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TÍTOL DEL TFG: Overview on Sustainable Aviation Technologies and Guidelines for its Application

TITULACIÓ: Grau en Enginyeria de sistemes Aeroespacials

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Resum

Tot i que l'aviació és actualment el més eficient que ha sigut mai, genera entre el 2% i el 3% de les emissions globals de gasos d'efecte hivernacle. A diferència d'altres industries, fer un canvi cap a les bateries elèctriques com a forma d'emmagatzemar energia no és trivial, ja que les bateries només poden emmagatzemar una fracció de l'energia que conté el combustible per kg. Això ha portat a la industria a buscar formes alternatives de reduir el consum de combustible

Aquest projecte es fixa en tres àrees de recerca diferents que l'autor ha cregut que s'adeqüen a la dimensió del treball, els recursos disponibles i que poden tenir un major impacte a l'aviació des del punt de vista d'optimització mediambiental.

El primer d'aquests objectius és determinar la ineficiència de les aeronaus que volen a l'espai aeri europeu. Com es veu al projecte, hi ha dues fonts principals d'ineficiència, tot i així l'arrel del problema és la mateixa: Operació de les aeronaus fora de la seva àrea de màxima eficiència. Ja sigui perquè l'avió ha sigut modificat per portar menys passatgers o perquè les aeronaus es fan servir per a rutes massa curtes, el resultat acaba sent el mateix: crema de combustible innecessària a l'espai aeri europeu. La solució proposada és utilitzar aeronaus més eficients per a determinats rols i rutes.

El segon front de treball es centra en les operacions a terra. Els motors turbofan són molt eficients en creuer. Però aquesta optimització a l'aire té un impacte a la seva operació a terra. Per exemple, la crema de combustible genera proporcionalment més producció de gasos d'efecte hivernacle, genera contaminació acústica als voltants de l'aeroport, i acurta la vida dels motors. I sobretot els motors consumeixen una gran quantitat de combustible durant aquestes fases. Una solució en la que ja estan treballant diverses empreses del sector són els sistemes auxiliars per al taxi i el pushback durant els quals els motors romanen apagats.

El tercer i últim objectiu és establir un procediment per modificar la planta motora convencional d'aeronaus simples (amb un sol motor i lleugeres), a un motor elèctric. El problema amb les aeronaus més grans és que realitzar una conversió elèctrica limita severament l'abast. Al model actual de negoci, l'abast hi juga un paper crucial ja que determina quines rutes pot monetitzar una aerolínia. No obstant, les aeronaus més petites no estan necessàriament vinculades a haver de realitzar vols llargs. De fet hi ha multitud de tasques que realitzen aeronaus actuals que no necessiten tenir llarg abast. Per exemple l'observació d'àrees rurals, l'entrenament de pilots, i els vols turístics són rols on el llarg abast no és necessari. Per tant convertir aeronaus convencionals a aeronaus elèctriques és una opció que, donats els baixos costos operacionals, els propietaris poden considerar rendible.

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Overview

Although aviation is arguably the most efficient it has ever been, it is to blame for the 2% to 3% of global greenhouse gas (GHG) emissions. In contrast to other sectors, switching to electric energy, is not a straightforward procedure. The energy density of batteries is only a fraction of that in fossil fuel, and weight plays a crucial role in aviation. This presents a challenge that the aviation industry is tackling in creative ways.

This project studies different topics the author considered to fit the scale of the project and of the available resources. And that would have the greatest impact on the industry from an environmental standpoint.

The first goal is to quantify the inefficiency of the aircraft in the European airspace. As seen in the project, there are two main sources of inefficiency, although, the root of said inefficiencies is the same: Operation of the aircraft outside their ideal efficiency area. This can happen either because an airplane has been modified to carry less passengers (pax) or because it is operating outside their efficient range. Both cases result in unnecessary fuel burn and should be avoided. The proposed solution is the implementation of aircraft better suited for those roles and routes in which present day aircraft are inefficient.

The second objective focuses on ground operation. Turbofan engines are very efficient during the cruise phase. This does, however, have an impact on their ground operation. For instance, the proportional generation of certain GHGs is considerably higher at this stage, acoustic pollution is produced, and the operative span of the engines gets shorter. Also, massive amounts of fuel burn during these phases. A solution in which some companies are working on is auxiliary taxi and pushback systems that keep the engines shut on ground.

The last objective is to study and explain the modification of simple aircraft (light, single engine), with a conventional, internal combustion powerplant to an electric one. The main issue with electric conversion in larger, commercial aircraft is the limited range. Range plays a crucial role in the commercial aviation industry because it determines which routes an airline make profit of. However, small aircraft are not as subject to range. In fact, many missions carried out by small aircraft such as surveillance of natural areas, pilot training, or touristic flights, do not need long range aircraft. Thus, given the low operational cost of an electric aircraft, small aircraft owners may consider converting theirs to an electric aircraft.

Voldria donar les gràcies a la meva mare, que sempre ha treballat perquè no em faltés de res, a ma germana, que m’ha ajudat a mantenir el seny, a mon pare que m’ha ensenyat a ser creatiu, a la Hanne, que sempre m’ha donat tot el seu suport, a l’Oscar, que sempre ha estat a disposició d’ajudar-me, a l’univers, per haver-me donat l’oportunitat de ser aquí, i a mi mateix, per no rendir-me mai. Gràcies a tots.

Abbreviations and clarifications

Taxi – Phase of the flight in which the aircraft goes from the terminal of the parking spot to the runway and vice versa.

Pushback – Manoeuvre in which the aircraft is towed from the terminal to the taxiway.

EGT – Exhaust Gas Temperature. Generally speaking, it is higher at higher power settings.

Turbofan – A kind of axial engine in which a turbojet drives a larger fan that moves a large volume of air to thrust the aircraft.

GHG – Greenhouse Gas

ICAO – International Civil Aviation Organisation

CO2 – carbon dioxide

NOx – Nitrogen Oxides

Induced drag – force in opposite direction to the movement of the aircraft. It is produced because of the wings creating vortices, thus, wasting energy.

Cd – drag coefficient. A number linked to the drag produced by a body in motion through a fluid.

MTOW – Maximum Take Off Weight of an aircraft.

OEW -Operative Empty Weight. Weight of the aircraft with everything that is required for it to operate, not considering the fuel mass.

MZFW – Maximum Zero Fuel Weight. Maximum weight an aircraft can withstand including OEW and Payload but no fuel.

EPATS – Electric Pushback And Taxi System.

EPM – Electric Powerplant Modification. A modification in an aircraft in which the conventional, fossil fuel powerplant is replaced by an electric one.

FOD – Foreign Object Damage. A situation in which an object enters the engine of the aircraft damaging it.

Boundary Layer – Area of moving air immediately in contact with a steady body. The thickness of this layer is defined between the particle that is in contact with the steady body and the particle that is travelling at 99% of the velocity of the air in the free stream.

Third gen – References to third generation aircraft, which are described in section 1.1.c.

Fuel Efficiency – a concept which determines how much fuel is burnt to accomplish a certain milestone. For instance to transport one kg of payload a certain distance. It is usually measured in (km/L)*pax.

Pax – passenger.

Loading index or percentage – percentage of used aircraft maximum payload.

APU – Auxiliar Power Unit. Generator generally located at the tail of the aircraft able to provide electrical, pneumatic, and hydraulic pressure to the aircraft while on ground and in emergency situations.

EASA - European Union Aviation Safety Agency.

MFW – Maximum Fuel Weight. Maximum fuel that an aircraft can carry.

ISA – International Standard Atmosphere.

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INTRODUCTION

In the last decades, many industries have seen the rising importance of sustainability. For instance, the automotive industry is quickly developing and commercializing electric models. Despite this kind of car is a minority, it is a well-known fact that the number of electric cars on the streets will only increase from this point forward. Comparing this trend to the field of aviation, commercial airplane manufacturers do not seem to adapt to the situation as fast as the car industry.

In 2016, aviation was accountable for 3.6% of the total EU28 greenhouse gas emissions and for 13.4% of the emissions from transport. Making aviation the second most important source of transport emissions after road traffic. Greenhouse Gas (GHG) emissions from aviation in the EU have more than doubled since 1990 [1].

Paradoxically, the efficiency of aircraft engines has increased dramatically since the 1980s, and the number of active three and four-engine airplanes has decreased. So how is this increase in emissions possible? It can be explained mainly due to the increment in the number of flights and passengers in the last decade. Although efficiency increases with every technological improvement, aviation is still one of the main greenhouse emitters due to the high number of flights.

While the car industry is a good example of the conversion of fossil fuel to electrically powered transportation, it cannot immediately be extrapolated to aviation. The critical importance of energy-to-weight ratio and safety makes this transformation a real challenge for the aerospace sector. Despite the complexity, different stakeholders in the sector such as operators, manufacturers, and governments are working to tackle the climate change problem.

This project has a series of objectives related to sustainability in aviation that are listed below:

- Spot, investigate and analyse sources of inefficiency in the context of European aviation.
- Develop models to quantify the environmental and economic impact of these sources as well as their solutions.
- Propose the most feasible set of actions to tackle these issues and make aviation more sustainable.

CHAPTER 1. BACKGROUND

1.1. A unified commitment

In the Paris air show of 2019, Airbus, Boeing, Dassault, General Electric, Rolls Royce, Safran, and United technologies signed an agreement on approaching the climate challenge in a unified manner. In the document [1], the different manufacturers commit to halving the amount of emissions generated by aviation in 2005 by 2050. This goal was set by ICAO in a program called Carbon Offsetting and Reduction Scheme for International Aviation, or CORSIA for short [2]. To reach this objective, the companies were to focus on three main strategies:

a) Aircraft and Engine Design and Technology

This strategy is based on improving present technologies or implementing new technologies in the present infrastructure to improve the overall fuel efficiency, along with CO2, NOx, and noise emissions.

This strategy has been developed in the last 40 years due to significant investment in R&D for materials, aerodynamic efficiency, digital design and manufacturing methods, turbomachinery developments, and aircraft systems optimization. Examples of the resulting outcomes are winglets, more fuel-efficient and higher bypass ratio turbofans, composite materials, and fuselage shapes with lesser Cd.

The Boeing 737 (B737 for short) is a living example of this strategy. Designed in the 1960s, it is widely used across the world due to constant innovations the aircraft goes through. Some of these innovations are winglets to reduce induced drag, optimized engines with sawed outlets to reduce noise, and a glass cockpit with improved FMS to simplify the operability of the aircraft. Obviously, these are technologies that the aircraft industry did not have in the 1960s but the B737 has adopted them as they appeared.

Fig. 1.1 B737-200, one of the early versions of the B737. [3]

Fig. 1.2 B737 MAX 8, One of the latest version of the B737. [3]

b) Fostering the Energy Transition: Sustainable Aviation Fuels

The agreement states that even in the most optimistic forecasts of electric aviation, liquid-fuelled aircraft will still be flying for the years to come. Therefore, alternative fuels are of key importance to reduce the amount of fossil fuel usage. Accelerating production scale-up of all commercially viable pathways while simultaneously developing additional lower-cost pathways, is believed to be the key to the success of this strategy. [4]

Alternative fuels have shown great results in commercial flights and still show a slow but steady increase in usage. This strategy is, however, mainly focused on the chemical nature of transforming organic matter into high energy density jet fuels. Therefore, this objective will not be studied in this project.

c) The Third Era of Aviation

The first era of aviation began with the Wright brothers. At the end of WWII, with the invention of jet-powered aircraft, the second era began. The growing interest in more sustainable means of transportation in the 2010s has been fuelling the evolution towards the third era of aviation. The third era of aviation will develop not only the proportionally lowest polluting commercial aircraft in history, but it will use revolutionary technologies to make it possible. Electric motors, hybrid architectures and artificial intelligence may be the technologies that enable the third era of aviation.

Despite its futuristic appearance, non-fossil-fuel-powered airborne vehicles have flown in the past; The first-ever electric airship in that Gaston Tissandier flew in 1883, and a three-bladed helicopter that was meant to replace the highly flammable hydrogen airships of WWI are great examples of this. However, none of these aircraft's main goal was to reduce emissions. The first aircraft that may be considered the pioneer of third era aviation was the MB-1E, a 1970s glider modified with an electric motor and a battery able to keep the aircraft in the air for 15 minutes.

Fig. 1.3 MB-1E [5]

Other aircraft that could be considered part of this group are solar and hydrogen-powered aircrafts. Examples are solar impulse 1 and 2 and a Russian tri-engine Tu-155, which had an engine running on hydrogen stored by cryogenic means.

Fig. 1.4 Solar Impulse 1 during its first “flea hop” test flight in Dubendorf on December the 3rd, 2009. [6]

Fig. 1.5 stored Tu-155 with right hydrogen engine [7]

1.1.1. Overview

The combination of all three strategies is the way aerospace manufacturers are going to tackle the objective established by ICAO; while still improving present aircraft efficiencies and burning less fossil fuel, third era aircraft can be studied and safely implemented in the long term.

Because the entire industry is putting their efforts in these objectives, this project will focus on them as well. To determine which challenges are to be overcome by these objectives, a little background is required on them first. Section 1.2 explores what possible sources of inefficiency can be solved by objective “a”, aircraft and engine design and technology. Section 1.3 does a has a similar aim as it explores the evolution of technologies relevant for the development of objective "c", the third era of aviation.

1.2. Influential factors for aircraft efficiency

1.2.1. Change of the model Paradigm

Historically, European airlines flew using the hub-and-spoke model. Airlines' route maps determined by the hub and spoke have one to three main airports which they fly from/to secondary airports. In a route map purely determined by the hub-and-spoke model, secondary airports are not connected with each other. This strategy is most popular amongst flag carriers. In contrast, low-cost airlines tend to operate using the point to point strategy. In this strategy airlines arrange their routes in a way that passengers only have to take a single flight from their origin to the destination regardless of the airline's base airport. The growth of low-cost airlines since the 2000s has favoured the point to point strategy over the hub to spoke one.

Because of this, the flying model in Europe has changed drastically within the last 20 years. However, most aircraft flown by airlines with a point to point strategy, still use A320s and B737. These aircraft were designed over 40 years ago and are well suited for short-distance hauls over 1000 km range. Many shorter routes are also covered by these aircraft, which may result in inefficient situations.

1.2.2. An overview of aircraft efficiency

Out of all aircraft flown today, the most popular ones are represented graphically in Fig. 1.6. As explained further in this project, airplanes have an optimal travel distance. At very short and long distances aircraft efficiency lowers, therefore the data in this plot is extracted from a transatlantic report. This plot shows the average efficiency of each aircraft and its MTOW in their high efficiency area. It is relevant to mention that many variables are not considered in this plot for the sake of simplicity. Nonetheless, the plot has enough data to extract three important conclusions. Firstly, quad-engined aircraft are less efficient than twin-engine aircraft. Secondly, newer aircraft are more efficient. And last, some short-haul aircraft are well below the average efficiency.

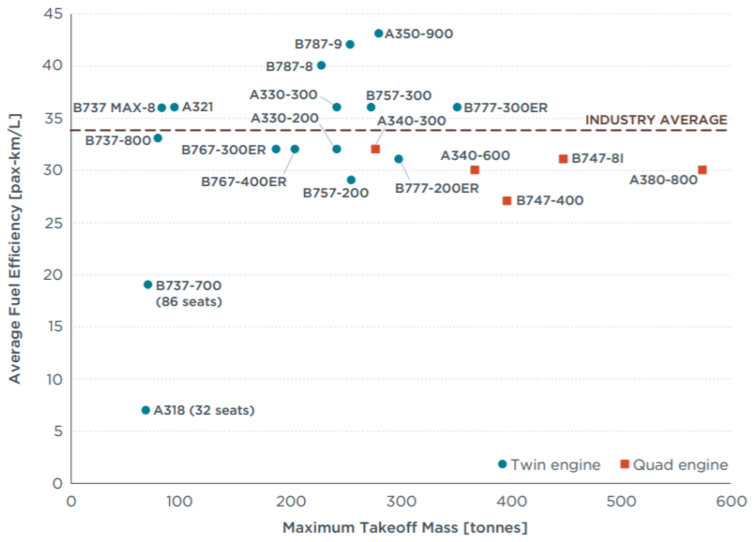


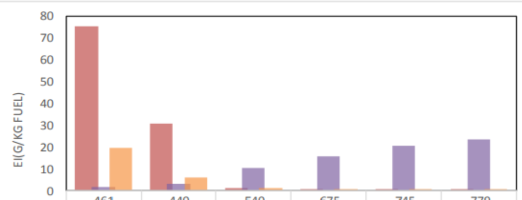
Fig. 1.6 Efficiency diagram for different airliners [8]

1.2.3. Emissions of taxi

As determined later in this study, most of the fuel during a flight is burnt in the air. While on the ground an aircraft burns fuel during taxiing, which usually lasts between 15 and 25 minutes in total. Nonetheless, a report from 2014 made the following statements:

- Hydrocarbons decreased with increasing power, at minimum thrust(%21) (power settings referred to as minimum idle), HCs were maximum concentrations.
- Emission index of HC was the highest at minimum idle thrust. CO emissions increased with decreasing power settings, CO Emission indices were the highest value at in minimum idle thrust. [9]

Thus, the HC and CO emissions during low power demand such as taxi, are proportionally higher than during high-power demand operations. The following graph shows the number of grams emitted per kg of fuel burnt, in function of the exhaust gas temperature.



	461	440	540	675	745	779
EF(CO)(g/kg fuel)	75.54	30.63	0.99	0.16	0.13	0.18
EF(NOx)(g/kg fuel)	1.63	3.01	10.29	15.85	20.57	23.44
EF(THC)(g/kg fuel)	19.49	5.94	1.34	0.38	0.26	0.17

Fig. 1.7 Emission indices of three exhaust species at Exhaust Gas Temperatures (EGT, ºC) [9]

1.3. The electric revolution

1.3.1. Recent history of rechargeable batteries

Batteries play a key role in the development of new technologies. In this section recent evolution of their energy density is shown in order to see which trends the industry is following. Lead-acid batteries are still used today for high power demand applications like engine start. This kind of battery was the most energy-dense rechargeable battery available until 1955. That same year, the Nickel-Zinc battery was commercialized and substantially and progressively improved energy density until the lithium-ion battery was invented in 1985. The overall specific energy density of secondary batteries has been increasing exponentially since the 1930s. However, lithium-ion batteries have kept a linear growth since the 1990s, thus slowing down the exponential increase. According to Chen-Xi Zu and Hong Li, a scientific breakthrough is required to keep the exponential growth of secondary batteries. In Fig. 1.8, a plot shows the progress of the secondary battery specific energy since the early 20th century. [10]

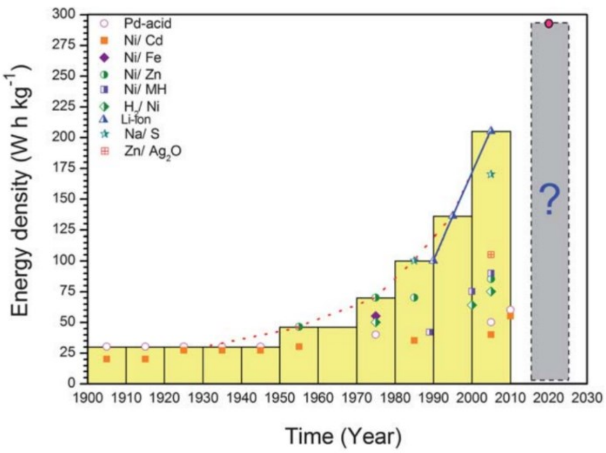


Fig. 1.8 History of development of secondary batteries in view of energy density. Dash line shows the progress between 1930 and 2005 and solid line represents the development of Li-ion batteries between 1990 and 2005. [10]

1.3.2. The Electric Vehicle (EV)

Without a doubt, the EV has improved its performance dramatically within the last 10 years. Because of commercial interests, more effort has been put to R&D on batteries. While it is impossible to determine when a technological outbreak will happen, it will most certainly happen in the following years. Replacing conventional cars with EVs and encouraging the use of renewable energies are goals in the agenda of many governments. Summing up, many stakeholders are putting their efforts on battery technology, therefore it is realistic to assume that a technological breakthrough in the field will eventually happen.

CHAPTER 2. OBJECTIVES

At this point, it is clear in what direction the aeronautical sector is working towards to make aviation more sustainable. An overview on Europe's aviation potential inefficiency sources has been presented. The background of battery evolution and electric influence in the transport sector has been briefly explained as well. The main goal of this project is to research and provide guidelines on what technologies can be used to tackle the climate change problem. Therefore, the following objectives are stated to achieve this goal.

- Research and analyse the inefficiencies of aircraft in the European airspace, suggest how said inefficiencies can be mitigated and determine what role can third-gen aircraft play to make aviation more sustainable.

- Develop a method to design an Electric Pushback and Taxi Systems (EPATS), determine its feasibility, and propose the best EPATS version to be commercialised.

- Provide guidelines on how to perform a replacement of a combustion engine for electric motor and batteries in general aviation aircraft. Estimate their economic feasibility, and forecast the impact of the battery evolution in this sector.

CHAPTER 3. State-of-the-art Technology

This chapter contains an overview of several state-of-the-art technologies in the sustainable aviation topic and other relevant factors for the development of this thesis. The following sections are either studied for feasibility later this thesis or do contribute to the content of the project.

3.1. Latest and future aircrafts

This section discusses the latest aircraft models that fly by 2020, both from a conventional and an alternative point of view. It also takes a look at models that are not built yet and have a strong chance of making it into production.

3.1.1. Conventional

These aircraft are the result of the first strategy described in the "unified commitment" chapter, in which the attention is put into improving the technology of aircraft and their engines. Despite not including any revolutionary technology, these aircraft are extremely efficient compared to their predecessors and are the only family of aircraft that currently allow medium and long-range travel.

Fig. 3.1 Most modern aircraft by 2020. From left to right: Airbus A220-300 [11], Airbus A350 XWB [12], Boeing B787 [13]

The Airbus A220 (former Bombardier C-Series), A350, and Boeing 787 are the best examples of state-of-art airliners by present-day standards. They incorporate very advanced technology such as composite materials, glass cockpits, and advanced avionics that make them some of the most fuel-efficient airliners flown by 2020.

For years, the industry has said that the next steps for conventional aircraft are to benefit from strong, lightweight composite materials and drastically change the fuselage shape to obtain a better payload-to-weight ratio. Another idea is to place the engines in places where they could benefit from the boundary layer effect.

Fig. 3.2 Conventional concept aircraft. From left to right: Double Bubble D8 [14], NASA's blended wing body (BWB) concept [15]

3.1.2. Electric aircraft

With the rise of the electric car, interests in electric aircraft increased through the early 2010s. In 2014, Airbus presented their prototype electric fixed-wing, single pilot, twin-engine, electric aircraft [16]. The program was cancelled in 2017. However, the advances set by Airbus, paved the way for other manufacturers in order to develop and commercialize their own models. All aircraft in this section are powered only by one or more onboard batteries. Therefore, they need to be charged in advance or use the propellers as generators while descending. These aircraft can be classified into many different categories since there is no rule set of qualifications for electric airplanes. This project will classify them by size.

3.1.2.1. Small aircraft

All operational electric aircraft are found in this category. Lower energy-to-weight ratio, general requirements, and price makes it feasible to operate small aircraft on electric energy. Most of these aircraft are based on single-engine ultralights, highly efficient small aircraft with exceptionally low drag coefficients to increase the performance of the plane. Manufacturers claim that small electric aircraft are the perfect match for pilot training. This kind of application does not require large cross-country speeds nor high performance and they include glass cockpits which are a plus on conventional training aircraft nowadays. However, certifying electric aircraft in the European Union is a difficult task and still may take a few more months or years. In fact as this thesis has been developed, the first electric aircraft for pilot training has been certified by EASA [17].

The endurance of these aircraft is around 1h plus reserve, their cruise speed 85 kt and their payload is limited to two persons on board with very little luggage as the battery accounts for a considerable part of the total weight of the airplane. Except for these numbers, their actual performance is quite reasonable and comparable to that of their conventional counterparts. The batteries can also be charged up to 30% while in flight as the aircraft descends.

