Key aspects of electric vertical take-off and landing conceptual design

Key aspects of Electric VTOL conceptual design

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Abstract

The recent advances in battery energy density and electric propulsion systems for automotive applications are enabling the development of the electric vertical take-off and landing aircraft (eVTOL). The eVTOL is a new means of transport that can fly like an aircraft and take off and land vertically like a helicopter, sometimes called personal aerial vehicle. This paper compares it to the existing vehicles that may compete with it and addresses the estimation of its performances in hover, cruise flight, and the transition phase. The main parameters affecting performances are then discussed. Considerable space is dedicated to the battery mass to total mass ratio.

Keywords

Electric VTOL, range, hover, transition, personal aerial vehicle,

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Nomenclature

A_{CS}	Cross-sectional surface of car and train
C_D	Drag coefficient
C_{D0}	Zero lift drag coefficient
C_L	Lift coefficient
E^*	Battery energy density, Wh/kg
F_{res}	Resistance (rolling + aerodynamic)
P_{req}	Power required
P_v	Power required to produce vertical thrust
P_h	Power required to produce horizontal thrust
T_h	Horizontal thrust
$\frac{T}{W}$	Thrust to weight ratio
T_{req}	Thrust required
T_v	Vertical thrust
a_{max}	Maximum allowed acceleration
f_0	Rolling resistance constant coefficient
k_p	Battery power to mass ratio
$m_{battery}$	Battery mass
$m_{payload}$	Payload mass
m_{empty}	VTOL empty mass. It is equal to the total mass minus the mass of the payload and the mass of the battery.
v_∞	Flight speed

η_{total}	Propulsive efficiency of the eVTOL. It consists of the efficiency of the electronic converter and controller, the electric motor, and the propulsive efficiency of the propeller.
W	Weight
A	Disk actuator area
AR	Aspect ratio
D	Aerodynamic drag
P	Power
R	Range
S	Wing surface
T	Thrust
V	Speed
VTOL	Vertical take-off and landing aircraft
c	Cost of energy in €
g	Gravity acceleration
k	Rolling resistance coefficient proportional to the square of the speed
k	Drag polar quadratic term coefficient
m	Total mass of the eVTOL
t	Flight time
α	Road or railway slope
ε	Oswald efficiency number
π	Pi
ρ	Air density

1. Introduction

The recent advancements of battery storage, electric motors, and power electronics are bringing these technologies to a level that will enable the development of the electric vertical take-off and landing aircraft (electric VTOL or eVTOL). In 2010, Moore [1] explained the advantages of these technologies applied to air travel. He proposed the new vehicle, the electric VTOL, able to fly like an airplane and take off and land vertically. As shown by Hepperle [2], the energy density of the batteries is not enough to completely electrify air travel. The range of the electric aircraft is much shorter than the range of a conventional aircraft. However, the high battery's specific-power and the small size of the electric motors enable vertical takeoff and landing designs. These electric VTOLs are also called personal aerial vehicle. Patterson [3] and Moore [4] studied them for on-demand aviation. Fredericks [5] analyzed hybrid-electric propulsion for VTOL aircraft. Patterson [6] and Gohardani [7] studied distributed propulsion. Moore [8] discussed the misconceptions about electric propulsion aircraft.

Lilium in Germany, Kitty Hawk and Joby Aviation in the United States are developing and testing their VTOLs. Airbus and Boeing are creating the spinoffs A^3 and Aurora flight sciences to develop and test their own VTOLs. Uber, the transportation network company, has launched a program to help the development of VTOLs and has gathered partners like Embraer, Pipistrel, Karem Aircraft, A^3, and Aurora flight sciences. In China, the drone company E-Hang has been testing the E-Hang184 passenger quadrotor for more than one year.

VTOLs are not a new concept. In the fifties and sixties, a great effort was put into creating military VTOLs. Many concepts were tested, but only the Harrier, the Yak-38, the V-22, and the F-35 became operational. No VTOL managed to become operative for commercial service yet.

The critical aspects of the electric motor technology underlined by Moore [1] are high reliability and efficiency, very low noise and vibration**,** zero emissions, low engine weight, low maintenance, low cooling drag, little volume required, and their scalability. With electric propulsion, the dream of the fifties and sixties, a practical vertical take-off and landing aircraft for civilian use, can be realized. Creating such a vehicle would revolutionize the way people commute. Traffic jams would be easily avoided and commutes that take one hour and a half by car would take 15 to 20 minutes with the VTOL. People could live in the countryside, in the mountains or wherever in the middle of nature, up to 100 km away from the city where they work and get there in only 20 minutes taking off from their back garden and landing directly on top of the skyscraper where they work. In the sixties, the technology for this new vehicle looked ready [11] [12], but noise, pollution, and cost prevented old VTOLs to be adopted. Electric propulsion and the new capabilities of artificial intelligence in navigation and control provide a solution to these problems.

The possible impact of electric VTOLs can be compared to the impact that automobiles had on our society. Cars allowed to live in the outskirts, in bigger and cheaper houses, and they gave the freedom to travel during weekends. In the same way, VTOLs will allow living further away from the city and into nature, respecting the ambient because electric propulsion produces no local polluting emissions.

The revolutionary difference between VTOLs and passenger aircraft is like the difference between trains and cars. Trains must start from the railway station at a fixed time scheduled by the railway company, and cars can be used when needed with no departure and arrival station. The same happens now: a conventional aircraft requires an airport for takeoff and landing, an electric VTOL will be able to take off and land from a small strip of land when needed.

In this paper, electric VTOLs are compared to existing alternative vehicles. The cruise and hover flight conditions are analyzed deriving the equations required to compute the range of an electric VTOL and the minimum area of the vertical thrust system required for hover and take off. The main parameters affecting hover and cruise flight are discussed, and the tradeoff between battery mass and payload mass is analyzed. Then the transition phase is analyzed, and possible future works are proposed.

2. Comparison with existing alternatives

To be economically sound, an electrical VTOL must be better than existing alternatives: road transport, rail transport, and helicopters. First, VTOLs are compared to road and rail transport, then to helicopters.

Flying has significant advantages compared to road and rail transport: traffic jams are not a problem because the aircraft moves in tridimensional space, it flies directly to its destination, and it does not have to win rolling resistance. At low speeds, flying is impractical because a large wing is required to produce enough lift, while cars and trains only need wheels. At high speeds, flying becomes excellent because a little wing is enough to produce the required lift, there is no rolling resistance, and the aerodynamic shape ensures a low drag coefficient. In figure 1, the power required per passenger at different speeds for the car, the train, and the aircraft, is shown. To represent the car, the Fiat Punto data is used, to represent the train, the Frecciarossa 1000 train data, and to represent the aircraft, the Cessna 172 data (tables 1, 2 and 3).

The aircraft power required is computed for a given velocity in level, unaccelerated flight [13]:

$$T_{req} = D \tag{1}$$

$$P_{req} = T_{req} \cdot V = D \cdot V \tag{2}$$

$$P_{req} = \frac{1}{2}\rho V^2 S C_D \cdot V \tag{3}$$

$$C_D = C_{D0} + k{C_L}^2 \tag{4}$$

$$P_{req} = \frac{1}{2}\rho V^3 S C_{D0} + \frac{W^2}{\frac{1}{2}\rho V S}\left(\frac{1}{\pi \varepsilon AR}\right) \tag{5}$$

The power required for the car and train is the sum of two factors: rolling resistance and aerodynamic resistance [14]. Equations 6 and 7 also consider the component of the weight when the ground is not level:

$$F_{res} = \left[mgcos(\alpha) - \frac{1}{2}\rho V^2 A_{CS} C_L\right](f_0 + kV^2) + \frac{1}{2}\rho V^2 A_{CS} C_D + mgsin(\alpha) \tag{6}$$

$$P_{req} = F_{res} \cdot V \tag{7}$$

Table 1: Parameters of the Cessna 172 used to model aircraft power consumption.

