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TITLE: Study and comparison of different types of powered aircrafts for the future commercial aviation.

TITULATION: Degree in Air Navigation Engineering.

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DATE: October 21st, 2022.

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Overview

These days commercial aviation is very important, it has a great influence on economy and social aspects. In 2019, IATA calculated that 65.5 million jobs in the world were created thanks to aviation and the total effect on the economy was about 2.7 billion euros.

During 2020 and 2021, commercial aviation suffered due to the restrictions of the COVID-19 pandemic, even reaching extremes where some airlines had to fly without passengers in order to avoid losing their slots. Since the end of the year 2021 and the beginning of 2022, the commercial aircraft has recovered considerably and is now on the same figures as in 2019.

Thanks to low-cost airlines, Europe and the United States are the regions with the highest volume of flights, but in countries like China and India, commercial aviation is expected to increase exponentially, especially due to the number of inhabitants in Asian countries.

A short and medium haul commercial aircraft like the A320 usually burns an average of 2,500 kilos of fuel every hour. Around the world there are near 200,000 flights every day, therefore the amount of burnt fuel is exorbitant. Also, knowing that 3.16 kilograms of CO_2 are generated for 1 kilogram of fuel, we can conclude that we have a major sustainability problem because of the tons of emissions that are emitted daily.

The main objective of this project is the study of new technologies that are capable of propelling aircrafts for commercial aviation while emitting fewer or zero emissions. More specifically, possible aircrafts powered by sustainable fuel, solar energy, electric energy, nuclear energy, hydrogen and electric plasma have been studied and evaluated. In addition, a comparison has been made of the characteristics of each technology and the forecast on which technology is the most suitable to replace fossil fuels and in what year it may appear.

Título: Estudio y comparación de diferentes tipos de aeronaves propulsadas para la futura aviación comercial.

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Resumen

Hoy en día la aviación comercial es muy importante, tiene una gran influencia en la economía y en el aspecto social. En 2019, la IATA calculaba que 65.5 millones de empleos en el mundo eran creados gracias a la aviación y el efecto total en la economía era de unos 2700 millones de euros.

Durante los años 2020 y 2021 la aviación comercial sufrió mucho debido a las restricciones de la pandemia del COVID-19 incluso llegando a extremos donde algunas aerolíneas tenían que volar sin pasajeros para no perder sus slots. Desde finales del año 2021 y principios del 2022, el avión comercial se ha recuperado considerablemente y ha vuelto a las cifras de 2019.

Debido a las aerolíneas de bajo coste, Europa y Estados Unidos son las regiones donde más volumen de vuelos hay, pero ahora con países como China e India se espera que la aviación comercial se incremente exponencialmente sobre todo debido al número de habitantes en los países asiáticos.

Un avión comercial de corta y media distancia como el A320 suele consumir alrededor de los 2500 kilos de combustible cada hora. En el mundo cada día hay alrededor de 200.000 vuelos por lo tanto la cifra en combustible gastado es desorbitada. Además, sabiendo que por 1 kilogramos de combustible se generan 3.16 kilogramos de CO_2 podemos llegar a la conclusión de que tenemos un gran problema de sostenibilidad debido a las toneladas de emisiones que se emiten diariamente.

El principal objetivo de este proyecto es el estudio de nuevas tecnologías que sean capaces de propulsar aeronaves para la aviación comercial emitiendo menos emisiones o cero emisiones. Más concretamente, se han estudiado y evaluado posibles aeronaves propulsadas con combustible sostenible, energía solar, energía eléctrica, energía nuclear, con hidrógeno y con plasma eléctrico. Además se ha hecho una comparación de las características de cada tecnología y la previsión sobre que tecnología es la más indicada para reemplazar los combustibles fósiles y en qué año puede aparecer.

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LIST OF SYMBOLS AND ABBREVIATIONS

A	Amps
ft	Foot
HP	Horsepower
in^3	Cubic Inches
K	Kelvin
kg	Kilograms
kg/h	Kilograms per hour
kg/L	Kilograms per litre
km	Kilometres
kN	Kilonewtons
kt	Knots
kW	Kilowatts
kWh/kg	Kilowatt-hour per kilogram
lb	Pound
lbf	Pound force
lbs	Pound thrust
m^2	Square meters
m	Meters
MJ/kg	Megajoules per kilogram
NM	Nautical miles
V	Volts
Wh/kg	Watt-hour per kilogram
Wh/L	Watt-hour per litre
^{o} C	Degrees

AC	Air Conditioning
AOA	Angle of Attack
APU	Auxiliary Power Unit
CD	Coefficient of Drag
CL	Coefficient of Lift
CO_2	Carbon Dioxide
EASA	European Union Aviation Safety Agency
ECAC	European Civil Aviation Conference
EPNdB	Effective Perceived Noise in Decibels
IATA	International Air Transport Association
ICAO	International Civil Aviation Organization
MTOM	Maximum Take-Off Mass
NREL	National Renewable Energy Laboratory
PV	Photovoltaic
SAF	Sustainable Aviation Fuel
WWI	World War I
WWII	World War II

INTRODUCTION

Since the 15th century, the creation of flying machines has been a desire of humans, beginning with Leonardo Da Vinci as one of the modern founders of aircrafts during that period. However, it was Sir George Cayley in the 19th century who invented the modern aeroplane design and identified the four vectors of forces that predominate in an aircraft (lift, drag, weight and thrust).

Commercial aviation began in 1914 with a flight of 23 minutes done using a modified boat. In 1952, the first ever commercial operation using a jet engine began with the Havilland Comet. Subsequently, jet engines dominated the engine market due to their high specifications. In the 1980s & 1990s, thanks to low-cost companies such as Southwest and Ryanair, commercial aviation suffered a change with more people wanting to fly because of affordable prices. Today, an average of 200.000 flights take-off daily, making commercial aviation a huge sector.

Sustainability is the main concern of aviation, with pressure from different sectors, a big change in aviation needs to happen, the real question is when and how it will happen. Today's planes are as efficient as ever, can carry more than 200 people at a time and can fly at high speeds, but they also produce millions of tons of CO_2 each year. With commercial aviation growing again after recovering from the pandemic, planes that produce fewer emissions will be important for the environment in the future.

In this project the main objective is to study and analyse different types of motorized aircrafts that can be an alternative to current jet aircrafts. The project is organized into 3 chapters, the first chapter is made up of the state-of-the-art-of aviation and the evolution of engines to date.

The second chapter deals with the types of jet engines and the basic working principle of each engine. Furthermore, it also focuses on the manufacturers that build those engines and the features of the newer engines. To end the chapter, aviation fuel is explained by describing the types of fuel that are available for commercial aircraft and their main characteristics such as the energy density or price for airlines.

The last chapter on the other hand is where the main part of the project is defined. Six possible different types of new power aircraft are studied, making an analysis of their aerodynamics, propulsion system and vehicle configuration. In addition, a comparison of its different characteristics is made and it is concluded by stating what technology will be the future to propel future commercial aircraft.

CHAPTER 1. STATE-OF-THE-ART OF AVIATION & ENGINES

1.1. Aviation evolution during the years

Several years before Christ in China it was usual to fly "kites", then it spread throughout the world but during those years no one ever designed or built larger flying machines for humans. The first modern founder of aviation and aeronautics appeared in the XV century. It was Leonardo da Vinci with his studies on the flight of birds and the creation of flying machines such as the ornithopter and the rotary-wing helicopter. But these creations were based on poor science as they had several flaws. After his death the work he had done was lost, but later in 1799 his work reappeared and was succeeded by Sir George Cayley.

Later, in the 17th and 18th centuries, the era of balloons became a reality. At the beginning of the 17th century, Galileo demonstrated through experiments that air has weight, this concept improved the science of that time and later in the middle of the 18th century the Montgolfier brothers began their experiments using paper balloons and smoky steam as lifting gas. They managed to get some releases done but the designs also had some flaws.

The 18th century is also highlighted by the discovery of hydrogen. The Scottish physicist and chemist Joseph Black proposed the theory of using the hydrogen as lifting gas for a balloon, but it was not until 1783 that the French physicist Jacques Charles and the brothers Robert offered a practical demonstration of a balloon been lifted using a chemical reaction made by hydrogen.

If Leonardo da Vinci is called one of the modern founders of aviation, the English engineer and inventor Sir George Cayley can be called the father of the aeroplane. The influence of some theories made in mechanics by physicists during the 17th and 18th century, particularly the fluid dynamics and Newton's laws of motions, led to the development of aerodynamics notably by Sir George Cayley. He identified the four vector forces that predominate an aeroplane (lift, drag, thrust and weight) and distinguished stability & control for the aeroplane's designs.

Some important remarks of Cayley's studies are:

1. Creation of the design of modern fixed wing aircraft stabilizing the tail with horizontal & vertical surfaces.
2. Creation of unmanned and manned flying gliders.
3. Introduction of the whirling arm test rig to study the aerodynamics of flights.
4. Identification & description of the importance of dihedral, diagonal bracing and drag reduction.
5. Invention of the tension-spoked wheel used for aircraft undercarriage.

6. Contribution of the understanding of designs regarding ornithopters and parachutes.

Eventually, in the 19th century Cayley’s ideas were refined, tested & expanded by Otto Lilienthal to end up doing successful experiments with gliders. Moreover, by the early 20th century huge advances in engine technology made it possible to create powered and controlled flights for the first time. Then in 1909 the final design of aeroplanes was established as the current modern aeroplane with its characteristic’s wings, engines, fuselage and tail. Thanks to the aeroplane fixed design, the rest of the history is tied to the creation of more powerful and more efficient engines.

In the following 20th century, dirigible balloons created by Ferdinand von Zeppelin became the predominant flying vehicle in long distance flights but in the 1930s after some serious accidents they were replaced by the current planes because of the insecurities regarding zeppelins designs and the use of highly flammable hydrogen gas as their main lifting gas. Also, late in the 1930s the creation of new and more powerful jet engines revolutionised the aviation sector and subsequently the air travel and military sector.

Finally, in the late 20th century advances in digital electronics helped to create more automated and precise systems. The fly-by-wire was born and used for the first time in the commercial aviation industry in the A320, one of the most used commercial aircrafts nowadays. In the 21st century the creation of fully automatic small aircrafts also known as drones were a reality, they are unmanned aircrafts that can fly remotely or automatically using software. They can be used for military and surveillance purposes.

1.2. Engines evolution during the years

Sir Isaac Newton in the 18th century was the first person to theorize that a rearward-channelled explosion could propel a machine forward at a great rate of speed. This theory was based on his third law of motion. As the hot air blasts backwards through the nozzle the plane moves forward.

The beginning is the steam engine era. Before the 19th century, steam engines were one of the most important machines. They did operate using a heat source to warm water and produce steam, the generated steam pressure then was used to drive a piston in a cylinder to obtain linear motion and which could be converted into rotational motion using a crankshaft.

The first aircraft engine was built by Henri Giffard, it was an airship which was powered by a 3 HP steam engine. But the problem was that it was very heavy, too heavy to fly. Moreover, the steam engine underwent a lot of improvement but nevertheless it was very powerless, inefficient and had a very poor power to weight ratio.

During the 19th century the internal combustion engines era began. The first successful commercial engine invented was the Lenoir gas engine made in 1860 by the Belgian-French engineer Jean Joseph Étienne Lenoir. It was a single-cylinder gas engine of 1.12 kW engine power (1.5 HP) that used to work with a mixture of 6% gas and 94% air and with a low engine efficiency of 4.65%.

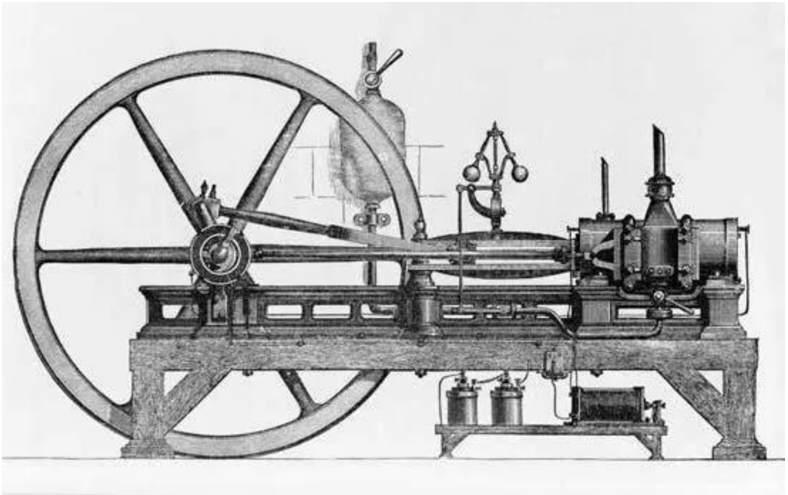

Fig. 1.1 Lenoir gas engine

The first modern internal combustion engine instead was the Otto engine, created by the German engineer Nicolaus August Otto. The Otto engine was an update of the Lenoir engine that was not very efficient because of the fuel consumption, the loud noise and because the gas-air mixture was not compressed and therefore the engine suffered from a lack of power.

In 1876, Otto produced an internal combustion engine that compressed the gas-air mixture in the cylinder prior to ignition and called it a four-cycle engine. The first atmospheric Otto engine had 2.2 kW of power or 3 HP and it had an efficiency of 12% making it superior to the Lenoir Engine. In the coming years, the engine never surpassed the 3 HP of power but after 15 years of the first Otto engine creation, at the beginning of the 20th century the improvements made the Otto engine power rose until it reached 1000 HP or 735.5 kW. The Otto engine was eventually adopted to run on ligroin and eventually gasoline, and other gasses.

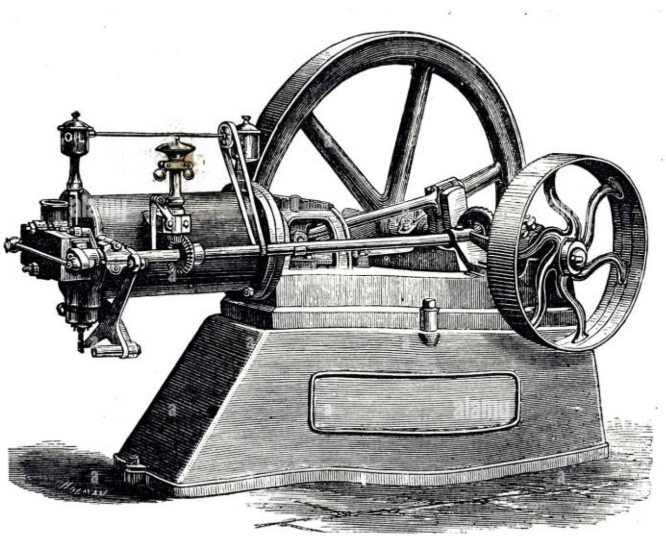

Fig. 1.2 First atmospheric Otto engine

Compressing the mixture improves the output power because more fuel and air can feed into the cylinder of the engine. This was indeed a very successful concept and that is still used today. In the 20th century, the internal combustion engine reached a maturity level that made it suitable for powering aircrafts. During WWII Otto engines were run on more than 62 different fuels, such as wood gas, coal gas, propane, hydrogen, benzene, and many more. The engine is limited to light fuels. A later development of this engine, known as the Diesel engine, can burn heavy fuels and oils.

At the start of the 20th century, aircraft engines were simple, low-powered machines that were designed and built one by one for specific aircrafts. The earliest aero engines were stationary, either radial in style or in line. From that point on, increasingly more sophisticated and powerful stationary in-line engines were developed until the arrival of the jet engine a couple of decades later.

The most advanced aircraft engine early in the century was powered by the 50 HP (37 kW) engine designed by Charles Manley. But because Langley's aircraft never succeeded in flying, these engines did not have the opportunity to demonstrate their potential. Instead in 1903, the engine designed and built by the Wright brothers for their “Flyer” project, was the first successful powered flight. Wright's engine was a 12 HP (9 kW) gas powered engine with four inline cylinders, was water-cooled, and weighed about 81 kg (179 lb) without the fuel.