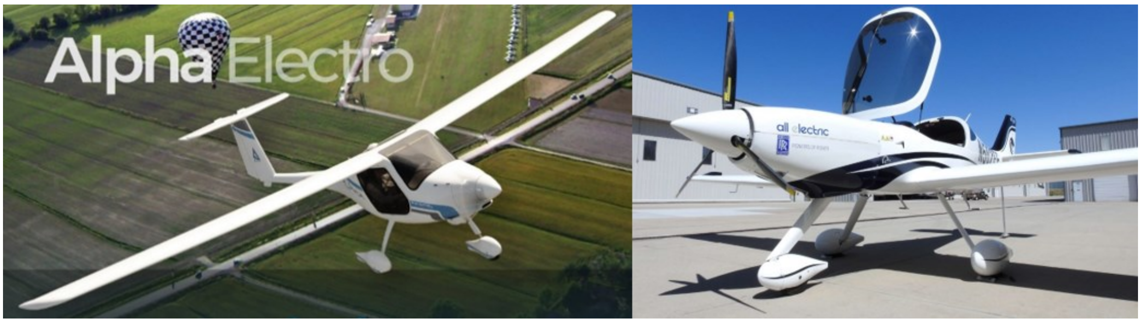


Fig. 3.3 Small, fully electric aircraft. From left to right: Pipistrel Alpha Electro [18], Bye Aerospace eFlyer [19].

3.1.2.2. Medium and large aircraft

The bottleneck in the first commercial electric aircraft will be range. This is the reason for the first prototypes to have such unconventional configurations, motor placements and overall construction of the airplane. This can be easily seen in the two most promising designs proposed by different manufacturers. The Alice is a medium electric aircraft that will be able to carry 9 pax plus 2 crew. Thanks to its efficient design it will be able to travel up to 540NM plus reserve at a speed of 240kt and altitude of 10000 ft [20]. The Wright one aims to carry up to 180 pax and interchangeable batteries but it will have only 290 NM of range. By these numbers, both airplanes fall short of today's conventional airplane standards. However, this aircraft's biggest strengths are operational costs. Expected to be around 80% lower than in conventional aircraft [21].

Fig. 3.4 Medium, fully electric aircraft. From left to right: Eviation Alice [22], Wright One [23].

3.1.3. Hybrid

A strategy to reduce fuel consumption, pollution and still achieve very decent endurance is by implementing hybrid technology. There are two architectures of hybrid implementations. Parallel and series. In the parallel architecture, the electrical motors help produce extra thrust in the most power demanding phases of the flight. Therefore, more efficient, less powerful engines can be mounted. In series architecture, the main electric motor is powered by batteries and an onboard conventional generator or range extender charges the battery as it gets discharged during the cruise.

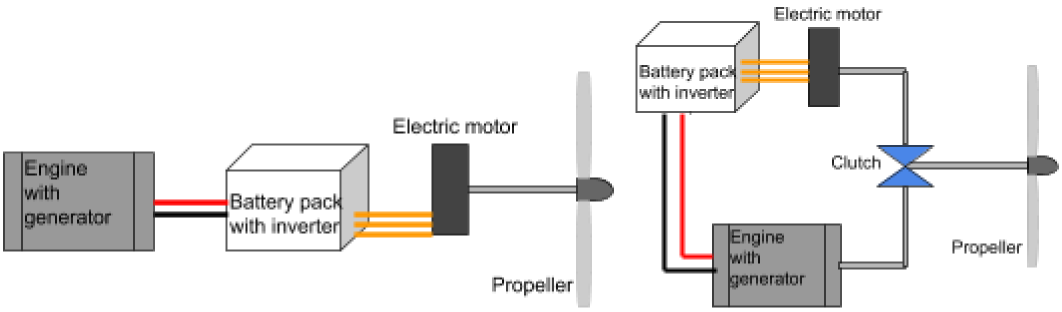


Fig. 3.5 Hybrid architectures. Left: Series. Right: Parallel.

3.1.3.1. Small aircraft

The best example of this is the airplane reviewed in section **Error! Reference source not found.**, the C-42 of Toni Roth. It has a series philosophy that allows it to consume around 6 L/h instead of 11. It also achieves a similar endurance and performances with a dual set of batteries and electric motors along with a 250cc range extender.

3.1.3.2. Medium and large aircraft

A project partly sponsored by the Spanish airline Volotea and led by Dante Aeronautical is working towards the manufacture of a 19-seat aircraft on its first stage that will eventually grow to 35. It has an estimated range of 400NM and is designed to fit the needs of present-day regional airlines and replace conventional regional aircraft.

Fig. 3.6 Dante Aeronautical DAX-19 with the Volotea livery [24].

3.2. Flying models

3.2.1. Urban mobility transportation

One of the latest bet companies are investing in is urban air mobility. Time is a resource whose value has dramatically increased within the last few years. While transportation is an event that takes away time. A solution that companies such as Boeing [25], Uber [26] or EHang [27] propose is VTOL electric aircraft capable of transporting passengers in the same city or even between close cities in very little time. One of the main benefits of this would be flying from city centre to city centre without the need for a big extension of terrain for a runway and a terminal. This concept does already exist in cities like Rio de Janeiro and New York through a helicopter taxi service. But this service is awfully expensive as helicopters have extremely high operational costs. Flying in drone-like aircraft would decrease the costs thus increase the number of potential customers.

3.2.2. Aerial taxi

This new strategy is based on stronger usage of secondary airports and large amounts of smaller planes to transport people. This strategy is based on heavy usage of low operating cost aircraft in order to transport fewer passengers while still having a relatively low price ticket and a considerable margin of benefits. The airports used by this strategy can be closer to the centre of the city because smaller aircraft produce less noise and need smaller runways and further reduce the total travel time. On the opposite side, these secondary airports can be non-city-focused, meaning that the service could be used for leisure purposes as well.

3.2.3. Covid19 scenario

Aviation has been so successful that making a big change involves a high risk of failure [28], however, with covid19 aviation has been put outside the “comfort zone” and this may enable greater changes in a larger scale. By mid-2020 some of these changes have already shown. A great example of this is the success of the A220. The A220 is an aircraft that was designed to cover basically secondary routes. However, the decrease in demand for major routes made the A220 a very appealing option to cover said routes rather than a more commonly used A320 or B737.

3.3. Electric Pushback And Taxi System (EPATS)

The time an aircraft spends on the ground is relatively small compared to the total time of flight, on top of that, the thrust required on ground is only a fraction of that required in for air operations. Therefore, the proportional amount of burnt fuel in ground is small. Nonetheless, the main engines are used during taxi and a pushback truck (i.e. tug) is used during pushback. This translates onto noise, risk of foreign object damage, engine running time, waste of fuel during long holds, and other drawbacks. One of the most surprising facts regarding taxi is that despite not using a lot of fuel, the proportion of polluting particles of CO and HCs emitted per kg of fuel are considerably larger, as seen in Fig. 1.7.

3.3.1. Wheeltug

Wheeltug [29], a company based in Gibraltar, is developing a system that powers the aircraft on the ground both for taxi and pushback through the nose gear. The system powers the aircraft with an electric motor inside the front wheels and with the APU, which generates electrical energy.

3.3.2. EGTS

A joint by Safran and Honeywell [30] [31] was made to develop the Electric Ground Taxiing System or EGTS by its initials. Like the Wheeltug, this system is powered by the APU and uses electric motors. The difference lies in the location of these motors: one in each main gear instead of in the nose wheel.

3.3.3. External electric tug (EET)

In contrast with the previous systems, which are permanently incorporated in the aircraft, an EET belongs to the airport. The difference between this system and a conventional tug lays in the purpose and methods. An external electrical tug is meant not only to perform the pushback but also the taxi [32]. In an ideal situation, these tugs are powered with electrical energy, and for the sake of this project, only these are considered. The tug can be operated from the cockpit so operational procedures change as little as possible.

Table 3.1 Comparative table between the different EPATS' strategies.

Characteristic	Wheeltug	EGTS	EET
Energy source	APU	APU	Batteries
Permanently incorporated in aircraft	Yes	Yes	No

Changes in aircraft	Severe	Severe	Minimal
Tractive wheels	Nose	Main	Nose
Weight put on the tractive wheels (% of aircraft's weight)	6-10%	90-94%	6-10% + tug weight

3.4. Electric Powerplant Modification (EPM)

The aerospace sector is known for its slow, expensive, and thorough certification processes. A process that experimental sport aircraft are not subject to. This means that as new technologies emerge, they can be implemented relatively easily into small aircraft. Thus, instead of manufacturing a brand-new aircraft that will fit an electric propulsion system, an old one can be modified to fit said system. Toni Roth, an aviation enthusiast replaced the conventional engine from his Ikarus C-42 with a twin set of electric motors, batteries, and an additional range extender [33]. This makes it possible to maintain performance and even improve the available peak power of the aircraft while halving fuel consumption.

A step-up from the C-42 is the de Havilland Beaver from Canada from Harbour Air, a regional commercial airline that operates in the surroundings of Vancouver with seaplanes. The 64-year-old de Havilland DHC-2 has been modified to fit the stacked version of the Magnix motor, an electric engine that delivers 750HP [34] [35]. According to the operator, it will be able to operate for 30 minutes when it enters service. Harbour Air plans on eventually replacing all conventional motors in their DHC-2s. Despite the lower endurance time (30 minutes), operational costs are expected to be significantly lower and just fit the mission they are meant to accomplish. Because it is a commercially aimed aircraft, it requires to be certified. Nonetheless, it confirms that an Electric Powerplant Modification (EPM) can be feasible even in the airline industry.

Fig. 3.7 DHC-2 modified with a fully electric power plant from harbour air. [36]

Fig. 3.8 Toni Roth’s C-42 on display in Aero Friedrichshafen 2019 [37]

CHAPTER 4. FLEET REPLACEMENT

This chapter is intended to improve the efficiency of the European airspace by questioning whether the airplanes operating in Europe are somehow burning more fuel than required. To do so, the operation of the most polluting aircraft according to Fig. 1.6, the A318, is analysed. On the other hand, while not especially inefficient according Fig. 1.6, the airbus A320 and Boeing B737 are the most popular airplanes in Europe. As explained previously, the airline model has changed a lot over the last few years. Thus, the efficiency of these models in the European airspace is to be analysed to determine how much inefficiency is generated by the A320 and B737 and how it can be mitigated.

4.1. Reduction of the A318 inefficiency

4.1.1. A318 replacement with the A220

The A318 is the aircraft with the worst efficiency amongst the most airliners used today. Out of the approximate 23 A318 that are still commercially flying, Air France operates 75% of them [38]. Because of the low efficiency, the low number of airplanes, and their concentration on a single airline, this airplane is analysed separately from the A320 and B737.

Instead of the 32-seat configuration used in Fig. 1.6, Air France uses a 131-seat configuration. The efficiency is the result of total fuel burn divided by the number of passengers, therefore, if a linear relation is assumed, the new efficiency is equal to 28 km/Litre per passenger. However, because of a phenomenon known as the “fuel for fuel” effect, the more weight carried, the more fuel will be burnt, thus the efficiency will be worse than the 28 km*pax/L. This efficiency, while better than the 32 seat configuration, still falls short of the efficiency achieved by the A320. This may seem illogical at first because both the A318 and the A320 use similar engines, and have similar aerodynamics. However, the A318 is in fact a “shrunk” A320, which generates design inefficiencies because with similar performances, can carry less passengers. In the case of Air France, this problem was noticed by the management and the A318 is in process of replacement by the A220, A much newer and more efficient aircraft designed for increased efficiency in an extended range span.

Table 4.1 Air France A220, A318 and A319 fleet [39]

Aircraft	In service	Orders	Passengers					Notes
			F	B	E+	E	Total	
Airbus A220-300	—	60[104]	—	—	—	149	149	Deliveries starting in September 2021. Replacing A318/A319 narrowbodies.
Airbus A318-100	18	—	—	—	—	131	131	To be replaced by Airbus A220-300.
				18		113	131	
Airbus A319-100	33	—	—	—	—	142	142	
						143	143	
					20	123	143	

4.1.2. A318 replacement with third-gen aircraft

As stated before, the main drawback of third-generation planes is their range which generally tops out at 500 NM. Fig. 4.1 shows a radius of 500 NM with its centre in the hub airport of Air France to judge whether third-gen aircraft could replace the A318 if they were available today. The green circles illustrate the airports the A318 flies to. Most airports the A318 flies to, are within this 500 NM range. If the range were extended by 100 NM, all of the airports would be within range. However, three factors should be considered. Firstly, the number of passengers that must be carried. While more efficient, third gen aircraft will not have the same loading capacity as the conventional competitors. Covering the route with more aircraft is a possibility in this case. Another altering factor is charging time. In case the aircraft is fully electric without interchangeable batteries, charging time is expected to limit the turnaround time. And lastly, this range covers a radius, therefore all the routes are considered to either depart from or go to Paris.

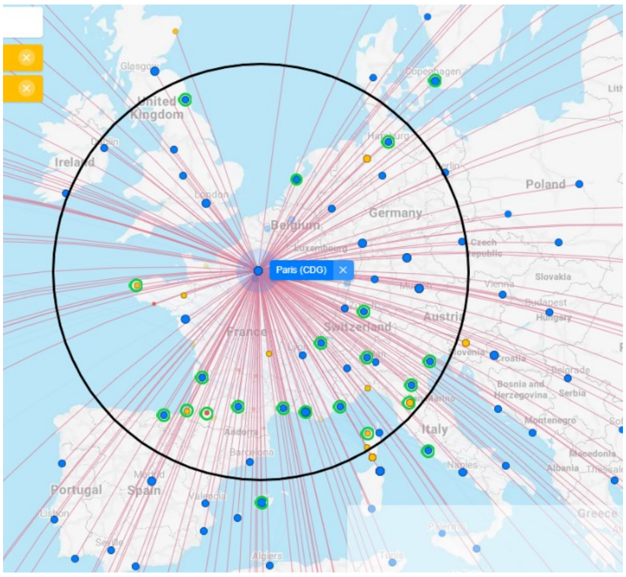


Fig. 4.1 To/from Paris routes flown by Air France. Green dots represent the destinations of the A318. Data from [40] and [41].

4.2. Reduction of the A320 and B737-800 inefficiency and replacement with third-gen aircraft in Europe

As stated in a previous chapter, the model on which airlines decide their routes have vastly changed within the last years but not the aircraft flown. This section aims to quantify the inefficiencies these aircraft are subject to due to flying routes that are not within their optimal range. Following this step, it will be analysed whether the less efficient routes could be covered by a third gen aircraft. It is relevant to mention that the database used in this project includes a worldwide route network with the airline that flies which route and with which aircraft type, but no information about the passenger flow or frequency is given.

4.2.1. Obtention and validation of the data

Openflights [42] is an open-source website with an exceptionally large amount of information of aviation statistics. Including databases of airlines, aircraft, and worldwide routes. Please note that the information from Openflights may not be completely accurate as the database has not been officially updated since 2014.

The first step is to obtain the frequency of routes within defined ranges to visualize and quantify the distribution of trip length in both the A320 and the B737 in Europe (departure and arrival in Europe). This is done through a spreadsheet that obtains the distance of each route from the coordinates of both the departure and arrival airport. Then a histogram graph is applied to the previous data and the frequency of each range of distances is obtained in Fig. 4.2 and Fig. 4.3.

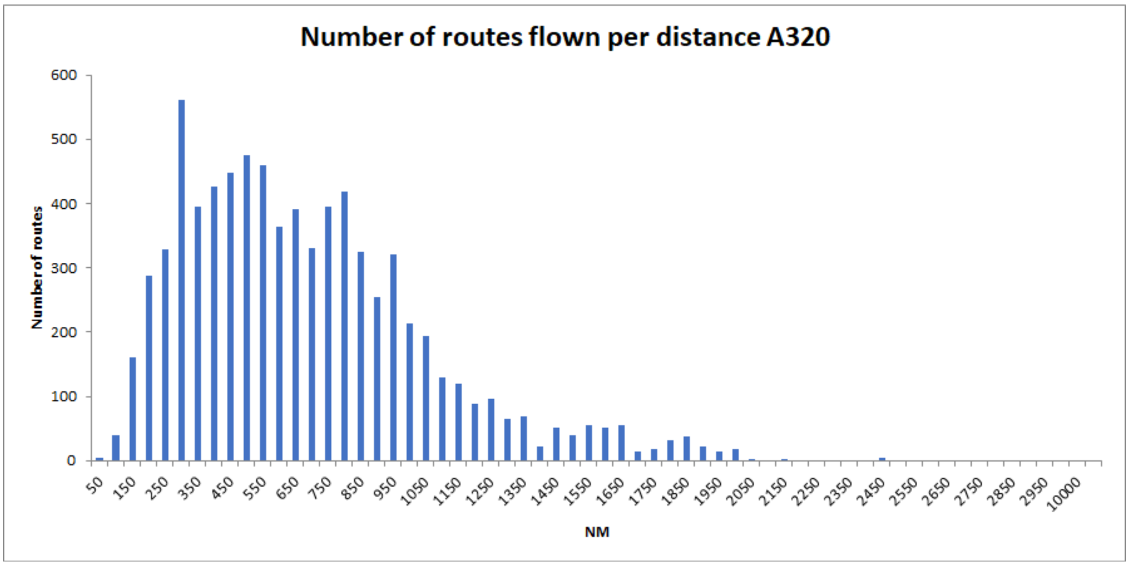


Fig. 4.2 Histogram of the length of the routes flown by the A320 with origin and destination within Europe. Data extracted from [42].

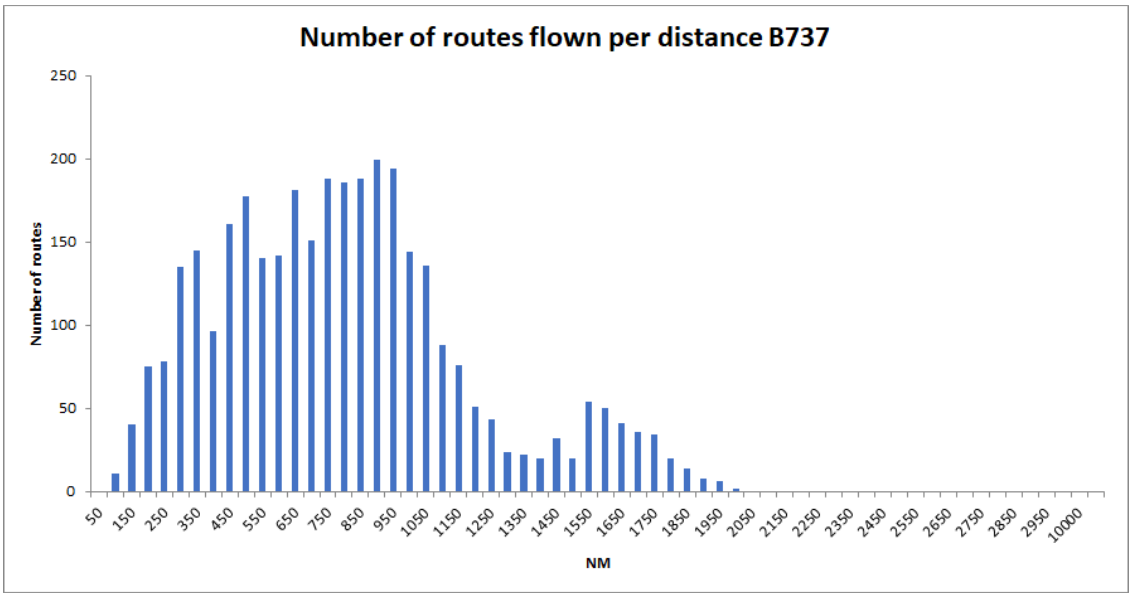


Fig. 4.3 Histogram of the length of the routes flown by the B737 with origin and destination within Europe. Data extracted from [42].

These plots show that a considerable part of the routes flown by both the A320 and the B737 fall within the 1000 NM range. In the case of the B737, a smaller peak at the 1600 NM range can be spotted. This is due to the different versions of the B737. Specifically, the -900 series which has extended range capabilities. This peak will be ignored because the analysis is based in the -800 series, which is more used in Europe.

4.2.2. Bathtub function to evaluate efficiency

Now that the statistical distance at which the A320 and B737 fly to, the efficiency of each of the aircraft in function of the distance flown must be determined. The best way to calculate this efficiency is using the bathtub function. Because of the nature of flight, a considerable amount of fuel is used during take-off and climb. This is an amount of fuel that will be burnt regardless of the distance of the flight. Once at cruise, the aircraft can travel a lot of kilometres burning relatively little fuel, thus is more efficient. To calculate the efficiency with the bathtub function, the total amount of fuel burnt is divided per the number of passengers. However, in exceptionally long flights, the flight may have to not accept some passengers to be lighter and travel further. Thus, the quantity of fuel burnt per passenger is larger. These characteristics give a flight an extremely high consumption of fuel per passenger at short and very large distances. Hence the very characteristic bathtub shape. A detailed process to perform this function is found in APPENDIX 1.

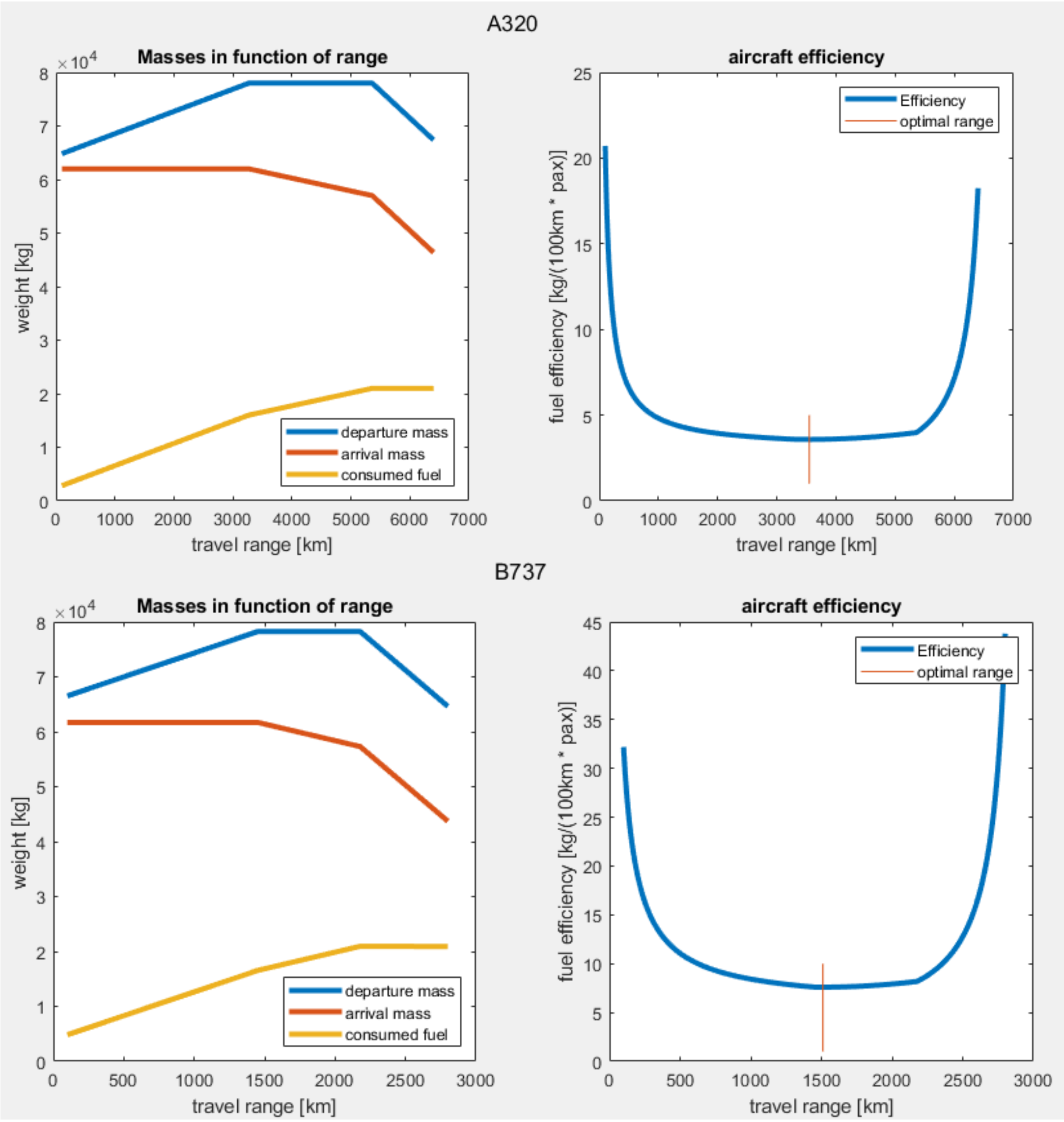


Fig. 4.4 Loading plots and bathtub functions of the A320 and B737

The bathtub function gives the range at which the aircraft is most efficient in a very visual manner. Essentially the lower the plot is at a given distance, the better. This range is located between 1000 km and 5500 km in the A320 and between 500 km and 2200 km in the B737.