Air density (ρ)	1.225 kg/m^3
Wing surface (S)	16.2 m^2
C_{D0}	0.03
Weight	1100 kg
Oswald factor (ε)	0.8
Aspect ratio (AR)	7.32
Number of passengers	4 (including one pilot)

Table 2: Parameters of the Fiat Punto used to model car power consumption.

Weight	1000 kg
Cross-section area (A_{CS})	2 m^2
C_L	0
C_D	0.3
f_0	0.01
k	$6.5 \cdot 10^{-6}$ s^2/m^2
Number of passengers	4

Table 3: Parameters of Frecciarossa 1000 used to model train power consumption.

Weight	500 tons
Cross-section area (A_{CS})	12 m^2
C_L	0

C_D	1.8
f_0	0.002
k	$6.5 \cdot 10^{-6}$ s^2/m^2
Number of passengers	440

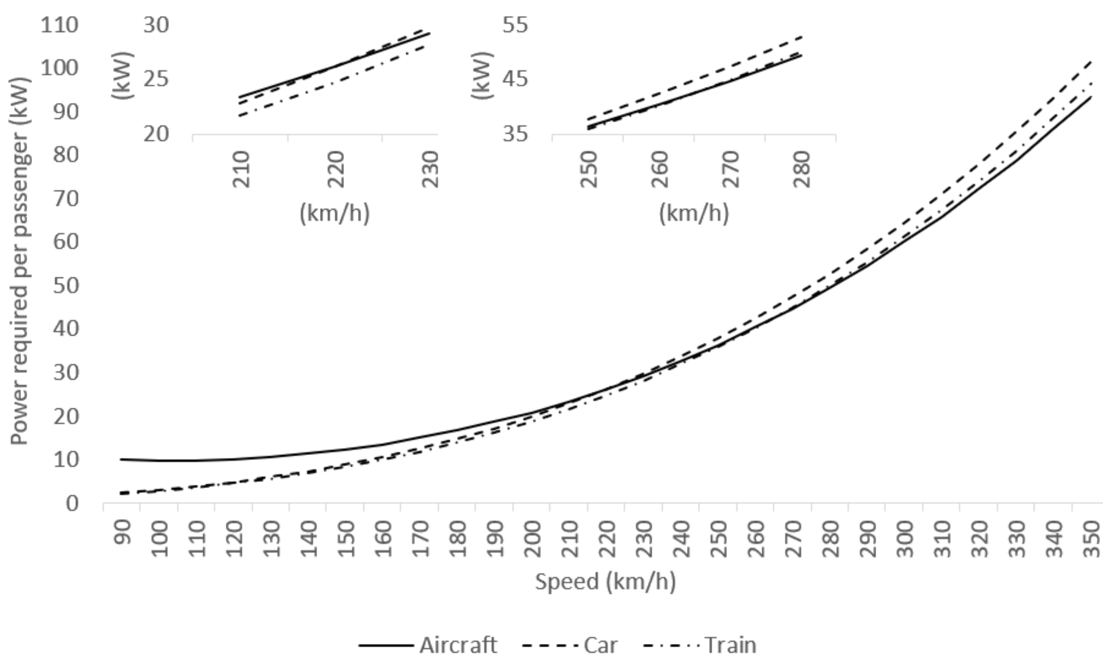

Figure 1: Road transport comparison, power required by car, train, and airplane, at different speeds.

Figures 1 shows that, at low speeds, the car and the train are more efficient than the airplane. The train is more efficient than the car because the rolling resistance between two hard surfaces, the steel of the train's wheels and the rail, is lower than the rolling resistance of the tires on the tarmac, and because it has a smaller frontal section per passenger. At higher speeds, the aircraft becomes competitive with the car and the train. Considering our assumptions, it becomes more efficient than the car at about 220 km/h and more efficient than the train at about 265 km/h. In practice, we find that considering the typical car (table 2) with four passengers, a trip by car usually is cheaper than a train ticket. The price of the train ticket comprises not only the cost of the energy, but also the cost of the railway personnel, the train itself, and the infrastructure. In computing the cost of a trip by car, we do not usually consider the cost of the car itself and the insurance. When there are fewer passengers and considering the cost of the car and the cost of insurance, the car is more expensive than the train. VTOLs will also be able to fly directly from the departing point to the destination, avoiding traffic jams and saving time.

The helicopter is already able to avoid traffic but is not widely used. The reason is the high costs of helicopter operation, and the noise generated. The cost of helicopter operations consists of propellant, pilot, and maintenance. Helicopters require many hours of maintenance because they are highly complex mechanical machines. The transmission and the rotor are single points of failure and need to be inspected routinely; the propellant cost is high because the helicopter is less efficient in cruise flight than the aircraft; the pilot is the highest operating cost. Creating a pilotless helicopter would remove the cost of the pilot. However, it might be difficult to certify. Autonomous helicopter flight in upright flight regime has seen considerable progress, but the only way to perform autonomously more complex maneuvers is using neural networks [15]. The process of certification would be quite long, expensive, and complicated, not much cheaper than building and certifying a new electric VTOL.

Noise generated by helicopters has three spectral components, the engine, the main rotor, and the tail rotor. The engine noise of an eVTOL is lower because electric motors are quiet. The propeller noise can be reduced because the rotor blade noise varies as an exponent of the tip speed. With electric propulsion, tip speed and thus noise can be reduced. A large rotor is no longer needed because electric motors are highly scalable, a small engine can have the same efficiency of a larger one. For combustion engines and turbo-generators, this is not true. A bigger machine is more efficient than multiple smaller ones. There could be VTOLs designed for efficient hovering with multiple small propellers or VTOLs designed for an efficient cruise with fewer and more powerful propellers or ducted fans.

With this technology, the helicopter's retreating blade problem can be solved. When a helicopter is in forward flight, the airspeed investing the advancing blade is the sum of rotational speed and flying speed, the airspeed investing the retreating blade is the difference between these two terms. The force produced by the two blades is different. To compensate this difference, the retreating blade flies at a higher angle of attack up to the point where it stalls. As the forward speed increases, this effect increases as well. At a certain speed, it is not possible to compensate anymore the difference of lift. This speed is the maximum speed of the helicopter, and this phenomenon explains why the helicopter's maximum speed is quite low compared to the aircraft's maximum speed. Helicopters are inefficient in forward flight because they are designed for hovering, their large rotor has the retreating blade problem, and they cannot reap the benefits of the wing-borne lift.

3. Electric airplane range

The mission of an eVTOL consists of two main phases: the cruise flight and the takeoff and landing.

The range of an electric aircraft can be computed with the Breguet equations modified for electric flight. The derivation of these equations can also be found in [2].

The range is the product of flight speed and flight time:

$$R = v_\infty \cdot t \tag{8}$$

For battery-powered aircraft, flight time is equal to the time to drain the battery.

$$t = \frac{m_{battery} \cdot E^*}{P_{battery}} \tag{9}$$

Where E* is the energy density of the battery, and $P_{battery}$ is the power supplied by the battery. Inserting it into the range equation yields:

$$R = v_\infty \cdot \frac{m_{battery} \cdot E^*}{P_{battery}} \tag{10}$$

The power drawn by the battery is related to the power required for forward flight, $P_{aircraft}$:

$$P_{battery} = \frac{P_{aircraft}}{\eta_{total}} \tag{11}$$

The power required for forward flight is proportional to the aircraft weight, lift to drag ratio and flight speed:

$$P_{aircraft} = D_{aircraft} \cdot v_\infty = \frac{m \cdot g}{\frac{L}{D}} \cdot v_\infty \tag{12}$$

Combining the two previous equations and inserting them in the range equation:

$$R = v_\infty \cdot \frac{\frac{m_{battery} \cdot E^*}{m \cdot g}}{\frac{L}{D} \cdot \eta_{total}} \cdot v_\infty \quad (13)$$

This equation can be simplified to the range equation for battery-electric flight:

$$\boxed{R = E^* \cdot \eta_{total} \cdot \frac{1}{g} \cdot \frac{L}{D} \cdot \frac{m_{battery}}{m}} \quad (14)$$

In figure 2, the results of the range equation for electric aircraft are plotted.