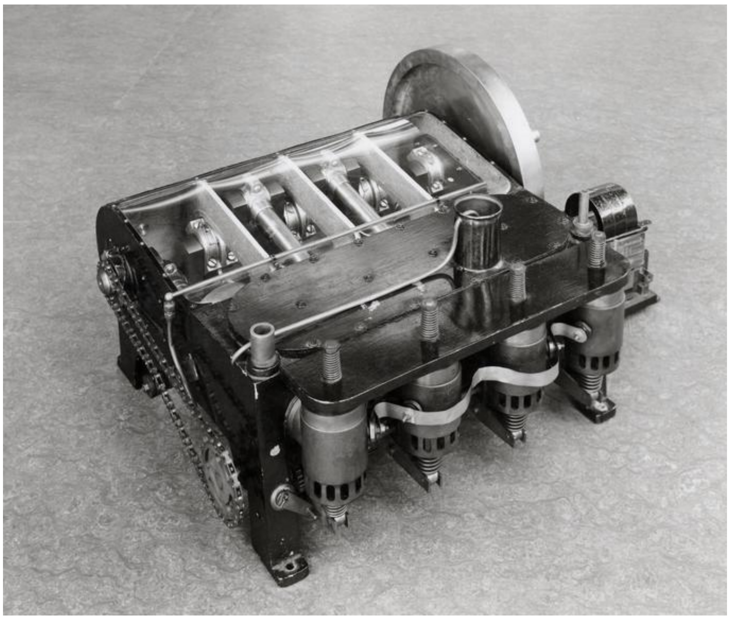

Fig. 1.3 Wright four cylinders gas-powered engine

The world's first commercial flight took place in 1914, it was a flight done with a "modified boat" that was powered by a fishing boat diesel engine and with a duration of just 23 minutes.

From 1903, the year of the Wright Brothers first flight, to the late 1930s the gas powered reciprocating internal combustion engine with a propeller was the sole means used to propel aircraft. During WWI, automobile manufacturers dominated the aero-engine field until companies that specialized in aircraft engines were established in the 1920s.

During the period between the World Wars, aircraft engines improved dramatically and made possible unprecedented progress in aircraft design. By 1950, aircraft piston engines had reached their pinnacle of development. They had become light, powerful, reliable, and fuel-efficient. But they had also reached their pinnacle of complexity and probably power with the creation of the R-4360 engine. Cylinders larger than around 200 cubic inches (in^3) or producing more than about 200 HP were not practical, and engines with more than 28 cylinders were not practical too. It follows that engines larger than 6000 or 7000 HP were also not realistic.

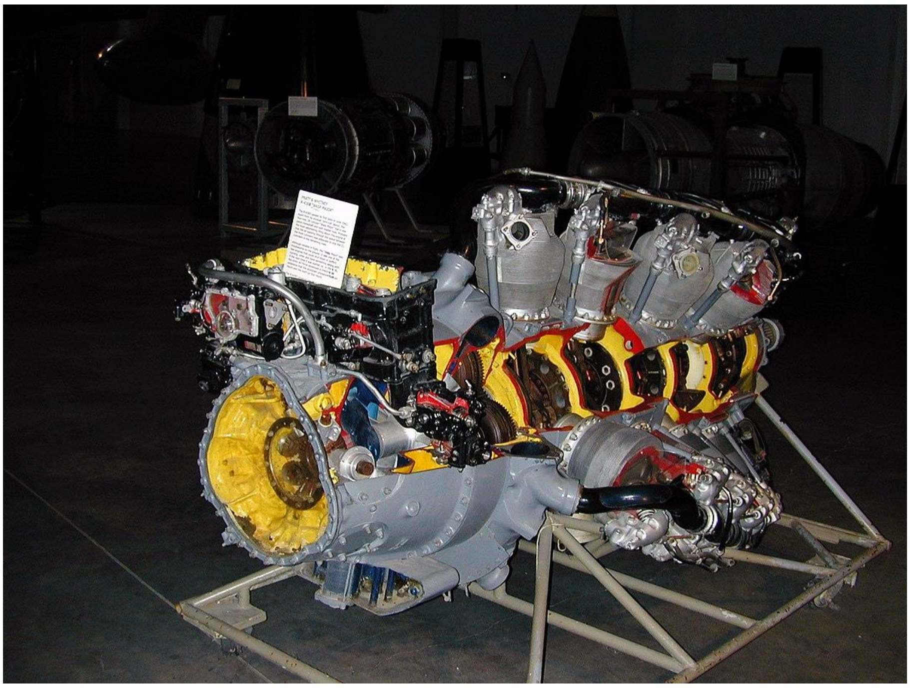

Fig. 1.4 R-4360 engine, the most complex piston engine of the 20^{th} century

Around 1945, engineering efforts at the major engine plants began to turn away from piston engines to engines with much greater potential for development, the jet engines. It was Frank Whittle, a British pilot, who designed and patented the first turbo jet engine in 1930. The Whittle engine first flew successfully in May, 1941. This engine featured a multistage compressor, and a combustion chamber, a single stage turbine and a nozzle.

At the same time that Whittle was working in England, Hans von Ohain was working on a similar design in Germany. The first airplane to successfully use a gas turbine engine was the German Heinkel He 178, in August, 1939. It was the world's first turbojet powered flight. Nevertheless, early jet engines were very powerful and gave dramatic increases in speed but they also showed poor fuel economy.

Fig. 1.5 Heinkel He 178

In 1952 the Havilland Comet jetliner initiated the first ever commercial operation with a jet engine. This new jet liner only had a capacity for 36 passengers at that time and was powered by two pairs of de Havilland Ghost 50 Mk1 turbojet engines, which produced 22.5 kN (5,000 lbf) of thrust and with a fuel consumption of 6000 kg/h (3000 kg/h for each turbojet). From that point on, commercial operations began to have an important economic effect for aircraft and engine manufacturers, the jet engines era began and it underwent a lot of improvements for being faster and for achieving a greater fuel economy. Commercial air travel since then has been more efficient, practical and profitable with the development of jet engines. Jet engine enhanced faster, quieter and comfortable flight experience satisfying the majority of the passengers.

Fig. 1.6 Havilland Comet jetliner

The pinnacle of “high speed commercial aviation” came with the Concorde aircraft in January 1976. With the first supersonic (Mach greater than 1.2) commercial flight reaching a cruising speed of 2,160 km/h (Mach 2). The original Concorde or the first Concorde airplane had a capacity of up to 100 passengers and was equipped with 4 Rolls-Royce/SNECMA Olympus 593s turbojet engines producing 89 kN dry thrust and 136 kN thrust with afterburner each engine. Its major drawback was the large amount of fuel it consumed, preventing it from being very profitable for its operators, since it meant that the price of the flight was not affordable for everyone. The Concorde consumed approximately 20,500 kg/h of fuel.

Since the late 1980s until today the popularity of bimotored aircrafts began to rise, more specifically narrowbody aircrafts such as the A320 & B737 are currently the most produced. Not just because they were quieter & more developed, but also because they were more fuel efficient than any other type of aircraft ever produced. Since then, low fares can be compatible with flights and affordable for most of the people around the world.

CHAPTER 2. TYPES OF JET ENGINES, ENGINE MANUFACTURERS AND AVIATION FUEL

2.1 Jet Engines

As we have seen in the state-of-the-art of engines, most modern passenger aircraft are powered by gas turbine engines, which are also called jet engines. The main parts of the jet engines are the inlet or intake, the compressor, the combustion chamber, the turbine and the nozzle.

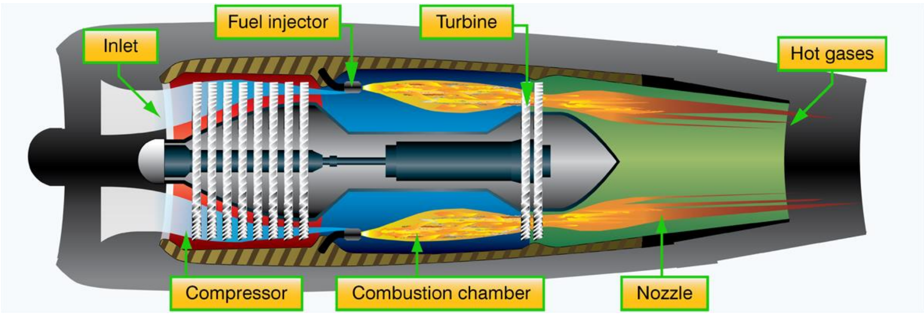

Fig. 2.1 Turbojet engine design [18]

The jet engine operates on a Brayton cycle in which the working fluid is a continuous flow of air ingested into the engine's inlet. The air enters through the inlet and it gets compressed by the compressor to a pressure ratio typically between 10 and 40 times the pressure of the airstream. It then flows into a combustion chamber, where a steady stream of the hydrocarbon fuel, in the form of liquid spray droplets, is introduced and burned at approximately constant pressure. During the combustion process, the high-pressure stream rises its temperature to a range between 950 ºC and 1520 ºC changing its state to gas stream. Then, the stream of gasses flows through the turbine, which is connected to the compressor by a torque shaft and which extracts energy from the gas stream to drive the compressor. After the turbine the gas stream has been expanded and it exits through the nozzle. Because heat has been added to the fluid in the combustion chamber, the gas stream that escapes at the nozzle contains a huge amount of excess energy, this excess energy is what we call propulsion THRUST.

2.1.1 Turbojets

The first type of gas turbine is the turbojet (same main parts as explained above). The turbojet engine has problems with noise and fuel consumption in the speed range that airliners fly (around Mach 0.8).

These engines are limited in range and endurance, but they take up little space and are capable of achieving high speeds and today they are mostly used in military aviation. But they were previously used for the first commercial jet engine flights.

2.1.2 Turboprops

Turboprops engines are also called “turbopropellers” because they are a combination of a turbojet, a gearbox and a propeller. The work principle of the turboprops is very similar to the operation of a normal turbojet, but the big difference is that in a turboprop engine the stream gasses go through extra stages in the turbine, which apart from the compressor, is also connected to the propeller and the gearbox. So, in order to obtain more energy for driving the propeller, the turbine needs additional stages.

The gearbox in the turboprops is a reduction gearbox that is necessary for the optimum propeller performance. The optimal propeller performance is achieved at lower speeds than the engine’s operating rpm. Moreover, 80 - 85% of the energy developed by the turbine is used to drive the propeller, while the rest of the energy is exhausted as thrust. The turboprop major drawback is that the gearbox is heavy and can break down.

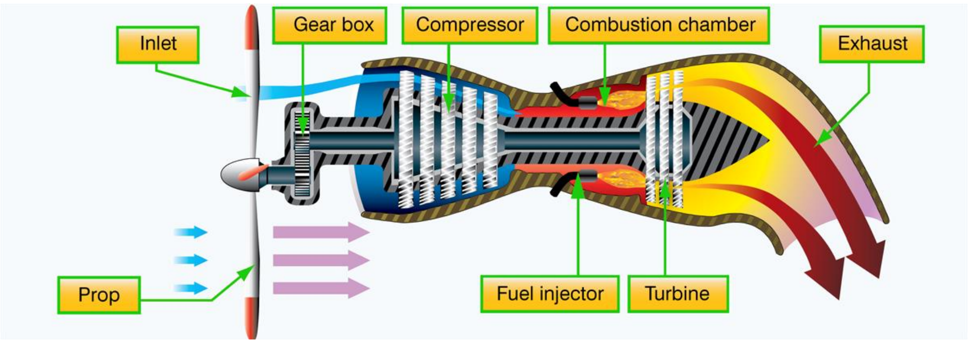

Fig. 2.2 Turboprop engine design [18]

Turboprops engines are more efficient at speeds between 250 and 400 kt (knots) and at mid-range altitudes between 18000 ft and 30000 ft. Also because of the high fuel efficiency, some airlines use turboprop aircraft for short-medium routes and for short runway airports where the turboprop is capable of landing at low speeds. For instance, a commercial turboprop aircraft like the ATR-72 has a fuel consumption of 760 kg/h at cruise speed and with a capacity of 74 passengers.

2.1.3 Turbofans

The turbofan engines are a combination of a turbojet engine with a fan at the front that sucks the air. A small part of the incoming air goes through the combustion chamber while the major part of the incoming air goes through the bypass of the fan, which is a low-pressure compressor, and is exhausted to the outside. The fluid that flows through the fan's bypass is the one that produces the most thrust of the engine, normally around 80% of the thrust in a turbofan engine is made by the fan’s bypass flow.

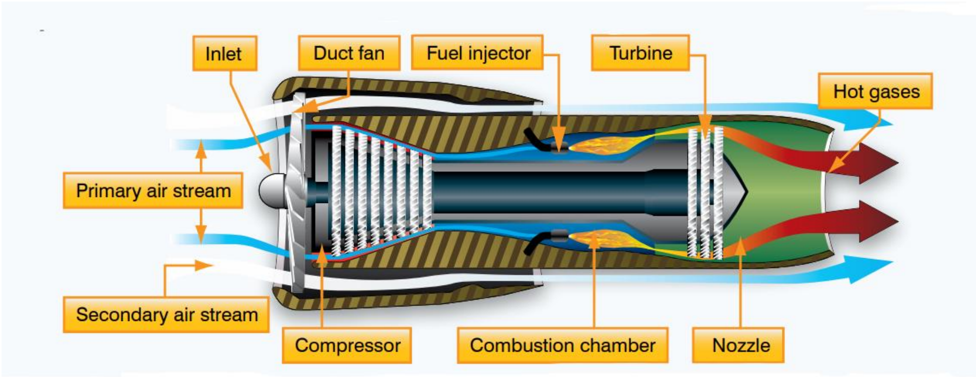

Fig. 2.3 Turbofan engine design [18]

Another difference between other types of jet engines is that the turbofan in order to power the fan for suctioning the air, also has integrated a low-pressure turbine. So overall, inside a turbofan there are 2 turbines, one low-pressure for powering the fan and one high-pressure for powering the compressor.

The fan of the turbojet not only makes most thrust of the engine, it also makes the engine very fuel efficient and a lot quieter. Depending on how much air goes through the chamber and how much air goes through the bypass, the bypass ratio can be determined. This ratio is very important, as bigger it is, usually the most fuel efficient is the engine. Nevertheless, this also makes the engine bigger and heavier, needing more space to fit into the wings of the aircrafts.

The turbofan engine is the most used engine in the world for commercial aviation nowadays. Today, aircraft commercial operations are made at Mach 0.8 and at altitudes around 36.000 ft (11.000 m) where the turbofan is the optimal engine in terms of fuel consumption, fuel efficiency and aircraft speed. And the thrust-to-weight ratio of the current most powerful turbofan GE90 is 5.98, which means that the engine produces 5.98 times of more thrust than its weight.

2.1.4 Turboshafts

Another type of jet engine is the turboshaft. The biggest difference between a normal turbojet is that the expanding gasses in turboshaft engines are used to drive the turbine, which is connected to a power shaft, rather than creating propulsion. Then the powered shaft is used to turn a transmission, widely used for helicopter transmissions and aircrafts APUs.

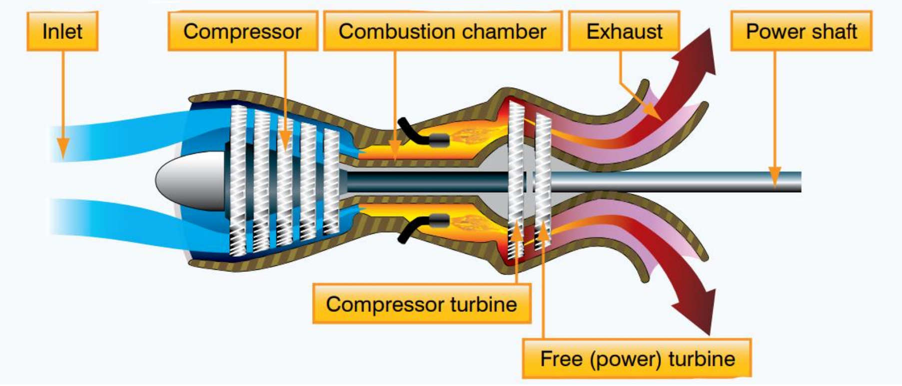

Fig. 2.4 Turboshaft engine design [18]

For example, the APU of the commercial A320 has a fuel consumption of 126 kg/h when it is used. The only negative point of turboshaft engines is that they are very loud.