4.2.3. Inefficiency penalization factor to find statistical inefficiency

At this stage, the statistical data of the A320 and B737 routes in Europe is obtained. On the other hand, the efficiency of each of the aircraft in function of distance is obtained as well. Now it is time to join these two parameters. The goal in this section is to determine where the most inefficiency of the A320 and B737 is generated in Europe (relative to distance). To achieve this goal, the efficiency of a given distance could be multiplied times the number of flights in that region of distance. However, doing this does not provide any useful data as the number of flown routes for a given distance has a much greater impact in the final plot. Instead, equation **(4.1)** is used.

$$F(R) = \left(\frac{E(R)}{E(R_0)}\right) - 1 \qquad \textbf{(4.1)}$$

In which F is the inefficiency factor, E is the fuel efficiency, R is an arbitrary range and R_0 is the optimal range. An F equal to 1 means that the amount of fuel consumed per pax per a hundred km is double the optimal consumption, 0.5 means an inefficiency of 50%, and so on. By multiplying the inefficiency factor with the ranges of the histograms, a statistical inefficiency plot is obtained.

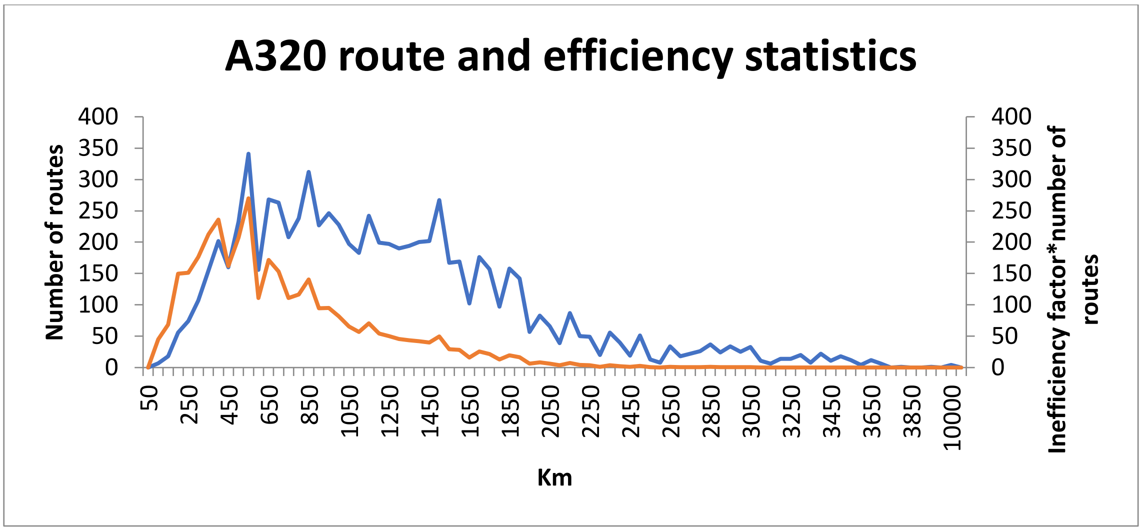


Fig. 4.5 A320 Inefficiency plot with both, raw data in Fig. 4.2 (blue, left axis) and data times inefficiency factor (orange, right axis).

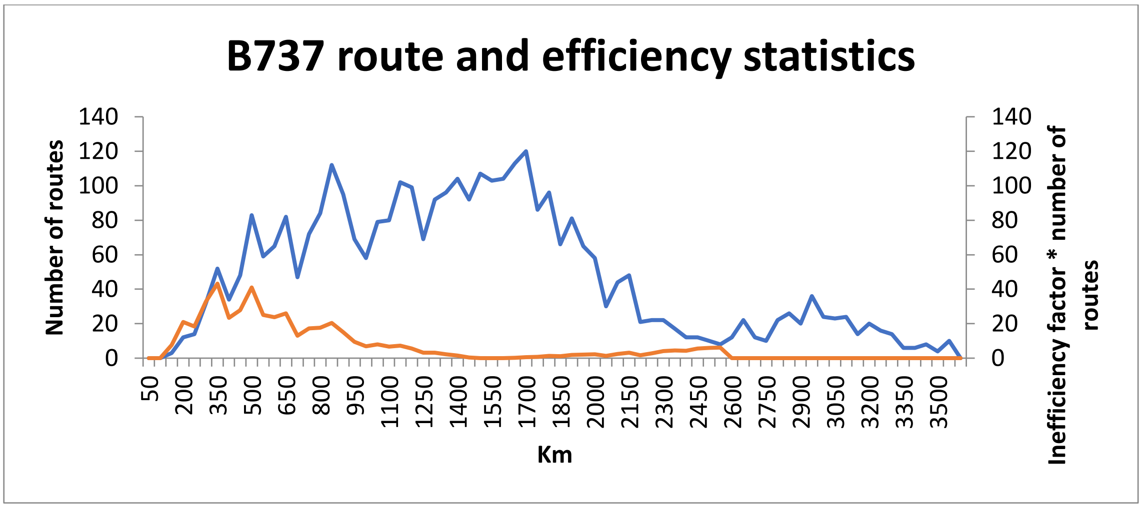


Fig. 4.6 B737 Inefficiency plot with both, raw data in Fig. 4.3 (blue, left axis) and data times inefficiency factor (orange, right axis).

The orange lines highlight the areas where aircraft fly the most without being the most efficient. These areas are located in the range of 200 to 800 km in the A320 and in 300 to 700 km in the B737.

4.2.4. Bathtub comparison of the A320, B737 and A220

In Fig. 4.7, a plot with a loading of 80% is simulated in the A320, the B737 as well as the replacement of the A318, the A220. In the plot, the efficiency of the A320 and the A220 are remarkably similar. However, the A220 needs less loading to reach 80% of its capacity which means that it can reach the same efficiency as the A320 with less demand. On the other side, the B737 falls short of both efficiency and range against its competitors.

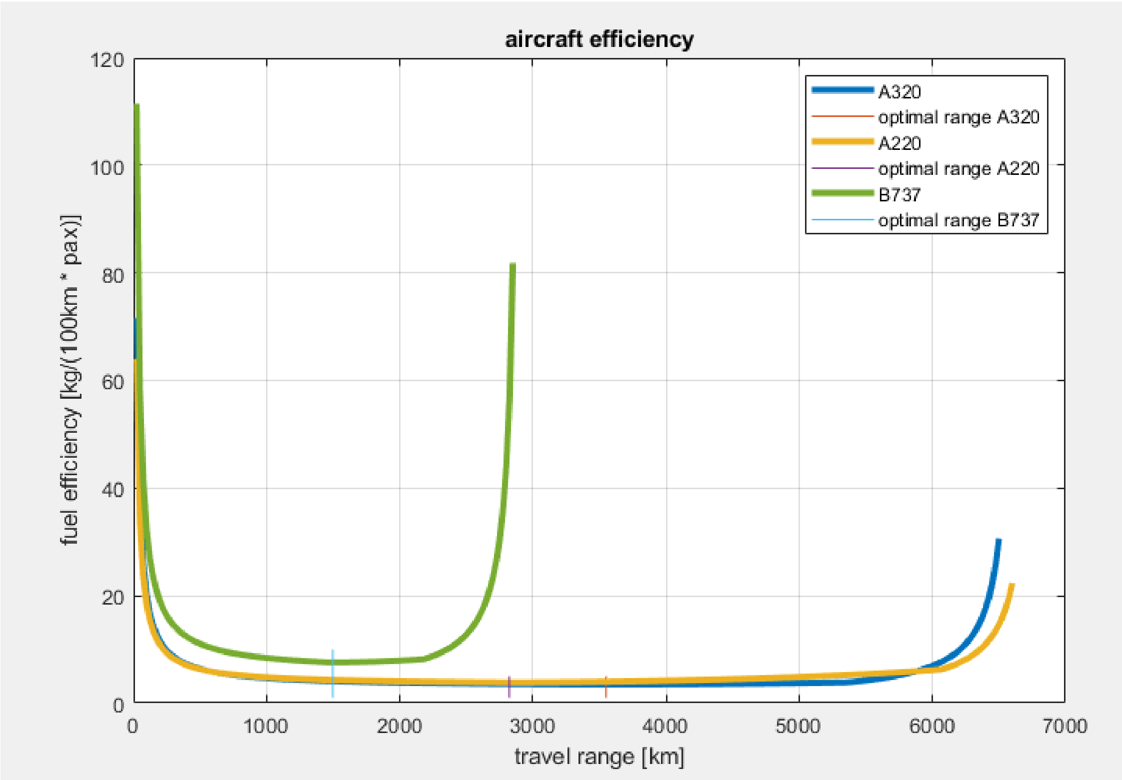


Fig. 4.7 Bathtub functions of the A320, A220 and B737 with an 80% loading.

In a hypothetical situation where there is a demand for 120 seats (which is the maximum capacity of the A220 and 66 to 80% of the capacity of an A320, the A220 would surpass the A320 efficiency at any range.

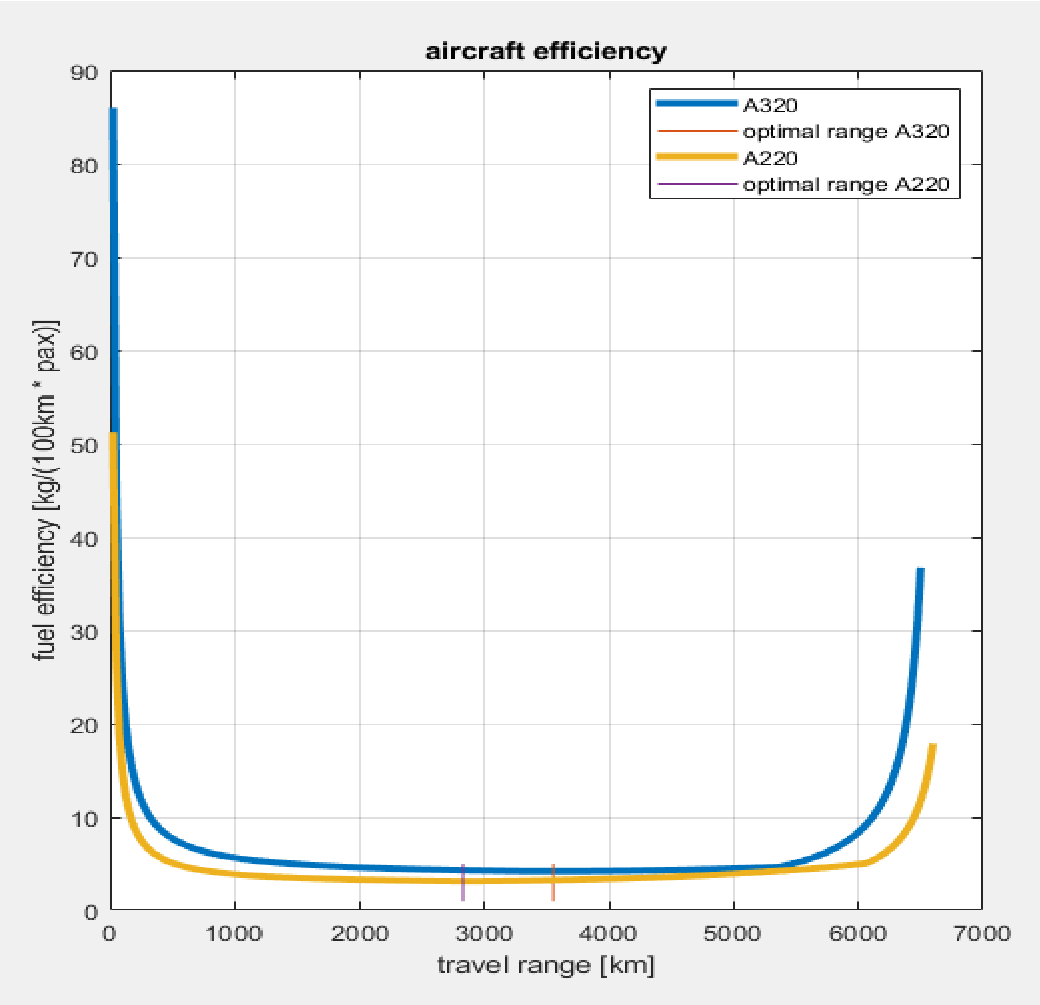


Fig. 4.8 Bathtub function with a loading of 120 seats. Which translates to 100% of loading in the A220 and 80% in the A320.

4.2.5. A320 and B737 replacement with third-gen aircraft

The first third gen aircraft are expected to have a range of 600 NM (1111 km) which would cover the routes of least efficiency of all the aircraft above. However, the payload will be a limiting factor. The Alice, the commercial electric aircraft in the most advanced stage of development, is expected to be able to carry 9 pax. So, to replace a single full A320 trip, 20 aircraft would be needed.

However, the later third generation aircrafts such as the DAX-19 are expected to have at least 19 passenger seats and rely on hybrid technology that would enable them to have an effective range of 1111 km. These aircraft will better fit regional routes, reduce the amount of aircraft required and therefore increase the efficiency of the aeronautical sector.

4.3. Third generation aircraft

The first commercially available aircraft will have limited payloads and range. Which raises the question: In which application can these aircraft be feasible?

4.3.1. Financial comparison of the Alice and the PC-12

While it is not possible to perform a quantitative analysis like in the previous section because of the lack of data, a qualitative study can be performed on the Alice. This aircraft has been chosen because it is the furthest developed, commercially aimed third-gen aircraft now. The Pilatus PC-12, due to its payload and performance similarity to that of an Alice, is considered as the Alice's direct competitor. The PC-12 Is an aircraft built for a broad set of purposes. Including private air transport, charter flights, and medicalized air transport. The operational costs of the Alice are still unknown; however, an estimation can be done based on prices for expenses like insurance, landing fees, and pilot salary equal to that of a PC-12. Expenses that differ from the PC-12 such as fuel and maintenance costs shall be addressed by other means.

This section studies the economic feasibility of the Alice compared to the PC-12. The only few differences in price between both airplanes are the selling price which is intended to be compensated in 10 years, plus fuel and maintenance costs. The costs are separated in three different categories. The first one can be considered costs that are paid yearly, thus regardless of the operation of the aircraft. The second one accounts for the hourly operational costs. Which means that the costs of this category are directly proportional to the number of flown hours. And the third one considers the costs that are paid once in every flight regardless of the length of the trip. Therefore, two constraints must be set: number of hours flown per year and the average endurance trip.

Table 4.2 Alice's fix and variable costs

Alice (8 of 9 seats)			
€	fix costs (yearly)	hourly	per flight
price	400000	-	-
storage	25000	-	-
fuel	-	29.37	-
landing fees	-	25 (estimation)	50
insurance	25000	-	-
pilots	-	150	-
maintenance	-	300 (estimation)	-

price of ticket	-	92	-

Table 4.3 PC-12's fix and variable costs [43] [44]

PC-12 (9 of 10 seats)			
€	fix costs (yearly)	hourly	per flight
price	500000	-	-
storage	25000	-	-
fuel	-	271	-
landing fees	-	25 (estimation)	50
insurance	25000	-	-
pilots	-	150	-
maintenance	-	565	-
price of ticket	-	92	-

One seat is assumed empty in both airplanes. If the average hours flown per year and average length of flight are known, the total cost of both aircraft can be computed with equation **(4.2)**.

$$C_t = C_f + C_v * h \tag{4.2}$$

Where C_t is the total cost, C_f the fixed costs, C_v the variable costs, and h the number of flown hours. Because factors such as storage and insurance are paid yearly, the total amount of hours shown in the Fig. 4.9 and Fig. 4.10, Fig. 4.9 economic pay-off plot for the Alice.correspond to an entire year of usage.

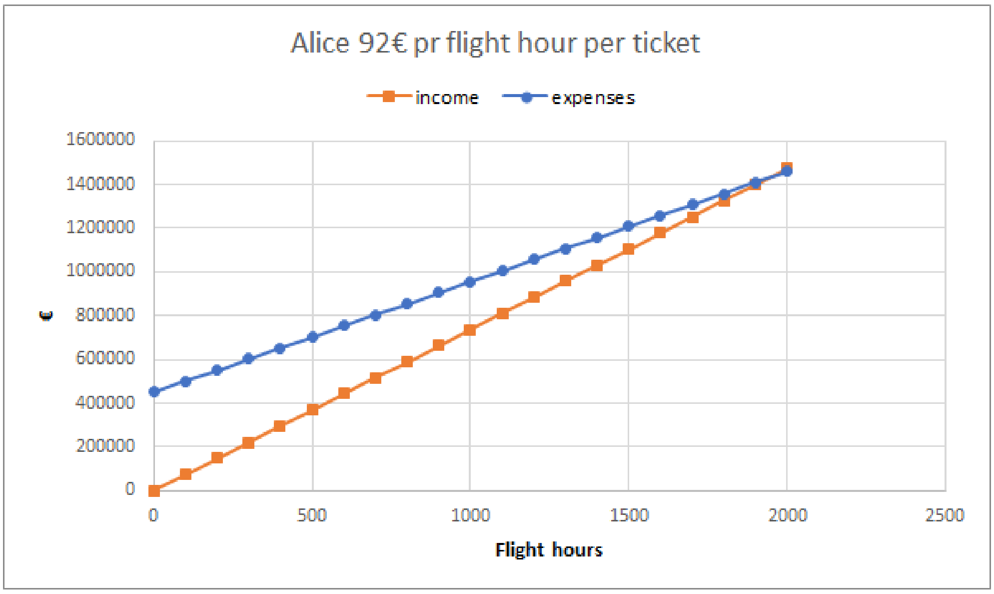


Fig. 4.9 economic pay-off plot for the Alice.

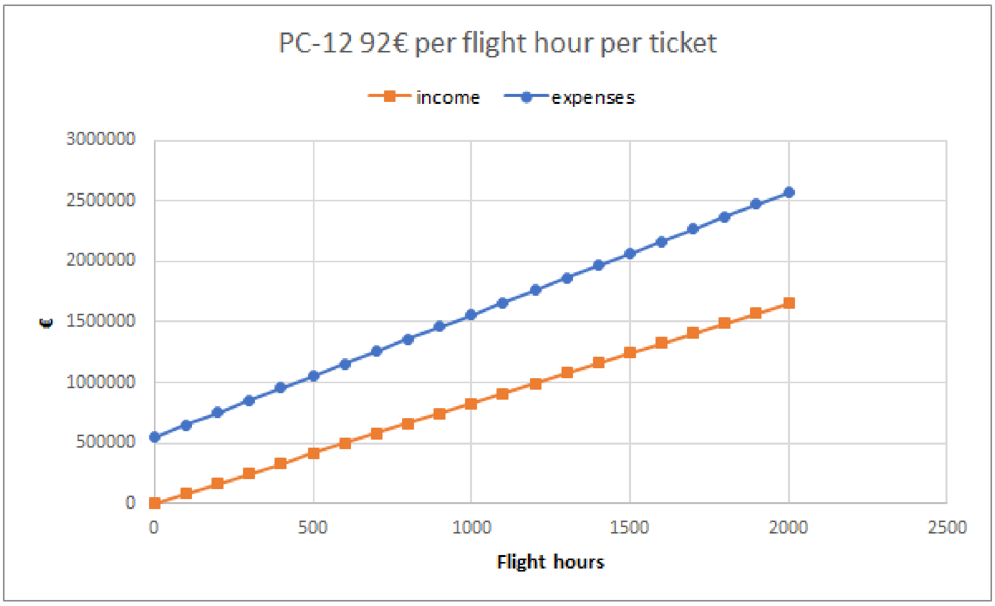


Fig. 4.10 Economic pay-off for the PC-12.

Although most of the costs are equal in both aircraft, the lower price of the Alice along with lower operational costs, grants the Alice a clear economical superiority over the PC-12. If compared to other sources, the variable costs computed in these tables (Alice: 500€/h, PC-12: 1000€/h) can be considered to be fairly pessimistic (Alice: 200€/h, PC-12:1265.2$/h) [45] [43], which means that the Alice's economic feasibility would be even higher. Despite these numbers, an aircraft without a commercial application will most certainly result in a failure. Therefore, the next section addresses this topic.

4.3.2. Applications

As any other aircraft, without a feasible commercial application, the Alice will not generate profit, thus fail. This challenge is addressed in this section. There are two different categories in which the Alice can be used: by replacing existing aircraft on their missions, or by implementing the Alice in a new kind of mission.

On the traditional, already existing side, the Alice could theoretically replace the A320 and the B737 in their minimum efficiency range, which is within range of the Alice. However, the difference of passengers that can be carried in the Alice and either of the aircraft is probably too large for most cases. Nonetheless, low frequency, low demand, short flights could be perfectly replaced by a more frequent schedule with the Alice. This concept can be defined as the aerial ferry. In which a reasonably constant flux of passengers needs to be transported.

Private jets provide the ability of very fast, very short notice transport. This is an extremely limited privilege, available only to a few people in the entire world. However, the Alice could provide better access to this service to more people. Not only in the matter of owning a private airplane but also of renting one of these aircraft for a short period of time. This could normalise the concept of the aerial taxi, in which the entire aircraft is rented by a group of people to carry them to a place of their choosing.

A new concept of inexpensive to operate, environmentally friendly aircraft will provide a new scenario. It is nearly impossible to determine how this scenario will look like and which roles will third gen aircraft play. But APPENDIX 2 shows a set of possible routes that because of their nature, could potentially be flown. Both because of their potential market and the ability of the Alice to fly these distances.

4.4. Results

With the extracted results, the following statements and recommendations can be addressed:

- Conventional aircraft will keep flying for the years to come as they have undisputed superiority in large loading and medium and long range.
- Conventional aircraft should be filled as much as possible as it increases efficiency.
- The ranges at which fossil fuel aircraft are the least efficient, are also those ranges at which third-gen aircraft can operate, which presents a great opportunity to minimize pollution generated by the industry.
- The creation of third gen aircraft will enable a fast and cheaper way of transportation for routes under 1000 km and/or poorly or inefficiently covered by other means.

CHAPTER 5. ELECTRIC PUSHBACK AND TAXI SYSTEM

In the previous chapter, the inefficiencies in the European airspace have been addressed. However, aircraft also spend a considerable amount of time burning fuel on ground. This chapter is intended to reduce the inefficiency generated by aircraft on ground and determine which of the proposed solutions is best.

5.1. Motivation

Many different companies are trying to tackle the challenge of implementing a successful traction device for movement on the ground. While a great way of powering the aircraft in the air, turbofan engines are not optimized for ground operations and generate many drawbacks. Acoustic pollution, wasted engine lifetime, risk of FOD, and need for pushback trucks are some of the issues created by operating turbofan engines on the ground. Not to mention the massive amount of fuel that turbojet engines use even when idling and the GHGs produced as a consequence.

5.2. Process and objectives

A handful of companies are already researching this topic to commercialize it; however, no system has yet been successfully implemented. This chapter aims to:

- Study the qualitative and quantitative benefits of having an Electric Pushback and Taxi System (EPATS).
- Calculate the requirements and performances of the EPATS.
- Analyse and quantify the possible drawbacks of an EPATS.
- Develop a methodology that allows a user to obtain the estimated outcomes of fuel, emissions, and economical balance from known inputs.
- Determine whether an EPATS can be implemented and if it can:
- Establish a series of recommendations on how to implement an EPATS.

5.3. Source of equations

Accurate in-flight fuel consumption models are kept under great secrecy of manufacturers and operators. In consequence, the functions to compute said consumption are extracted from empirical data and economic reports [46]. These models provide conceptual data but cannot be considered highly accurate.

5.4. Fuel savings

The most important consequence of using an EPATS instead of conventional taxi methods is the fuel save. But computing exactly how much fuel is spent during

this phase is a rather complicated procedure as there are is no official data from the manufacturers. ICAO establishes a baseline fuel consumption of 7% throttle setting for taxi procedures. However, a scientific paper [47], provides better estimation models which are used in this project. Two possible models are published on the paper, however, the second model is more accurate. Therefore, the first model is discarded.
This second model considers only the number of severe accelerations and total taxi time as relevant data to compute fuel consumption. The motivation behind this decision is that flow rates increase drastically with sudden accelerations but barely increase when the acceleration is gradual.

$$\frac{f}{\sqrt{T_{amb}}} = a_2 + b_2 * t + c_2 * n_a \quad \textbf{(5.1)}$$

Where f is the total amount of fuel used in the taxi procedure, T_{amb} is the ambient temperature outside the aircraft, a_2, b_2 and c_2 are constants that depend on each aircraft, t is taxi time, and n_a the number of acceleration events. Table in APPENDIX 3 shows the constant values used in different aircraft. The B737 can be assumed to be equal to the A320 or A321 depending on the version.