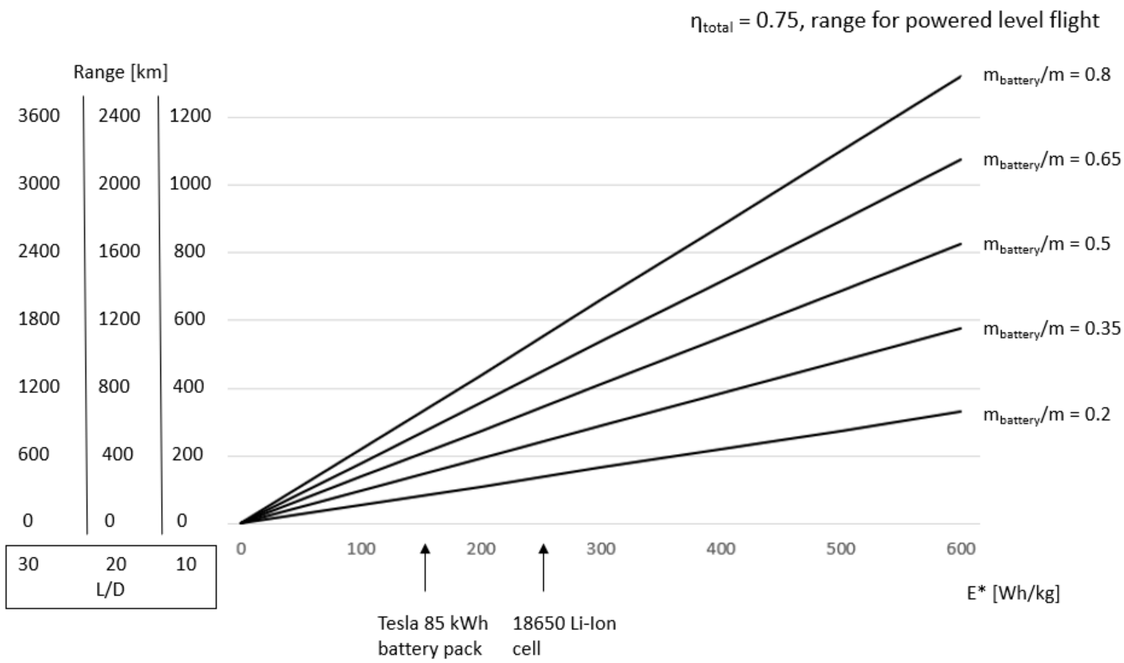

Figure 2: Range of an electric airplane for different L/D, varying the energy density of the batteries and at different values of the battery mass ratio.

Figure 2 shows that the range of electric aircraft is much lower than the range of passenger jets, but it is enough to perform short-distance commutes. With this figure, we can compute the range of an eVTOL built with the 85 kWh battery packs produced by Tesla for its Model S electric car which have an energy density of 157 Wh/kg [16]. We enter the graph from the x-axis selecting the specified energy density, we choose the battery mass fraction line (0.5 for instance), and on the y-axis, we can find the range for different L/D ratios of the vehicle. If this eVTOL has an L/D of 10, its range will be about 200 km. The other point highlighted on the x-axis is the energy density of a representative Li-Ion cell. The energy density of a single cell is higher than the energy density of the battery pack because the battery pack also includes the connections, casing, thermal management system, and the digital control system. The Tesla value has been selected because these batteries are used in a consumer product in a high-power application, and they represent the state of the art of high specific-power, high energy density batteries.

Equation 14 shows that to improve the range of an electric aircraft, each one of the following five factors has to be maximized.

The term E* is the energy density of the batteries. The present lithium-ion technology has an energy density of around 200 Wh/kg. It has been constantly but slowly improving in the last century. Fuel cells may provide higher E* and improve the range [17] [18]. However, their specific-power must be enough to hover, which is the most power-demanding phase of every eVTOL mission.

The term η_{total} is the total propulsive efficiency and is expressed as the product of the efficiency of the motor and the efficiency of the propeller. Electric motors have efficiencies in the order of 0.95 and propellers or ducted fans can be designed to reach efficiencies of about 0.8, then a reasonable value for the total efficiency, as suggested in [2], can be 0.75.

Lift to drag ratio represents a measure of the design overall aerodynamic efficiency and depends on the configuration arrangement. At subsonic speeds, the L/D is most directly affected by wingspan and wetted area.

The term 1/g cannot be controlled, but it shows that on a low gravity high atmospheric density astronomical object like Titan, electric flight could be a practical way for exploration. In fact, on Titan, an electric aircraft powered by a radioisotope generator might be able to fly for years.

The $\frac{m_{battery}}{m}$ ratio has vast effects on the range. This parameter can be increased reducing as much as possible the weight of the structure, the electric motors, the power electronics, the computers, the other systems, and the cabin furniture.

The total weight of the VTOL can be considered as the sum of empty weight, battery weight, and payload weight [19]. In figure 3, the empty weight fraction, the fuel fraction (in the case of electric aircrafts the fuel fraction corresponds to the parameter $\frac{m_{battery}}{m}$) and the payload fraction of many representative aircraft, rotorcrafts, and VTOLs are plotted. The first group of vehicles represents fixed-wing propeller-driven aircraft. The operating empty weight fraction varies from 77% of the old Spitfire to 40% of the Pipistrel Alpha Electro, which is built using composite materials. The Alpha Trainer and the Alpha Electro are two versions of the same aircraft, the difference in their empty weight fraction is because the gas engine is more massive than the electric motor. Commercial jet airliners have empty weight fractions of about 50%. Helicopters have empty weight fraction varying from 50% of the Chinook to 60% of the smaller R-22. The E-Hang 184 is built of composite materials and has an empty weight fraction of 44%. The

V-22 and AW609 tiltrotors and the Yak-38 and Harrier VTOL jets have empty weight fractions of about 60%. Fighter jets have empty weight fractions of about 67%. The vehicles with the lowest empty weight fraction are the Rutan Voyager and the GlobalFlyer designed to fly around the globe. The Rutan Voyager has an empty weight fraction of 22% and the GlobalFlyer of 16%. Rockets have empty weight fractions even lower, in the order of 15%.