2.2 Engine Manufacturers

Before WWI, the aviation market was not very important and it was dominated by car companies from that time. In the 1920s after WWI, the aviation industry became very crucial, especially for military services, and aviation specialized companies began to set up in Europe and USA. During the following years, the aviation sector was divided into two important branches, the engine manufacturers and the aircrafts manufacturers.

Later over the years, different aircraft companies were founded and some of them became bankrupt and disappeared. Currently, the biggest and most important companies for manufacturing commercial aircrafts are Airbus & Boeing, whereas in the engine manufacturing sector the companies that stand out are General Electric, Rolls-Royce, CFM international, Pratt & Whitney and IAE.

2.2.1 General Electric

General Electric Aviation or GE Aviation is a subsidiary company of the General Electric conglomerate corporation. The company was founded in 1917 in the United States and is one of the “big 3” engine manufacturers alongside Rolls-Royce and Pratt & Whitney. GE aviation apart from assembling aircrafts engines it also manufactures aircrafts avionics systems and high-power military engines for the U.S. Air Force. Since 2020, GE aviation holds 55% of the engine market share.

Fig. 2.5 General Electric logo on GE9X engine powering a B777X

Nowadays, GE aviation's best engine ever made is the GE9X turbofan engine with a thrust of 490 kN (110.000 lbf) and a bypass ratio of roughly 10:1 (high bypass turbofan). It’s predecessor the GE90 has a thrust of 510 kN (20kN more powerful), however is 10% less fuel efficient and in a widebody commercial aircraft such as a 777-200ER the GE90 has a fuel consumption of 6630 kg/h. On the same aircraft the GE9X engine have a fuel consumption of 5967 kg/h, which makes it more fuel efficient with a little reduction on thrust, less polluting and more attractive for airlines.

Just for comparison, the first turbofan engine made by GE aviation was the GE CJ805 made in the 1950s which had a thrust of 51.8 kN (11.650 lbf), a low-bypass ratio of 1.46 and the average fuel consumption on aircrafts was of 7797 kg/h. So, comparing the modern engines with the oldest one, modern engines can produce 10 times more thrust with a slightly lower fuel consumption but capable of powering bigger aircrafts.

2.2.2 Rolls-Royce

Rolls-Royce is a British company that was established in 1904 as a luxury car and later in 1907 started to design aero engines. In 1987 the aerospace section was sold to the public and now it can be found as Rolls-Royce Holdings plc. Since 2022 it’s the third placed engine manufacturer company holding around 18% of the engine market share.

Rolls-Royce currently only manufactures engines for widebody aircrafts. The best and most powerful engines of the company as of today are the Rolls-Royce Trent XWB powering the A350 and the Rolls-Royce Trent 1000, which powers the B787 Dreamliner. The Trent 1000 produce thrust up to 360 kN (81.000 lbf) and the Trent XWB can produce thrust up to 431 kN (97.000 lbf) and they both are a high-bypass engine with a bypass ratio of almost 10:1. The fuel consumption of both engines is also very similar, the Trent 1000 on a B787 consumes 5600 kg/h of fuel while the Trent XWB on the A350 burn 5800 kg/h.

Fig. 2.6 Rolls-Royce logo on Trent 1000 engine powering a B787 Dreamliner

Comparing these modern engines to the first turbofans manufactured by Rolls-Royce, there is also a huge difference regarding the fuel efficiency, power and the bypass ratio. The Rolls–Royce Conway in the 1940s was the first turbofan ever manufactured and it entered service in the 1950s. There were a lot of versions of this engine as it underwent a lot of development but just for comparison the B707-420 was a popular aircraft during the 1950s and it was powered by the Rolls-Royce RCo.10. The RCo.10 version had a thrust of 73 kN (16.500 lbf) and a bypass ratio of 3:1, powering the B707-420 the fuel consumption at that time was 6400 kg/h.

2.2.3 Pratt & Whitney

Pratt & Whitney is an American aerospace manufacturer of aircraft engines and gas turbines. It was founded in 1925 in the United States and supplies aircraft engines to civil aviation and military aviation. Currently, the American manufacturer holds 26% of the total engine market share.

In the recent years, the company has been focusing more on narrowbody aircrafts powering the types like the A320, the A220 and Embraer E-jets rather than widebody aircrafts. The company's most powerful engines today are the Pratt & Whitney PW1000G series. The PW1100G engines that normally powers the newly assembled A320neo are called ultra-high-bypass engines because its bypass ratio is 12.5:1, more than 20% more than its competitors. The engine can produce up to 147 kN (33.110 lbf) of thrust and powering an A320neo its fuel consumption is around 2066 kg/h.

Fig. 2.7 Pratt & Whitney logo on PW1000G series engine powering an A320

Pratt & Whitney was the first engine manufacturer to achieve high thrust with good fuel economy on jet engines. Its J-57 turbojet engine, which was the first fuel efficient jet engine, first ran on a test stand in 1950. The turbojet first variant had 45 kN (10.000 lbf) of thrust and it was very used for powering fighter jets of that time.

2.2.4 CFM International

CFM International is a joint venture between General Electric and France's company Safran Engines Aircraft that was founded in 1974. Since 2019 it holds 39% of the engine market share, that’s the reason why GE has 55% of the total engine market share (39% CFM + 16% GE). CFM manufactures the CFM56 series and LEAP engines, which can be found extensively on the B737 and A320 families of aircraft which are the two most produced commercial jets ever.

2.2.5 International Aero Engines

International Aero Engines is a Zürich-registered joint venture between Pratt & Whitney, MTU Aero Engines and Japanese Aero Engine Corporation that was founded in 1983. The collaboration produced the IAE V2500, the second most successful commercial jet engine program in production today (in terms of volume), and the third most successful commercial jet engine program in aviation history.

2.3 Aviation fuel

For current commercial aircrafts, fuel is the most important source of energy in order to activate the engine and power the whole aircraft. Aviation fuels are indeed petroleum-based fuels, more specifically kerosine-based. Also, there can be mixed fuels that contain synthetic fuel blends and are certified to be used in some types of aircrafts.

Aviation fuels have more stringent requirements than other fuels, for instance they should have good combustion characteristics and a high energy content, that's why kerosine based fuel is the best option as of now. They also contain additives to enhance and maintain properties important to fuel performance and fuel handling. The density and the volume of the kerosine at certain temperatures is also a factor to use them rather than other fuels.

There are two types of conventional aviation fuel used in the airports and aerodromes. The jet fuel (for jet engine aircrafts) and the Avgas which is aviation gasoline that is used by small piston engine aircrafts and light helicopters. Jet fuel has 4 types of different grades, Jet A-1, Jet A, Jet B and TS-1.

Jet A-1 is a kerosine grade fuel used widely all over the world except in the USA and Russia. It has a flash point of 38 ºC, a freezing point of -47 ºC and normally it has an energy content of 43.15 MJ/kg and at 15 ºC its density is 0.804 kg/L, in other words 1000 L of Jet A-1 fuel has a weight of 804 kg at 15 ºC.

Jet A is a kerosine grade fuel normally available in the USA. It has a flash point of 38 ºC, a freezing point of -40 ºC. Its energy content is 40.69 MJ/kg and at 15 ºC its density is around 0.8 kg/L.

Jet B is a distillate covering the naphtha and kerosine fractions. It can be used as an alternative to Jet A-1 fuel. But there is not much demand because it is more difficult to handle (higher flammability), and is used in very cold climates where its performance is better.

TS-1 is a kerosine type fuel with slightly higher volatility and it is the main fuel available in Russia. It has a flash point of 28 ºC, a freezing point of -50 ºC. Its energy content is 43.20 MJ/kg and at 15 ºC its density is around 0.787 kg/L.

In terms of contamination, according to ICAO 1 kg of jet fuel produces 3.16 kg of CO_2 emissions. If we look at the consumption table in appendix A, the A320neo consumes 2066 kg/h, that's 6528 kg of CO_2 made every hour by the most efficient narrowbody aircraft. So, billions of tonnes of CO_2 are made by aviation each year, representing between 2.5% - 3.5% of the global CO_2.

The cost of Jet fuel does normally vary with the price of the crude oil, which is normal because it is petroleum-based. So, if the crude oil price rises so does the jet fuel price.

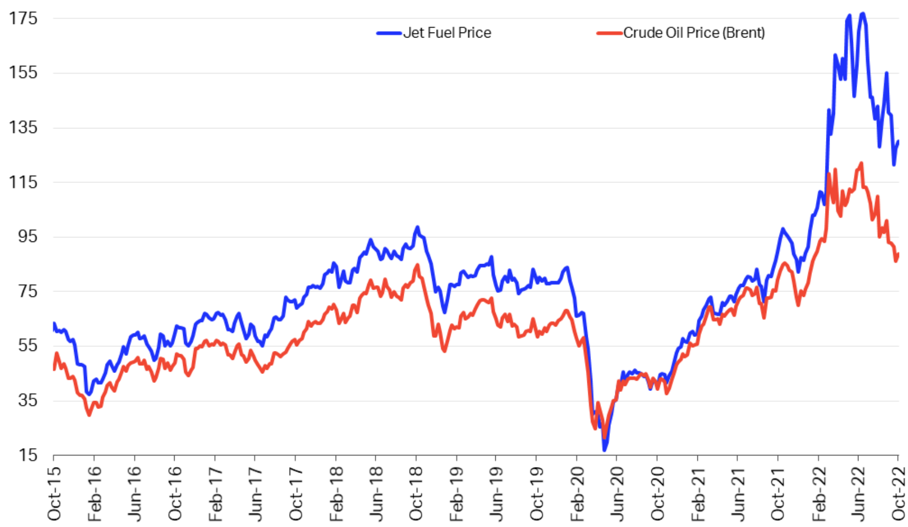

Fig. 2.8 Jet fuel & Crude Oil price evolution in dollars per barrel (159 litres) [IATA]

The fuel at the airport is driven normally through pipeline systems. And companies such as Shell manage and supply the fuel to the airline's aircrafts. The price does vary depending on the airport, as a curiosity, on June 25th, 2022 in LEBL airport the price of 1000 litres of Jet A-1 fuel had a cost of 1125.87 euros (see figure 2.9). And comparing this price with the price evolution in the figure 2.8, the cost of the jet fuel has almost doubled in 2022 and before the Covid-19 jet fuel normal price was averaging 80 dollars per barrel, which is 0.503 dollar per litre of jet fuel or 503 EUR / 1000 L.

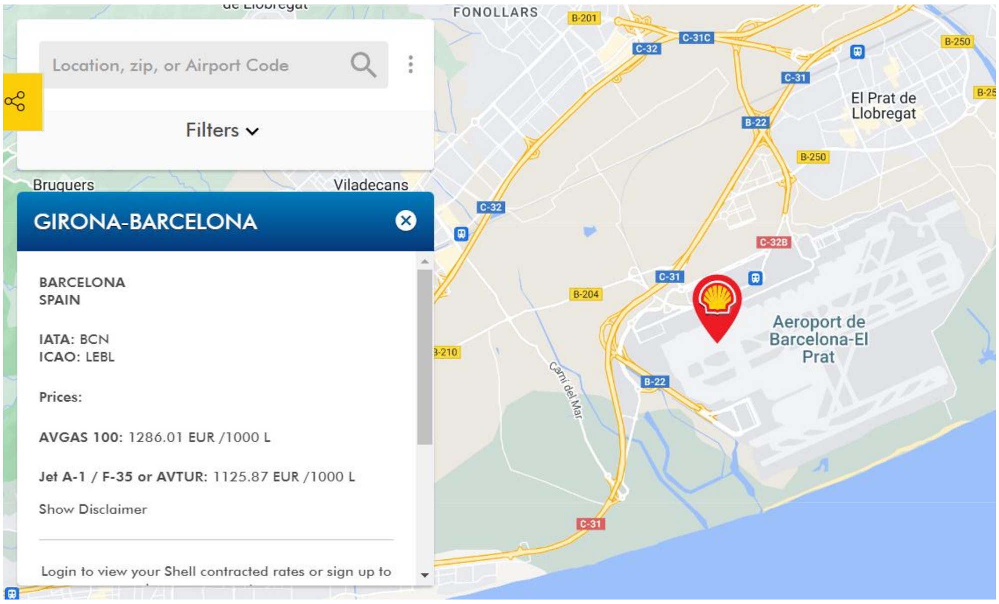

Fig. 2.9 Fuel cost in LEBL airport as of June 25th, 2022

CHAPTER 3. Study and analysis of different types of powered aircraft for the future commercial aviation

3.1 Commercial aviation at present days

Commercial aviation gained a lot of popularity & importance in the United States in the late 1970s and in Europe since Ryanair began its multiple operations in the 1990s with low-cost fees for air traveling. A lot of people started to use airplanes as the main way of transportation instead of trains & cars, especially for large scale distances and for foreign countries trips.

Nowadays, long haul flights are done with widebody aircrafts such as an A330, A350, B777 and B787. These widebody aircrafts are twin-engine aircrafts that consume between 4500 – 7500 kg/h of fuel (see Annex A). And compared to the four engine commercial jets like the B747 or A380, they are more interesting for airlines nowadays as they consume less fuel. The tendency is that quad-engine jets will sooner or later disappear because airlines are focusing more on twin-engine jets, not only because they consume less fuel than other aircrafts (up to 50% less) but also because they can carry up to 300 - 400 passengers which is only 20% less passenger capacity than quad-engine jets.

The most widely used commercial aircrafts are the Airbus A320 and the Boeing B737. Although they are often used for short & medium haul flights, variants with more fuel tanks & fuel capacity are beginning to appear for longer routes. The A320 was first introduced in 1988 and it has a capacity of 186 passengers (depending on the seats configuration), it is powered by 2 engines IAE V2500 that provide 110 kN of thrust each. The cruise speed of the A320 is 830 km/h (Mach 0.78) and has a fuel consumption of 2430 kg/h. The B737 instead was introduced in 1968 but its modern variant is very similar to the A320, passenger capacity of 177 people and powered by CFM56-7 series engines that provide 117 kN of thrust each. The cruise speed of the B737 is 838 km/h (Mach 0.785) and has a fuel consumption of 2530 kg/h. In the annex attached there is more information about the fuel consumption per hour of several commercial aircrafts and others non-commercial aircrafts.

Omitting the years 2020 & 2021, when Covid-19 did strike the world and with the aviation industry being the most affected sector not just because a few people were able to fly but also because some airlines were forced to fly with empty aircrafts in order to save their airport slots. Two years later, in 2022 commercial operation returned to the same levels of flights as in the year 2019. Looking at the graph below we can see that an average of 215.000 flights are flying every day.

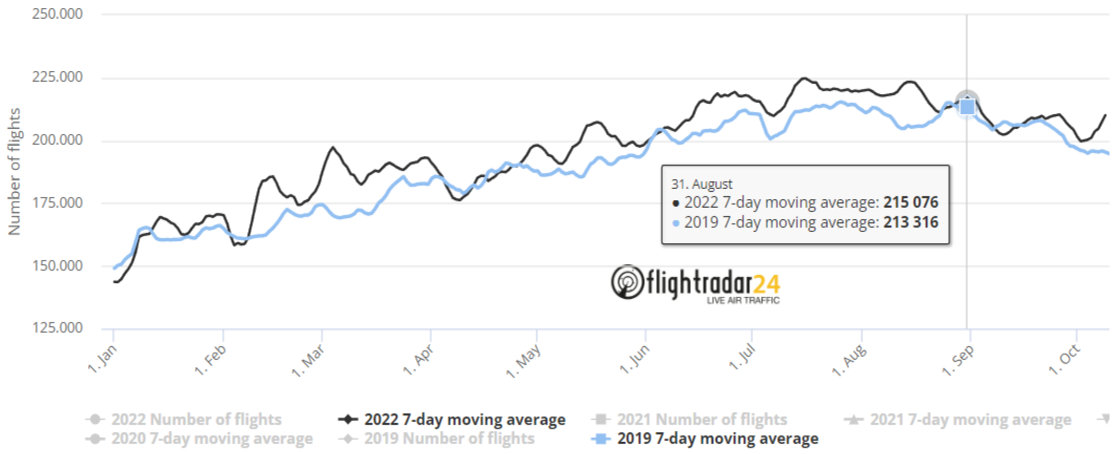

Fig. 3.1 Average number of flights per day as of August, 2022 [21]

This number of total flights corresponds to the sum of Commercial flights above + business jet flights + private flights + cargo flights + gliders + most helicopter flights + most ambulance flights + government flights + some military flights + drones.