Despite the good results, the authors also remark that the pilot behaviour is a parameter to be taken into account as some pilots use a technique called “riding the brakes” in which a throttle is set to an advanced setting and manoeuvres are performed by using only the brakes.

From this model, the average fuel consumed for different aircraft can be estimated. In this case, a 15-minute taxi (taxi-out only), 3 acceleration events, and 15ºC of ambient temperature is assumed. To calculate the total amount of burnt fuel over a year, an average of 4 legs a day, 2 for long haul aircraft, are considered. Which is rather conservative given that short-haul airplanes tend to perform 6 legs a day.

Table 5.1 Fuel burnt during taxi in a single flight and in the period of a year in different aircraft.

Aircraft	Taxi fuel consumption (kg)	Burnt fuel over a year (tons)
A319	195.94	286.072
A320	197.01	287.634
A321	206.35	301.271
A330-243	415.37	303.220
B777	525.53	383.636

This table gives an idea of the magnitude of fuel the EPATS could avoid burning in a single airplane. However, the APU must provide hydraulic, pneumatic, and electric energy while taxiing. Therefore, the fuel savings will differ from those above. Additional advantages of operating on an EPATS are less fuel consumed in unforeseen long holding times, noise reduction, reduced engine wear, and non-dependence of tugs.

5.4.1. Emissions

When fuel is burned, a series of chemical reactions result in the production of greenhouse gasses. These greenhouse gases, or emissions, are not proportionally generated to the thrust setting in a turbofan engine. In fact, some of the emissions are produced exclusively at the low end of the exhaust gas temperature (EGT) range while others increase as does the EGT. A study made in 2014 by the Anadolu University of Turkey in collaboration with Turkish Airlines on the CFM-56 engine [9], one of the most popular engines for B737s, shows the actual distribution of greenhouse gas emission in function of the EGT in Fig. 5.1.

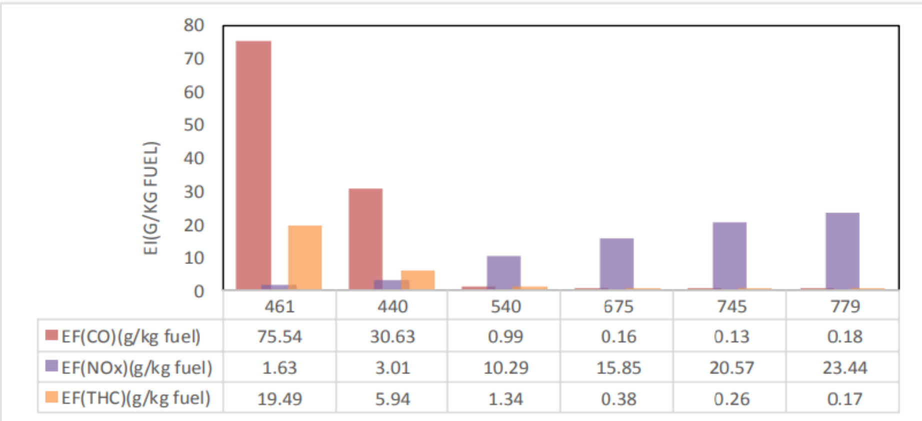


Fig. 5.1 Production ratio of GHGs of the CFM-56 in function of its EGT (ºC) [9].

It can be clearly seen that CO and THC emissions are far larger at the low end of the plot, which is the area at which engines operate while on the ground. This may seem counterintuitive at first but makes more sense when the engines spend most of the time at cruising speed which means higher EGT. Therefore, engines are optimized for cruising EGT. However, when on the ground, aircraft are the closest to cities and other populated areas, which mean a threat to the population's health. More detailed data for each phase of the flight can be found in Table 5.2.

Table 5.2 Detailed data of the GHGs emitted by a CFM-56 in function of the throttle setting both from experimental data and as reported by ICAO. [9]

Power Seg-ments	N1 rpm	CO_2 (%)	CO (ppm)	HC (ppm)	NOx (ppm)	EI(CO) (g CO/kg fuel)	EI(HC) (g CH_4 / kg fuel)	EI(NOx) (g NO_2/ kg fuel)	A/F (air/fuel ratio)	FF(fuel flow) kg/s
21%	1016	2.22	872,3	392.9	11.4	75.5	19.5	1.6	87.1	0.920
Idle*						22.0	2.4	4.4		0.109
32%	1584	2.00	307.1	104.1	18.5	30.6	5.9	3.0	100.3	0.770
App*						2.2	0.1	10.1		0.316
67%	3291	2.77	13.5	32.1	86.5	1.0	1.3	10.3	73.7	6.085
Climb*						0.6	0.1	20.5		0.910
86%	4195	3.64	2.9	12.0	175.1	0.2	0.4	15.9	55.8	13.397
94%	4593	4.07	2.7	9.0	253.8	0.1	0.3	20.6	49.9	15.362
97%	4770	4.27	3.8	6.3	303.4	0.2	0.2	23.4	47.5	12.210
Takeoff*						0.4	0.1	25.3		1.103
32% (App.idle.cold)	1559	2.00	311.9	68.2	19.9	31.2	3.9	3.3	100.4	1.373
21% (Min.idle.cold)	1023	2.05	637.4	198.2	14.2	60.9	10.9	3.2	96.1	0.988

5.4.2. Economic balance

From an economic standpoint, many factors have an influence on the final balance. In this analysis, the following are considered: total fuel balance, CO2 tax, passenger removal (if necessary), electricity, battery, certification, installation, motor and auxiliary systems costs. On top of that, tug rental and brakes and tires savings are added to the equation with conservative values due to the lack of reliable data.

5.5. Requirements of an EPATS

This section will determine the actual performances the EPATS needs to meet to be safe and effective. The requirement finding procedure will be performed in an A320.

5.5.1. Ground friction

This section discusses the feasible power transfer to the ground methods to move the aircraft. There are three main methods: front gear, main gear, and external tug. Wheeltug features a tractive nose wheel philosophy which seems very clever because it emulates the concept of a pushback tractor and allows the manufacturer to put a single motor instead of two. However, the nose wheel is not designed to stand heavy weights. The weight put on the nose wheel is around 6-10% which is enough to gradually increase speed on the pavement with very gentle inclination and good grip conditions. But this configuration is completely unable to accelerate quickly enough to resolve a runway intrusion situation and provide enough grip in wet, icy, or any slightly slippery condition as stated by Daidzic N. E. [48] and Hospodka J. [49]. Instead, EGTS uses a tractive main gear philosophy. Which ensures safe operation. An external tug is also a safe proposal to address the EPATS. The extra weight of the tug on top of the aircraft's', plus the possibility to add weight and ground contact grants virtually as much grip as required.

5.5.2. Power

This section discusses the amount of power required by the aircraft to ensure safe operation. So far, the power to taxi is provided by the main engines. The exact amount of power required to move an aircraft is often neglected. Factors such as aircraft weight, outside temperature, and airport altitude affect considerably the power required to move the aircraft. Thus, pilots use "as much power as is needed". Despite this lack of empirical data, a paper published in 2017 made estimations on the total amount of resistance during the taxi phase. Including aerodynamic drag, rolling resistance, a +2% slope, and a 1kt/s acceleration that an EPATS would have to overcome. This data was then illustrated into plots for different kinds of aircraft including the required amount of power to counteract these resistant forces. Despite the A320 plot not being present, the paper claims the results for the A320 are virtually equal to that of a B737 [48].

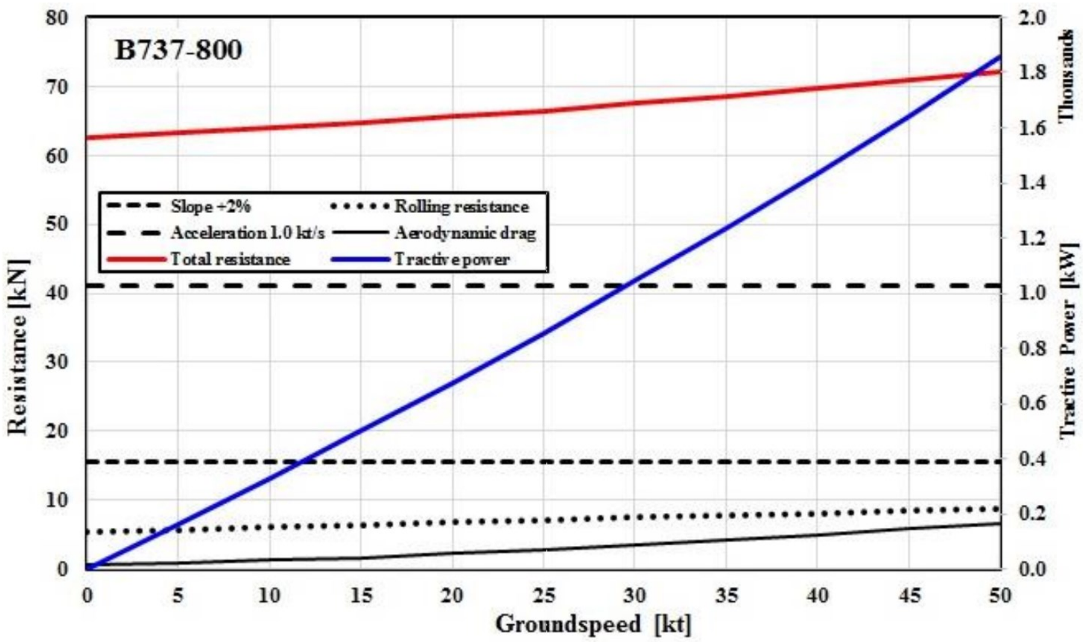


Fig. 5.2 Total resistive force generated by a B737-800 on ground and the required power to overcome it. [48]

This graphic shows the theoretical amount of tractive power an EPATS must overcome to accelerate a B737 in function of the ground speed. Taxi speed must be kept under 40 kt but for the sake of safety, the system is assumed to be able to perform at 45 kt. In this scenario, the peak power required is 1600 kW. However, as can be seen in the plot, acceleration means more than half the total resistance, which means that during constant speed at 35 kt, +1% of inclination, and a 20kt of headwind, the system would only require 414 kW of tractive power.

Therefore, the specifications of the system for an A320 should have the following requirements:

- Deliver 1600 kW for 5 seconds
- Supply a constant of 400 kW for 15 minutes → 100 kWh of stored energy

5.5.3. Power source

Most modern and powerful APUs produce up to 1340 kW. Which may trick the reader into thinking that the APU is an already usable source of energy for the EPATS. However, there are two problems with this assumption. Firstly, such APUs are found in wide body aircraft such as the B787 and A380. The APUs in A320s use to make 447 kW instead. Secondly, APUs provide Hydraulic pressure, air conditioning and electricity for other systems in the aircraft. Thus, an APU upgrade is needed if the APU is also to power up the EPATS, which will have a severe economic impact considering certifications, maintenance, etc. An alternative to this method is the storing electric energy in batteries. Both philosophies are studied in this chapter and are analysed at the end. An additional method that will not be studied is adding supercapacitors to remove some workload from either of the systems.

5.6. Calculation of system

5.6.1. Powerplant

Axial flux motors are state-of-the-art electric motors with outstanding power-to-weight ratio. Magnax claims that the motors they manufacture produce up to 400 kW, and 510 Nm of torque with mass around 25 kg [50]. Their nominal voltage is set between 400 and 800V. For an A320 four of these motors are required. Each one weighs around 40kg. The manufacturing and performances of these motors are kept under great secrecy. However axial flux motors and radial flux motors work in a remarkably similar way. Their operation is quite simple thus shall not be addressed in this project.

5.6.2. Energy source

Two different philosophies are studied in this section: An all-electric EPATS supplied by a battery and an APU-driven EPATS. The first philosophy will be possible due to a completely new battery set completely independent of the present aircraft systems and could even be implemented as an external device. In contrast, the APU-based philosophy the energy source does already exist and would be upgraded to a more powerful and capable part.

5.6.2.1. All-electric EPATS

NMC batteries with a pouch shape are the most used by EVs. It is the newest kind of Li-ion battery. It is also heat resistant, has the lowest self-discharge rate and has the greatest specific energy [51]. The battery model 10059156-5C is selected. Its characteristics are shown in APPENDIX 4.

With the requirements and the specifications of the battery in mind, the characteristics of the battery can be determined. APPENDIX 5 accurately explains the procedure used to achieve this goal. In this case, the resulting battery for an A320 with an average taxi out and in time of 15 and 4 minutes respectively, 6 acceleration events total and 15ºC of average temperature would have the characteristics shown in Table 5.3.

Table 5.3 Computed characteristics of the electric EPATS battery pack.

Battery weight	607.6 kg
Battery cost (18€/cell)	54684 €
Stored energy	112406 Wh
Cells in series	217
Cells in parallel	14
Total number of cells	3038

With these numbers, along with additional parameters, a viability estimation can be performed. A detailed explanation can be found in APPENDIX 6. The results are found in Table 5.4.

Table 5.4 Computed performances and economic output of an electric EPATS

Outcome	Value	Units	Outcome	Value	Units
Battery life	83	Days	Fuel save	212	kg/flight
Payoff time	4201	flights	CO2 save	18.56	kg/flight
System mass	967	kg	Save balance	39.43	€/flight

5.6.2.2. Hybrid EPATS

APUs are devices aimed at only supplying enough energy for the electric, pneumatic and hydraulic systems, which in the case of an A320 results in a total demand of 450 kW. Considering the 1600 kW demand of the EPATS, a 2050 kW APU is required. Given that such an APU does not yet exist, a compromise is made and the most powerful APU in existence (1342 KW) is accepted to be fitted in the aircraft. A realistic power to weight ratio of 3.78 KW/kg is assumed as well. Following a similar procedure as in the electric version, the parameters in Table 5.5 and Table 5.6 are obtained.

Table 5.5 Characteristics of an hybrid EPATS.

Extra APU weight	238 kg
Upgraded APU cost	500000 €
Provided power to EPATS	1000 kW (1150 kW for short bursts)

Table 5.6 Computed performances and economic output of an hybrid EPATS

Outcome	Value	Units	Outcome	Value	Units
Payoff time	4083	flights	CO2 save	5.34	kg/flight
System mass	598	kg	Save balance	163.51	€/flight
Fuel save	189	kg/flight			

Needless to say, expenses on fuel and CO2 are higher, however, the economical balance is better than the all-electric version at this stage of the analysis.

5.7. Marginal Fuel Burn

If the EPATS is incorporated in the airplane like in the Wheeltug or EGTS philosophies, the costs of doing so must be computed. The extra weight translates to an increased OEW and if the MTOW is not increased, a consequent reduction in the payload is required. This situation presents two different scenarios. In the first one, the maximum payload of the aircraft is not reached, and therefore the cost of carrying the system in the aircraft is translated to an increased fuel burn, higher polluting emissions and the economical cost because of it. This extra burnt fuel is known as Marginal Fuel Burn (MFB). MFB is also increased by increasing distance. In the second scenario, the maximum payload is reached, and the economic cost is increased also because of the unsold payload.

5.7.1. First scenario: maximum payload is not reached

The increase in OEW of the aircraft and consequently increased fuel burn result in higher emissions and increased costs. To compute this increase in fuel burn, it is important to understand how marginal fuel burn works. Given a distance, the aircraft burns a certain amount of fuel. If mass is added, a certain extra mass of fuel must be carried. Now that extra fuel is loaded to carry extra mass, more fuel must be carried to carry said fuel. This is a reciprocating loop known as the “fuel for fuel” effect in which more fuel is carried to carry more fuel. The total addition of fuel because of an extra mass in the flight, is called marginal fuel burn. At a practical level, this can be approximated with equation **(5.2)**. [46]

$$F_t = F_{OEW,2000} + \left(MFB_{pl,2000} + \frac{\Delta f}{\Delta pl} * d\right) * pl + \left(MFB_{d,2000} + \frac{\Delta f}{\Delta d} * d\right) * d \quad \textbf{(5.2)}$$

Where F_t stands for total burnt fuel, $F_{OEW,2000}$ the amount of fuel burnt because of the OEW at 2000 km, f is the added fuel, pl stands for payload and d for distance (starting at 2000km). This equation can be divided in three sections: the first one, $F_{OEW,2000}$ assumes a linear correlation between fuel burn and distance. The second one, highlighted in yellow, adds more fuel the more payload is transported given a distance. And the third one, highlighted in green, accounts for the “fuel for fuel” effect. This equation can be computed both with and without the EPATS on board. The difference between the two will result in the extra fuel burn due to the EPATS.

With this procedure, the fuel burn in function of payload and distance is obtained. The left plot shows the total amount of fuel used by the aircraft with a certain payload, and with the same payload plus the weight of the EPATS. In Fig. 5.3, the plot at the right shows the total increase of fuel burn because of the EPATS weight in function of range. Please note that because this function does not consider the payload limitations of the aircraft, the MTOW would be exceeded in certain cases making the left plot a non-completely reliable source of information. On the other side, because the fuel used by the extra payload of the EPATS does not change with different payloads, the rest of the operations are performed solely on the range variable.

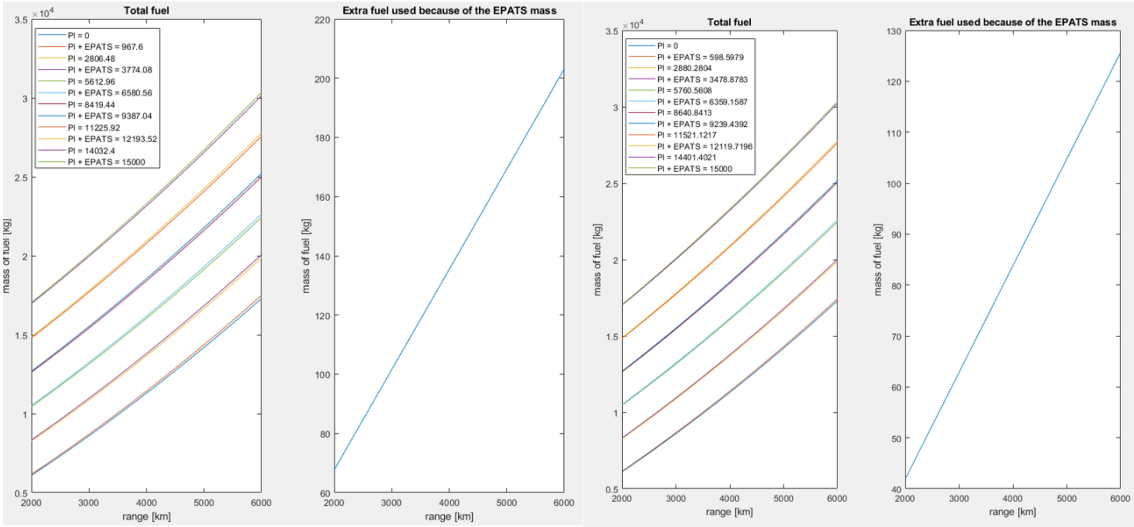


Fig. 5.3 Marginal Fuel Burn (MFB) for an electric EPATS (left) and a hybrid one (right). These plots can be seen in larger scale in APPENDIX 9.

5.7.2. Second case scenario: MTOW is reached

In this case, on top of the extra fuel expense because of the EPATS, less payload can be carried so the efficiency explained in section 4.2.2 (bathtub function) would decrease because fewer passengers can be carried. From an economic standpoint, the cost of the payload will have to be split amongst the remaining passengers, therefore, increasing their cost.

On the fuel efficiency side, an A320 with the maximum seat configuration of 186 seats, 10 of them should be left free to compensate for the 967.6kg of the EPATS. This would result in a slight efficiency loss. Especially in the optimal range area it is little notable, however it must be considered. The bathtub function is used to highlight the efficiency difference.

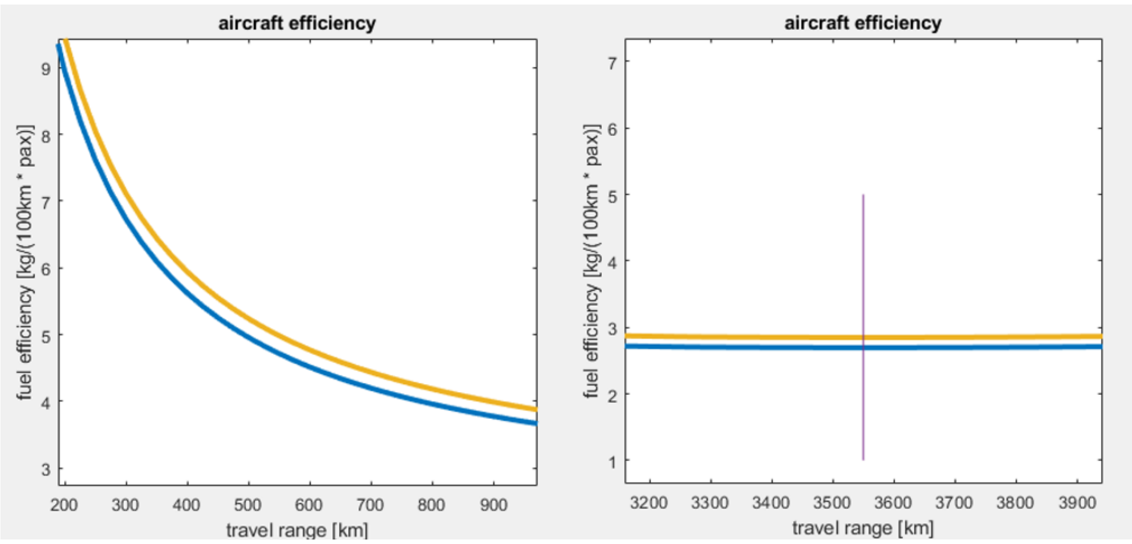


Fig. 5.4 Efficiency difference of the A320 with and without an EPATS on board.

5.8. EPATS overall balance

Finally, three main parameters are computed, both under and at MTOW. These three parameters are the total amount of fuel saved, the greenhouse gas emission compensation, and economical savings (if any) from the implementation of the EPATS. This is done by comparing all these parameters in a non-EPATS and an EPATS implementation scenario. The final outputs can be seen in Fig. 5.5 and Fig. 5.6.

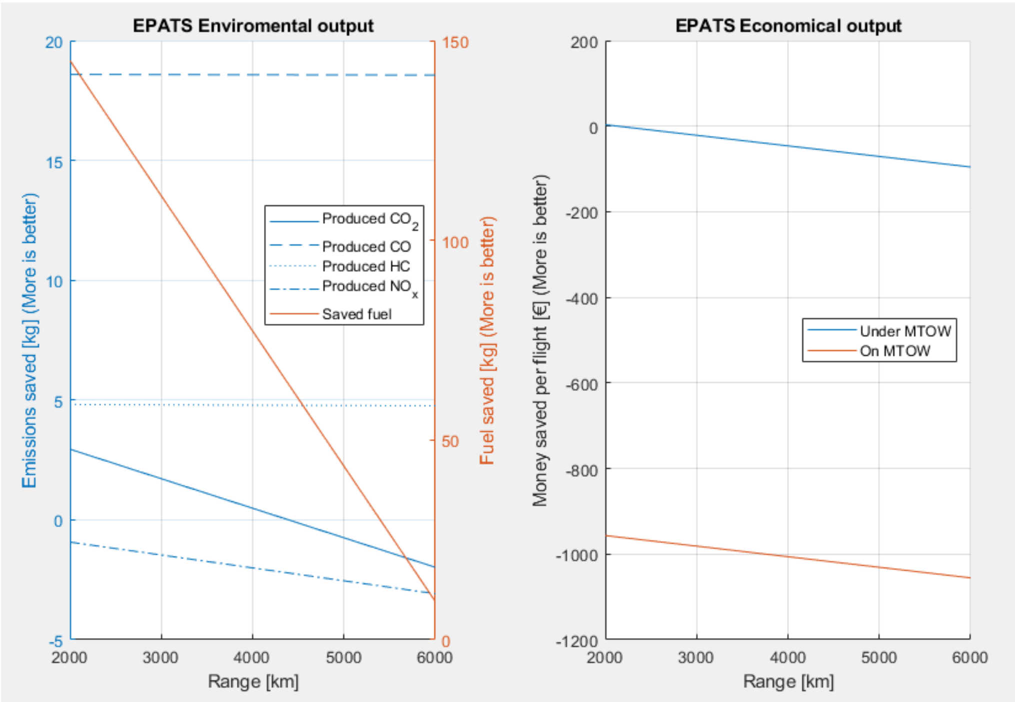


Fig. 5.5 Final outcomes of the electric EPATS.