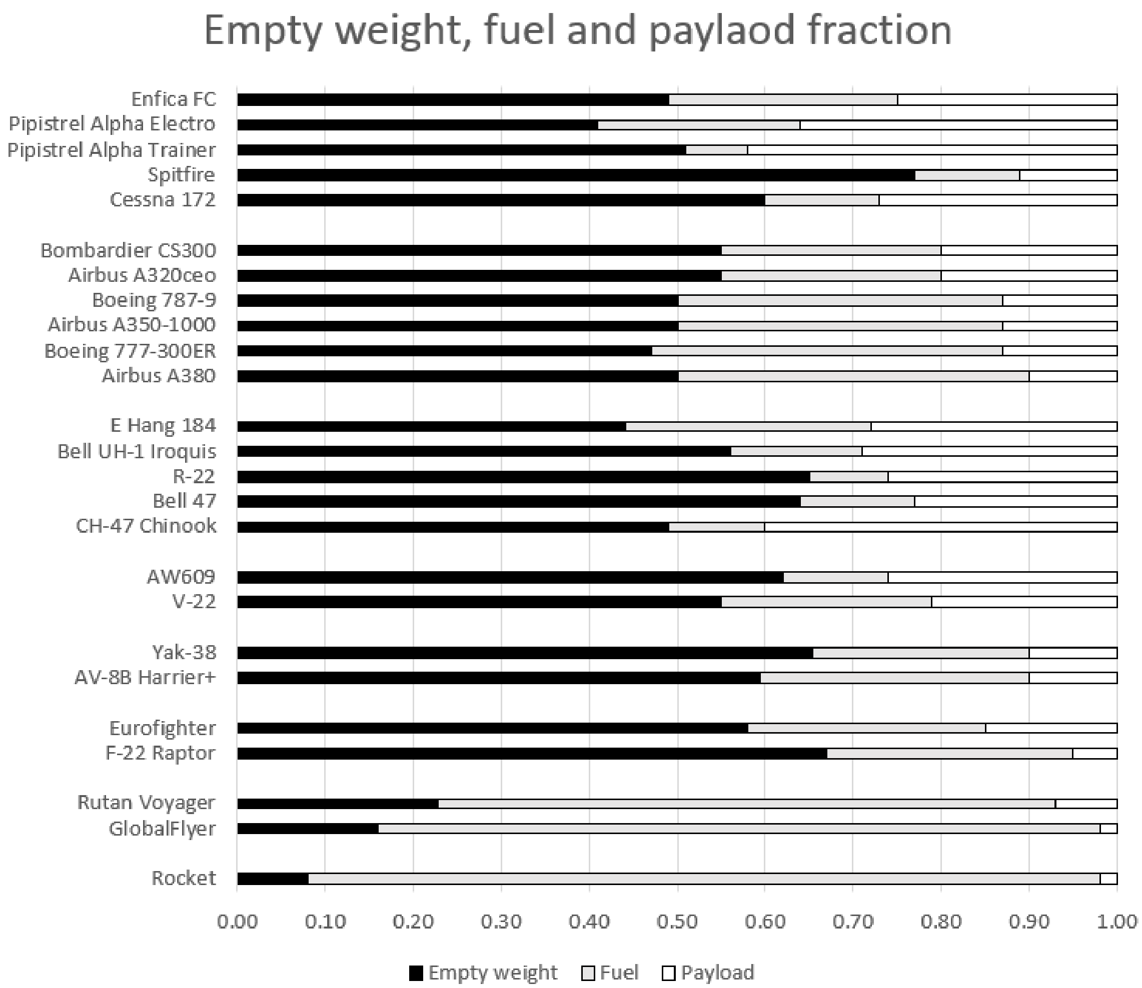

Figure 3: Empty weight, fuel, and payload fraction of existing aircraft, rotorcraft, and VTOLs [20].

Figures 4 and 5 provide data about standard values of the lift to drag ratio and the speed of the different aircraft.

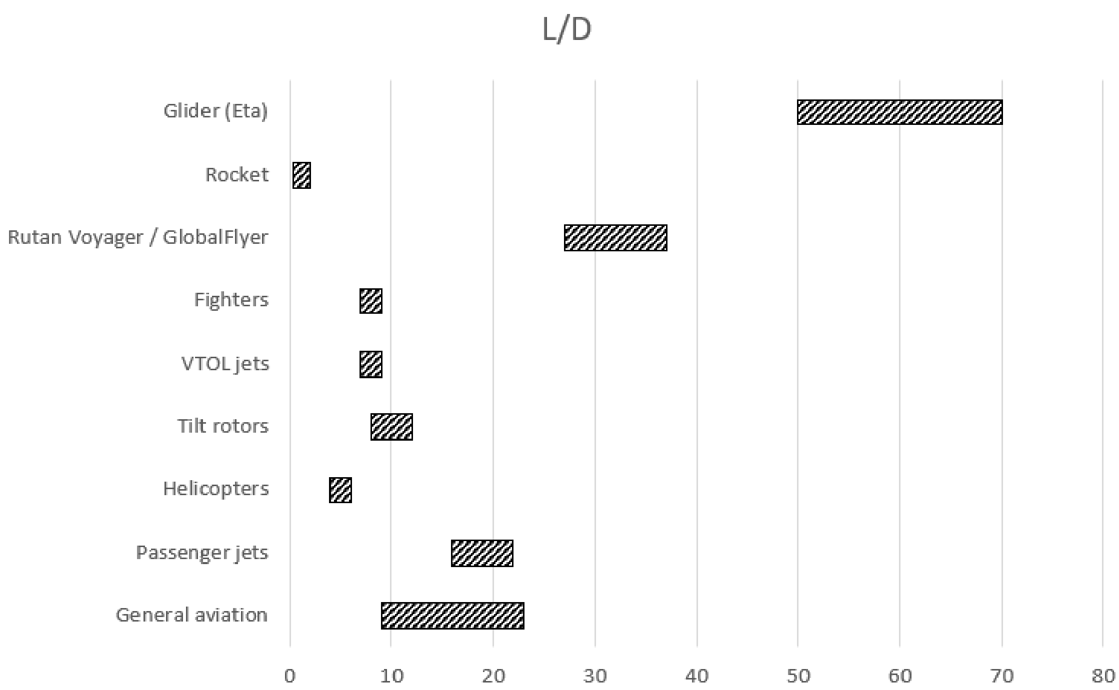

Figure 4: Lift to drag ratio of the different aircraft and rotorcraft types [20].

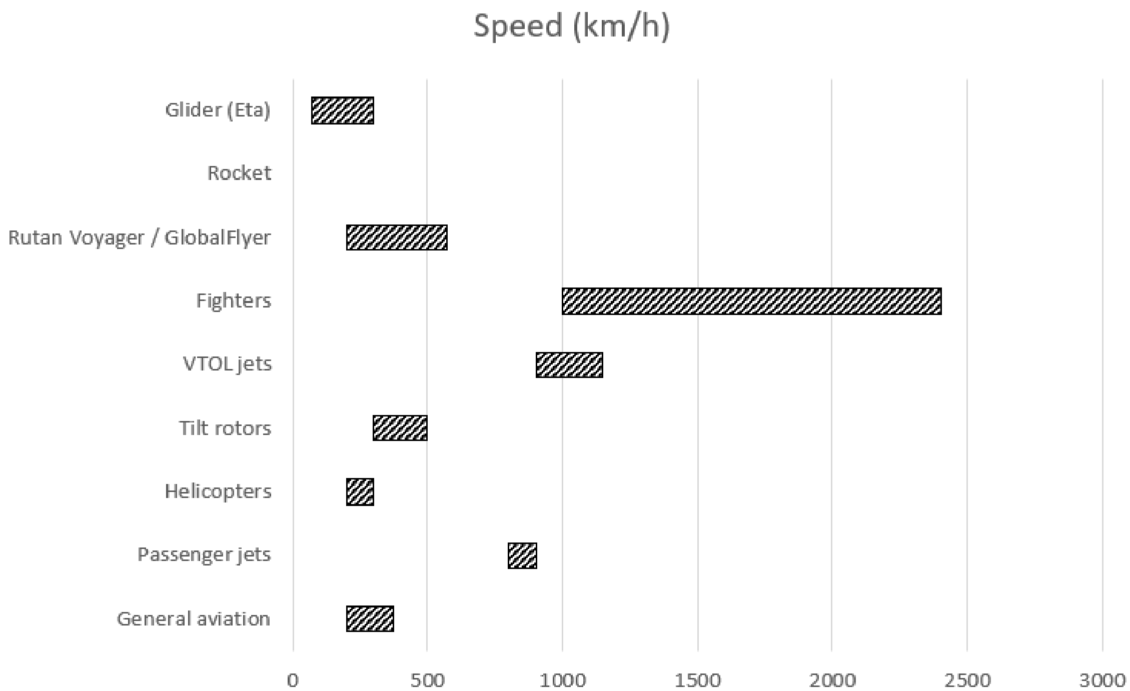

Figure 5: Flying speed of different aircraft and rotorcraft types [20].