Inside of this huge number of all types of flights we can separate the commercial flights. The commercial flights are classified as sum of normal commercial passenger flights + charter flights + some business jet flights. So, subtracting we have that 105.000 flights out of 215.000 total daily flights are commercial. The result is that 48.8% of all daily flights are commercial in 2022. This number might not represent the total magnitude of the commercial flights because as of September 2022 there is war going on in the northeast of Europe, so if we compute the percentage of the year 2019, we have that an average of 57.8% of the flights in the year 2019 were commercial flights.

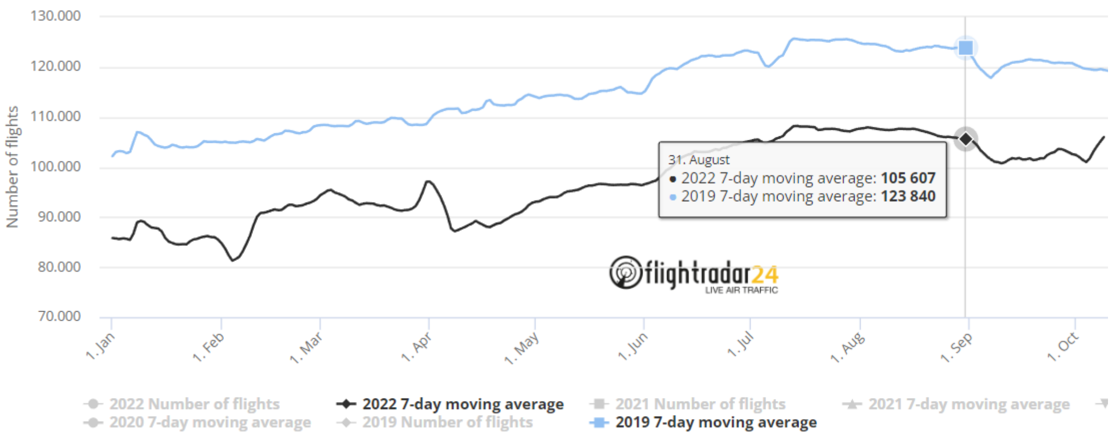

Fig. 3.2 Average number of commercial flights per day as of August, 2022 [21]

From all the commercial flights, in Europe and USA is where the major part of flights take-off and land. It is not only because of the fact that in Europe and the

USA there is more economic wealth and therefore more purchasing power, but also because of the business model that is established by low-cost airlines such as Ryanair and Southwest.

But this is now beginning to change, for a few years now both in China and India (the countries with the most people in the world) low-cost airlines are emerging, trying to make flying affordable for the population. In the Middle East there is also a very large flow of widebody aircraft with hubs created in Qatar and the UAE.

Therefore, the number of flights in the coming years will grow dramatically, especially depending on how fast commercial flights evolve in Asian countries. This will cause more planes to be in the air, therefore more fuel will be needed and since there is not infinite fuel and this added to the fact that we must try to pollute less, we have to look for alternatives to be able to fly sustainably. So, we need to look for sustainable solutions for the future and find out how aircraft will be powered in the future.

3.2 Potential types of powered aircraft in the future

For the increasing commercial aviation industry, we need to solve its main problem which is sustainability and fossil fuel consumption. Fuel consumption is not especially a critical problem right now even if modern aircrafts still consume tonnes of fuel per hour. That’s because some of the modern turbofan engines powering the commercial jet are the most fuel efficient possible and they cannot be improved too much as they have potentially reached the pinnacle of development regarding fuel efficiency with high bypass ratio turbofans. So, we need to look into developing new technologies that can improve high bypass turbofans efficiency. The potential powered aircrafts of the future can be:

1. Current commercial aircrafts powered with sustainable aviation fuel
2. Solar-powered
3. Electric-powered
4. Hydrogen-powered
5. Nuclear-powered
6. Electric Plasma-powered

Some important points of the new technologies or new sources of power is that we need to have in consideration some crucial aspects of current modern aircrafts.

First of all, we need to analyse and study if those potential powered aircrafts can be an adapted version of our current aircraft airframes. In other words, if new engines using a sustainable energy source or other energy sources that pollute less can power our current narrowbody or widebody aircrafts. For example, if we are capable of developing an engine that works with hydrogen, to save a lot of money and time, the best solution is first trying to adapt the engine to our current most developed aircraft airframe (B787, A350 or A320).

Just the creation of a new aircraft (airframe + systems + subsystems) has a cost between 10 - 20 billion dollars and an average development time of 10 years + years of testing & certification. If it’s not possible a new design or prototype should be made starting from the beginning.

Talking about the aspects of the future powered aircrafts. The most important aspect is the thrust-to-weight ratio, for example the current A320neo has a thrust-to-weight ratio of 0.312 or the A380 which has a thrust-to-weight ratio of 0.227. So, taking into account these two examples, the future powered aircraft should have a similar or higher thrust-to-weight ratio in order to at least achieve some important flight characteristics such as the velocity (near Mach 0.8), altitude (35.000 ft - 40.000 ft) and to be able to power the entire systems and subsystems of the aircraft such as pneumatic and air conditioning system.

The second most important characteristic is the size of the engine. In order to be adapted, the engine cannot exceed the space inside the wing, because it would not fit and also depending on where it is placed it could create momentum and increase the AOA of the aircraft when flying.

Then, the temperature of the engine would also be very important. Currently, we only have the technology to reach temperatures up to 1700 ºC because of the highly effective thermal barrier coatings that line the inside of the turbofan chamber. So, the new engine must reach temperatures below 1700 ºC until we develop more advanced materials.

And the final important aspect is the noise of the engine or adapted aircraft. Acoustic contamination is one of the main problems that we have when airports are near big cities. The noise level is measured in EPNdB, and using the ICAO annex 16 Volume I we can compute the maximum noise level allowed during the approach, flyover and the lateral noise of the aircraft depending on the number of engines and MTOM.

All noise levels are in EPNdB

MTOM** 0 20.2 28.6 35 48.1 280 385 400

Lateral		94	80.87 + 8.51 log M	103
Fly-over	≤ 2*	89	66.65 + 13.29 log M	101
	3 *	89	69.65 + 13.29 log M	104
	≥ 4 *	89	69.65 + 13.29 log M	106
Approach		98	86.03 + 7.75 log M	105

* number of engines
** MTOM in 1000 kg

Fig. 3.3 ICAO Maximum Noise levels [22]

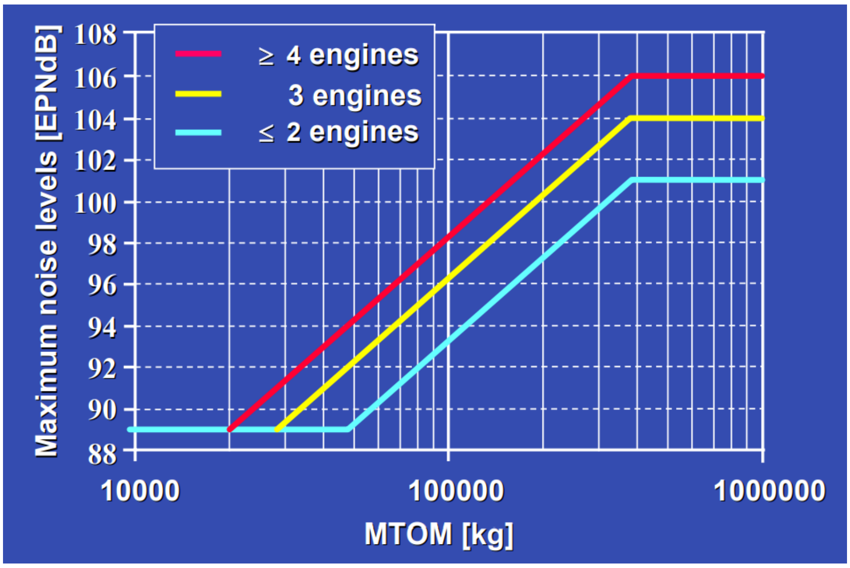

Fig. 3.4 ICAO Maximum noise levels at Flyover reference point [22]

Just as an example, an A320 is a twin-engine that has a MTOM of 78.000 kg and has a maximum allowed flyover noise of 91.79 EPNdB and 100.69 EPNdB during approach.

3.3 Aircrafts powered by SAF

Sustainable aviation fuels (SAF) are basically biofuels that reduce the carbon emissions of the powered aircrafts and thus impact the carbon footprint of aviation. Biofuels that are suitable for aviation are made by using the biomass to liquid method, so they are biomass-derived fuels. The biomass to liquid method is a multiprocess technique that produces synthetic hydrocarbon fuel from biomass using thermochemical processes such as gasification or pyrolysis.

Fig. 3.5 Biofuel tank refuelling an aircraft

Biomass is a plant-based material that is normally used to produce heat or electricity at homes. Depending on the quality of the biomass and the types of plants used, the emissions of CO_2 are reduced normally between 25% - 95%. Biomass just made of plants emit the same number of green gasses as previously absorbed by the plants, that means, if the biomass used for the creation of biofuel is made by plants that only have 0.2 kg of CO_2 absorbed per 1 kg of plant, the biofuel made with 1 kg of biomass will only produce 0.2 kg CO_2.

Biofuels are also classified in different generations, more specifically there are 4 generations of biofuels. The first generation of biofuels are biofuels that are made using agricultural crops such as vegetable oils and which can cut emissions up to 80%. The second generation of biofuels are the ones that are made from non-food crops and forest residues, they produce savings in CO_2 emissions up to 91%. The third generation is designated for biofuels that are made using algae and aquatic plants with a minimum natural oil content of 50%, they have savings of CO_2 emissions up to 95%. And finally, the fourth-generation biofuels which are also considered the advanced generation biofuels, are the ones made using photosynthetic algae that is genetically modified to produce 98% less emissions than conventional jet fuel. The only problem with the advanced generation is that the biofuels made using photosynthetic algae are still in the development phase and they are still not available nor certified for commercial aviation.

Biofuels that have been labelled as SAF have the advantage that no modifications are needed in the aircraft engines, aircraft fuel tanks or the aircraft itself because the biofuel characteristics such as the specific energy, density and volume are very similar to the conventional jet fuel. Also, biofuels meet specifications for lubricity as well as adequately swelling elastomer seals in current aircraft fuel systems. The only technical challenge that biofuel can provoke is that pure biofuels that aren't mixed with petroleum and don't contain paraffin-based additives may cause rubber seals and hoses to shrink in the refuelling systems.

Fig. 3.6 Hose refuelling an aircraft

The real usage of biofuels in commercial aviation is another topic. The first commercial flight that used biofuel took place in 2008. Since then, there was just a little growth to 500 flights a year in 2016, but later in 2021 there were already 450.000 flights that used SAF. Although 450.000 does seem a huge increase in sustainable flights, from the average of 68 million flights that took place in 2021 that amount only represent 0.67% of the total flights and 1.14% of the commercial flights during the year. Still in 2022, SAFs face political and economic barriers that prevent a great number of flights incapable of being sustainable. For the year 2019, the price of jet fuel was between 0.3€ - 0.6€ per litre (50€ - 100€ per barrel) and during that time the price of biofuel production was between 0.7€ - 1.6€ per litre that's an increase of 233 % - 266 % of the price compared to conventional jet fuel. Today, even with aviation taxes and subsidies, the price difference hasn't even been close, but has narrowed a bit.

In 2050 however, it will be a different story. ICAO have committed to net-zero emissions by 2050 with the pledge of all the 193 member states conforming the ICAO in their last assembly that took place in September, 2022. IATA also participated in the assembly by advising further advancements to international policy. So, the final aim is to remove the political and economic barriers that currently are affecting the production of SAFs. By 2030, it is aimed to fly at least a significant percentage of flights using SAFs. The increase of biofuel production and the reduction of biofuels cost thanks to the government's aid is also expected to happen especially in the most developed countries. By 2050, thanks to the commitment all the flights or at least the most will be done using SAFs.

3.4 Solar-powered aircrafts

Solar-powered aircraft are by definition aerial vehicles capable of maintaining a sustainable flight at a certain flight level and that operate using the solar radiation that impacts the airframe of the aircraft as their primary energy source. The working principle is to have solar cells in the aircraft wings to transform the solar radiation into electrical energy. The real question is indeed if we currently have well developed solar powered technologies in order to be capable of powering an aircraft and making a flight with the same or similar characteristics as most of the conventional commercial jets.

The short answer is not yet, but to know how far we have progressed at the present we need to analyse our current most advanced solar powered aircraft, evaluate the systems and subsystems involved in the aeroplane and compare its characteristics & aspects to the one that commercial jets have nowadays. Latest solar-powered aircraft design is a combination of several multidisciplinary aspects which include aircraft structural design, propulsion system design, electrical system design, and power and control system design.

Fig. 3.7 Solar Impulse 2, the most developed solar powered aircraft at present

The solar impulse 2 aircraft is an experimental aircraft that flew around the world without using a single litre of fuel. The characteristics of the solar aircraft are:

- Lithium Nickel Manganese Cobalt (NMC) batteries offering 260 Wh/kg.
- Four battery packs of 41 kWh each weighing 633 kg and offering 164 kWh in total with 150 Ah cells.
- 70 HP (52 kW) of total propulsion power with 4 engines of 17.5 HP each.
- The thrust of the aircraft at maximum speed (140 km/h) was around 1.34 kN or 302 lbf.
- 2300 kg of total weight with 80% of the aircraft made of carbon fiber.
- The thrust to weight ratio is 0.1182.
- Wingspan of 72.3 m & aircraft length of 22.4 m.
- 17.000 photovoltaic cells in the 270 m^2 of the wing and elevator surface.
- Unpressurized cabin without AC and with a capacity of 2 people.

Fig. 3.8 Solar Impulse 2 size on ground

Knowing the previous data, we need to make an analysis of different aspects of solar-powered aircrafts. These aspects are the vehicle configuration & design, the aerodynamics and the propulsion system. Comparing them to other aeroplanes such as the actual commercial aircrafts will show the flaws and big-differences between them.

3.4.1 Vehicle configuration & design analysis

The first most critical aspect is to determine the final layout of the aircraft. To select the best configuration of the airframe some key characteristics such as the stability, design simplicity, robustness of the structure, minimizing weight and maximizing lift need to be compromised between them.

In the evolution of the current solar-powered aircrafts we can see how the trend is to reduce as much as possible the fuselage in order to reduce the weight. The most predominant structure becomes the wing because its surface is needed especially for the collocation of more photovoltaic cells and thus obtain more power and lift.

To obtain good stability a tailless aircraft design is not feasible, a tailless aircraft design although it reduces the overall weight of the aircraft and provides longitudinal stability, it also results in an undesired aerodynamic performance, lateral instability, wake disturbance and limited choice of airfoils sections.

To sum up, the best solar-powered aircraft design possible is to have a span loaded airframe (large wings) with a low pitching moment airfoil, a reduced fuselage and the integration of a tail to get good aerodynamic performance & stability, minimize power consumption and achieve gradual flight manoeuvres.