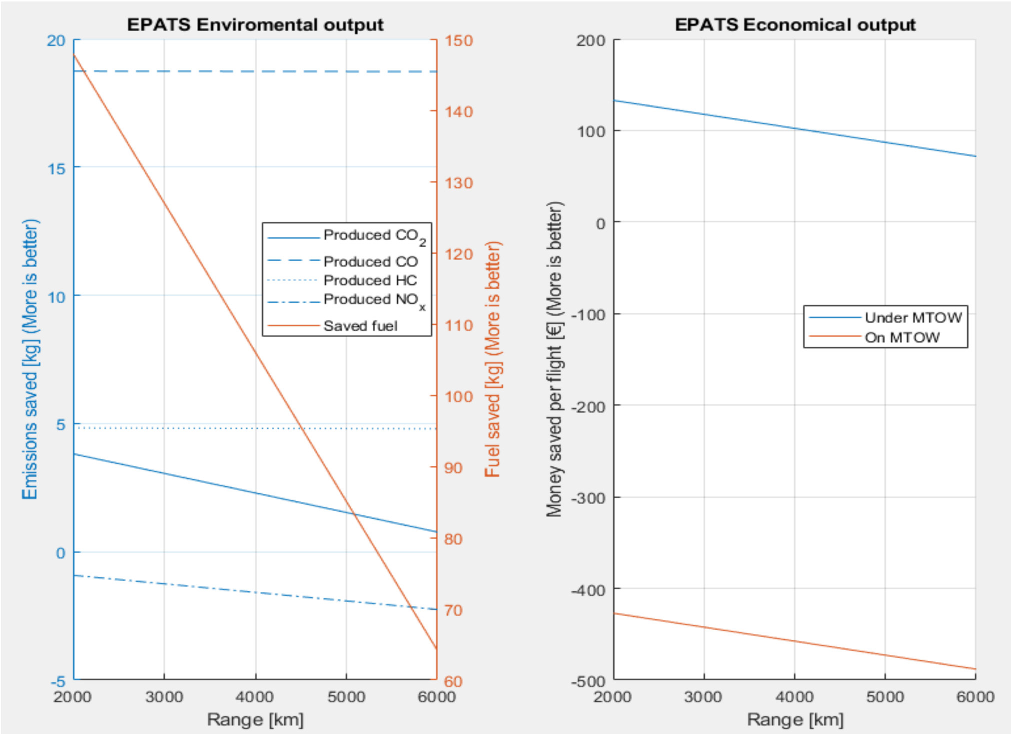


Fig. 5.6 Final outcomes of the hybrid EPATS.

On the environmental side, both configurations perform satisfactorily in both the decrease of overall fuel consumption and emission of greenhouse gases. However, because of the notorious impact of the system weight in flight performance, the electric version falls short regarding fuel savings, hence produces more gas emissions. A 60% battery weight reduction is required to match the Hybrid philosophy performances.

Two factors have a severe impact on the economics of an EPATS: range and loading factor. In both cases the shorter the average trip and the less pax rejected because of the extra weight, the better. Although the savings decrease notoriously with increasing range, the most punishing factor is clearly having to not accept passengers because of increased OEW. Therefore, if the aircraft is to be operated under 93-96% of loading capacity most of the time, profits will be generated. However regularly operating over this threshold will generate losses.

This challenge can be tackled with different strategies. Increasing the MZFW to fit more passengers, increasing the ticket price to the rest of passengers to reduce the losses or improve the performances or price of the systems. A series of possible profit maximisation scenarios are presented below.

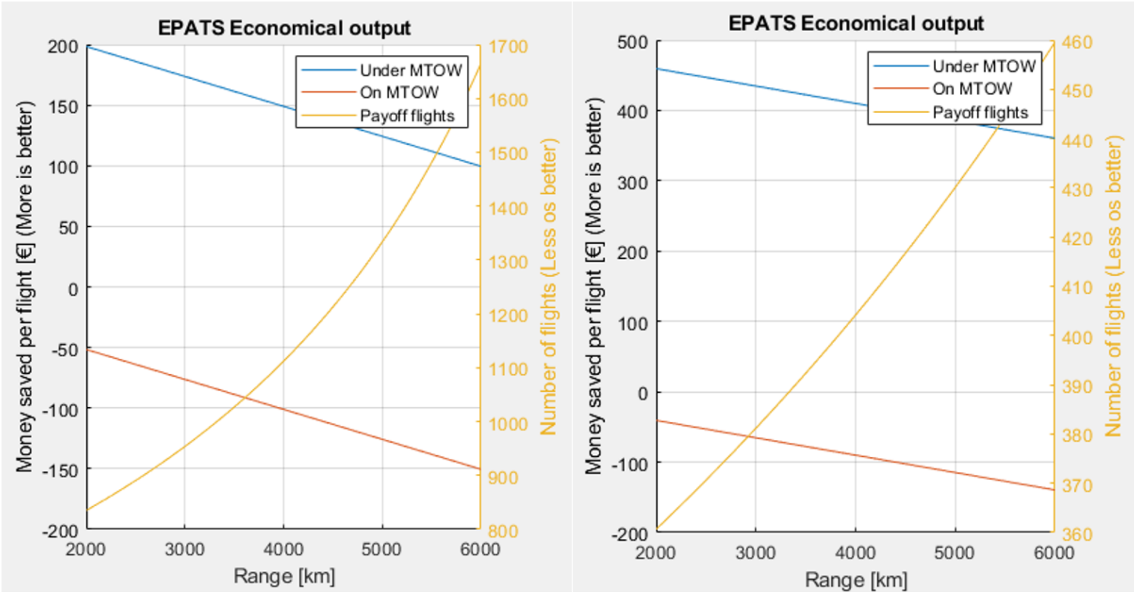


Fig. 5.7 Economical output in the electric EPATS implementing compensation actions given different scenarios. Left: cell weight reduced to 0.0785kg, assumed base ticket price of 25€, increased price of ticket to the remaining pax by 0.5€. Right: cell weight stays at 0.2kg, assumed base ticket price of 50€, increased price to the remaining pax by 2€, single cell price reduced to 5€ instead of 18€.

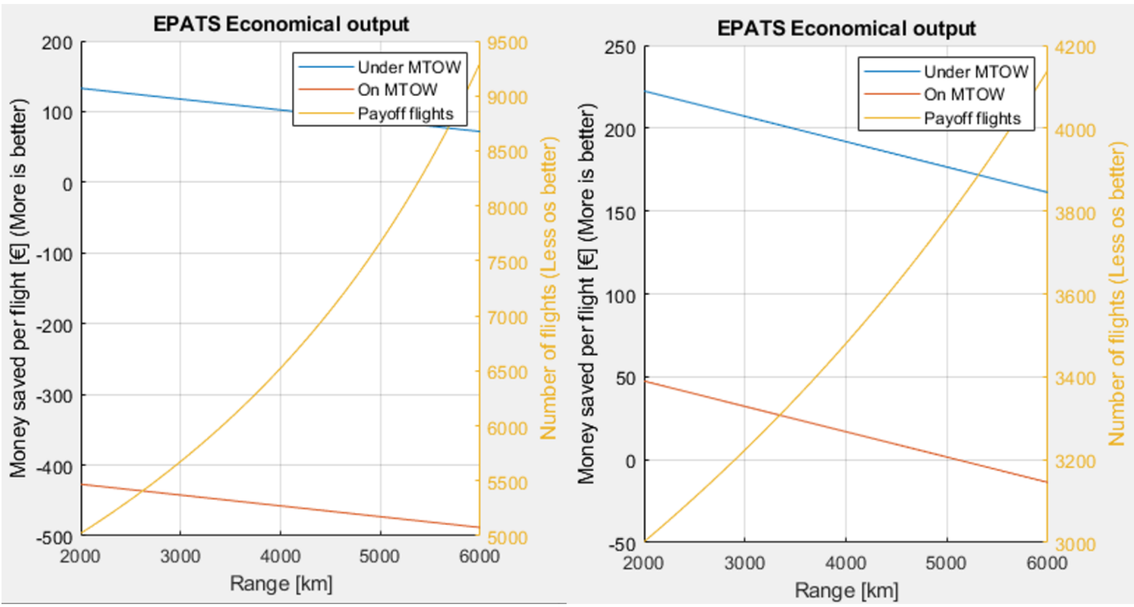


Fig. 5.8 Economical output in the hybrid EPATS implementing compensation actions given different scenarios. Left: assumed base ticket price of 80€, no compensation action is taken. Right: assumed base ticket price of 25€, increased price to the remaining pax by 0.5€.

5.9. Results

In this chapter a method to design an EPATS and calculate its outputs has been established. This method allows the user to input some basic known data and extract the outputs that will determine the characteristics of such a system as well as its implementation consequences such as fuel burn, emissions, and estimated economical balance.

With mid 2020 technology, implementing an airborne EPATS results more feasible with a hybrid configuration in which the APU is used as a power source rather than a heavier electric alternative. However, if the EPATS is installed in an external platform, the electric version will be more economically feasible as weight does not matter as much.

Regarding the different strategies, onboard EPATS do not present as a highly feasible alternative to taxi as they are both very heavy and expensive therefore it is discarded as a feasible option in the short term. Nonetheless, in a short haul, low loading factor scenario, an onboard EPATS is to be considered. On the other hand, an outboard EPATS is a reasonable option as it has virtually all the benefits from an onboard EPATS but is not carried during the trip hence no additional fuel is spent because of the EPATS. A similar conclusion was reached in a paper [52], and by Safran [53].

CHAPTER 6. ELECTRIC POWERPLANT MODIFICATION

6.1. Objective and motivation

An Electric Powerplant Modification (EPM) in airplanes is something rare as the technology is very new and limited to specialised companies and highly skilled engineers. This project will provide an easy method to calculate the principles on an electric conversion in most piston single engine aircraft. By the end of this chapter any pilot, engineer or mechanic will be able to estimate the physical and performance-related properties of an electrically modified aircraft as well as the economical outcome of said conversion, and even a forecast of the future costs of maintaining and operating these aircraft.

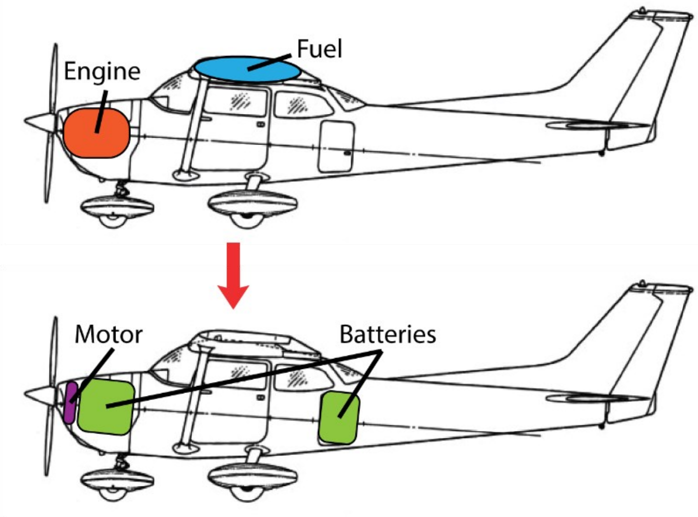


Fig. 6.1 Visual representation of the goal in this chapter, replace the conventional fossil fuel powered engine powerplant to an electric battery fed motor.

6.2. Estimation of characteristics and performances of an aircraft

When a powerplant replacement like this is performed, the options are nearly endless. Parameters such as the weight of the airplane, the power of the motor or the location of the centre of gravity are parameters that can vary massively depending on the designer’s constraints. The method in this project keeps all the original aircraft’s characteristics in exchange for endurance. This way the method is not only appliable to as many aircraft as possible, but it also requires the easiest certification process. Therefore, the total mass of maximum fuel and engine is equal to that of the motor and battery set. The centre of gravity is kept at the same place. And the motor has the same power output as the conventional engine.

6.2.1. Weight and centre of gravity

In this section, the goal is to develop a method to design an electrical system that matches the aircraft's original performances. These performances include the peak power delivery of the engine, the required cruise power and original weight. Other parameters such as the centre of gravity and mass of the engine and fuel must be considered to keep a new aircraft as faithful to the original one as possible. This is calculated by forcing the weight of batteries plus motor to be equal to the total amount of engine and fuel weight. Then to maintain the centre of gravity, two different sets of batteries are installed in the airplane. The total battery weight is distributed in two different compartments so the centre of gravity changes as little as possible. The equations and specific steps follower to reach these goals can be found in APPENDIX 8.1.

6.2.2. Electrical properties

By today's standards, EV batteries are made from thousands of batteries, however, their distribution and properties are not randomly chosen. In this section the calculation of such a battery is explained conceptually. A more detailed explanation along with the equations used is found in APPENDIX 8.2.

The first constraint is defined by the motor voltage. This determines how many batteries are mounted in series to reach the desired voltage. Secondly, the number of parallel threads is defined with the total battery weight and the mass of a single cell. Now the total energy stored can be obtained with the energy of a single cell. The other relevant characteristic from the battery is the flight time that can theoretically be achieved. Which if the output power and efficiency factor are known, can be computed.

6.3. Validation of methodology

In this section, the previously defined method is tested by applying it to real life cases in which an electrical conversion has been performed, to define whether the method is realistic enough.

6.3.1. Alpha electro

The SW121 is a new and efficient aircraft that has a commercial electric version called the Alpha Electro [18]. The SW121 is a light sport aircraft with glider-like characteristics which help the efficiency of the airplane.

Table 6.1 Characteristics of the SW 121 the Alpha Electro.

Virus SW 121			Alpha electro		
Parameter	Value	Units	Parameter	Value	Units

Peak Power	73.5	kW	Peak Power	60	kW
Cruise Power	-	kW	Cruise Power	20	kW
Max. Endurance Power	-	kW	Max. Endurance Power	16	kW
Fuel Mass	80	kg	Fwd battery mass	63	kg
Fuel placement	0.2	m	Fwd battery placement	-0.9	m
Engine mass	56.6	kg	Aft battery mass	63	kg
Engine placement	-0.8	m	Aft battery placement	1.16	m
			Motor mass	11	kg
			Motor placement	-1.070	m
			Endurance claim	1.5	h
			Specific energy claim	21	kWh

Table 6.2 Results of the methodology described in section 6.2 applied to the Virus SW 121.

Obtained results					
Parameter	Value	Units	Parameter	Value	Units
Endurance max power	20	minutes	Total battery mass	125.5	kg
Endurance cruise power	55	minutes	Fwd battery mass	78.52	kg
Endurance min. power	70	minutes	Aft battery mass	46.96	kg
Specific energy	19.541	kWh			

By looking at the results, it can be said that the estimation is fairly accurate. There are however a few discrepancies. These discrepancies are the positioning of the battery, which can be explained by design restrictions and the endurance time, which can be explained by the overestimation of the manufacturer. The magazine *the aviation consumer* [54] gives credibility to these assumptions. Overall, the method can be determined to be realistic in this case.

6.3.2. Harbour's Air DHC-2

The de Havilland Canada DHC-2 is an old aircraft which is equipped with either a rotary engine of a turboprop. Despite its age, it is a very popular choice in the amphibious market. The airline Harbour Air is planning on modifying all their DHC-2s with an electric powerplant. In the end of 2019, the first prototype of electric DHC-2 performed its first 10 minute test flight on which the data below is based [35].

Table 6.3 Characteristics of a conventional and an electric DHC-2. [55] [56]

Conventional DHC-2			HarbourAir DHC-2		
Parameter	Value	Units	Parameter	Value	Units
Peak Power	336	kW	Peak Power	560	kW
Cruise Power	-	kW	Cruise Power	336	kW
Fuel Mass	388	kg	Fwd battery mass	unk	kg
Fuel placement	0.58	m	Fwd battery placement	-2.28	m
Engine mass	300	kg	Aft battery mass	unk	kg
Engine placement	-1.9	m	Aft battery placement	2.38	m
			Motor mass	133	kg
			Motor placement	-2.7	m
			Endurance claim	1	h
			Specific energy claim	135	Wh/kg

With these parameters the aircraft was able to perform an 8-minute inauguration flight. The company claims that the aircraft will begin flying passengers in around two years. By then 400 Wh/kg batteries should be available and along them, a 1h endurance time.

Table 6.4 Results of the methodology described in section 6.2 applied to the DHC-2.

Obtained results					
Parameter	Value	Units	Parameter	Value	Units
Endurance max power	21	minutes	Total battery mass	555	kg

Endurance cruise power	35	minutes	Fwd battery mass	283	kg
Specific energy	221.993	kWh	Aft battery mass	271	kg

The outcomes calculated with this methodology do not fall far from the claims of the manufacturers and operators. Especially considering that manufacturers tend to publish the best-case scenario. Again, the method proves to give accurate numbers of a real case.

6.4. Economical balance example

One of the strongest selling points of this conversion is the lower operational costs that an electric plane would have. Not only from not burning fuel, but from many maintenance costs as well. This does not come however with some drawbacks. The battery is an economic and endurance bottleneck.

The Velis electro is the evolution of the Alpha electro. It is the first electric certified aircraft by EASA. Given the amount of reliable data available from the manufacturer and users, and the existence of a conventional version, this specific aircraft is selected to estimate the economic output. The existence of accurate data on the model is particularly important as the following sections are based on long term estimations. Thus, having precise data to start with, guarantees a minimum deviation from reality. To fit the aim of this chapter, a simulation is performed. In this simulation there are two brand new identical SW 121. One is kept as is, and the other one is converted to electric. The costs of both aircrafts are listed in APPENDIX 7. This data is later used to compare the economic feasibility of both cases.

Because the total costs depend on the number of yearly flown hours, two scenarios are plotted. In the first one both aircraft fly 100 hours every year and in the second one, they fly 1000 hours every year as seen in Fig. 6.2. This figure shows how, if flown 100 a year, the electric conversion investment will not be paid off. However, if flown 1000 hours a year, the investment will be paid off in approximately 10 years. Thus, the more flown hours, the faster the investment will be paid off. According to former flight instructor Oriol Ribera, conventional training aircraft do fly more than 1000 hours per year, thus it is a realistic statement.

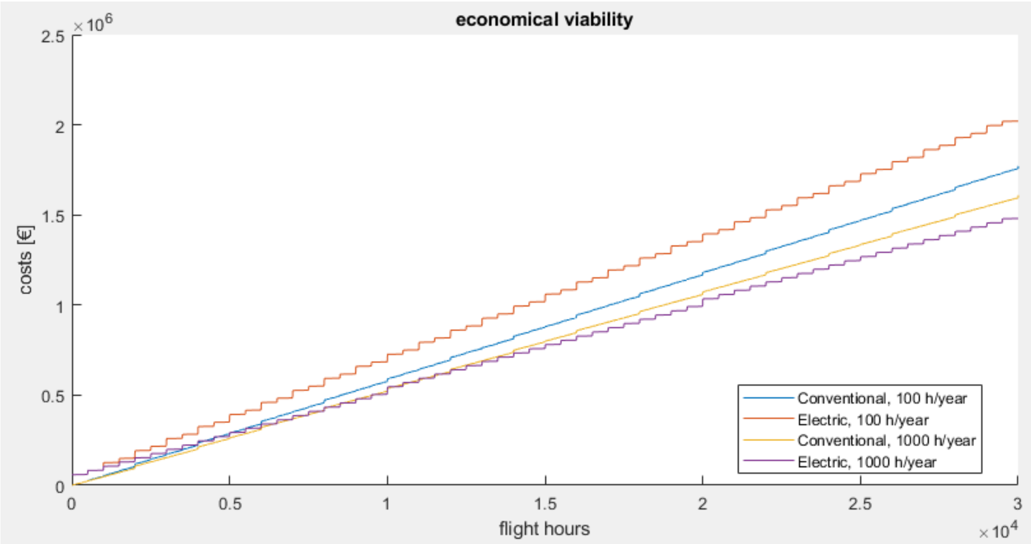


Fig. 6.2 Economic costs of a SW121 and a Velis Electro given two different scenarios.

Another concept that must be considered is the forced ground time. Conventional, general aviation airplanes use to spend quite some time on ground during maintenance procedures. Because of the complexity of a combustion engine, every given number of hours, engines need to be completely disassembled, checked, and repaired. This process takes several months. Electric aircraft are not subject to such procedure. Instead, charging time is the reason for most of this ground forced time.

6.5. Electric aircraft evolution forecast

At this point it may seem like an electric conversion is not a particularly good idea given the limited endurance, the 10 year pay off and the extended charging time. Therefore, in this section, the evolution of different electric aircraft related characteristics, such as energy capacity and price, will be forecasted. And then, said characteristics will be applied to the Velis Electro, the aircraft with the most accurate available data to see how the evolution of battery technology will affect real aircraft performances.

6.5.1. Energy density

As seen in Fig. 6.3, the capacity of secondary batteries has increased since the 1930s. It is impossible to perfectly forecast how batteries will evolve in the future. But it is possible to make an approximation of its characteristics as the specific energy curve has been increasing in a quite regular manner that can be approximated with the exponential equation **(6.1)**.

$$y(x) = m^x + n \quad \textbf{(6.1)}$$

Where y is the energy density of the secondary battery, x is the year since the “bottom” of the curve, m is a constant to be determined and n the initial offset in energy density. By taking a few control points from Fig. 6.3 these parameters are estimated to be m equal to 1.07 and n equal to 30 Wh/kg. Again, this is not perfectly fit to reality, but it is the best available approximation to consider the past evolution.

Now that the “optimistic” approach is obtained, the “pessimistic” forecast is to be obtained as well. In this case, instead of the evolution of the last 90 years, only the evolution of Lithium-ion (Li-ion) batteries are considered. In this scenario it is assumed that no technological breakthrough is made, and battery technology is subject to the linear grow seen so far seen from Li-ion batteries hence the equation **(6.2)**.

$$y(x) = mx + n \qquad \textbf{(6.2)}$$

Where m is the yearly growth of capacity and n the offset.

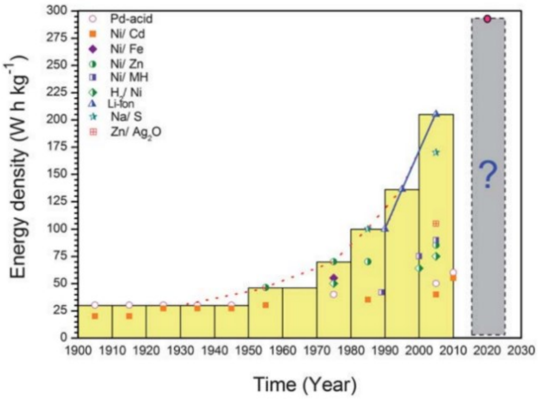


Fig. 6.3 History of development of secondary batteries in view of energy density. [10]

With these equations, the best case and worst-case battery capacity evolution forecast are obtained (upper left plot in Fig. 6.4). If combined with the power consumption of the Velis Electro at three different throttle settings, the forecasted endurance time is obtained. The blue (or upper) line shows the “optimistic” forecast, the orange (or lower) line represents the linear Li-ion forecast, and the yellow (or middle) line shows an intermediate point. Please note that a degrading offset has been applied to the yellow line as it is supposed to be the most realistic forecast, thus it takes into account not only the energy density of the batteries but also packaging, cooling system and other auxiliary systems that degrade the energy density of the battery pack. To obtain the offset, the real Velis Electro energy density (around 150 Wh/kg) has been set as a constraint.