The battery mass fraction can be reduced to increase the payload fraction. However, reducing the battery fraction means reducing the range. On the other hand, if the payload is reduced to increase the battery mass and the range, the number of passengers is reduced, and the cost of the trip per passenger in terms of electric energy increases. This cost can be computed writing the payload mass fraction as [19]:

$$\frac{m_{payload}}{m} = 1 - \frac{m_{empty}}{m} - \frac{m_{battery}}{m} \tag{15}$$

Assuming, as payload, one passenger and his luggage weighing $m_{payload} = 100\ kg$, the total mass can be computed:

$$m = \frac{m_{payload}}{m_{payload}/_{m}} \tag{16}$$

and the battery mass:

$$m_{battery} = m \cdot \frac{m_{battery}}{m} \quad (17)$$

Then the cost of the maximum amount of energy that can be stored in a battery of that size is computed:

$$Energy\ cost = m_{battery} \cdot E^{*} \cdot c \quad (18)$$

Where E* is the battery energy density in [Wh/kg], and c is the cost of the energy. E* = 200 Wh/kg and c = 0.12€ / kWh are assumed.

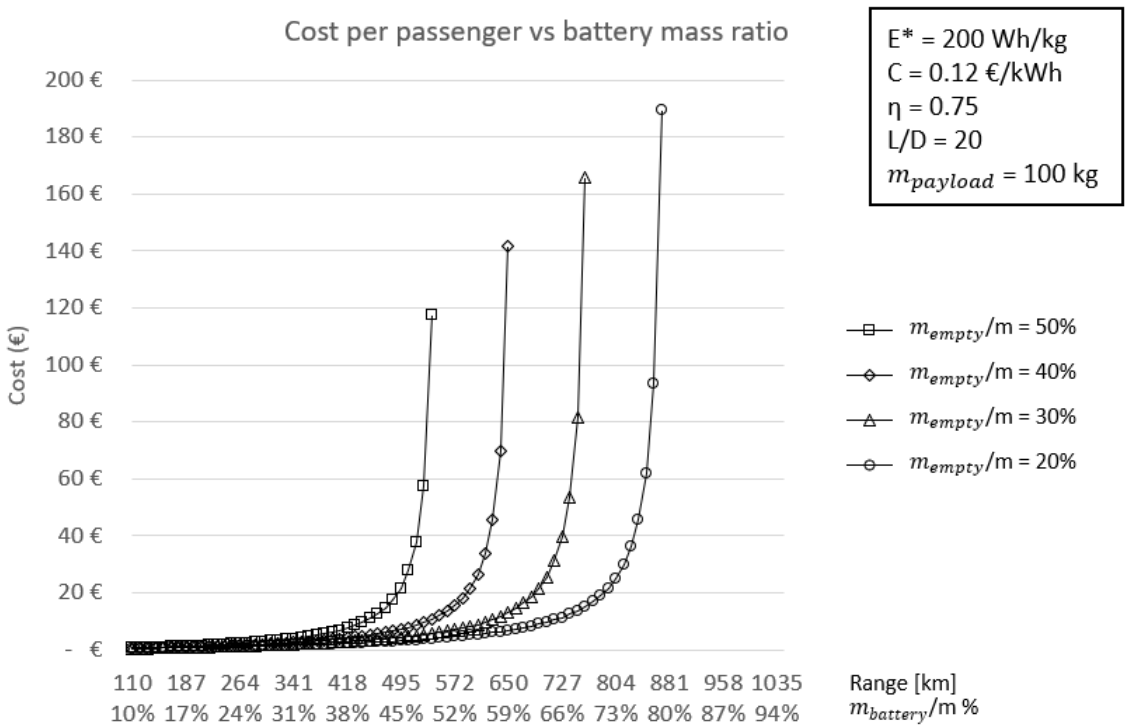

Figure 6: Energy cost to perform the maximum range trip at different empty weight fractions (m_{empty}/m) varying the battery to total mass ratio ($m_{battery}$/m).

In figure 6, each line represents an empty weight technology level. The graph shows that, for a given empty weight fraction, the range can be increased, increasing the battery weight fraction and the energy cost required to achieve that range. Each curve increases dramatically as the payload fraction approaches zero. Good electric aircraft designs will be at the beginning of the rapid increase. The ones remaining on the left are losing additional range at little cost, the ones on the right have huge total mass and high operating costs.

4. Take-off and landing

The first analysis showed that to improve the range, the total mass and aerodynamic drag must be reduced. For takeoff and landing, a system consisting of propellers or jets is required. This system is massive and increases the drag of the eVTOL. The range of the eVTOL reduces as the drag increases. The vertical thrust system can be made smaller increasing its power, or it can be mechanically retracted inside the fuselage like Krossblade Aerospace's SkyProwler [21]. Another idea is to use the same system that provides thrust during forward flight to generate the thrust required for hover. This is the idea adopted by Lilium [22]. Even if these and other techniques may be used to reduce drag, the area occupied by the vertical thrust system can be used to evaluate how much the vertical takeoff and landing capability affects the range. With the disk actuator theory [23], the minimum vertical thrust system area required for an electric VTOL is estimated. The result of the disk actuator theory applied to hover is:

$$P = \sqrt{\frac{T^3}{2\rho A}} \tag{19}$$

P is the required power to hover, T is the thrust or the weight of the eVTOL, ρ is the air density, and A is the actuator disk area. Equation 19 shows that the power required to hover decreases as the disk actuator area increases. To have the best vehicle for hover, the disk actuator area must be increased. However, this large disk actuator area increases the aerodynamic drag in forward flight. This formula is valid for free propellers, but it can be easily extended to ducted fans knowing that, without viscous losses, a ducted fan of the same size and same power can produce 25% more thrust than a free propeller [24]. For missions with short hover time compared to cruise flight, the vertical thrust system area can be reduced as much as possible to reduce the drag it produces in cruise flight. The smallest disk actuator area required to provide enough vertical thrust for vertical takeoff and landing can be computed rewriting equation 19 for a battery-powered eVTOL:

$$m_{payload} \frac{m_{battery}/m}{m_{payload}/m} k_p = \sqrt{\frac{\left(\frac{T}{W} \frac{m_{payload}}{m_{payload}/m} g\right)^3}{2\rho A}} \quad (20)$$

Where $m_{payload}$ is the payload mass, k_p is the specific-power of the batteries, $m_{battery}/m$ is the battery mass fraction, $m_{payload}/m$ is the payload mass fraction, $\frac{T}{W}$ is the thrust to weight ratio of the vehicle and g is the gravity acceleration.

In equation 20, the power required to hover and the thrust produced are rewritten. Hover and vertical ascent are the most power demanding phases of the VTOL flight; for this reason, the battery pack is sized to provide enough power for hover plus a margin. The power available is written in this form because this is the maximum power that can be extracted from the batteries. The total mass of the vehicle is $\frac{m_{payload}}{m_{payload}/m}$; multiplying it by $m_{battery}/m$ gives the total battery mass; multiplying again by k_p the total power available is found. The power found is not a physical limitation to the maximum power available. It can be significantly augmented using supercapacitors. However, this means reducing the energy density of the battery plus supercapacitors pack. Decreasing the energy density E*, the range of the eVTOL decreases.

The thrust has been rewritten following the same procedure. The total weight is $\frac{m_{payload}}{m_{payload}/m}\, g$ and it has been multiplied by the thrust to weight ratio desired.