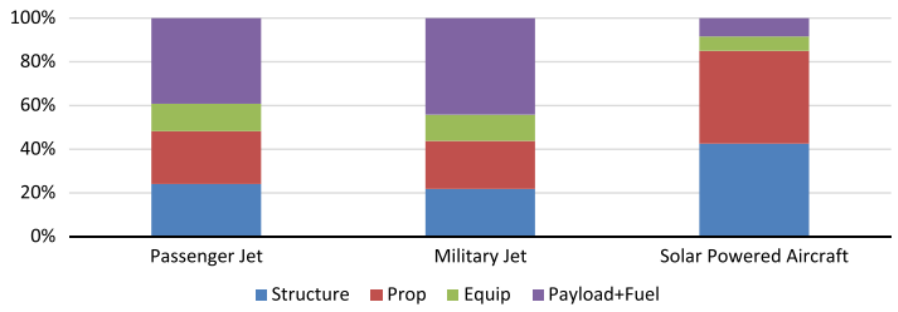

Fig. 3.9 Relative mass breakdown [3]

The figure 3.9 shows the mass comparison between commercial jets, military jets and solar-powered aircrafts. Although solar aircrafts have the lowest mass percentage of payload + fuel, the structure & propulsion system consists of more than 80% of the MTOW. In the commercial & military jets this value is only around 40%. So, designing the solar aircraft to be as light as possible will ensure more thrust-to-weight ratio and will allow to accommodate more equipment and payload.

3.4.2 Aerodynamic analysis

In the solar-powered aircrafts, the power obtained by the cells mounted on the upper wings surface and horizontal tailplane surface is directly proportional to the surface areas. This has an influence on important aircraft parameters such as lift, drag, weight and velocity and these parameters affect the overall performance of the aircraft, thus it is very important to analyse and evaluate these variables in order to predict the flight performance and the power requirements of any aircraft.

We've discussed that span loaded airframes or large wings are the best design of solar-powered aircrafts. But for the aerodynamic aspect, the airfoil selection is crucial, from the airfoil selection and span dimensions we can compute the maximum lift coefficient and from this coefficient we can obtain other factors such as the minimum operational speed, the maximum wing loading and the aircraft manoeuvres limitations. Like other aircrafts the density of the air at different altitudes also has an influence on these factors.

The air viscosity effect (Reynolds number) also affects the aircraft depending on the flight conditions and the size of the vehicle. The air compressibility effect does affect when the Mach number is higher, the current most advanced solar-powered aircraft has a Mach number of 0.128 at 30.000 ft & with a velocity of 140 km/h so the air compressibility effect does not affect right now due to the low speeds that solar-powered aircrafts can achieve.

The last important parameter for the performance of the flight is the ratio between the coefficient of lift (CL) & coefficient of drag (CD). To obtain the maximum range and maximum wing efficiency a maximum CL/CD ratio is desired, this ratio also gives the minimum power requirement for the aircraft depending on the flight mode. So, flights done by using solar power combine a high aerodynamic glide ratio (CL/CD) and a large wing area with low wing loading, they are basically a solar-powered glider.

3.4.3 Propulsion analysis

The power distribution with respect to the wing area of a solar aircraft is represented in the figure below.

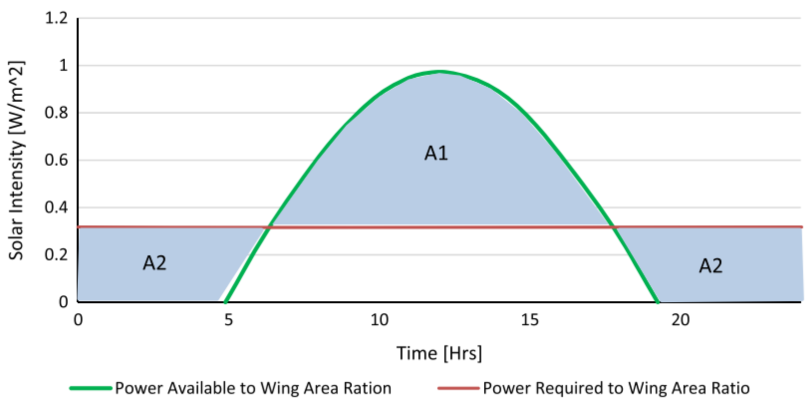

Fig. 3.10 Power distribution diagram of solar aircrafts [3]

The power required by the aircraft is constant if the flight is always at the same altitude, this required power is the red line represented in the figure. The green curve instead is the power that is obtained by the photovoltaic cells on the wing surface. The curve is determined by the solar intensity and the hours where there is sunlight during the day. The shaded area 1 (A1) represents the excess energy received that is stored in the batteries, whereas the shaded area 2 (A2) represents the energy required during the night hours.

The power system works together with the power management system and the propulsion system. It is important to have an efficient power management system in order to lose as little energy as possible and to regulate the power to the loads. The primary source of energy generation are the solar panels during insolation, the amount of power obtained from these cells depends on various factors including geographical location, time of day, day of the year and the cell orientation. The excess power generated by the solar cells that is not consumed during daylight flight is saved in the batteries and later used during the night. The batteries selection evaluation will be studied in the next section when discussing the electric-powered aircrafts.

The propulsion system is made up of electrical motors with or without gearboxes and propellers for producing thrust; this combination is normally identical in all the solar-powered aircrafts. Many current solar-powered aircrafts feature distributed propulsion with an advanced propeller design and a strong coupling between the propulsion system and the flight controls.

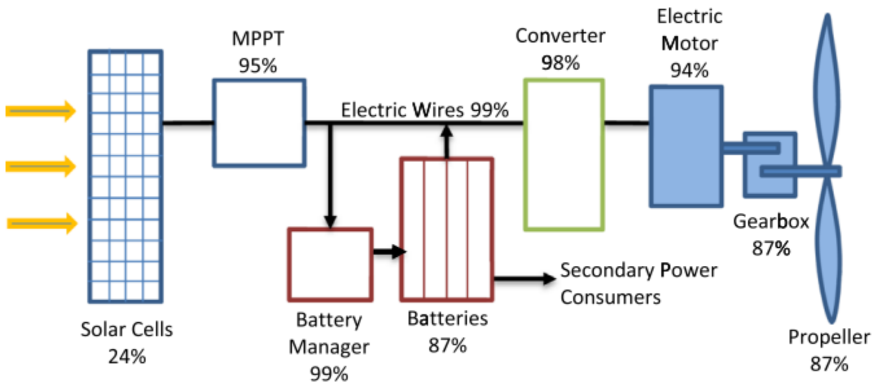

Fig. 3.11 Subsystem efficiencies of solar aircrafts propulsion system [3]

The figure 3.11 shows a scheme of the subsystems involved in the solar aircrafts and their mean efficiencies. The overall propulsion & power system efficiency in the system showed above is 15.58%. The solar cells subsystem has the lowest efficiency with 24.2% and is the main culprit for the low efficiency of the overall propulsion & power system of solar-powered aircrafts.

To develop this efficiency, we need to analyse photovoltaic technology (PV technology). PV technology is a direct conversion of sunlight into electric power (flow of electrons) by using solar panels composed of photovoltaic cells. There are three main classes of solar cells that have been developed, thin film solar cells, single junction solar cells and multiple junction solar cells. These three solar cell classes have the same principle of energy conversion but vary in terms of materials used and manufacturing.

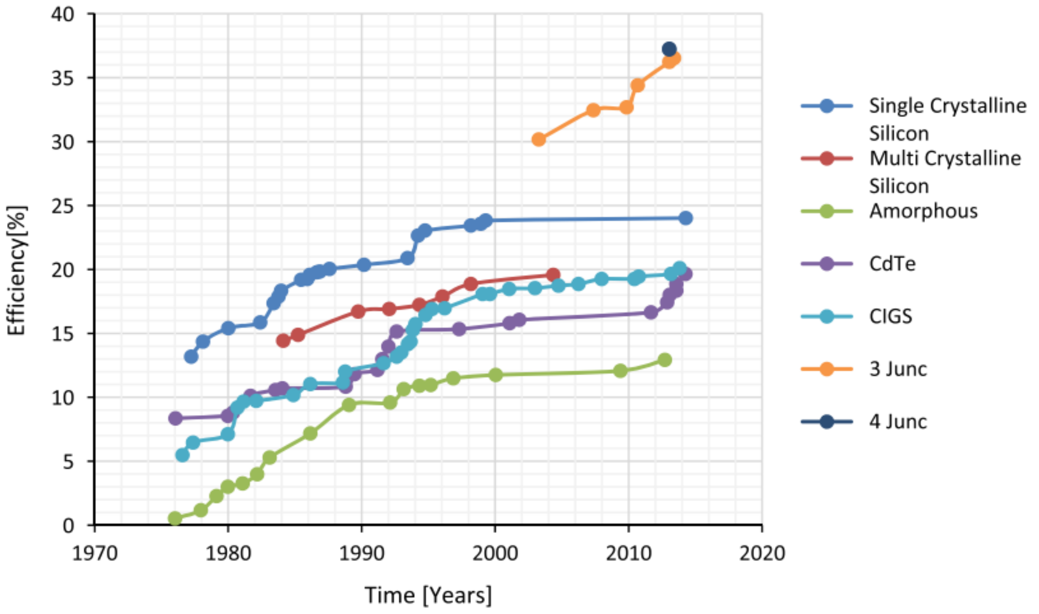

Fig. 3.12 Solar cells efficiency evolution during the years (United States NREL)

The figure 3.12 shows the evolution of solar cells during the years with different solar cells classes. Single crystalline silicon & multi crystalline silicon are classified in the class of single junction solar cells. Crystalline silicon (Si) wafers are the dominant material in the market for solar cells with a 75% share. They are reliable and have a relatively good efficiency with the record of 24.2% efficiency using monocrystalline technology. On the other hand, the material is expensive and at certain high temperatures the efficiency declines. Thus, solar manufacturers are investing more in polycrystalline product lines that have lower-manufacturing cost and to be able to meet the rising demands.

Amorphous, CdTe and CIGS are thin-film technology. Thin-film technology is manufactured by low-cost semiconducting materials and materials that are non-crystalline. These materials are amorphous silicon (a-Si:H), highly absorptive cadmium telluride (CdTe) and copper indium gallium selenide (CIGS). Amorphous silicon is made from the waste silicon of the computer chips waste but it only has an efficiency around 13%. CdTe typically bonded by cadmium sulphide can arrive at an efficiency up to 19%. And CIGS is the best thin-film material because they are electrically high resistant and cost-effective, they can reach efficiencies up to 20%.

The last multiple junction class is made up of 3 junction cells and 4 junction cells. Multiple junction cells will be the future used cells because of their superior efficiency. These cells are able to capture and convert much larger light frequencies than other types of cells and achieve efficiencies near 40% and they do not lose efficiency with higher temperatures. In the future with the development going forward it is probably that the efficiency will reach at least 50% or higher. The three-junction cells are typically made from gallium indium phosphide (GaInP), gallium arsenide (GaAs), and germanium (Ge) while into the four-junction cells there is one more material added.

Increasing the efficiency of the solar cells to at least 50% using multiple-junction cells, then the power & propulsion system efficiency will be around 28.24% which is nearly double than using crystalline silicon. With higher propulsion efficiency, the solar-powered aircraft could reach higher velocities and become more sophisticated due to the availability of a major amount of power.

3.4.4 Fuel cells energy storage technology

Fuel cells are a very interesting application of energy storage and an alternative to batteries. Fuel cells are an energy conversion technology that were created by NASA for space missions in the late 1950s and early 1960s. Fuel cells systems can be regenerative or non-regenerative and its main characteristic is the energy conversion using the electrolyser. The regenerative fuel cell system is very efficient and it has an energy density potential up to 3 times greater than conventional rechargeable batteries.

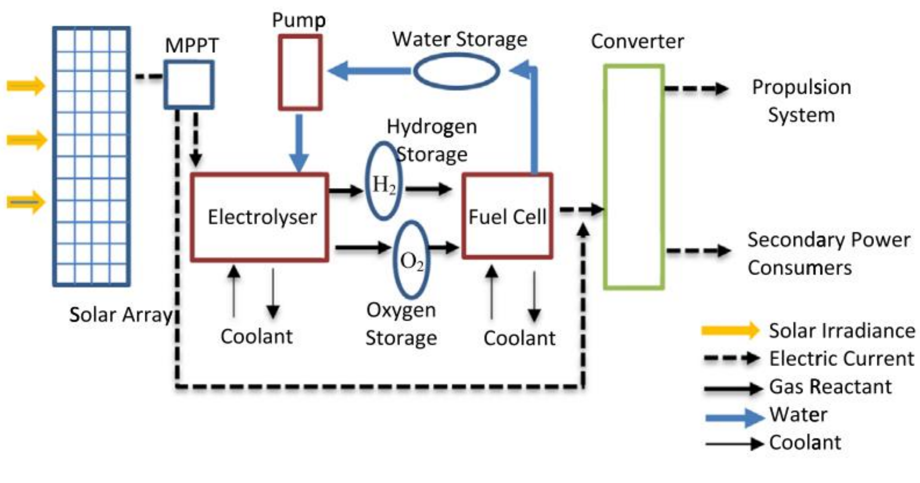

Fig. 3.13 Regenerative fuel cell concept [3]

The figure 3.13 is the representation of the regenerative fuel cell concept. The system is made up of a fuel cell, an electrolyser, a solar array, a pump, a MPPT, a converter and 3 different storages of oxygen, water & hydrogen. The working principle consists of using the application of hydrogen electrolysis. The energy generated from the solar cells is used to dissociate water molecules (hydrogen and oxygen). The hydrogen & oxygen are separated and stored in different tanks. The objective is to transform solar energy into electrical energy, and store the electrical energy in the form of hydrogen. When the solar array is inactive and cannot generate energy, the reverse process is used. So, at night the hydrogen & oxygen gasses are converted into water in order to get electrical energy and to power the propulsion system & other subsystems.

The non-regenerative system is characterized by not having an electrolyser but supplying hydrogen and oxygen gasses in order to produce electrical energy. For solar-powered aircrafts, fuel cell regenerative systems can be very useful if the weight of the tanks are similar to the weight of the batteries and that does not disturb the overall performance of the aircraft. And naturally there are several types of fuel cells depending on the used electrolyte that are under development and can be very useful in the near future.

Type of fuel cell	Electrolyte	Operating temperature	Efficiency	Energy output
Polymer Electrolyte Membrane (PEMFC)	Proton exchange membrane	50ºC - 120ºC	40% - 60%	1kW - 100kW
Alkaline (AFC)	Aqueous potassium hydroxide solution	90ºC - 100ºC	60%	10kW - 100kW
Phosphoric acid (PAFC)	Liquid phosphoric acid	150ºC - 200ºC	40%	5kW - 400kW
Solid oxide (SOFC)	Solid zirconium oxide stabilized with yttrium	700ºC - 1000ºC	60%	1kW - 2MW
Molten carbonate (MCFC)	Solution of lithium, sodium or potassium carbonates	600ºC - 700ºC	45% - 50%	300kW - 3MW

Table 3.1 Fuel cells comparison [3]

For aircraft applications the two best fuel cell systems are the proton exchange membrane fuel cell (PEMFC) and the solid oxide fuel cell (SOFC). PEMFC operates at low temperatures offering a really good efficiency but requires pure gaseous hydrogen as fuel. On the other hand, SOFC operates at high temperatures but because of the high heat produced it can be complemented with a turbine to achieve better efficiencies.

3.4.5 Future design concept

There are already new concept designs for solar powered aircraft. One of them that we could see in the future is the Falcon Solar made by the company Lasky design. The features of the Falcon Solar design are the large wings curving upwards inspired by birds of prey and a pointed cockpit & tail. The shape of the fuselage allows the aircraft to generate more lift and provides more surface area to the allocation of more PV cells.