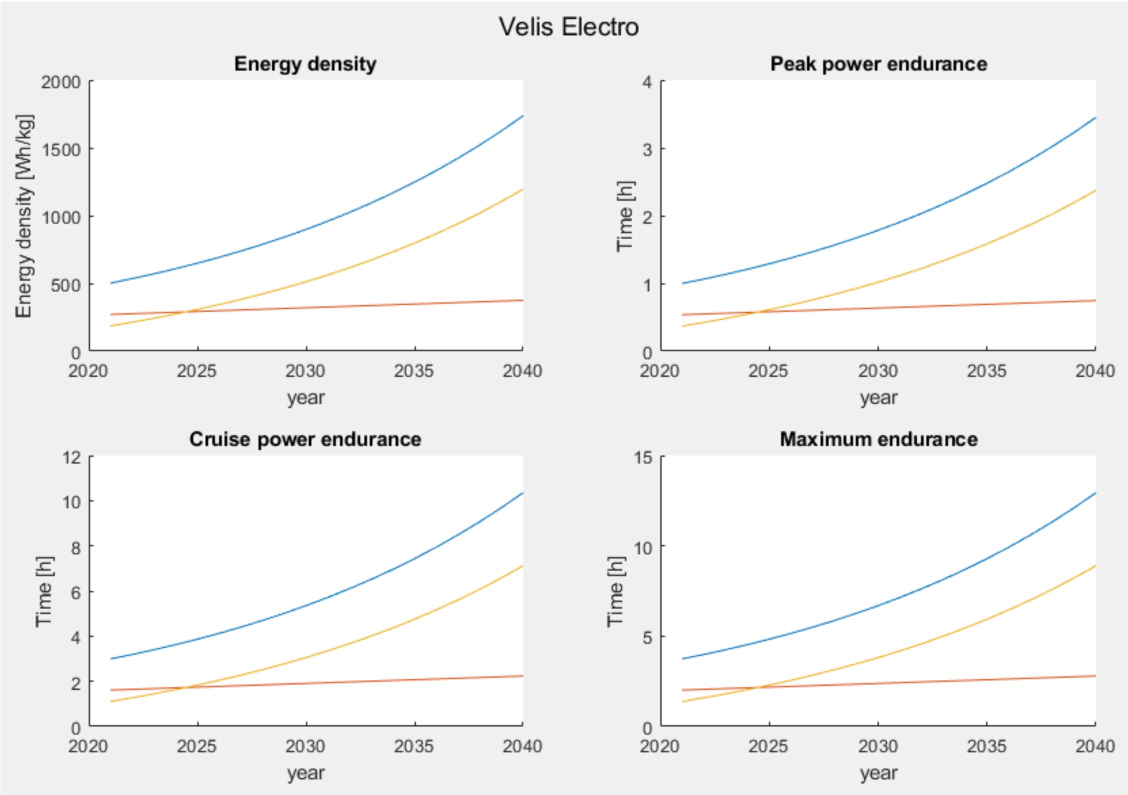


Fig. 6.4 Forecasted energy density of secondary batteries from 2020 to 2040 and its impact on endurance of electric aircraft.

6.5.2. Price

The batteries used in the Velis Electro have a selling price far higher than its automotive equivalent. This can be explained by the far greater safety tests carried on and the costly certification. The price of the battery this point forward will only decrease. According to BloomerNEF [57] regarding the Li-ion battery costs of EVs, their price has decreased an average of 18% every year. In other words, in a period of 8 years (2010-2018), the price of batteries has dropped an average of 85%. If that were to happen in the case of the Velis Electro, the price of the full battery will drop to 4256€ in a 5 year period. In this scenario, the economical balance would be as in Fig. 6.5.

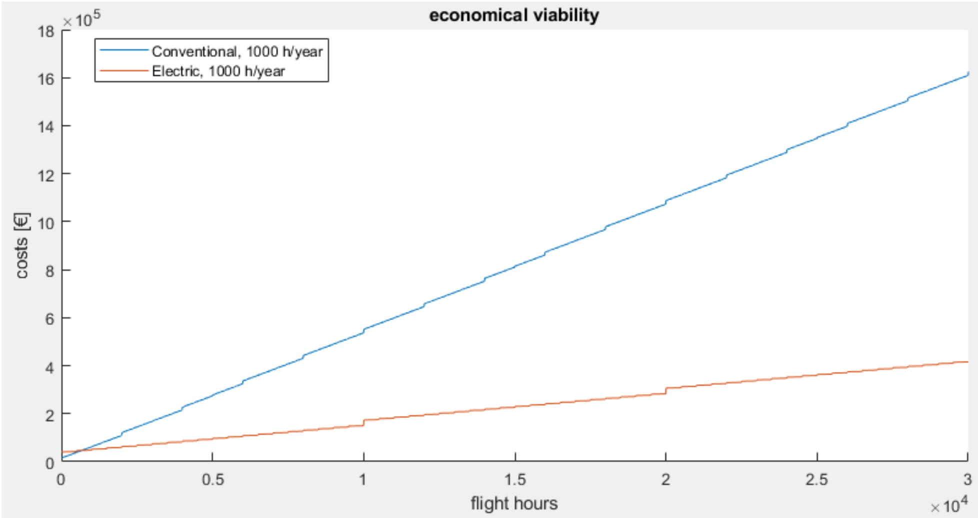


Fig. 6.5 Forecasted Economic output of performing an electric powerplant swap in 5 years.

In this scenario the costs of operating the Velis Electro instead of an internal combustion SW 121, would be around 74% cheaper regarding power plant costs. However, due to low production rates, most probably aircraft batteries will still be considerably higher.

6.5.3. Life cycles

The life cycle of different kinds of battery varies broadly from type to type. To set an example, LFP batteries have a life cycle 4 times larger than that of a NMC battery. On top of that, while safe, the behaviour of batteries as airborne power suppliers is still relatively unknown. Especially in the long term. A consequence of this ignorance is the short life cycle of airborne batteries. However, when asked about the topic, A pipistrel distributor (Roberto Jiménez Quinones) said that the manufacturer is putting a lot of effort into extending the battery life to reduce costs. In this case the battery life will be assumed to be extended by 1% every year.

6.6. Final economic outcomes

In this section, all the estimation data is put into practice with one simulation. In this case a Velis Electro is pretended to be bought and the costs and performances for the following years are compared to a Virus SW 121. A ratio of 15% cheaper batteries every year with a bottom price of 5000€ is assumed. With these inputs, the plots in Fig. 6.6 and Fig. 6.7 are obtained. In this case, the “evolution” of the batteries towards cheaper prices and extended life, lead to much lower operational costs. In contrast to the previous examples in which the price and life cycles were “frozen” to present standards, the initial investment is paid off in just 4 years and further savings increase with time. The procedure to find the financial outcomes taking into account the evolution of battery prices and technology is explained with greater detail in APPENDIX 8.3.

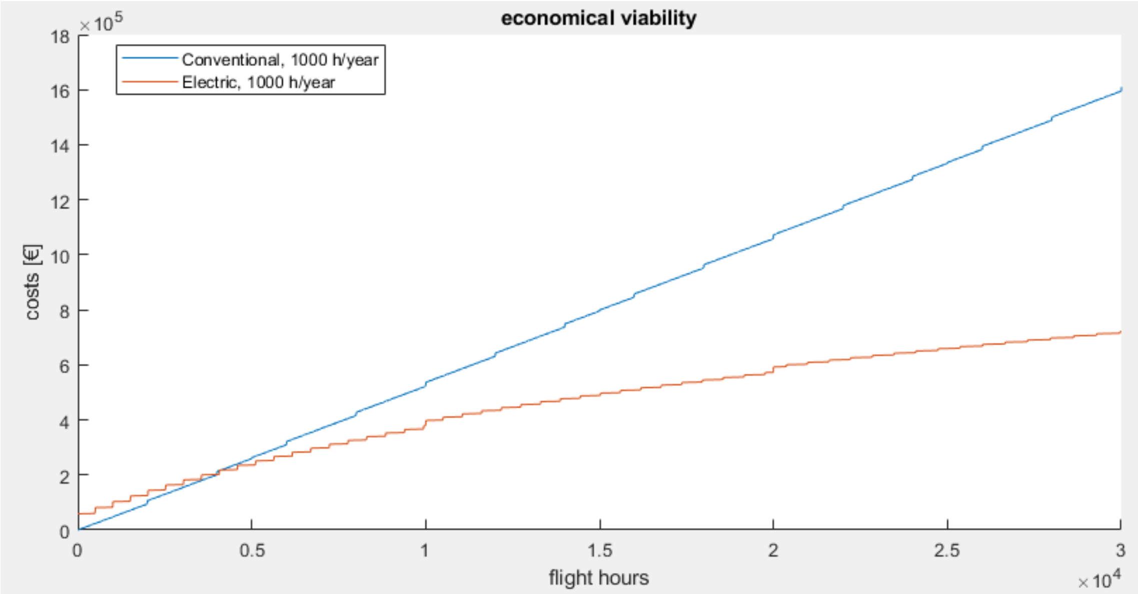


Fig. 6.6 Economic output forecast of performing an EPM taking into account the forecasted life cycle improvement and drop in cost of batteries.

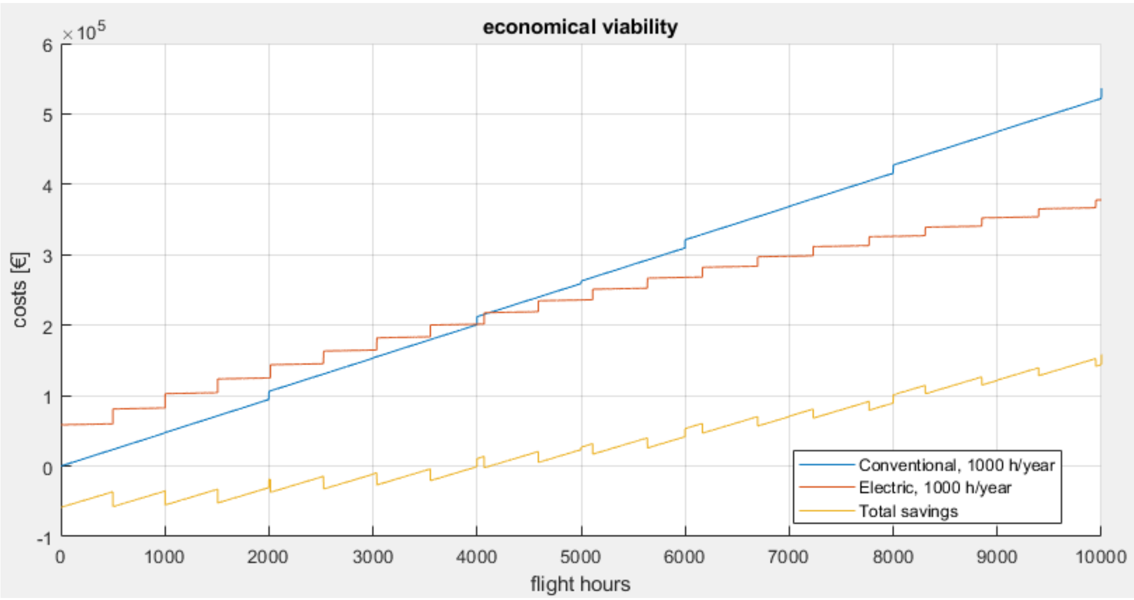


Fig. 6.7 More detailed economic output forecast of performing an electric powerplant swap considering the forecasted life cycle improvement and drop in cost of batteries of the next 10 years.

6.7. Results

The entire procedure explained above can be found in a more straight-forward methodology in APPENDIX 8.

By the analysis of the aircraft mentioned above, studying their performances, and forecasting their future performances and economic feasibility the following statements can be made:

1. The methodology developed in this project to estimate the characteristics of an electric conversion are quite accurate and provide an idea of the characteristics of an electrically modified aircraft.

2. Efficient planes show outstanding capabilities to perform an EPM, therefore when performing an electric motor swap, factors such as the glide ratio, Cd and such should be looked upon.

3. As seen also in the automotive industry, battery performances are improving at a considerable rate and so are their prices. In the case a conversion is declared not to be feasible in an aircraft, chances are it will be feasible within the very next few years.

4. Whether an electric swap is or not feasible, ultimately depends on the usage the aircraft is going to have and its application. For example, an electric swap in a light aircraft that is going to be intensely used for pilot training in touch-and-go’s and is going to be upgraded with cheaper, longer-lasting batteries with more capacity is most probably a good investment. While an old aircraft that is going to be used for cross country flights, mainly landing in isolated areas, probably should not be converted now.

Given that the methodology can be applied to any aircraft with a single piston engine, said methodology has been applied to two aircraft with no present electric versions. The results can be found in APPENDIX 8.4.

CHAPTER 7. Conclusions

All the objectives set at the beginning of the project have been achieved.

The following topics have been spotted, investigated, and analysed as they are a pollution and inefficiency source.

a) Inefficient aircraft placement in the European airspace due to the length of the routes they fly.
b) Pollution generated by the aircraft during ground operations.
c) Use of conventional engines in general aviation instead of using electric technology.

Development of models to quantify the environmental and economic impact of the previous sources and of the proposed solutions, has also been a success as:

a) Models have been implemented to quantify the inefficiency created by conventional commercial aircraft due to suboptimal trip length.
b) Models to quantify the inefficiency of conventional taxi methods has been implemented. And a methodology and models have been successfully established to determine the environmental and economic feasibility of the EPATS.
c) A methodology and models have been successfully established to calculate the properties and characteristics of an electric power plant replacement in single piston engine aircraft.

Finally, a set of recommendations have been proposed at the end of each chapter so each of the technologies have the greatest chance of success. The main outcomes being:

a) Conventional, “old” aircraft (A318, A320 and B737) that cover short routes should be replaced by more efficient present aircraft in the short term, and by third generation aircraft in the long term.
b) An EPATS is a feasible option to reduce fuel consumption, especially in its electrical, external form.
c) Electric Powerplant Modifications (EPM) are a feasible alternative to conventional engines for aircraft if the scenario is adequate.

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APPENDICES

TÍTOL DEL TFG: Overview on Sustainable Aviation Technologies and Guidelines for its application

TITULACIÓ: Grau en Enginyeria de sistemes Aeroespacials

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DATA: Octubre del 2020

APPENDIX 1. Bathtub Function

The methodology followed in this appendix is based on the project of Marcus Burzlaff [58]. Fuel burn functions are of high value for airlines, therefore it is not trivial to find them. However, aircraft manufacturers publish some basic information on their aircraft models for operators to have some guidelines on how their aircrafts will operate and which performances they will have. Some of this information is the payload-range plots and aircraft's MTOW, OEW and MFW. In this example an A320 study is shown. In most cases, there are several versions of the same aircraft with different performances each. Therefore, it is important to stick to a single version. In this case an A320-200 WV017 with sharklets. It is relevant to mention that this plots and calculations are performed under ISA conditions and therefore are not completely accurate.

Table 7.1 Weight data of different versions of the A320. [59]

Aircraft Characteristics					
	WV015	WV016	WV017	WV018	WV019
Maximum Ramp Weight (MRW) Maximum Taxi Weight (MTW)	78 400 kg (172 842 lb)	73 900 kg (162 922 lb)	78 400 kg (172 482 lb)	71 900 kg (158 512 lb)	70 400 kg (155 205 lb)
Maximum Take-Off Weight (MTOW)	78 000 kg (171 961 lb)	73 500 kg (162 040 lb)	78 000 kg (171 961 lb)	71 500 kg (157 630 lb)	70 000 kg (154 324 lb)
Maximum Landing Weight (MLW)	64 500 kg (142 198 lb)	66 000 kg (145 505 lb)	66 000 kg (145 505 lb)	66 000 kg (145 505 lb)	64 500 kg (142 198 lb)
Maximum Zero Fuel Weight (MZFW)	61 000 kg (134 482 lb)	62 500 kg (137 789 lb)	62 500 kg (137 789 lb)	62 500 kg (137 789 lb)	61 000 kg (134 482 lb)

Table 7.2 A320's seating number and fuel related data. [59]

****ON A/C A320-200 A320neo**

3. The following table provides characteristics of A320-200 and A320neo Models, these data are common to each Weight Variant:

Aircraft Characteristics	
Standard Seating Capacity	180 (Single-Class)
Usable Fuel Capacity (density = 0.785 kg/l)	23 859 l - 26 759 l * - 29 659 l ** (6 303 US gal - 7 069 US gal * - 7 835 US gal **)
	18 729 kg - 21 005 kg * - 23 282 kg ** (41 290 lb - 46 308 lb * - 51 328 lb **)
Pressurized Fuselage Volume (A/C non equipped)	330 m^3 (11 654 ft^3)
Passenger Compartment Volume	139 m^3 (4 909 ft^3)
Cockpit Volume	9 m^3 (318 ft^3)
Usable Volume, FWD CC	13.28 m^3 (469 ft^3)
Usable Volume, AFT CC	18.26 m^3 (645 ft^3)
Usable Volume, Bulk CC	5.88 m^3 (208 ft^3)
Water Volume, FWD CC	15.56 m^3 (549 ft^3)
Water Volume, AFT CC	20.77 m^3 (733 ft^3)
Water Volume, Bulk CC	7.76 m^3 (274 ft^3)

* OPTION: 1 ACT
** OPTION: 2 ACT

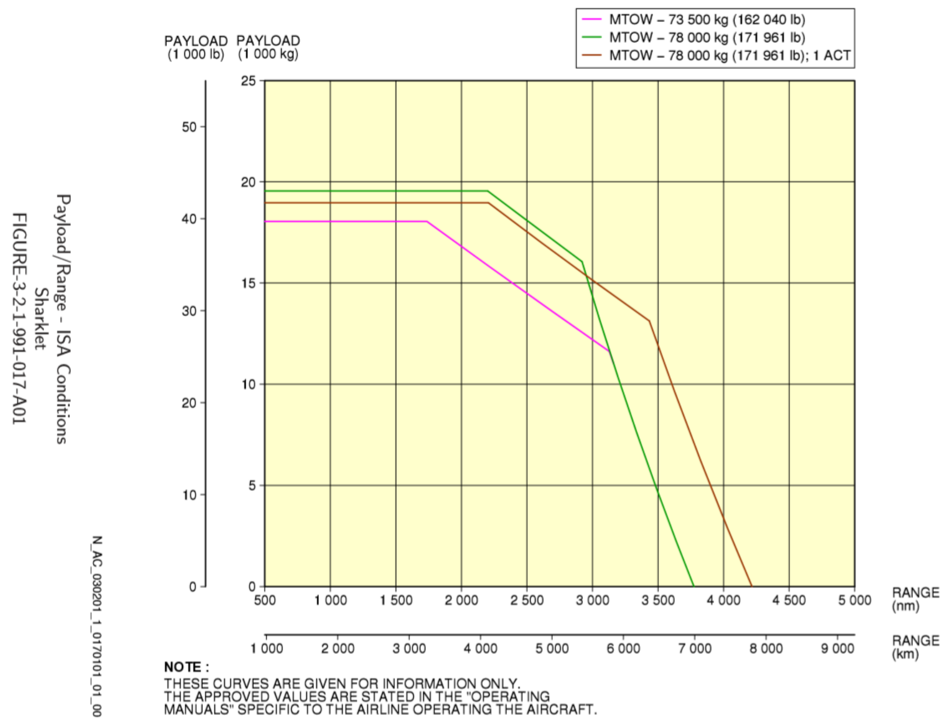

Fig. 7.1 Payload vs Range diagram of the A320 [59]

Now that the data is obtained, we can set our attention on the qualitative data of this aircraft. The payload-range diagram in Fig. 7.2 basically shows the amount of payload (or weight of cargo or passengers) that can be carried for a certain distance. This range depends on two parameters. The fuel carried and the weight of the payload. In the point “A” ideally a linear correlation between used fuel and distance is stablished. Therefore, the more fuel burnt, the further the aircraft goes in a linear manner. Once it reaches the point “B”, MTOW is reached, therefore, payload must be removed to add more fuel. In point “C” the maximum capacity of the fuel tanks is reached. Therefore, the only way to travel further is to make the airplane lighter by unloading payload. On a practical level, the burnt amount of fuel per passenger can be determined by dividing the total amount of burnt fuel per all the passengers and by the amount of times 100km have been travelled. To simulate non-optimal routing, take off fuel and other factors, an offset of the calculated range is set. For example, If the goal is to obtain the burnt fuel per passenger in a 100 trip, a “reserve factor” is set, for example 5%. On top of that, a 300km trip to an alternate airport and 45 minutes of weight which is roughly equivalent to 204km is added to the total distance. In this case the range is set to 609 km. The fuel that would be burned for this trip and the payload of the aircraft can be obtained because the take-off weight and landing weight are obtained from the computations.

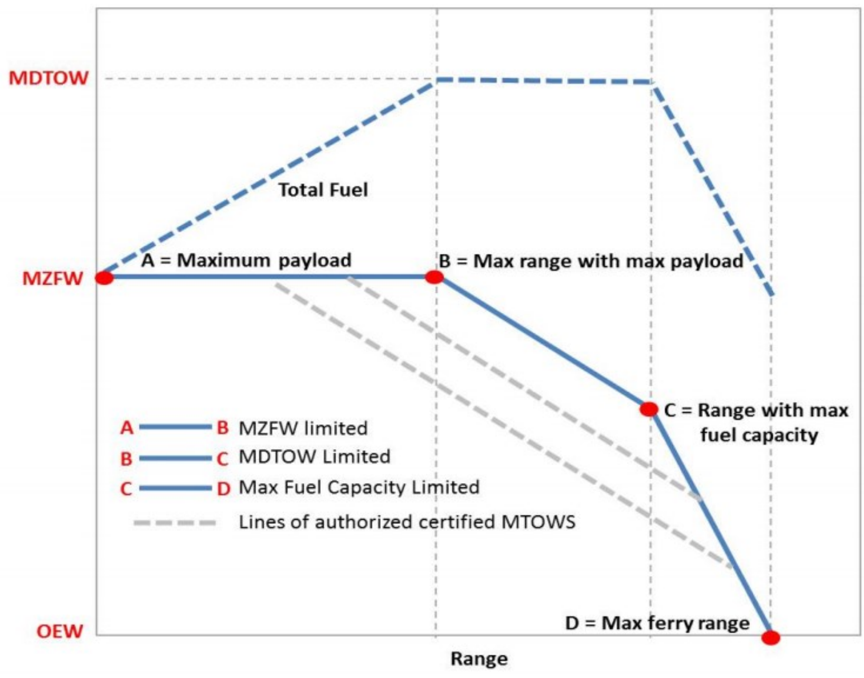

Fig. 7.2 Payload vs range chart that also takes into account the fuel consumed. [60]

This concept can be translated to a Matlab function.

