does not represent the optimal choice for the project, as it must have a larger fuel reserve. Therefore, the best criterion for selecting a combustion engine is finding one that can supply enough power and energy to the generator, adding the minimum of mass to the aircraft.

During this work, it is clear to notice the advantage of obtaining a hybrid electric system when analyzing the possibilities that the system allows, being able to promote endurance up to 530 % greater than pure electric systems.

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