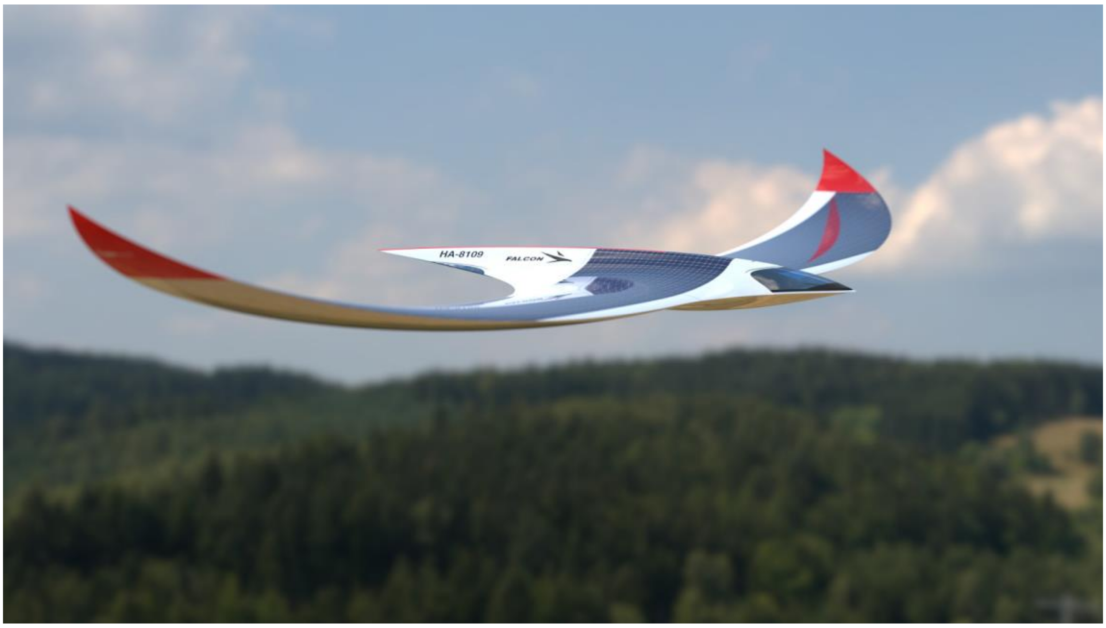

Fig. 3.14 Falcon Solar design concept

Fig. 3.15 Solar cells distribution in the Falcon Solar fuselage

3.5 Electric-powered aircrafts

Electric-powered aircrafts are vehicles whose primary source of energy for the aircraft operation is provided by a set of batteries onboard the aircraft. Electric-powered aircrafts are very similar to solar-powered aircrafts in terms of simplicity, systems & subsystems involved on the aircraft. The major difference is that in an electric aircraft the energy is never generated, rather it is previously stored in the batteries for the use during the flight.

Currently, only small types of electric-powered aircrafts are feasible. The specific energy requirement is one of the major drawbacks. The specific energy tells how much energy the battery contains for its weight. To make a comparison with commercial aircrafts, jet A-1 fuel has an energy density of 11.94 kWh/kg and an average specific energy of 43 MJ/kg. The most used batteries for these applications are lithium-ion batteries, they have a maximum energy density of 0.260 kWh/kg and a specific energy of 0.936 MJ/kg. That’s a difference of about a factor of 46, in other words our current best batteries are 46 times less powerful or less energetic than jet fuel used for powering conventional jet aircrafts.

However, that does not mean that we will never have a pure electric-powered aircraft. In order to develop more information about electric-powered aircrafts we need to analyse and evaluate current batteries and search for emerging battery technologies that can improve our current batteries' lack of specific energy.

3.5.1 Batteries & Supercapacitors

Depending on the electrochemistry batteries are classified into two different types, primary batteries and secondary batteries. Primary batteries are batteries that cannot be recharged after discharging, while secondary batteries are rechargeable during a certain period of cycles. In order to evaluate current most developed batteries, we need to analyse their characteristics using the table 3.2.

Characteristic	Lead-acid	NiCd	NiMH	Li-ion	Li-Po	Li-S	Zn-Air
Energy density	33-40 Wh/kg	40-60 Wh/kg	30-80 Wh/kg	150-260 Wh/kg	130-265 Wh/kg	350-550 Wh/kg	230 Wh/kg
Energy Volume	50-100 Wh/L	50-150 Wh/L	140-300 Wh/L	270 Wh/L	250-670 Wh/L	600 Wh/L	270 Wh/L
Power density	80-300 W/kg	200-500 W/kg	250-1000 W/kg	1800 W/kg	2800 W/kg	2800 W/kg	105 W/kg
Recharge time	8-16 h	1 h	2-4 h	2-3 h	2-4 h	2-4 h	10 min
Cycle efficiency	82%	80%	70%	99.9%	99.8%	99.8%	96.9%
Lifetime	-	-	-	2-3 years	2-3 years	2-3 years	240 h
Life cycles	300	500	500-1000	2000	>2000	>2000	>3000
Nominal voltage	2 V	1.2 V	1.2 V	3.6 V	3.7 V	3.7 V	1.2 V
Operating temperature	15-25 ºC	-20 to 60 ºC	-20 to 60 ºC	-40 to 60 ºC	-20 to 60 ºC	-20 to 60 ºC	-20 to 70 ºC

Table 3.2 Current common battery characteristics

Lithium-ion (Li-ion) batteries are the most used battery nowadays all over the world. Some aircrafts have implemented the use of Li-ion batteries in the avionics of the cockpit or in some other systems involving the passenger's cabin. Analysing the table 3.2, lithium batteries are the most efficient, powerful, long-lasting and energetic of all the types used commercially. From the 3 types of lithium batteries although Li-ion batteries are the most used, but lithium Sulphur batteries are gaining popularity because of its improvement in the energy density with respect to Li-ion batteries. Some developed Li-S batteries can arrive to have a specific energy of 550 Wh/kg, that's more than double of the capacity of Li-ion batteries. So, for new electric-powered vehicles using Li-S batteries is possible and in comparison, with jet fuel the difference of specific energy can be reduced to a factor around 22 instead of a factor of 46 with Li-ion batteries.

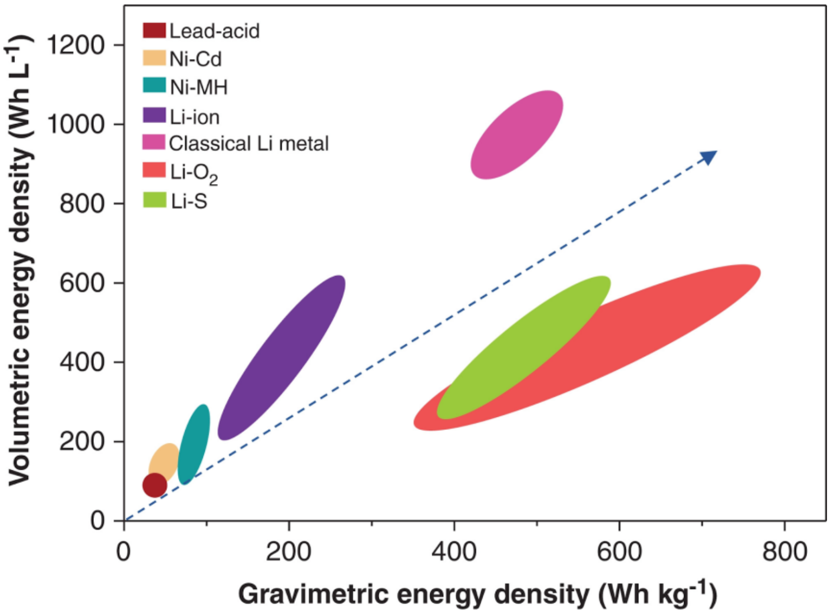

Fig. 3.16 Battery's energy comparison plot [38]

New emerging battery technologies that are not developed enough to be used on aircraft are the Lithium Oxygen batteries (figure 3.16) and the Lithium-Air batteries. In the future they can be an option for powering electric vehicles. Li-O2 batteries can arrive up to 750 Wh/kg with a lower battery volume (energy density around 600 Wh/L). Li-Air on the other hand, can be the battery with the most specific energy content ever. Theoretically, Li-Air batteries have a specific energy of 11.140 Wh/kg (11.14 kW/kg), so they are roughly as energetic as conventional jet fuel used to power commercial aircrafts. But they have a huge drawback, no one within the industry has been able to make Li-Air batteries rechargeable to its theoretical capacity. Therefore, with the Li-O2 technology also not being mature enough until further development, we can only evaluate powering electric vehicles with Li-S batteries with its maximum specific energy of 550 Wh/kg.

In addition, when analysing capacitors & supercapacitors as an alternative to batteries the conclusion is that they do not have a great amount of specific energy but they do offer a big amount of specific power. Moreover, capacitors & supercapacitors suffer from accelerated degradation effects from parameters such as electrical aspects, temperature, vibrations, pressure and humidity. The performance comparison between capacitors, supercapacitors, batteries & fuel cells is plotted in the figure below.

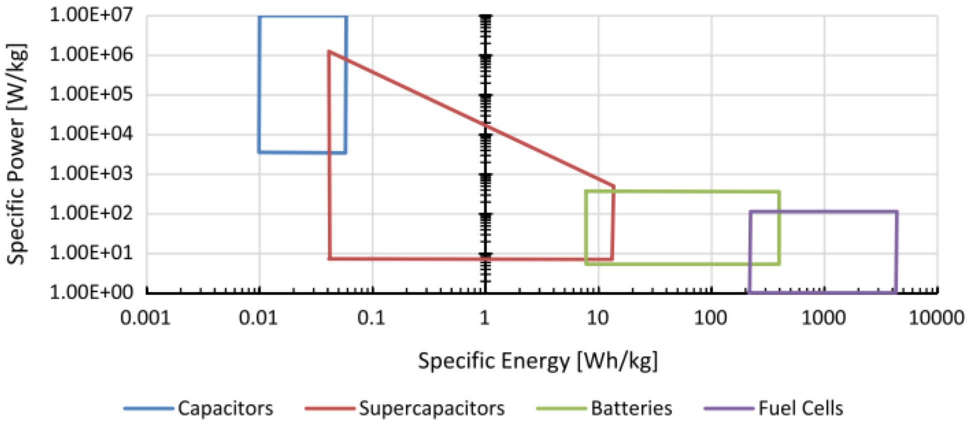

Fig. 3.17 Power & energy comparison of different energy storage technologies [3]

3.5.3 Vehicle configuration & design analysis

The idea of creating an electric-powered aircraft can be carried out by adapting current narrowbody commercial aircrafts [28]. The fuel will be replaced by batteries and the jet engines by electrical engines or by propellers attached to an electric motor & gearbox. On the vehicle configuration side, we need to evaluate which location of the aircraft is the best one for the allocation of the batteries. One of the options can be using the cargo compartments of the aircraft and the other options are allocating the batteries where the fuel tanks are. To avoid damaging the wing structure and design if the batteries suffer from problems such as little explosions or swelling due to adverse factors, the best option is the allocation of batteries in the cargo compartments. Also, allocating the batteries in the cargo compartments makes the batteries replacement easier and for commercial use the time needed for recharging the batteries can be heavily reduced.

A study done by Roland Berger [28], after completing different simulations with the Dornier 328 regional, proved that by the replacement of turboprop engines with electric engines and the utilization of batteries with a specific energy density of 180 Wh/kg, the aircraft could range up to 200 km with similar characteristics as commercial aircrafts. The original flight range of the Dornier 328 is 1200 km, to achieve this range, is possible if some modifications are made. These modifications according to Roland Berger are the reduction of drag by 20%, an increment of 50% of the wing span to reduce the induced drag, reduction of the 20% of the structural mass and the improvement of batteries specific energy density to at least 500 Wh/kg.

All these modifications are now possible with the current technology. The most developed batteries right now are the Li-S with a specific energy of 550 Wh/kg. The structural mass can also be reduced, the Dornier 328 airframe structure was made of aluminium alloy and now materials such as carbon fiber can reduce the structural weight of the aircraft by 42%. The modifications involving aerodynamics will be evaluated in the next section.

3.5.4 Aerodynamic analysis

Different to solar-powered aircraft, an exhaustive aerodynamic analysis is not necessary, as for electric-powered aircraft adapting some existing small commercial aircrafts models is possible. To adapt an aircraft such as the Dornier 328 model, Roland Berger proposed the modification of 20% reduction in aerodynamic drag and an increment of 50% in the wing span [28].

The increment of the wing span by 50% will affect a little in the overall weight of the aircraft and in the CL/CD ratio as this ratio will probably increase. The increment of the wing span will also change the aerodynamic drag, but alongside the reduction of weight done by the use of carbon fiber in the airframe will make a great reduction in drag. Furthermore, if more drag reduction is needed the change in the wing & elevator airfoil section can fulfil this reduction.

In addition, the effects of compressibility & air viscosity if the aircraft can achieve high velocities and certain altitudes with electrical propulsion will not impact the aircraft performance because the aircraft design & configuration was previously made for conventional commercial flights operations.

3.5.5 Propulsion analysis

The performance of aircraft combustion engines largely depends on the concentration of oxygen in the ambient air, which changes with the flight altitude. The operating performance of electric motors does not vary with altitude. Moreover, the maintenance and servicing of electric engines is easier, faster and cost-effective than jet engines because of their simple design & structure.

An electric-powered aircraft can have three types of propulsion architecture. These systems can be hybrid-electric, turbo-electric & pure-electric.

The pure electric system when the propulsion is done by just using electric energy is designed in the figure 3.18 below. The main components of the pure electric propulsion system are the batteries, the motor and the propeller. The efficiency of the system in the design below is around 60% with average components efficiency, but the efficiency can increase up to 80-85% depending on the quality of the components used and if the efficiencies of the main components are improved to at least 95%.

Hybrid-electric propulsion architecture is a combination of the pure-electric propulsion design and the conventional jet propulsion design. The final aircraft design is a combination where we have batteries for powering the electric motors and jet fuel for powering jet engines. During the take-off for maximum thrust both motors & jet engines propel the aircraft and in the cruise phase when less thrust is required the electric motors are in charge of providing thrust to the aircraft. The advantage of the hybrid propulsion is that less jet fuel is required and used but makes the propulsion system complex.

And the last propulsion architecture is the turbo-electric propulsion. This propulsion system is made of a turboshaft engine that provides power shaft to a generator, this generator converts the power shaft into electrical energy to power the electrical motors and the fans or propeller of the aircraft. The advantage of this propulsion system is that more motors allocation is possible for propulsion. Also adapting current commercial aircraft with this system is very possible and easier as the turboshaft engine in commercial aircraft is the APU.

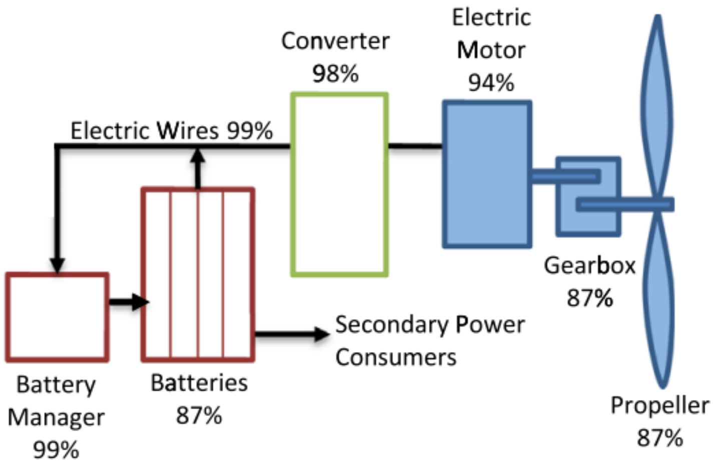

Fig. 3.18 Simple design of a pure electric propulsion system [3]

Four main types of motors are used on electric vehicles, these include induction motors, brush direct-current motors, brushless direct-current motors (BLDC) and switched reluctance motors (SRM). For aircraft propulsion the most used are BLDC & SRM motors due to their high specific power and reliability. These motors are simple, durable and compact synchronous machines that do not require electrical current to be supplied to the rotors. In opposition, they need complex control circuitry based on pre-programmed microchips and solid-state switching. Insulated gate bipolar transistors (IG-BTs) are the preferred electronic switches used for high-voltage propulsion systems whose current levels are usually in excess of 50A (typically required for aircraft systems).