Equation 20 can be rearranged to show the disk actuator area required:

$$A = \frac{\left(\frac{T}{W}\, \frac{m_{payload}}{m_{payload}/m}\, g\right)^3}{\left(m_p\, \frac{m_{battery}/m}{m_{payload}/m}\, k_p\right)^2} \frac{1}{2\rho} \tag{21}$$

$$A = \frac{\left(\frac{m_{payload}}{m_{payload}/m}\right)^3}{\left(m_{payload}\, \frac{m_{battery}/m}{m_{payload}/m}\, k_p\right)^2} \frac{g^3}{2\rho}\left(\frac{T}{W}\right)^3 \tag{22}$$

$$A = \frac{g^3}{2\rho}\left(\frac{T}{W}\right)^3 m_p \left(\frac{1}{k_p}\right)^2 \frac{\left(\frac{1}{m_{payload}/m}\right)^3}{\left(\frac{m_{battery}/m}{m_{payload}/m}\right)^2} \tag{23}$$

$$A = \frac{g^3}{2\rho}\left(\frac{T}{W}\right)^3 m_p \left(\frac{1}{k_p}\right)^2 \frac{1}{m_{payload}/m \left(m_{battery}/m\right)^2} \tag{24}$$

The final formula is:

$$\boxed{A = \frac{g^3}{2\rho}\left(\frac{T}{W}\right)^3 m \left(\frac{1}{k_p}\right)^2 \frac{1}{\left(m_{battery}/m\right)^2}} \tag{25}$$

The disk actuator area is directly proportional to the cube of the gravity and inversely proportional to the atmospheric density. This fact has exciting consequences for planetary exploration. A Martian quadrotor is feasible and can be tested in Earth's atmosphere at about 12 km altitude where the parameter $\frac{g^3}{2\rho}$ has the same value it has in the Martian atmosphere just above the ground. On Titan the $\frac{g^3}{2\rho}$ parameter is extremely low due to the low gravity and high atmospheric density. This fact makes Titan suitable to be explored by flying machines. Using the same radioisotope thermoelectric generator used by the Curiosity rover, a VTOL for Titan could be built.

The disk actuator area is proportional to the cube of the thrust to weight ratio. This parameter must be higher than 1 to provide a margin for vertical takeoff and landing.

The disk actuator area is directly proportional to the total mass of the vehicle, limiting the total dimension of electric VTOLs. Existing designs cannot be scaled up because the mass is proportional to the cube of the reference length, while the thrust system area is proportional to the square of the reference length. Equation 19 shows that the power required grows with the mass raised to the 1.5 power.

The disk actuator area is inversely proportional to the square of the battery specific-power. This fact is essential when considering alternative power systems such as fuel cells. At the present technology level, the fuel cell specific-power is lower than the battery specific-power. Fuel cells might be used if coupled with supercapacitors which increase the power for takeoff and landing. However, supercapacitors have very low energy densities which reduce the total energy density of the power system.

Finally, the ${m_{battery}}/{m}$ ratio is found once again. The disk actuator area is inversely proportional to the square of this parameter, meaning that the higher this parameter is, the smaller the disk actuator area required is. The ${m_{battery}}/{m}$ ratio has also been found in the range analysis. Increasing this parameter improves the range and allows to hover with a smaller disk actuator area.

Some numerical values of the thrust system area required, computed with equation 25, are shown in figures 7, 8, and 9. The values used for the computations are listed in table 4.

Table 4: Data used for hover computations.

Gravity	9.81 m/s^2
Density	1.225 kg/m^3
Thrust to weight	1.3
Total mass	750 kg
Battery specific power	800 W/kg
Battery mass ratio	40%

High specific-power, in the order of 800 W/kg, is required to have reasonably small thrust system areas. Batteries have higher specific-power than fuel cells, and this is their advantage.

The $m_{battery}/m$ is essential both for hover and range. It should be at least 30% to have a small vertical thrust system area.

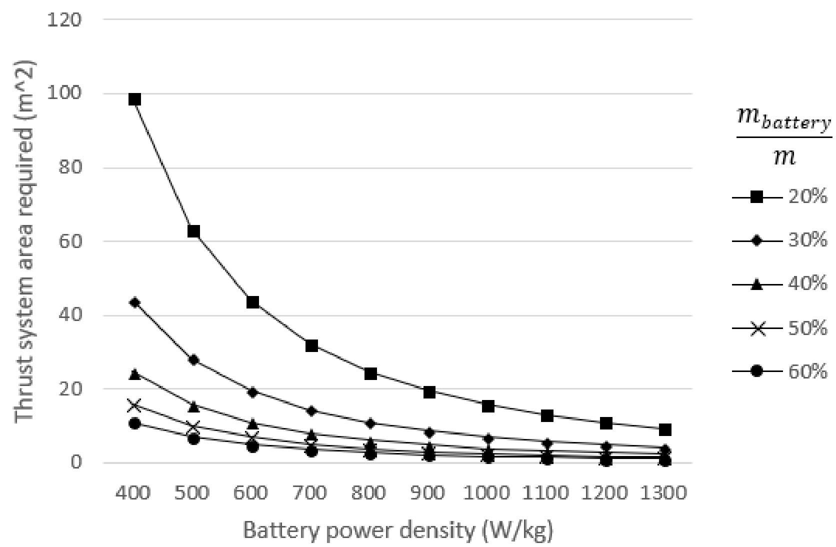

Figure 7: Thrust system area required function of the battery specific-power for various battery to total mass ratios.

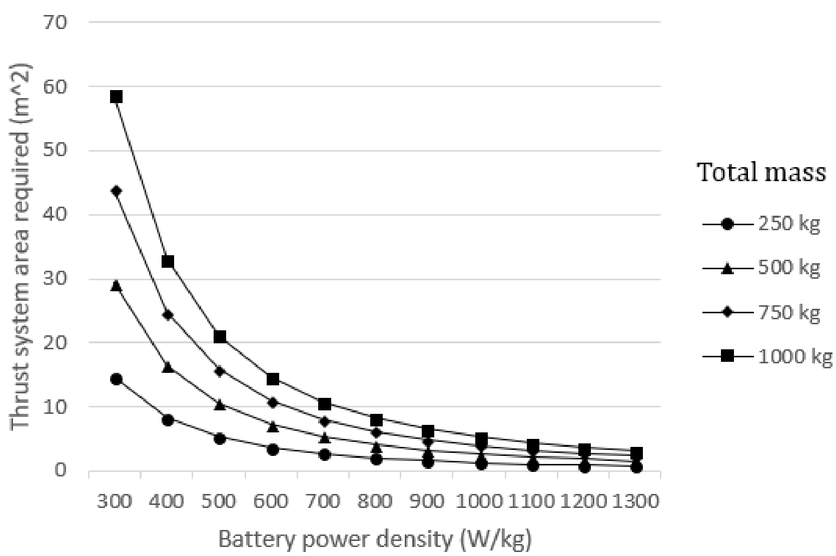

Figure 8: Thrust system area required function of battery specific-power for various total mass.

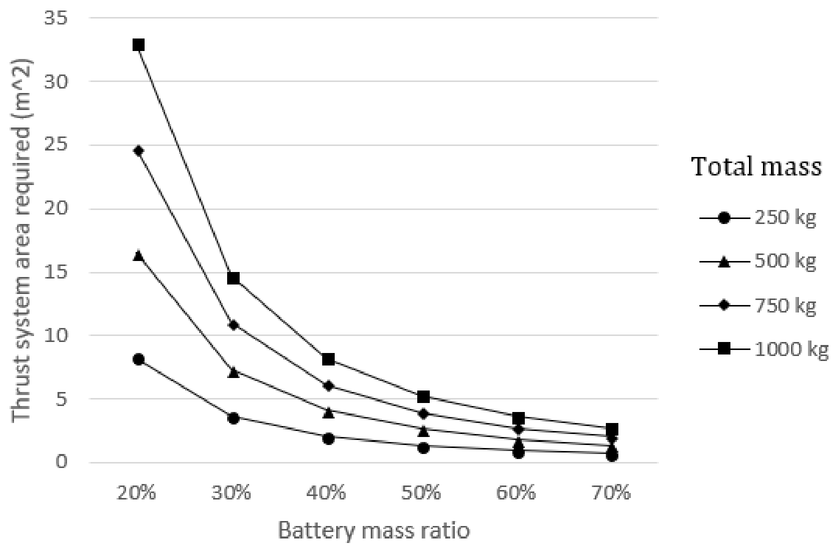

Figure 9: Thrust system area required function of the battery to total mass ratio for various total mass.