Table 7.3 Matlab code to compute the bathtub function.

```
function [Fuel, Fuel_pp, range, optimal_range, optimal_fuel_pp, dep, arr] = Bath_tub(MTOW,
MZFW, MFW, OEW, Seat_capacity, Rg_A, Pl_A, Rg_B, Pl_B, Rg_C, Rg_min, Rg_max, res,
Reserve)
%the vectors are defined with the same length. Range, total fuel used, fuel
%used per person every 100km, departure weight and arrival weight
range = Rg_min:res:Rg_max;
Fuel = zeros (1,length(range));
Fuel_pp = zeros (1,length(range));
dep = zeros (1,length(range));
arr = zeros (1,length(range));
optimal_range = 0;
optimal_fuel_pp = 100;
for k=1:length(range)

        if (range(k)*1.1 + Reserve)<Rg_A %first sector, constant maximum payload and
increasing                                  weight of fuel and take off weight
        m1 = (MZFW) + ((MTOW - MZFW)/(Rg_A))*(range(k)*1.1 + Reserve);
        m2 = OEW + Pl_A ;

        elseif (range(k)*1.1 + Reserve)<Rg_B %second stage, constant takeoff weight =
MTOW and decreasing payload
        m1 = MTOW;
        m2 = OEW + Pl_A +(((OEW + Pl_B) - (OEW + Pl_A))/(Rg_B - Rg_A))*((range(k)*1.1
+   Reserve) - Rg_A);

        else %maximum fuel capacity is reached, takeoff weight and payload descend
        %at the same ratio.
        m1 = MTOW +(((OEW+MFW) - MTOW)/(Rg_C - Rg_B))*((range(k)*1.1 + Reserve) -
Rg_B);
        m2 = (OEW + Pl_B) +((OEW -(OEW + Pl_B))/(Rg_C - Rg_B))*((range(k)*1.1 +
Reserve) - Rg_B);
        end

        if m2<OEW %if landing weight is lower than operating weight, doesn't make sense.
therefore we've reached maximum range
        break
   end
        Fuel(k) = m1-m2; %fuel burnt for range(k)
        seats = Seat_capacity*((m2-OEW)/(MZFW-OEW)); %equivalent of passengers the
fuel must be distributed amongst. (not quite realistic because does not take into account
cargo and because it should be an integer but it fills the purpose)
        [Fuel_pp(k)]=(Fuel(k)*100)/(seats*range(k)); %distribution of fuel per pax and
normalisation  to 100km
        dep(k)=m1; %addition of weights in the vectors to be able to plot them later
        arr(k)=m2;
        if Fuel_pp(k)<optimal_fuel_pp %test to find the optimal range and its efficiency
                optimal_fuel_pp = Fuel_pp(k);
                optimal_range = range(k);
        end
end
```

In the case of the A320 the inputs are as follow:

Table 7.4 Matlab code to obtain the A320 bathtub plotted

```
function [] = MainA320()
MTOW = 78000; %Maximum take off weight [kg]
MZFW = 62500 ; %Maximum zero fuel weight. maximum weight of payload plus OEW [kg]
MFW = 21005; %Maximum fuel weight. maximum weight of fuel the aircraft can carry [kg]
OEW = 44000; %Operative empty weight. weight of the aircraft with pilots, equipment and
consumables inside (it results of MZFW - max PL but can be adjusted to match the physical
logic of the problem) [kg]
Seats = 140; %number of seats occupied by passengers. this number is used to calculate the
amount of fuel required to move a single passenger 100km
Range_A = 4100; %range in which the MTOW is reached and payload has to be removed to
add fuel [km]
Payload_A = 18000; %payload at point A [kg]
Range_B = 6400; %range at which maximum fuel capacity is reached and payload has to be
dumped in order to lighter the airplane and travel further [km]
Payload_B = 13000; %payload at point B [kg]
Range_C = 7800; %Maximum theoretical range of the aircraft or ferry range. No payload is
carried at this point [km]
Minimum_range = 100; %range at which the iteration starts [km]
Maximum_range = 6400; %range at which the iterations stop [km]
Resolution = 10; %resolution at which the iterations are plotted [km]
Reserve = 504; %reserve distance that is included in the calculation. despite being marked
as reserve, most of the times reserve fuel is not burned but it can be assumed to be the fuel
burnt to takeoff. [km]

[Fuel, Fuel_pp, Range, Optimal_range, Optimal_efficiency, Departure, Arrival] =
Bath_tub(MTOW, MZFW, MFW, OEW, Seats, Range_A, Payload_A, Range_B, Payload_B,
Range_C, Minimum_range, Maximum_range, Resolution, Reserve);

subplot(1, 2, 1);
plot(Range,Departure,'linewidth', 3);
hold on
plot(Range, Arrival,'linewidth', 3);
plot(Range, Fuel,'linewidth', 3);
title('Masses in function of range')
xlabel('travel range [km]')
ylabel('weight [kg]')
legend('departure mass', 'arrival mass', 'consumed fuel')
legend('location', 'southeast')

subplot (1, 2, 2);
plot(Range, Fuel_pp,'linewidth', 3);
hold on
plot([Optimal_range, Optimal_range],[1 5]);
title('aircraft efficiency')
xlabel('travel range [km]')
ylabel('fuel efficiency [kg/(100km * pax)]')
legend('Efficiency', 'optimal range')

sgtitle('A320')
```

Which results in the following plots

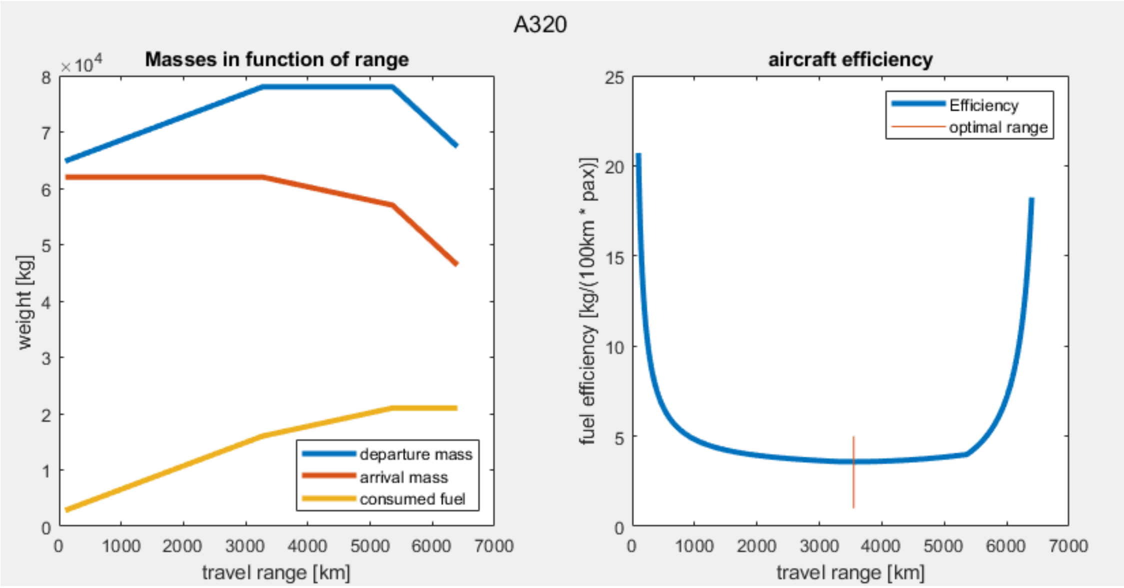

Fig. 7.3 A320's payload and fuel vs range chart and the bathtub function out of it.

In the case of the 737-800 with winglets:

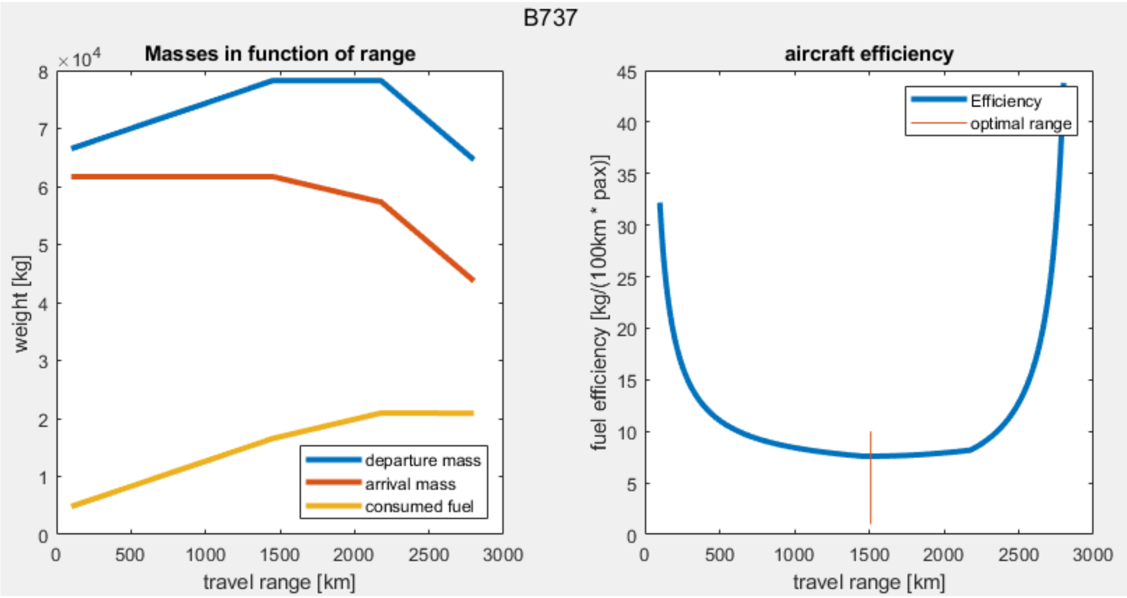

Fig. 7.4 B737's payload and fuel vs range chart and the bathtub function out of it.

This data can now be exported to excel to compare with the data of the aircraft routes.

APPENDIX 2. Alice routes

A set of possible commercial routes that could be flown by the Alice are shown in this chapter.

Table 7.5 Madrid – Baqueira coverage with the Alice and other transportation methods. [61] [62]

Madrid - Baqueira				
	Minimum time (center to center)	Maximum Time (center to center)	Minimum price per person (€)	Maximum price per person (€)
Car	6h 30m	7h	12	90
Train + car	6h	6h 30m	62	113
Bus	11h	11h 30m	30	50
Ferry	-	-	-	-
Plane	-	-	-	-
	Time (center to center)		Price per person (ferry) (€)	Price per person (taxi) (€)
Alice	1h 50m		96	193

To reduce even more the travel time, a small airport could be built in Pla de Beret. Which falls in a valley right at the base of the skying resort. This would result in an extremely short time from Madrid or Barcelona to the mountains while keeping a competitive price, low noise levels and zero emissions.

Table 7.6 Madrid – Sanxenxo coverage with the Alice and other transportation methods. [61] [62]

Madrid - Sanxenxo

	Minimum time (center to center)	Maximum Time (center to center)	Minimum price per person (€)	Maximum price per person (€)
Car	6h	6h 20m	13	100
Train	9h	10h	38	67
Bus	9h	9h 45m	44	55
Ferry	-	-	-	-
Plane	3h	5h	60	300
	Time (center to center)		Price per person (ferry) (€)	Price per person (taxi) (€)
Alice	2h		92	184

Table 7.7 Menorca – Eivissa coverage with the Alice and other transportation methods. [61] [62]

Menorca - Eivissa				
	Minimum time (island to island)	Maximum Time (island to island)	Minimum price per person (€)	Maximum price per person (€)
Car	-	-	-	-
Train	-	-	-	-
Bus	-	-	-	-
Ferry	10h	12h	60	235
Plane	1h (300 seats every week on weekends)	3h 15m	45	120

	Time (flying time)	Price per person (ferry) (€)	Price per person (taxi) (€)
Alice	30 min	46	92

Table 7.8 Mallorca – Menorca coverage with the Alice and other transportation methods. [61] [62]

Mallorca - Menorca				
	Minimum time (island to island)	Maximum Time (island to island)	Minimum price per person (€)	Maximum price per person (€)
Car	-	-	-	-
Train	-	-	-	-
Bus	-	-	-	-
Ferry	2h	3h	16	180
Plane	40m	1h	26	60
	Time (flying time)		Price per person (ferry) (€)	Price per person (taxi) (€)
Alice	20m		30	60

Table 7.9 Mallorca – Eivissa coverage with the Alice and other transportation methods. [61] [62]

Mallorca - Eivissa				
	Minimum time (island to island)	Maximum Time (island to island)	Minimum price per person (€)	Maximum price per person (€)

Car	-	-	-	-
Train	-	-	-	-
Bus	-	-	-	-
Ferry	3h 30m	4h	30	180
Plane	35m	1h	25	110
	Time (center to center)		Price per person (ferry) (€)	Price per person (taxi) (€)
Alice	20m		30	60

Table 7.10 Tenerife – Gran Canaria coverage with the Alice and other transportation methods. [61] [62]

Tenerife - Gran Canaria				
	Minimum time (island to island)	Maximum Time (island to island)	Minimum price per person (€)	Maximum price per person (€)
Car	-	-	-	-
Train	-	-	-	-
Bus	-	-	-	-
Ferry	1h 10m	1h 30m	38€	-
Plane	30m	1h	24	110
	Flying time		Price per person (ferry) (€)	Price per person (taxi) (€)
Alice	30m		23	45

Table 7.11 Barcelona – Empuriabrava coverage with the Alice and other transportation methods. [61] [62]

Barcelona - Empuriabrava				
	Minimum time (center to center)	Maximum Time (center to center)	Minimum price per person (€)	Maximum price per person (€)
Car	1h 40m	2h 15m	5	23
Train	3h 18m	3h 30m	15	19
Bus	3h	3h 30m	5	30
Ferry	-	-	-	-
Plane	-	-	-	-
	Flight time		Price per person (ferry) (€)	Price of the entire aircraft both ways(€)
Alice	45m		52	840

APPENDIX 3. Constants for model 2

Table 7.12 Constants to compute fuel burn during taxi of different aircraft. [47]

Type	Constant		Taxi Time		# Acc. Events		Corr.	Std. Dev.
	a_2 (kg/$K^{0.5}$)	p_{a2}	b_2 (kg/s-$K^{0.5}$)	p_{b2}	c_2 (kg/$K^{0.5}$)	p_{c2}	ρ	σ (kg)
A319	0.0811	0.31	0.0122	0.0	0.0965	0.0004	0.9938	6.85
A320	-0.0896	0.24	0.0124	0.0	0.1174	0.0000	0.9924	8.90
A321	0.0942	0.37	0.0129	0.0	0.0832	0.0184	0.9858	8.14
A330-202	0.2904	0.02	0.0217	0.0	0.3809	0.0001	0.9816	14.44
A330-243	-0.0903	0.25	0.0265	0.0	0.1007	0.0312	0.9965	9.12
A340-500	0.3626	0.10	0.0375	0.0	0.3984	0.0137	0.9918	30.59
ARJ85	0.0973	0.00	0.0102	0.0	0.0366	0.0203	0.9928	4.12
B757	0.2133	0.03	0.0173	0.0	0.0699	0.2007	0.9861	8.83
B767	0.1584	0.20	0.0202	0.0	0.1929	0.0012	0.9795	16.50
B777	-0.1223	0.02	0.0335	0.0	0.1385	0.0093	0.9985	8.75

APPENDIX 4. Cell datasheet

Table 7.13 10059156-5C battery cell specifications. [63]

<table>
<tr><th colspan="2">Item</th><th>Specifications</th><th>Remark</th></tr>
<tr><td colspan="2">Typial Capacity</td><td>10000mAh±5%</td><td>25℃，0.2C_5A discharge</td></tr>
<tr><td colspan="2">Nominal Voltage</td><td>3.7V</td><td>25℃，Average Voltage at 0.2C5A discharge</td></tr>
<tr><td colspan="2">Charge Current</td><td>Standard：0.2 C_5A；Max：1C_5A</td><td>Working temperature：0~45℃</td></tr>
<tr><td colspan="2">Charge cut-off Voltage</td><td>4.20±0.05V</td><td></td></tr>
<tr><td colspan="2">Discharge Current</td><td>Continuously:4C_5A；Max：10C_5A</td><td>Working temperature：0~60℃</td></tr>
<tr><td colspan="2">Discharge cut-off Voltage</td><td>2.75V</td><td></td></tr>
<tr><td colspan="2">Cell Voltage</td><td>3.76~3.90V</td><td>When leave factory</td></tr>
<tr><td colspan="2">Impedance</td><td>≤5mΩ</td><td>25℃，AC 1KHz after 50% charge</td></tr>
<tr><td colspan="2">Weight</td><td>Approx：200g</td><td></td></tr>
<tr><td rowspan="3">Storage temperature</td><td>≤1month</td><td>-10～45℃</td><td rowspan="4">Best 20±5℃ for long-time storage</td></tr>
<tr><td>≤3month</td><td>0～30℃</td></tr>
<tr><td>≤6month</td><td>20±5℃</td></tr>
<tr><td colspan="2">Storage humidity</td><td>65±20% RH</td></tr>
</table>

APPENDIX 5. Battery calculation EPATS

The goal of this appendix is to compute the structure and characteristics of the battery that will feed the EPATS given a series of requirements. The first parameter that must be met by the battery is the required voltage. To meet the motors' voltage batteries must be staggered in series until achieving the desired voltage.

$$n_{cs} \geq \frac{V_m}{V_c} \quad \textbf{(7.1)}$$

Where n_{cs} is the number of cells in series, V_m the voltage of the motor and V_c the voltage of a single battery. To establish the number of sets of cells in series or batteries in parallel, the attention must be set to the required energy to be stored.

$$n_{cp} \geq \frac{E_b}{E_c * n_{cs}} \quad \textbf{(7.2)}$$

Where n_{cp} refers to the number of batteries in parallel, E_b is the energy required from the battery and E_c the energy that a single cell can provide. The multiplication of n_{cs} and n_{cp} results in the total number of cells needed for the battery set. If that number is then multiplied for the weight of a single battery, the total mass of the battery set is obtained. Following this method, the cost of the battery set, and the real stored energy are obtained.

$$n_{ct} = n_{cs} * n_{cp} \quad \textbf{(7.3)}$$

$$M_b = n_{ct} * M_c \quad \textbf{(7.4)}$$

$$C_b = n_{ct} * C_c \quad \textbf{(7.5)}$$

$$E'_b = n_{ct} * E_c \quad \textbf{(7.6)}$$

Where n_{ct} means the total number of cells, M_b is the total weight of the battery, M_c the mass of a single cell, C_b to the total cost of batteries, C_c the cost of a single cell, E'_b is the real energy stored by the battery and E_c, the energy stored in a single cell.

APPENDIX 6. Characteristics Calculation EPATS

A methodology to find the different the rest of relevant characteristics of the EPATS is found in this section. Factors such as the life expectancy of the battery, total fuel and CO2 saved as well as the economic outcomes. The first characteristic to be computed is lifetime. To estimate its lifetime, the number of cycles a single cell can withstand is divided by the average number of flights it is expected to operate in a single day.

$$L = \frac{Cy_c}{n_l} \tag{7.7}$$

Where L refers to lifetime in days, Cy_c to number of cycles of a single cell and n_l to legs performed in a single day. To estimate the economical outcome, the save per flight is computed, then the expenses generated per flight are computed as well, and to compute the pay-off time, the financial outcome per flight is compared to the initial investment. Several factors must be considered. The most obvious factor is fuel, however the CO2 tax and the operational cost of renting the airport tug must also be considered. Another factor is the save in brakes and tyres because of electromagnetic braking and previous-to-touchdown rolling wheels. These last two factors are however strictly involved to flight operations and safety and also the economical save may not be as considerable to an airline, therefore they are neglected as a quantitative value but they are included as a parameter.

$$S_{pf} = (F_{to} + F_{ti}) * \left(C_f + \left(\frac{C_{co2}}{1000}\right) * \left(\frac{R_{co2,eng}}{1000}\right)\right) + S_{ty,pf} + C_{tug} \tag{7.8}$$

Where S refers to saved money, F to quantity of fuel, C to the cost, R_{co2} to the ratio at which CO2 is produced per kg of burnt fuel, pf is the abbreviation of "per flight", to and ti mean taxi out and taxi in respectively, f means fuel, ty to means tyre, and tug is the pushback truck used in airports. While one of the main goals of the EPATS is to be economically feasible to an airline, the EPATS also has its costs and so, those are computed in this appendix. The EPATS has two costs, variable (per flight) and fixed costs (initial). The variable costs address the costs that increase with every flight and the fixed ones, the costs that are independent of the amount of usage of the system

$$C_{pf} = C_{maint,pf} + \frac{C_b}{Cy_c} + (F_{APU}) * \left(C_f + \frac{C_{CO2}}{1000} * \frac{R_{CO2,APU}}{1000}\right) + \frac{C_{MWh}}{1000000} * E_b' \tag{7.9}$$

$$C_{ini} = C_m * n_m + C_{other} + C_{inst} + \frac{C_{hom}}{n_{ac}} - V_b \quad \textbf{(7.10)}$$

Where C_{pf} is the cost of the system per flight, $maint$ refers to maintenance, b to the entire battery pack, c to a single cell, APU to the APU, ini to initial, m to motor, MWh to the electrical energy in MWh, hom to homologation, ac to aircraft in which the EPATS is installed and Vb to the resell value once the battery finishes its useful life. The balance per flight will be the simple subtraction of variable costs cost on save per every flight (equation **(7.11)**).

$$B = S_{pf} - C_{pf} \quad \textbf{(7.11)}$$

If the initial cost is divided by the balance per flight, the payoff time is obtained.

$$T = \frac{C_{ini}}{B} \quad \textbf{(7.12)}$$

Now to obtain the environmental outputs. To obtain the average save in fuel in each flight, the fuel burnt by the APU is subtracted to the total fuel burnt by the engines at the same time.

$$S_{f,pf} = F_{to} + F_{ti} - F_{APU} \quad \textbf{(7.13)}$$

To compute the save in CO2, the equation is virtually the same, but the production ratio of CO2 must be considered.

$$S_{CO2,pf} = (F_{to} + F_{ti}) * \frac{R_{CO2,eng}}{1000} - FAPU * \frac{R_{CO2,APU}}{1000} \quad \textbf{(7.14)}$$

Later in the process the total mass of the system plays an important role. This is obtained by adding the mass of the motors, the battery, and other parts such as cable, casing, and cooling.

$$M_{sys} = M_{othr} + n_m \cdot M_m + M_b \quad \textbf{(7.15)}$$

The numbers used in this specific example are as follows:

Table 7.14 Economic inputs of EPATS implementation

Variable	Value	Units	Variable	Value	Unit
C_f	0.729	€/kg	C_m	9000	€
Cy_c	500	-	C_{other}	50000	€
n_l	6	flights/day	C_{inst}	15000	€
C_{CO2}	25	€/ton	C_{hom}	2000000	€
$R_{CO2,eng}$	75	g/kg(of fuel)	n_{ac}	30	-
$R_{CO2,APU}$	3.155	g/kg(of fuel)	V_b	2000	€
$S_{ty,pf}$	0	€/per flight	M_{other}	200	kg
C_{tug}	50	€/per flight	n_m	4	-
$C_{maint,pf}$	50	€/per flight	M_m	40	kg
C_{MWh}	60	€/MWh			

APPENDIX 7. Costs of Conventional and electric SW 121

Table 7.15 Costs break-down of an SW121 and a Velis electro [64] [65]

Conventional SW121					
Parameter	Value	Units	Parameter	Value	Units
Cost of engine	0	€	(SP) Number	4	-
Gearbox overhaul (GO)	500	€	(SP) Performed every...	200	hours
(GO) Performed every...	1000	hours	Rubber parts replacement (RP)	3000	€
Complete overhaul (CO)	11000	€	(RP) Performed every...	5	years
(CO) Performed every...	2000	hours	Fuel cost	1.8	€/L
Oil filter change (OC)	18	€	Fuel density	0.71	kg/L
(OC) Performed every...	50	hours	Fuel flow	18.4	kg/h
Spark plug change (SP)	2	€			
Velis electro					
Parameter	Value	Units	Parameter	Value	Units
Installation	10000	€	Batteries (B)	22000	€
Avionics	6000	€	(B) Replaced every...	500	hours
Charging station	600	€	Average endurance	0.8	hours
Motor (M)	20000	€	Energy	0.09	€/kWh
(M) Replaced every...	10	years	Battery capacity	24.8	kWh

APPENDIX 8. Entire procedure for a user

This appendix includes the entire procedure of converting a conventional single piston engine aircraft into an electrically powered aircraft. The methodology described here is best suited to be written in Matlab, However, it can be easily extrapolated to any program. Please note that this methodology is to be checked under own responsibility when building a real aircraft. Nonetheless, it will provide with approximations of performances and economics of performing such a modification.

APPENDIX 8.1. Performances calculation

Table 7.16 Summary of the required inputs to compute an electric power plant replacement.

Conventional aircraft			Electric properties		
Parameter	Units	Abbreviation	Parameter	Units	Abbreviation
Mass of engine	kg	M_e	Power-to-weight ratio of motor	W/kg	R
Position of engine	m	X_e	Position of motor	m	X_m
Mass of fuel	kg	M_f	Position of battery #1	m	X_{b1}
Position of fuel	m	X_f	Position of battery #2	m	X_{b2}
Peak power of engine	W	$\mathrm{P_p}$	Voltage of motor	V	V_m
Cruise power of engine	W	P_c	Voltage of cell	V	V_c
Maximum endurance power of engine	W	P_e	Mass of cell	kg	M_c
			Energy density of cell	Wh	E_c
			Peak discharge rate of cell	A	I_p
			Maximum continuous	A	I_c

			discharge rate of cell		
			Efficiency	-	η

All the positions are respect to the datum of the aircraft.

The structural properties are computed first.

$$M_m = \frac{P_p}{R} \quad \textbf{(7.16)}$$

Where M_m is the mass of the motor.

$$M_{b1} = \frac{M_e * X_e + M_f * X_f - M_m * X_m + X_{b2} * \left(M_m - M_e - M_f\right)}{X_{b1} - X_{b2}} \quad \textbf{(7.17)}$$

Where M_{b1} is the mass of the forward battery pack.

$$M_{b2} = M_e + M_f - M_m - M_{b1} \quad \textbf{(7.18)}$$

Where M_{b2} is the mass of the after battery pack.

$$M_b = M_{b1} + M_{b2} \quad \textbf{(7.19)}$$

Where M_b is the total mass of batteries.

APPENDIX 8.2. Electrical properties calculation

With the structural properties in mind, the electrical technology available is fitted in the aircraft. The first step is to calculate the electrical properties themselves. Following this step, the performances that the electric power plant provides are obtained.

$$N_s = ceil\left(\frac{V_m}{V_c}\right) \quad \textbf{(7.20)}$$

Where N_s is the number of cells in series. The number is rounded up in order to achieve the goal voltage.

$$N_p = floor\left(\frac{M_b}{N_s * M_c}\right) \quad \textbf{(7.21)}$$

Where N_p is the number of cells in parallel. The number is strictly rounded down to not exceed the maximum weight of the aircraft.

$$I_{pb} = I_p * N_p \quad \textbf{(7.22)}$$

Where I_{pb} is the peak current the battery can deliver.

$$I_{cb} = I_c * N_p \quad \textbf{(7.23)}$$

Where I_{cb} is the maximum continous current the battery can deliver.

$$P_{pb} = (V_c * N_s) * I_{pb} * \eta \quad \textbf{(7.24)}$$

Where P_{pb} is the peak power delivered by the battery.

$$P_{cb} = (V_c * N_s) * I_{cb} * \eta \quad \textbf{(7.25)}$$

Where P_{cb} is the maximum continuous power the battery can deliver.

$$E_b = N_s * N_p * E_c \quad \textbf{(7.26)}$$

Where E_b is the total energy stored in the battery. At this step it is necessary to check if P_{pb} and P_{cb} are greater than P_p and P_c respectively. If not, the battery cannot deliver the power required by the previously set restrictions and a different model or version of cell will have to be selected.