Some examples of electrical motors used in some aircraft's propulsion are the E-811 motor, which was the world's first electric motor certified for general aviation by EASA, and the YASA-750R. The E-811 is a BLDC motor with permanent magnets in the rotors that provides 49.2 kW (66 HP) of continuous power and 57.6 kW (77 HP) of peak power, weighing only 22.7 kg. The Rolls-Royce YASA-750R, is also a BLDC motor and that can provide 200 kW of peak power and has a weight of 37 kg.

Some speed velocities that can reach these propulsion systems are, 180 km/h when using the E-811 motor in a 2-seater pure-electric aircraft. The hybrid electric aircraft can reach the same amount of speed as conventional commercial aircrafts because they have jet engines also as a power source. And finally, turbo-electric aircrafts can reach speeds up to 300 km/h.

3.5.6 Current projects

The first and only pure-electric powered aircraft that is certified to fly for EASA is the Velis Electro. Some of the aircraft characteristics are cruise speed of 170 km/h, maximum speed of 181 km/h, 15:1 lift-to-drag ratio and the batteries can provide 1 hour of flight duration and 30 min of emergency flight.

Fig. 3.19 Velis Electro flight

Rolls Royce Spirit of Innovation in pure-electric airplane that made its maiden flight in 2021. The aircraft is powered by three YASA-750R electric motors that can provide up to 372kW (500 HP) of power. The airplane propulsion system has an efficiency of 90% thanks to which the aircraft reached a top speed of 556 km/h in November of 2021 making a record of the world fastest electric aeroplane.

Fig. 3.20 Spirit of Innovation airplane

There are also more projects further going on with aircraft such as the Airbus E-fan-X and Airbus ZEROe hybrid aeroplane, that can be interesting in the future in order to analyse how far electric-powered technology can arrive. Although the E-fan-X is cancelled right now, in the future it is possible that the project will be retaken.

3.6 Hydrogen-powered aircrafts

Hydrogen-powered aircrafts are aerial vehicles that mainly use hydrogen as their energy source. Hydrogen can be used in conventional jet engines powering today’s commercial aircrafts, so the use of hydrogen as alternative to jet fuel in commercial aircrafts is very feasible. Hydrogen fuel cells are another alternative as explained in the solar-powered aircraft section.

The use of the hydrogen in aircrafts throughout history is quite large as it was first tested in 1783 to fly gas balloons. In 1988 in the Soviet Union, a commercial Tupolev 154 was adapted to fly using hydrogen as its main fuel source; it was the first maiden hydrogen flight done in an advanced aeroplane. From that time, big developments & studies have been conducted to achieve the creation of the pure hydrogen aircraft for commercial aviation.

The specific energy of the hydrogen is 142 MJ/kg or 39.44 kWh/kg, compared to jet fuel which has a specific energy around 43 MJ/kg, hydrogen 3.3 times richer in energy density than conventional jet fuel. Therefore, using hydrogen which is also the most abundant element in the universe is one of the best solutions for long-term sustainable aviation. However, all elements have flaws and in the case of the hydrogen although it is the highest element in gravimetric energy density, on the other hand its volumetric energy density is very low (8.5 - 10 MJ/L) meaning that for a certain amount of hydrogen weight the volume occupied for the hydrogen is larger. There are two main types of hydrogen that can be used as fuel, Liquid Hydrogen (LH2) and compressed hydrogen gas. And from these two types, for airborne applications the best one is LH2 because it is higher in volumetric energy (10 MJ/L).

Aside from the high volume that hydrogen requires, the liquid hydrogen is cryogenic and entails insulated low-pressure tanks to be kept. Compressed hydrogen gas on the other hand, needs carbon fiber high-pressure tanks reaching up to 700 bars to be kept safely. As a consequence, conventional jet fuel tanks are impractical for the storage of LH2 or compressed hydrogen gas and new special tanks configuration needs to be evaluated. In addition, in 2002 Airbus initiated the “Cryoplane project” to study the viability of using LH2 fuel for aviation. The study concluded after 2 years and showed that for an equivalent amount of energy density, liquid hydrogen requires 4 times the volume of conventional aviation fuel. The fuel tanks must be 4 times larger when compared to conventional aircraft fuel storage. Overall operating costs of hydrogen fuelled aircraft would increase from 4% to 5% based on fuel alone.

3.6.1 Vehicle configuration & design analysis

The vehicle configuration and design analysis will be done regarding the usage of liquid hydrogen as primary fuel source for powering common commercial aircrafts. The tanks can be implemented in two different configurations, integral tanks inside the fuselage or non-integrals tanks outside the fuselage.

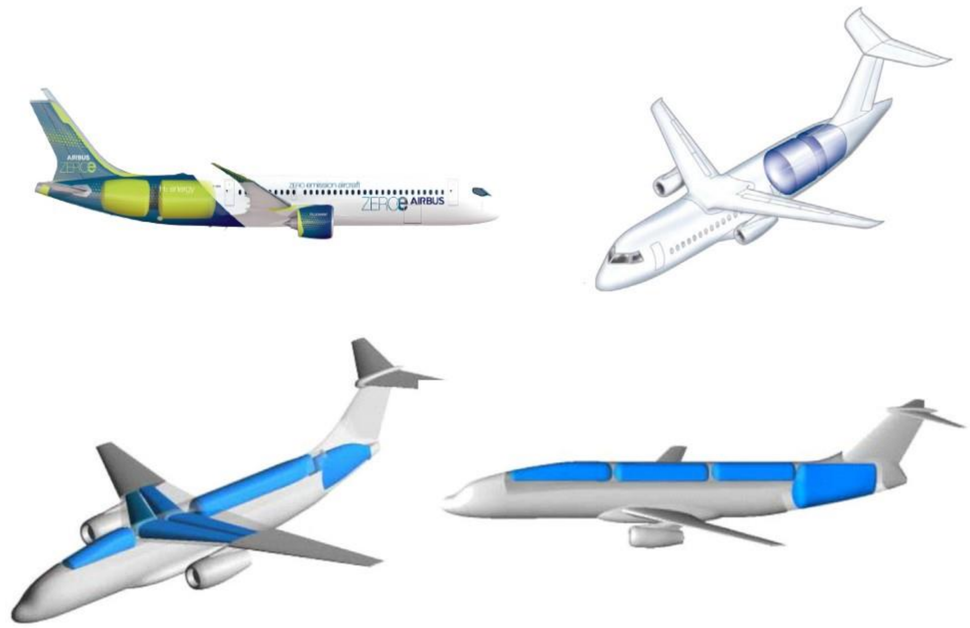

Fig. 3.21 Possible integral tanks designs [9]

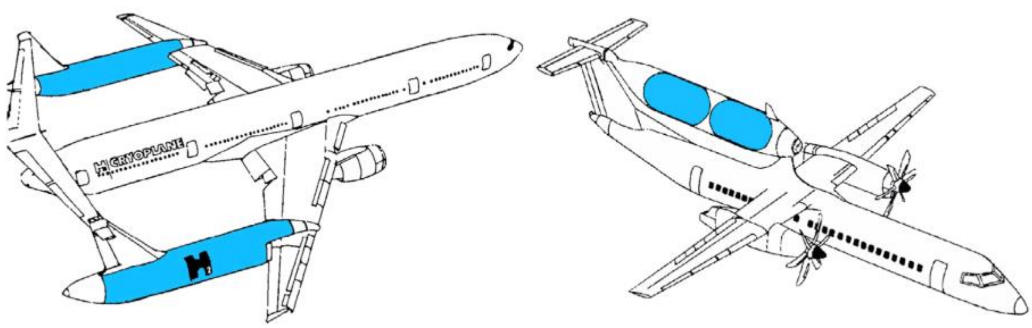

Fig. 3.22 Possible non-integral tanks design [9]

Comparing possible designs for integral and non-integral tanks, the best option is to use the configuration of integral tanks inside the fuselage. The major drawbacks of non-integral tanks are the aerodynamic effect on the final aircraft design and the airframe integration. The tank's optimal design is usually a capsule or cylindrical shape.

Integral tank configuration can be made in different locations inside the fuselage, usually the locations used for studies & analysis are with the tanks allocated at the end of the fuselage or at the back of the aircraft. One of the constraints of integral tanks is the loss of passenger capacity, depending on the final size of the tank and type of aircraft between 14% and 23% of passengers' capacity can be reduced [9]. This capacity can be restored by making aircrafts variants with a longer fuselage. The weight of liquid hydrogen is 2.8 times lower than kerosene or jet fuel, nevertheless due to the fact that special insulated low-pressure tanks are needed to keep the liquid hydrogen and because of the excess surface area occupied by the tanks, the energy consumption of the aircraft increases between 9% - 14%.

3.6.2 Aerodynamic analysis

Two different aerodynamic analyses can be made. Using integral tanks, the aircraft design mostly remains the same in terms of wing design and airfoil section but the use of a longer fuselage has an effect on aerodynamics. A longer fuselage has more induced drag due to the skin friction and more wave drag due to more wetted areas.

The passenger allocation done by the airlines could also have a small effect on the centre of gravity of the aircraft inducing weight & balance variations during the flight, but it will also depend on the final size of the fuel tank and the new MTOW of the aircraft.

With the integration of non-integral tanks, the aerodynamics of the aircraft's changes drastically. Just the new design of the aircraft with the tanks allocated in the wings of other locations will make the flight very inefficient. Some aerodynamic parameters that will have a huge impact are the interference drag, induced drag, form drag and CL/CD ratio, they all will get worse. Moreover, more thrust will be needed to maintain commercial aircraft speeds (Mach 0.8) and thus more fuel will be required, making the overall flight inefficient.

3.6.3 Propulsion analysis

Hydrogen powered aircrafts can have few propulsion systems. Liquid hydrogen can be used as fuel for jet engines or hydrogen fuel cells can be used for generating electrical energy and thus powering an electric aircraft. The fuel cell system is explained in the solar-powered aircraft while the electric propulsion with electricity is explained in the electric-powered aircraft section and the same propulsion system can be used for a hydrogen aeroplane (figure 3.18).

Using liquid hydrogen for jet propulsion is the finest option, because in that way adapting a current commercial aircraft is cheaper and time-efficient rather than creating a new hydrogen fuel cell electric aircraft. Jet propulsion hydrogen aircrafts are also more efficient than the current fuel cell systems and provides more thrust and power for achieving higher speeds and for powering bigger aircrafts. In the emissions topic, hydrogen fuel cells make zero emissions but jet engines burning hydrogen fuel in the air lead to the production of oxides of nitrogen (NOx).

For achieving the same flight conditions as conventional aircrafts (speed & altitude), the quantity of hydrogen fuel used needs to be proportional to jet fuel energy. To create the same amount of thrust as jet fuel, the same amount of mass energy density is needed. Jet fuel has 43 MJ/kg of mass energy density and 33 MJ/L of volume energy density, for liquid hydrogen fuel the values are 142 MJ/kg & 10 MJ/L. Looking at the values, we can arrive at the conclusion that 3.3 times less hydrogen mass is needed to achieve 43 MJ/kg while 3.3 times more volume of hydrogen is needed to achieve jet fuel 33 MJ/L. To sum up, jet engines using hydrogen will consume approximately 3.3 times less mass of fuel but 3.3 times more volume to arrive at the same jet fuel energy values and probably the engines will need some modifications in the combustor & fuel injector system.

Fuelling prices also are a big factor in the use of hydrogen for commercial aviation. There are several types of hydrogen and their price per kg varies a lot. As an example, green hydrogen costs in 2022 are between 12€- 17€ per kg while electrolysis hydrogen costs are between 3€ - 6€. Hydrogen prices are expected to drop significantly during the next decade as more hydrogen will be produced and their price could drop near SAFs prices. By 2040 the expected price is around 2€ per kg of hydrogen fuel.

3.6.4 Current projects

Currently there are a few projects going on for the study & implementation of hydrogen-powered aircraft within the aviation industry. Airbus ZEROe, H2FLY, FlyZero and ZeroAvia are some interesting projects.

Fig. 3.23 Airbus ZEROe aircrafts concept [37]

Airbus ZEROe aircrafts project consists of three liquid hydrogen-powered aircrafts. These are turboprop, turbofan and blended-wing body aircrafts. The turboprop aircraft is powered by hybrid turboprop engines that will emit zero emissions, the capacity of the aircraft will be less than 100 passengers and range up to 1000 NM. The other two aircraft will be powered by two hybrid turbofan engines and will have a capacity of less than 200 passengers and range up to 2000 NM.

Fig. 3.24 FlyZero aircrafts concept [32]

The Flyzero project [30] is also composed of different aircrafts concepts. One regional concept with a capacity of 75 passengers, cruise speed of 325 kt and range of 800 NM. A narrowbody concept with a capacity of 180 passengers, cruise speed of 450 kt and range of 2400 NM. And a widebody concept with a capacity of 279 passengers, cruise speed of 473 kt and range of 5750 NM [32].

3.7 Nuclear-powered aircrafts

Nuclear technology is not a modern technology, in fact nuclear power has been under development since it was invented in the 1930s by Enrico Fermi. In the aeronautic sector however, the technology has been used to power several aircrafts such as the NB-36H in 1951 or the Tupolev Tu-95LAL in 1961 but the projects were cancelled due to the disadvantages produced by radiation. Nuclear power is still used to power rockets and satellites where the radiation cannot harm individuals.

There are two types of ways of using nuclear power, fission technology and fusion technology. Fission technology is the one used in the past for powering aircrafts and that is still used nowadays in the nuclear plants in order to generate electric energy. Fusion instead is supposed to be the future technology because the energy created using fusion is between 3-4 times greater than the energy released by fission, and 1 million times greater than a chemical reaction. Unlike fission, fusion technology does not produce radioactive nuclear waste and does not present any danger or produce a nuclear accident because it is not based on a chain reaction.

Fusion is the process by which a gas is heated up and separated into its ions and electrons, when the ions get hot enough, they can overcome their mutual repulsion and collide, fusing together. When this happens, they release a lot of energy. Lockheed claims [6] that a compact fusion reactor can be small enough to fit in an aircraft or a truck and provide enough energy to power up the plane for 1 year with unlimited range using only a few bottles of gas (hydrogen).

Supposedly, nowadays the most developed Compact Fusion Reactor (CFR) is the one developed by Lockheed Martin and whose project began in 2010 [6]. The first prototype was claimed to provide 100 MW of power and to have dimensions of 2.1m by 3m which theoretically is true that could fit inside a truck or conventional aircraft really. However, since 2015 several prototypes have been announced such as the T-4, the T-4B in 2016, the TX reactor and the T-5 in 2019. Each of them did increase in dimensions as they were made larger and also in weight (T-4B weight is 20 tons and T-X weight is 2000 tons). Besides, some reports claim that Lockheed Martin CFRs were not as powerful as expected with some of the prototypes proving only 1 MW instead of the 100 MW firstly announced.