5. Transition from hover to forward flight

The phase in which the VTOL is accelerating from hover to cruise flight is called transition. This phase has been problematic for VTOLs of the fifties and sixties because the lift provided from the thrust system and by the wing varies nonlinearly. There may be a lack of control power [25] as mobile surfaces do not receive enough airspeed to be effective, and reaction control systems lose effectiveness.

Besides the engineering challenges posed by each different configuration, it is interesting to study the dimensions of the wing to optimize the VTOL for its mission. For a conventional aircraft, the wing surface of an aircraft is constrained by the stall speed requirement. VTOLs do not have this constraint, and their wing can be optimized for cruise flight. In figure 10, a free body diagram of the transition of two different VTOLs is shown.

Configuration A has a smaller wing than configuration B's, its stall speed is higher, and the transition phase will require more energy. However, configuration A is more efficient at high speeds having less drag. Configuration B has a bigger wing. It requires less energy to reach the stall speed, but it has more drag.

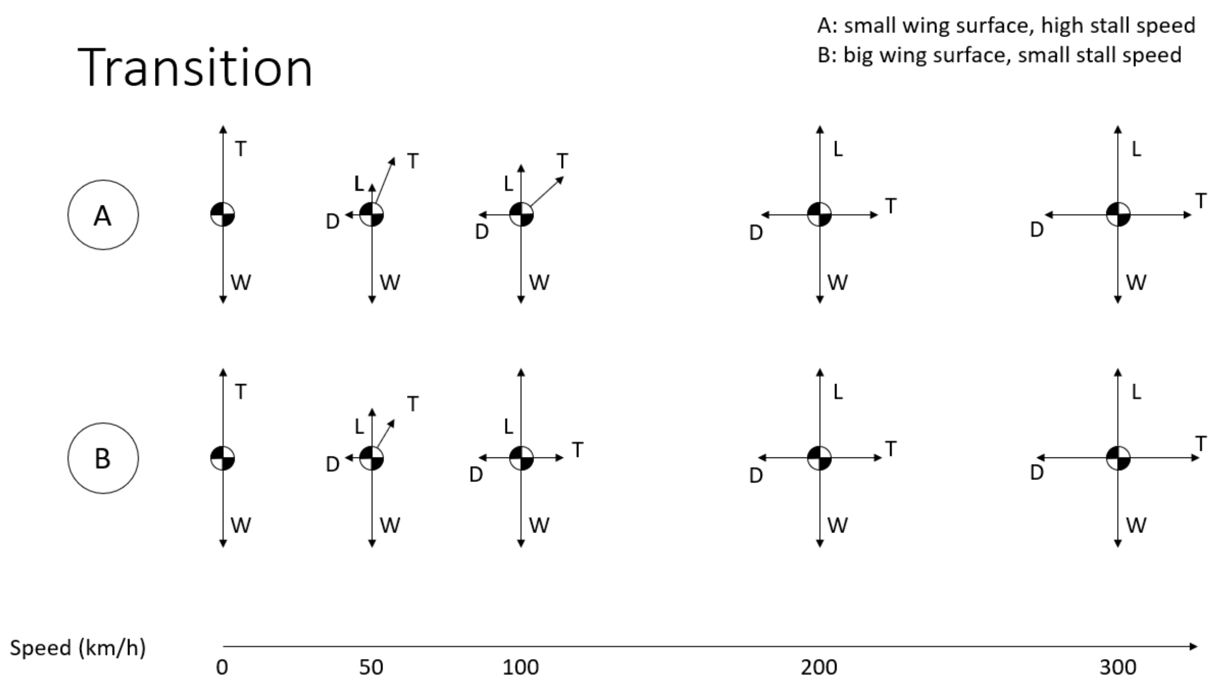

Figure 10: Free body diagram of the transition from hover to forward flight for two VTOLs. Configuration A has a smaller wing surface while configuration B has a bigger wing surface.

At fixed cruise speed, an optimal wing surface can be found to reduce the mission energy costs. The influence of the wing surface on the energy required to get from hover to cruise flight is analyzed. The aspect ratio of the wing and the cruise speed are fixed. The data used in the following calculations are listed in table 5.

Table 5: Data used for transition computations.

Total mass	500 kg
Cd0	0.022
K	0.03
Wing surface	2 m^2
Thrust system area	6 m^2
Battery power	147 kW
Total efficiency	75%
Aspect ratio	10
Cruise speed	300 km/h @ sea level
Maximum horizontal acceleration	3 m/s^2

A vectored thrust eVTOL is considered. The thrust system can provide a maximum thrust constrained by the power available, and it can be vectored to produce vertical thrust and horizontal thrust. The vertical thrust required is computed as the weight minus the lift produced by the wing.

$$T_v = W - L \tag{26}$$

It varies from the total weight of the VTOL when it is hovering, to zero after the stall speed. The horizontal thrust is computed in order to have accelerations lower than an imposed threshold of 3 m/s^2, chosen to ensure a comfortable passenger experience. To perform this computation, full power is considered and the thrust angle producing the required T_v is computed:

$$\alpha = \sin^{-1}\frac{T_v}{T_{max}} \tag{27}$$

Then the maximum available horizontal thrust is computed:

$$T_{h\,max} = T_{max}\cos\alpha \tag{28}$$

With this thrust the acceleration is computed as maximum available horizontal thrust minus aerodynamic drag divided by the total mass:

$$a = \frac{T_{h\,max} - D}{m} \tag{29}$$

If this value is less than the maximum acceleration allowed a_{max}, the value found of horizontal thrust is kept, else a new value of horizontal thrust is computed as the maximum allowed acceleration times total mass plus aerodynamic drag:

$$T_h = a_{max}m + D \tag{30}$$

To compute the total energy required for the transition, the power required has been integrated in time. This process has been carried out with a simple Euler method that updates the speed at each time step.

$$v_{n+1} = v_n + a \cdot \Delta t \tag{31}$$

Then lift, drag, horizontal thrust, and vertical thrust are computed again for each time step. The energy consumed at each time step is computed multiplying the average power of the two successive time steps by the Δt:

$$E_n = P_{avg} \cdot \Delta t \tag{32}$$

The total energy required to get from hover to cruise is computed adding all the energies of the steps from horizontal speed equals zero to cruise speed.