To compute the endurance time, the following equations are used.

$$T_c = \frac{E_b * \eta}{P_c} \quad \textbf{(7.27)}$$

$$T_e = \frac{E_b * \eta}{P_e} \quad \textbf{(7.28)}$$

Where T_c is the endurance using cruise setting and T_e is the endurance using maximum endurance throttle setting.

APPENDIX 8.3. Economic output calculation

At this point the performances are calculated. However, the greatest strength of an electrical conversion is the economic balance linked to it. Therefore, below is the method to calculate these as well. Unlike performances, costs are tightly related to a timeline. Therefore, vectors and iterations are used from this point. In these vectors, each position represents one flight hour. Please note that only those parameters that differ between the airplanes are considered, e.g. hangar rental and insurance are not taken into account because it will cost the same in either aircraft.

Table 7.17 Required inputs to compute the economic outcome of an electric powerplant replacement.

Conventional aircraft			Electric conversion		
Parameter	Units	Abbreviation	Parameter	Units	Abbreviation
Cost of engine	€	C_{eng}	Initial costs (Installation, Avionics and charging station)	€	C_i
Gearbox overhaul (G)	€	C_g	Motor (M)	€	C_m
(G) Performed every...	hours	T_g	(M) Replaced every...	years	T_m
Complete overhaul (OH)	€	C_{oh}	Batteries (B)	€	C_b
(OH) Performed every...	hours	T_{oh}	(B) Replaced every...	hours	T_b
Oil filter change (Oil)	€	C_{oil}	Average endurance	hours	Avg_{edr}

(Oil) Performed every...	hours	T_{oil}	Price kWh	€/kWh	P_{kWh}
Spark plug change (SP)	€	C_{sp}	Battery capacity	kWh	Egy_b
(SP) Number	-	N_{sp}	Minimum price of battery	€	P_b
(SP) Performed every...	hours	T_{sp}	Battery cost reduction	1/year	C_{br}
Rubber parts replacement (RP)	€	C_{rp}	Battery life extend	1/year	BLE
(RP) Performed every...	years	T_{rp}	Other parameters		
Fuel price	€/L	P_f	Parameter	Units	Abbreviation
Fuel density	kg/L	ρ_f	Final time of computation	hours	T_f
Fuel flow	L/h	FF	Average yearly flight hours	1/year	Avg_{fh}

At this point, each of the costs is converted to a vector of length T_f in which the cost is added up every certain number of hours. This is done in the following manner:

Vectors related to the **conventional aircraft**:

- Engine
- Gearbox overhaul
- Complete overhaul
- Oil filter
- Spark plugs
- Rubber parts
- Fuel

Vectors related to the **electric conversion**:

- Initial costs
- Motor
- Battery

- Energy

To compute the evolution of batteries the vectors of the following are required as well:

- Battery cost timeline
- Battery life timeline

Once the vectors for the costs are created, it is important to distinguish the "frequency of payment" which means how frequently they are paid. This element is explained below:

Engine and **initial costs** are paid only once at the beginning.

Gearbox overhaul, **complete overhaul**, **oil filter** and **spark plugs** are paid every given number of hours, starting at the first iteration.

Motor and **rubber parts** are paid every given number of years starting at the first position of the vector. Thus, the following equation is needed to transfer the known data in years to flight hours. Where T_i is the interval between expenses. and T is the interval between expenses in years.

$$T_i = T * Avg_{fh} \tag{7.29}$$

Fuel is paid hourly, to compute the cost of fuel per hour, the following equation is used. Where C_f is the hourly cost of fuel in €.

$$C_f = \frac{P_f}{\rho_f} * FF \tag{7.30}$$

Electric energy does as well have a cost, which is computed in a similar way as fuel: Where C_{egy} is the hourly cost of electricity.

$$C_{egy} = P_{kWh} * \frac{Egy_b}{Avg_{edr}} \tag{7.31}$$

Three factors influence the **battery** vector: the drop in prices as time passes, the extension of battery life cycles as time passes and the actual cost of a battery. Given that both the price of battery and life cycles change evolve yearly, the yearly cost is transferred to a virtual hourly value to fit the vector characteristics. To compute these, the following iterations are created:

Table 7.18 Matlab code used to compute the battery price drop and extension of life.

```
for i=0:Tf-1
    Battery_price = (Cb-Pb)*((1-Cbr)^(i/Avg_fh))+Pb;
    Bat_cost_timeline(i+1)=Battery_price;
end

for i=0:Tf-1
    Num_cycles = floor(Tb *((1+BLE)^(i/Avg_fh)));
    Bat_life_timeline(i+1)=Num_cycles;
end
```

These iterations provide vectors of the corresponding battery information. The following iteration includes the initial cost of a battery set above. Which will be changed after an initially given number of hours. Once this first change of battery is made, the price in that virtual flight hour is assumed as a cost. The next battery change iteration is assumed from the expected life cycle in that virtual flight hour as well. If put into code, this is the result:

Table 7.19 Matlab code used to estimate the total cost of the battery vs time.

```
i=1;
while(i<=Tf)
    vec_battery(i)=Bat_cost_timeline(i);
    i=i+Bat_life_timeline(i);
end
```

Now that all the costs are computed, the costs of the conventional and electric aircraft are added up in the pertinent group and can be compared to each other.

APPENDIX 8.4. Examples

APPENDIX 8.4.1. Flight design CTLS

Table 7.20 Inputs for a Flight Design CTLS simulation of an electric powerplant replacement.

Conventional aircraft			Electric properties		
Parameter	Units	Value	Parameter	Units	Value
Mass of engine	kg	56.6	Power-to-weight of motor	W/kg	5400
Position of engine	m	-0.75	Position of motor	m	-0.9
Mass of fuel	kg	94	Position of battery #1	m	-0.75

Position of fuel	m	0.2	Position of battery #2	m	1
Peak power of engine	W	73500	Voltage of motor	V	600
Cruise power of engine	W	50000	Voltage of cell	V	3.7
Maximum endurance power of engine	W	18000	Mass of cell	kg	0.2
			Energy density of cell	Wh	42
			Peak discharge rate of cell	A	100
			Maximum continuous discharge rate of cell	A	40
			Efficiency	-	0.9

Table 7.21 Obtained results of the characteristics of an electric CTLS.

Outcomes					
Parameter	Units	Value	Parameter	Units	Value
Mass of motor	kg	13.61	number of cells in parallel	-	4
Mass of battery #1	kg	84.79	Energy stored in battery	kWh	27.38
Mass of battery #2	kg	52.19	Endurance time with cruise power	minutes	29.4
combined battery mass	kg	136.98	Endurance time with minimum power	minutes	81.6
Number of cells in series	-	163			

Table 7.22 Economic inputs for the CTLS

Conventional aircraft			Electric conversion		
Parameter	Units	Value	Parameter	Units	Value
Cost of engine	€	0	Initial costs (Installation, Avionics and charging station)	€	16600
Gearbox overhaul (G)	€	500	Motor (M)	€	20000
(G) Performed every...	hours	1000	(M) Replaced every...	years	10
Complete overhaul (OH)	€	11000	Batteries (B)	€	22000
(OH) Performed every...	hours	2000	(B) Replaced every...	hours	500
Oil filter change (Oil)	€	18	Average endurance	hours	1
(Oil) Performed every...	hours	50	Price kWh	€/kWh	0.09
Spark plug change (SP)	€	2	Battery capacity	kWh	27.38
(SP) Number	-	4	Minimum price of battery	€	5000
(SP) Performed every...	hours	200	Battery cost reduction	1/year	0.1
Rubber parts replacement (RP)	€	3000	Battery life extend	1/year	0.01
(RP) Performed every...	years	5	Other parameters		
Fuel price	€/L	1.8	Parameter	Units	Value
Fuel density	kg/L	0.71	Final time of computation	hours	10000
Fuel flow	L/h	18.4	Average yearly flight hours	1/year	1000

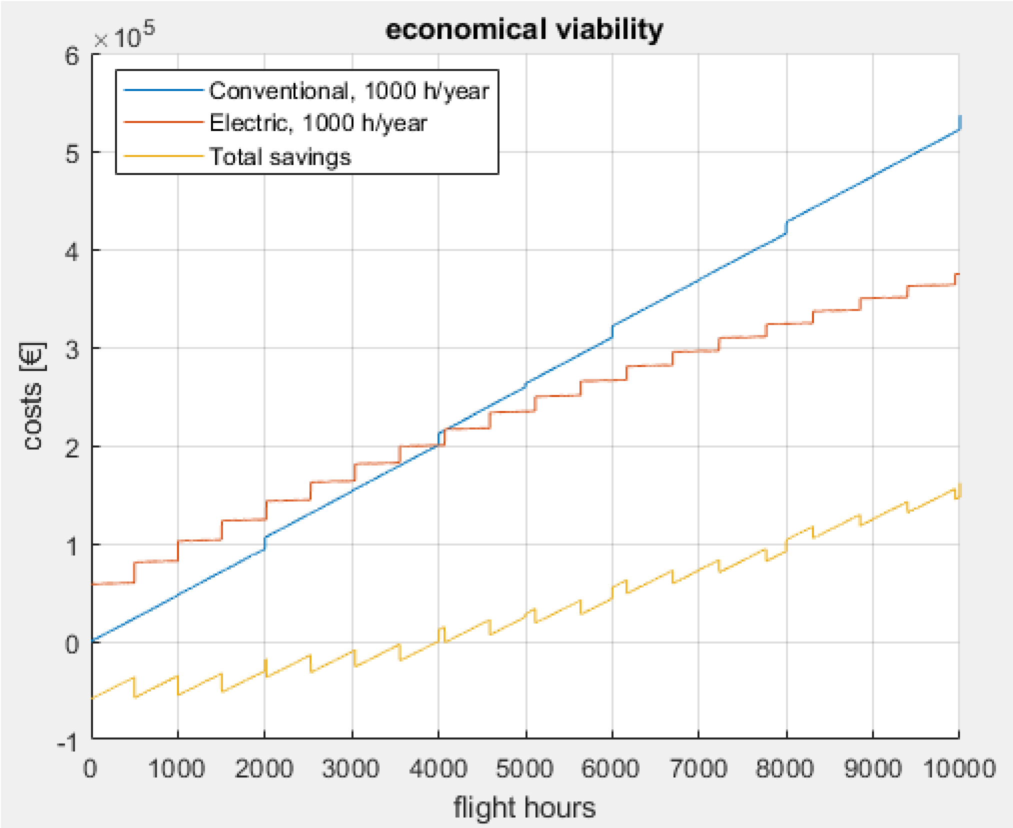

Fig. 7.5 Obtained Economic balance output for a conventional CTLS vs a modified one.

APPENDIX 8.4.2. Cessna 152

Table 7.23 Inputs used for a C152 simulation of an electric powerplant replacement. [66] [67]

Conventional aircraft			Electric properties		
Parameter	Units	Value	Parameter	Units	Value
Mass of engine	kg	112.5	Power-to-weight of motor	W/kg	5400
Position of engine	m	-0.64	Position of motor	m	-0.9
Mass of fuel	kg	102	Position of battery #1	m	-0.6
Position of fuel	m	1	Position of battery #2	m	1.9
Peak power of engine	W	88000	Voltage of motor	V	600

Cruise power of engine	W	63000	Voltage of cell	V	3.7
Maximum endurance power of engine	W	36900	Mass of cell	kg	0.2
			Energy density of cell	Wh	42
			Peak discharge rate of cell	A	100
			Maximum continuous discharge rate of cell	A	40
			Efficiency	-	0.9

Table 7.24 Obtained results of the characteristics of a C152.

Outcomes					
Parameter	Units	Value	Parameter	Units	Value
Mass of motor	kg	16.3	number of cells in parallel	-	6
Mass of battery #1	kg	132.76	Energy stored in battery	kWh	41
Mass of battery #2	kg	65.43	Endurance time with cruise power	minutes	34.8
combined battery mass	kg	198.2	Endurance time with minimum power	minutes	60
Number of cells in series	-	163			

Table 7.25 Economic inputs for the C152. [68] [69]

Conventional aircraft			Electric conversion		
Parameter	Units	Value	Parameter	Units	Value

Cost of engine	€	25000	Initial costs (Installation, Avionics and charging station)	€	16600
Gearbox overhaul (G)	€	-	Motor (M)	€	20000
(G) Performed every...	hours	-	(M) Replaced every...	years	10
Complete overhaul (OH)	€	15000	Batteries (B)	€	22000
(OH) Performed every...	hours	2000	(B) Replaced every...	hours	500
Oil filter change (Oil)	€	20	Average endurance	hours	45
(Oil) Performed every...	hours	50	Price kWh	€/kWh	0.09
Spark plug change (SP)	€	2	Battery capacity	kWh	41
(SP) Number	-	4	Minimum price of battery	€	7000
(SP) Performed every...	hours	200	Battery cost reduction	1/year	0.1
Rubber parts replacement (RP)	€	3000	Battery life extend	1/year	0.01
(RP) Performed every...	years	5	Other Parameters		
Fuel price	€/L	1.8	Parameter	Units	Value
Fuel density	kg/L	0.71	Final time of computation	hours	10000
Fuel flow	L/h	22.7	Average yearly flight hours	1/year	1000

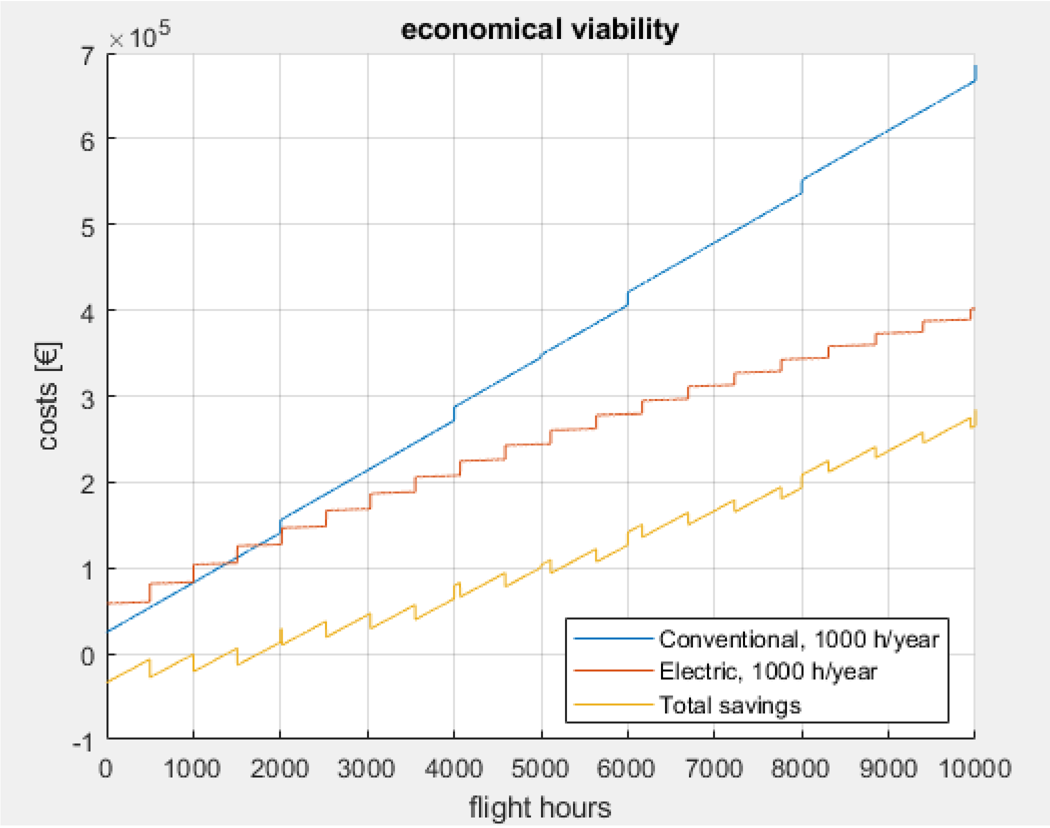

Fig. 7.6 Obtained Economic balance output for a conventional C152 vs a modified one.

APPENDIX 9. Marginal Fuel Burn results for an Electric and a Hybrid EPATS

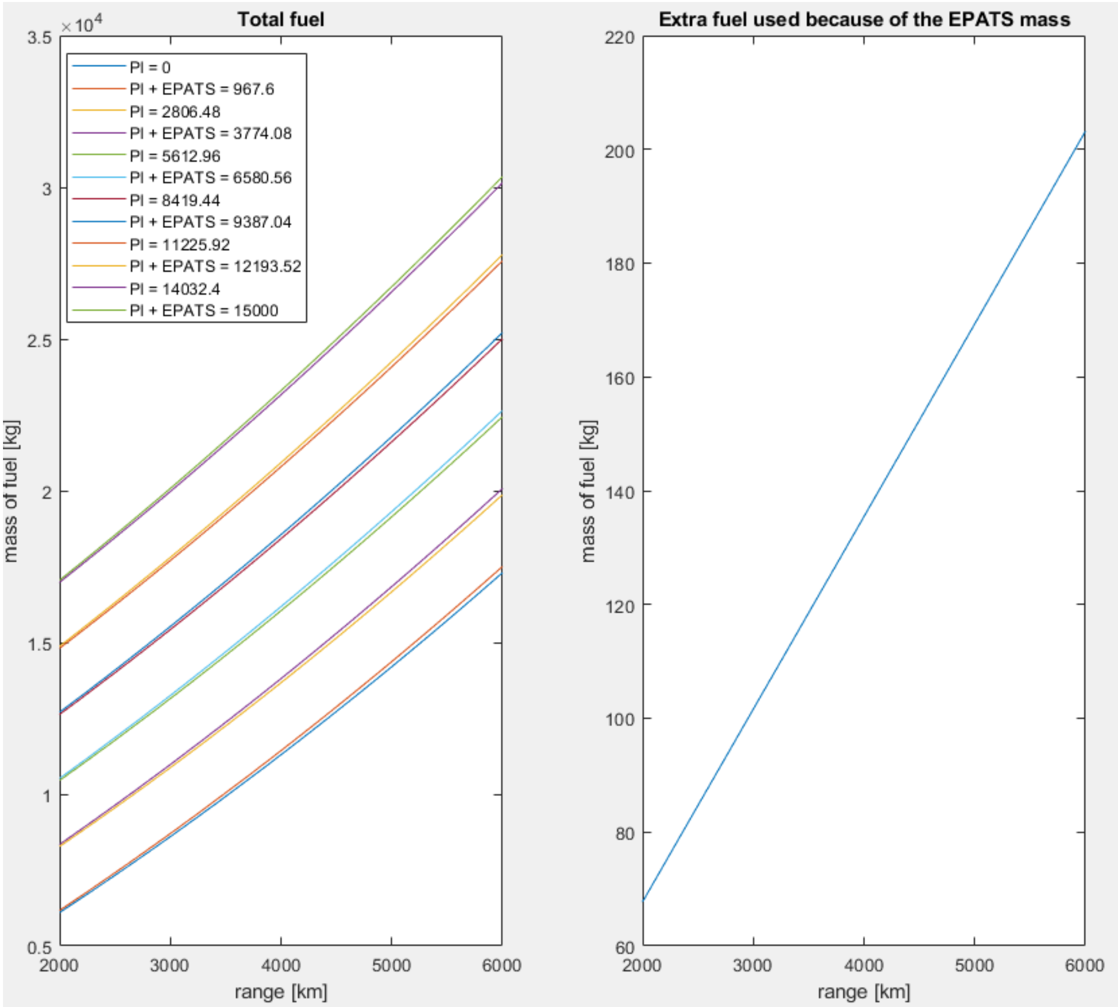

Fig. 7.7 Electric EPATS Marginal Fuel Burn. The plot at the left shows the total fuel burnt with different payloads with and without the EPATS on board. The one at the right shows the total extra fuel burnt because of the extra weight. Regardless of the payload, the EPATS has the same impact on fuel burn depending on the distance.

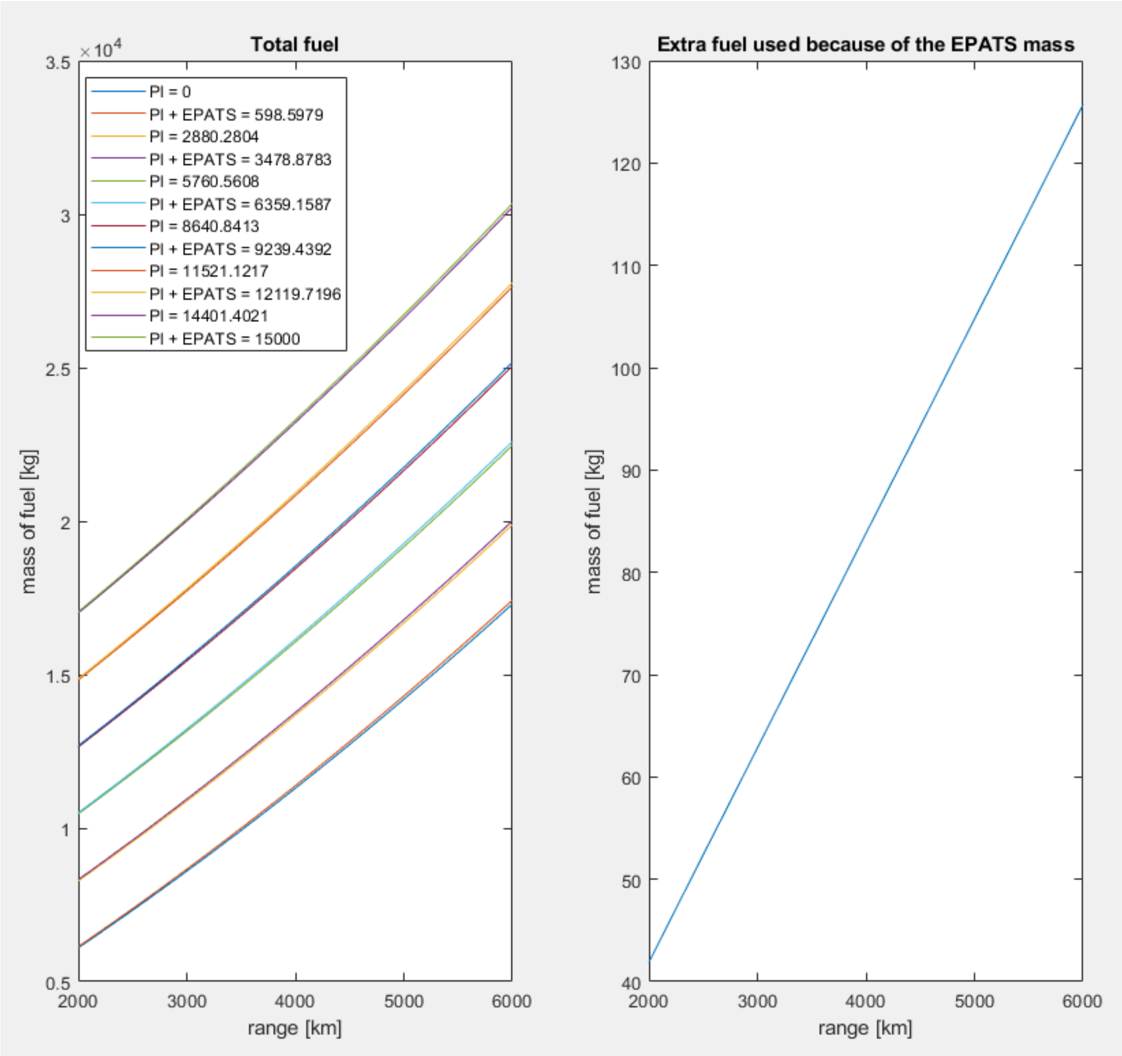

Fig. 7.8 Hybrid EPATS Marginal Fuel Burn. Equally to the Electric one, the payload does not have an impact one the fuel burnt “by the EPATS”.