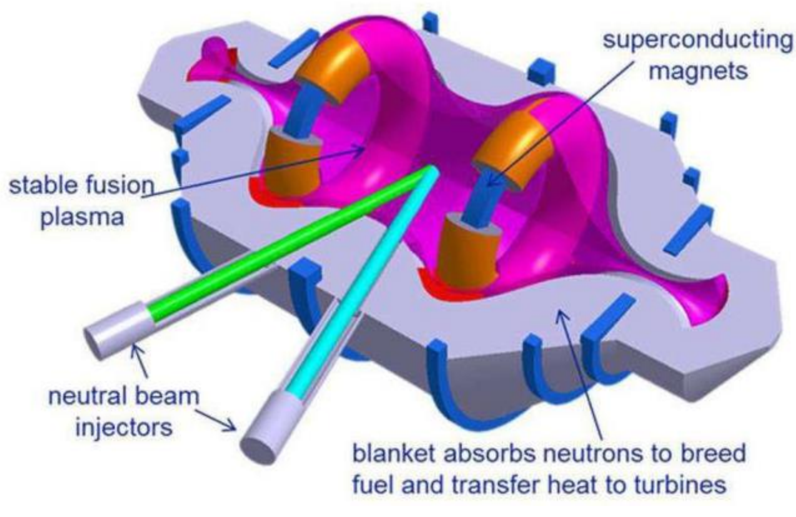

Fig. 3.25 Lockheed Martin CFR prototype design [6]

Fig. 3.26 Lockheed Martin first CFR prototype in a laboratory [6]

To make some comparisons, the A320ceo aircraft has an empty weight of 42.6 tonnes and when powered with two IAE-2500V engines, the power that the engines provide at 500 kts is around 50769 HP or 37.85 MW. If we compute the power-to-weight ratio of the aircraft, the A320ceo has a ratio of 0.889 kW/kg. Now considering we can allocate the T-4B reactor (which weighs 20 tons and provides 1 MW of power) inside the A320, if we compute the new power-to-weight ratio with the new total weight of 62.6 tonnes and 1 MW of power, the ratio is around 0.01597 kW/kg which is 55 times lower than the A320 powered by jet engines. So, we can arrive to the conclusion that nuclear-powered aircrafts are not feasible at the moment especially due to the CFRs high weight. Unless there is further development with more powerful CFRs variants that have reduced weight and can achieve power-to-weight ratios near 0.9 kW/kg, nuclear-powered aircraft are not realistic.

3.8 Electric plasma-powered aircraft

Plasma is a state of matter that contains charged particles (ions and electrons) and can be artificially created by heating a neutral gas (xenon, hydrogen, etc) or by applying a strong electromagnetic field to the neutral gas. Plasma propulsion engine is a type of electric propulsion where thrust is generated through “quasi-neutral” plasma and electric plasma powered vehicles are machines propelled by using plasma as their main energy source. Electric plasma propulsion is different from ion propulsion or ion thrusters, ion engines operate by extracting ion current from an accelerated plasma source performing at high velocities.

In 2020 a study in the Wuhan University of China developed a device that doesn't use a noble gas to create plasma instead they use ionized compressed air with the help of electrodes to create “low temperature plasma” in a tube. The quartz tube where the plasma is ubicated is also connected to another waveguide tube that is carrying magnetron generated microwaves. When the plasma and the microwaves collide, the plasma is bombarded with the microwaves inducing the violent shaking of the charged ions (oscillation of the ions) releasing energy and heating up to 1000 ºC and thus creating THRUST. The device was called “microwave air plasma jet thruster”.

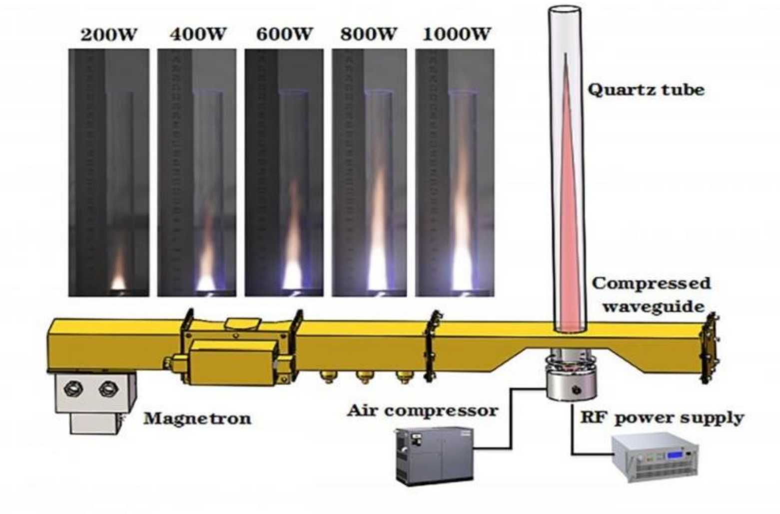

Fig. 3.27 Schematic diagram of the microwave air plasma jet thruster [36]

Moreover, some researchers say that the thrust produced in a small scale is quite good, but in a greater scale such as an aircraft due to the atmospheric friction the remaining thrust is not enough. But they are quite useful outside the atmosphere where the air friction is not a problem, in space NASA has been using electric plasma engines for some years.

Definitely, the electric plasma technology is still under development and it is not mature enough to jump to conclusions. Although theoretically they offer great advantages in space such as achieving high velocity near to 55 km/s, being simple and efficient they also have big drawbacks. Some challenges are to reduce the high energy requirements for producing thrust (which could be reached using CFRs), solve the plasma erosion problem and be capable of producing high thrust in the atmosphere.

Some engine prototype types that have been studied are helicon plasma thrusters, magnetoplasmadynamic thrusters, pulsed inductive thrusters, electrodeless plasma thrusters and VASIMR. The thrust that electric plasma engines produce in the atmosphere is around a couple of pounds (2 lbs) and some prototype engines need around 40 kW of power in order to produce 1 N of thrust. If more research and investment is made in electric plasma propulsion the technology will probably power future spacecrafts for long trips, but never commercial aircraft because electric plasma engines cannot perform air friction.

3.9 Comparison table

Characteristic	Jet Aircraft (A320)	SAF aircraft (A320)	Solar Aircraft (Solar Impulse II)	Electric Aircraft (Velis Electro)	Hydrogen Aircraft (FlyZero narrowbody)
Thrust-to-weight ratio	0.312	0.312	0.1182	0.177	0.259
Max engine temperature	1083 ºC	~1083 ºC	90 ºC	110 ºC	-
Aircraft max noise in EPNdB	91.79 - 100.69	~91.79 - ~100.69	-	60	Less than 90 EPNdB
Emissions	3.16 kg of CO_2	2.37 - 0.158 kg of CO_2	0 kg	0 kg	0 kg
Energy source & price	Jet A fuel 1.12587 € per L	SAF 2.62 - 2.99 € per L	Solar Light & Batteries 0 €	Batteries 0.22 - 0.40 € per kWh	LH2 12 - 17 € per kg
Energy source specific energy	43 MJ/kg	44-45 MJ/kg	260 Wh/kg	260 Wh/kg	142 MJ/kg
Energy source specific volume	33 MJ/L	30.5 - 34.5 MJ/L	270 Wh/L	270 Wh/L	10 MJ/L
Passengers' capacity	174	174	2	2	180
Max Range	6150 km	~6150 km	4522 km	200 km	4444 km
Max Speed	871 km/h	~871 km/h	140 km/h	181 km/h	833 km/h
Max altitude	39800 ft	~39800 ft	27900 ft	16000 ft	35000 ft
Year of introduction	Already introduced in 1988	Already introduced in 1988	Already introduced in 2015	Already introduced in 2020	Expected to be in 2035
Aircraft unitary cost	101 million of euros	101 million of euros	170 million of euros	185.000 €	-

Table 3.3 Comparison between future powered aircrafts and nowadays commercial aircrafts

Some important remarks:

1. Nuclear-powered aircrafts and electric plasma aircrafts are not compared in the table because they are not realistic for commercial aviation until further development.
2. The data involving the A320 is when powered with PW1000G engines.
3. The data in the table is current as of September 2022 and may change in the future.

The table 3.3 displays the comparison of different characteristics and aspects of jet engine aircrafts and future powered aircrafts. For commercial aviation, the most important fact is that new aircrafts should be able to at least achieve similar flight characteristics. Fuel economy is also important but at the present being sustainable is equivalent to spending more money on alternative fuels such as SAFs.

Looking at the table the only two alternatives for jet aircrafts that can achieve similar flight characteristics are aircrafts powered by SAF and hydrogen aircrafts. Comparing all the potential aircrafts, the thrust-to-weight ratio is the lowest for solar and electric powered aircrafts. The temperature of internal combustion engines such as jet engines is higher but for electric motors and propellers the engine temperature does not rise more than 110 ºC.

In terms of noise made by the aircrafts or engines, it happens the same as with the temperature, the noise contamination is higher in internal combustion engines and lower in electric aircrafts. In emissions jet engines are the worst while SAF powered aircrafts can reduce emissions by 98%, and hydrogen, solar and electric aircrafts do not produce CO_2.

Overall, electric and solar aircraft have worse specifications of passengers' capacity, range, maximum speed and specific energy. Besides, solar aircrafts projects have great costs and sometimes the cost is higher than narrowbody jets aircrafts. To conclude, energy source price is the aspect that differs from all the cases. Hydrogen is the most expensive fuel, while electricity for batteries is the cheapest and solar energy is free.

CONCLUSIONS

The main objective of the project was to study and analyse alternatives powered aircrafts to replace current commercial jet aeroplanes. The aviation sector globally contributes to 2.5% of the CO_2 emissions, in order to reduce pollution new sustainable technologies were evaluated. The potential powered aircrafts of the future that have been studied were hydrogen powered aircrafts, aircrafts powered by SAF, electric aircrafts, solar aircrafts, nuclear powered aircrafts and aircrafts powered by electric plasma.

For commercial aviation, future aircrafts need to fulfil some characteristics related with commercial flights nowadays. These requirements are similar flight speed, similar passengers' capacity, similar flight range and less or similar aircraft noise. Only hydrogen and SAF powered aircrafts fulfil the requirements.

It is expected that from today the first imminent alternative for jet aircrafts will be the same jet aircrafts but powered with SAF, and the use of SAF will probably grow during the years until 2050 as they can reduce up to 95% - 98% of the CO_2 emissions. Hydrogen aircraft are under development, they will not be able to arrive until 2035 and probably even later if the unitary cost of the new aircrafts is higher than expected and liquid hydrogen prices are not significantly reduced.

Electric and solar aircrafts are also under development, but some small aircrafts are already on the market. For commercial aviation with its current specifications, it is impossible that they will be used in a large scale unless there is a huge change in aviation where people start to use small electric aircrafts for transport as the cars are used nowadays. However, they could be used for very small routes involving small airports and small airdromes, an example can be flying from Andorra to Barcelona using the Velis Electro electric aircraft. Compared to the jet aircraft, SAF aircrafts and hydrogen aircrafts, it's clear that electric and solar aircrafts are slower, have less capacity and they cannot fly long distances. Their main problem is the batteries' shallow specific energy which restricts them from powering heavier and bigger aircrafts. Besides, solar arrays have a low efficiency problem, with current most advanced panels having only 40% efficiency.

For all the facts explained above, commercial aviation will evolve into using SAF in common commercial aircraft until 2050. Between 2030 - 2050 it will be possible that hydrogen prices will drop and new certified hydrogen commercial aircrafts will appear to be used as the new technology. Electric and solar aircrafts could appear in the late 2060s if the specific energy of the batteries is heavily increased or new materials are developed which can reduce even more the aircrafts weight.

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APPENDIX A. AIRCRAFT FUEL CONSUMPTION TABLE

Aircraft type	Fuel Consumption
An-2	131 kg/h
An-2P	140 kg/h
An-3T	200 kg/h
An-12	1983 kg/h
An-38-100	380 kg/h
An-24PB	800 kg/h
An-26	1087 kg/h
An-28	300 kg/h
An-30	900 kg/h
An-32	1229 kg/h
An-74	1800 kg/h
An-140-100	550 kg/h
An-148-100E	1650 kg/h
An-225	15900 kg/h
An-124-100	12600 kg/h
IL-18	2247 kg/h
IL-62	7300 kg/h
IL-62M	6600 kg/h
IL-86	10600 kg/h
IL-96-300	7300 kg/h
IL-96-400M	7500 kg/h
IL-76T	8262 kg/h
IL-114-100	590 kg/h
Yak-40	1240 kg/h
Yak-42D	3100 kg/h
Tu-104	6000 kg/h
Tu-134B	2500 kg/h
Tu-114	5300 kg/h
Tu-154B-2	6200 kg/h
Tu-154M	5300 kg/h
Tu-204-100	3460 kg/h
Tu-204-120	3420 kg/h
Tu-204-300	3250 kg/h
Sukhoi Superjet 100	1700 kg/h
L-410	314 kg/h
Fokker F27	500 kg/h
Fokker 100	2200 kg/h
Embraer EMB-120ER	390 kg/h
Embraer RJ145	1120 kg/h
Embraer E-170	1530 kg/h

Aircraft type	Fuel Consumption
Embraer E-175	1650 kg/h
Embraer E-190	1970 kg/h
Embraer E-195	1950 kg/h
De Havilland Comet 1	6000 kg/h
De Havilland Comet 4B	5200 kg/h
De Havilland Comet 4	4400 kg/h
De Havilland Comet 4C	4000 kg/h
Hawker-Siddeley Trident 2E	4400 kg/h
Hawker-Siddeley Trident 3B	4260 kg/h
Vickers VC-10	6530 kg/h
BAC One-Eleven 500	2800 kg/h
Sud-Aviation Caravelle 11R	2450 kg/h
Dassault Mercure	2700 kg/h
Concorde	20500 kg/h
BAe 146-200	1880 kg/h
BAe 146-300	1920 kg/h
British Aerospace ATP	800 kg/h
Jetstream J41	452 kg/h
Bombardier Dash 8-Q300	900 kg/h
Bombardier Dash 8-Q400NextGen	860 kg/h
Bombardier CRJ 200	1100 kg/h
Bombardier CRJ 700	1450 kg/h
Bombardier CRJ 900	1600 kg/h
Bombardier CRJ 900ER	1700 kg/h
Bombardier CRJ 1000	1740 kg/h
Bombardier CS300	2100 kg/h
Beechcraft 1900C	400 kg/h
ATR 42-320	450 kg/h
ATR 72-500	620 kg/h
Saab 2000	950 kg/h
Lockheed L-188A Electra	2000 kg/h
Lockheed L1011-500 Tristar	8000 kg/h
Convair 880	5600 kg/h
Convair 990	6300 kg/h
Convair 990A	5800 kg/h
Boeing 707-320	7200 kg/h
Boeing 707-420	6400 kg/h
Boeing 707-320B	5500 kg/h
Boeing 707-120B	5000 kg/h
Boeing 717-200	2200 kg/h
Boeing 727-100	4140 kg/h
Boeing 727-200	4500 kg/h
Boeing 727-200 Advanced	4860 kg/h
Boeing 737-100	2500 kg/h
Boeing 737-200	2800 kg/h

Aircraft type	Fuel Consumption
Boeing 737-300	2400 kg/h
Boeing 737-400	2600 kg/h
Boeing 737-500	2400 kg/h
Boeing 737-700	2420 kg/h
Boeing 737-800	2530 kg/h
Boeing 747-100	11800 kg/h
Boeing 747-300	11300 kg/h
Boeing 747-400	10230 kg/h
Boeing 747-8	9600 kg/h
Boeing 757-200	3320 kg/h
Boeing 777-200	6080 kg/h
Boeing 777-200ER	6630 kg/h
Boeing 777-200LR	6800 kg/h
Boeing 777-300ER	7500 kg/h
Boeing 767-200	4500 kg/h
Boeing 767-300	4800 kg/h
Boeing 767-300ER	4940 kg/h
Boeing 787-8	4900 kg/h
Boeing 787-9	5600 kg/h
DC-8-61	5900 kg/h
DC-8-62	5300 kg/h
DC-8-63	5400 kg/h
DC-8-73	4880 kg/h
DC-9-20	2500 kg/h
DC-9-40	2900 kg/h
MD-83	3060 kg/h
MD-90	2800 kg/h
DC-10-10 Domestic	6940 kg/h
DC-10-20	8140 kg/h
DC-10-30	8300 kg/h
MD-11	7650 kg/h
Airbus A300	4770 kg/h
Airbus A319-100	2374 kg/h
Airbus A320	2430 kg/h
Airbus A320neo	2066 kg/h
Airbus A321-100	2885 kg/h
Airbus A321-231	2740 kg/h
Airbus A330-200	5590 kg/h
Airbus A330-300	5700 kg/h
Airbus A340-300	6500 kg/h
Airbus A340-500	8000 kg/h
Airbus A350-900	5800 kg/h
Airbus A380	12000 kg/h