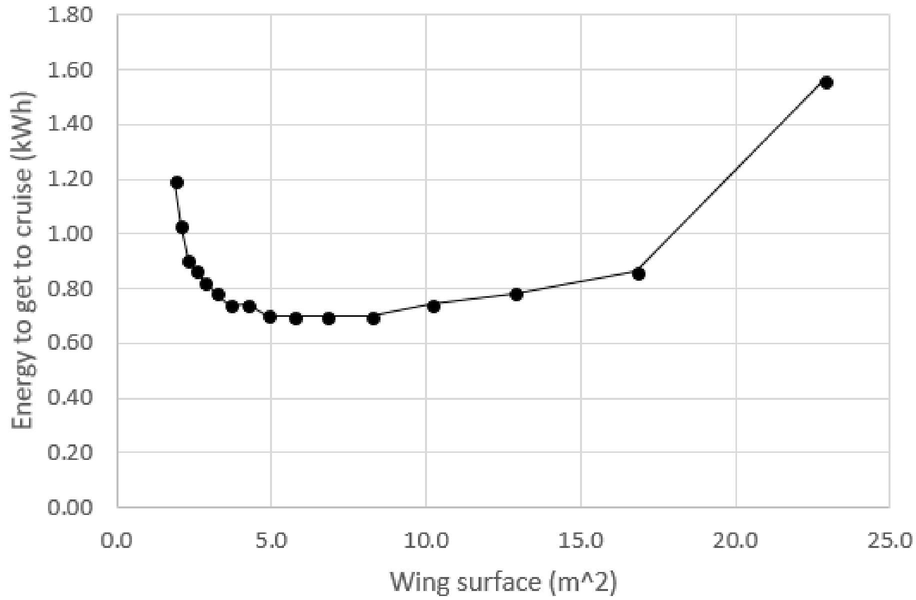

Figure 11: Energy required to get from hover to cruise speed function of the wing surface.

The results of these computations are plotted in figure 11. This image shows the energy required to get to cruise for different wing surfaces. Configuration A discussed earlier represents VTOLs on the left in figure 11, configuration B represents VTOLs on the right in that figure. At low wing surface, the energy required is high because high power is required to supplement the little lift produced by the wing at low speed. The energy required drops as the wing surface increases. Then, the energy required increases again, when the increase in wing surface creates an unnecessary increase in wetted area. The integration with the Euler method is the reason why the curve in figure 11 is not perfectly smooth.

With the same data, it is possible to analyze the power required at every flight speed. The power required is the sum of its two components, horizontal and vertical.

$$P_v = \sqrt{\frac{{T_v}^3}{2\rho A}} \tag{33}$$

$$P_h = D \cdot v \tag{34}$$

The vertical component is computed like in equation 19, with the disk actuator theory. The horizontal component is computed multiplying the drag by the flight speed. These two sources of power requirements are plotted in figure 12. In a vectored thrust VTOL the balance between vertical and horizontal thrust is achieved tilting the motors, in a lift + cruise configuration controlling the power given to the motors.

In figure 12, it is possible to see that there is no advantage in flying at a speed slower than the stall speed providing the required vertical thrust with the motors instead of the wing. The power required would be higher and time would be lost flying at lower speeds. The minimum of the required power is after the stall speed, where ${C_L}^{3/2}/C_D$ is maximum. The speed that allows having the highest range is the speed at which L/D is maximum, and it is higher than the speed of minimum power required. For commercial applications, the optimal speed might be higher because it would allow saving additional time.

Another consideration suggested by figure 12 is that for an electric VTOL the wing surface should not be designed for takeoff and landing requirements, but it should be designed for cruise and maneuverability, minimizing the total energy required for the mission.

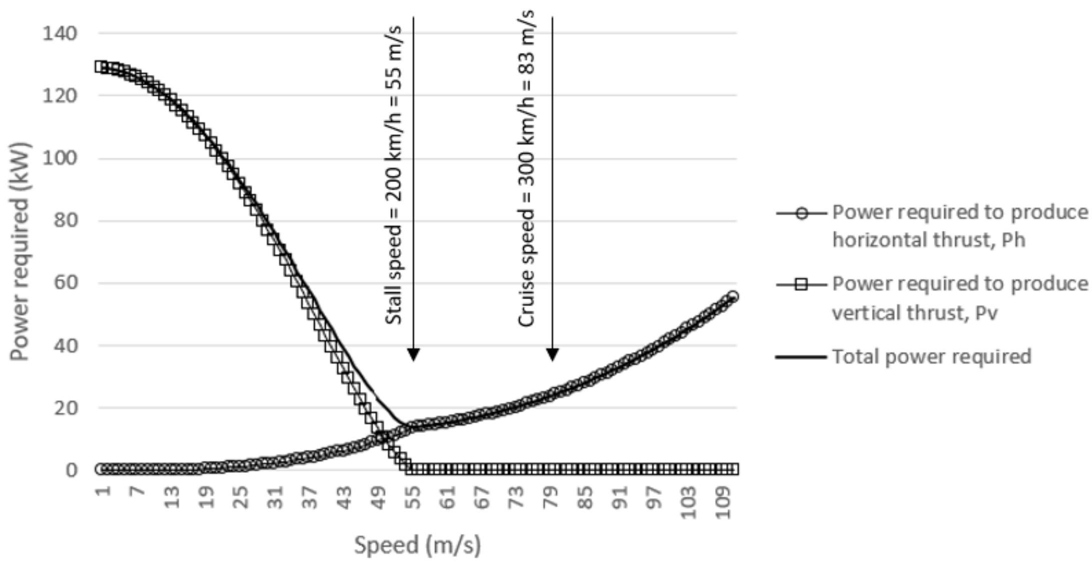

Figure 12: Power required for any flight speed.

6. Future work

In this article, the range, the hover, and the transition of the electric VTOL have been discussed. To better analyze eVTOL design, three work topics seem promising.

First of all, a comparison of the many different eVTOL configurations should be carried out. Multirotors are less-complex machines and may be better suited for short-range missions. Lift plus cruise, and vectored thrust electric VTOLs seem more promising for longer-range missions [26].

Analyzing the eVTOL configuration, the second topic arises. Should an electric VTOL have a tail like a conventional aircraft? A tail would provide more stability, but it would increase its weight decreasing the battery to mass ratio, the range, and the payload.

The third topic for possible future work is the comparison between different power sources. In this study, we assumed electric VTOLs powered by batteries. Fuel cells and internal combustion engines or turbine + battery hybrids may be good alternatives.

7. Conclusions

The state of the art battery energy density does not allow to electrify the aviation industry. Long-range electric jets cannot be built yet, regional electric aircraft could be built to service small distance routes in the order of 500 km, but some problems may remain concerning the lack of reserves for holding at the destination airport and the infrastructure that must be added to current airports. However, this same technology and the advantages of electric propulsion enable the creation of a new means of transport, the electric VTOL.

This new means of transport could be better than road and rail transport because it does not get stuck in traffic jams, flies straight to the destination and does not have to win the rolling friction. Electric VTOLs have the chance to be also better than helicopters. Helicopters are not widely used because they are too expensive and noisy. The cost is due to the propellant, the maintenance, and the pilot, which are all components that would not be required for electric VTOLs. Noise can be reduced distributing the electric propulsion and optimizing the architecture.

The cruise flight, the hover, and the transition of an electric VTOL have been analyzed, and the main parameters that affect these phases have been derived.

The range of electric VTOLs with present battery technology is in the order of 200 km enabling long-range commutes. The factors affecting it are the lift to drag ratio, the propulsive efficiency, battery energy density and the battery mass to total mass ratio. The tradeoff between battery mass and payload mass has been further studied.

Electric VTOLs must be designed as a compromise between hover efficiency and long-range, high-speed cruise. High hover efficiency requires large disk actuator area which increases the parasite drag during cruise flight. For missions with short hover time compared to cruise flight, the vertical thrust system area can be reduced as much as possible to reduce the drag it produces in cruise flight. The equation to compute the smallest disk actuator area required to provide enough vertical thrust for vertical takeoff and landing has been derived (25). It shows that this area is proportional to the cube of the thrust to weight ratio, proportional to the total mass of the vehicle, inversely proportional to the square of the battery specific-power, and inversely proportional the square of the battery mass to total mass ratio.

This analysis highlighted the importance of the battery mass to total mass ratio that affects both range and hover capabilities.

The transition phase has been analyzed, and some remarkable results have been derived. The wing of an electric VTOL must not be sized for the takeoff and landing requirement, but it can be smaller and optimized for cruise.

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