# Life Cycle Assessment of Hybrid-Electric Conceptual Aircraft using Biofuels

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**Abstract**

The aviation sector has grown significantly in recent years. This growth has made aviation one of the sectors responsible for the significant increase in pollutants emitted into the atmosphere in recent years. In order to reduce pollutant emissions in this sector, alternatives that are viable from an environmental and financial point of view have been sought. One of the alternatives explored in this work is the use of biofuels based on biomass. The use of the biofuel produced using the HEFA process, based on jatropha, has been shown to have less environmental impacts in relation to fossil fuel, more precisely due to the less significant use of resources for its production. On the other hand, the use of biofuel has shown concerns regarding human health, mainly due to the particulate matter emissions. Another field explored in this work is the change in the propulsion system, where a design methodology based on the conventional methodology was used to obtain hybrid-electric aircraft, since the electric propulsion system is not yet viable for aviation, due to the reduced energy capacity of battery cells. Batteries and fuels were subjected to life cycle assessment in order to quantify their emissions taking into account the stages of production, use and end of life.

**Keywords:** biofuels, propulsion system, lithium-sulfur (Li-S) batteries, lithium-air (Li-O2) batteries, life cycle assessment

## 1. Introduction

The commercial aviation sector is one of the sectors that has grown the most over the years. In 2019 the growth in the number of flights worldwide was 63 % compared to 2004, and an average annual growth of 4.3 % is expected between the years 2019 and 2038 [1, 2]..

On the one hand, this explosive growth in the aviation sector causes the economy to grow, but on the other hand, public health and the well-being of society are profoundly affected due to the increase: (1) in noise near the airport; (2) of particulate matter emissions that can enter the airways; (3) air pollution by toxic substances and emissions of gases into the atmosphere, mainly greenhouse gases, which would result in the warming of the planet. In 2009, international negotiations on climate change were held in Copenhagen with the aim at finding solutions to reduce the speed of global warming. The goal is to keep the planet warming with growth below 2 ° C, compared to the pre-industrial era, because if the warming is not stopped it will have implications that include food and water shortages, melting of polar caps of the north pole, changes in climatic patterns and even extinction of some species of animals among other catastrophic effects [3, 4, 5, 6].

Climate change is caused by greenhouse gases, the main one being carbon dioxide ($CO_2$). According to the IPCC (Intergovernmental Panel of Climate Change), annual anthropogenic emissions of greenhouse gases grew by around 81% in the period from 1970 to 2010, with carbon dioxide representing around 77% of all man-made greenhouse gases in the above range [7, 8].

What was found by the IPCC is directly reflected in aviation, and during the flight path, among the pollutants emitted, carbon dioxide stands out again, with around 71% [9]. Efforts have been made to reduce the use of energy sources that produce a high amount of polluting gases into the atmosphere. Some alternatives have been proposed and are being developed to reduce dependence on fossil fuel for aviation. Among them are biofuels, fuel cells, liquid hydrogen and electric propulsion. For this work, biofuels and electric propulsion alternatives will be studied.

The International Energy Agency (IEA) estimates that in 2050 biofuels will account for 27% of the fuel used in aviation compared to the 2% used in 2011 [10].

The use of electric propulsion is limited to the specific low energy of the battery cells, but the combination of electricity and fuels can guarantee results that help to meet goals imposed by competent entities such as NASA, to reduce noise by 55dB, 75% of NOx emissions and 70% in fuel consumption in 2030 compared to 2006 [11].

## 2. Background

### 2.1. Biofuels

Biofuels are certified by ASTM (American Society for Testing and Materials) according to two regulatory standards: ASTM D4054 (Standard practice for evaluating new fuels for aviation turbines and fuel additives) and ASTM D7566 (Standard specification for fuel aviation turbine containing synthesized hydrocarbons) [12]. Biofuels can be produced from coal, natural gas and biomass, with only the last raw material considered a renewable source. Renewable sources have advantages over non-renewable sources due to their sustainability, increased local economy due to less dependence on foreign oil, carbon recycling, in addition to environmental benefits at the expense of using non-renewable sources [13, 14].

The certification of biofuels does not depend on the characteristics of the fuel itself, but on the production process used. According to the Commercial Aviation Alternatives Fuels Initiative (CAAFI) there are 7 certified processes for the production of biofuels [15]. Due to the difference in lubrication and cetane number compared to fossil jet fuel, biofuels must be mixed with conventional fuel in order to solve the fuel ignition problem [16]. The processes certified by ASTM are the following: Fischer-Tropsch Synthetic Paraffinic Kerosene (FT-SPK), Hydroprocessed Fatty Acid Esters and Free Fatty Acid Synthetic Paraffinic Kerosene (HEFA-SPK), Hydroprocessing of Fermented Sugars - Synthetic Iso-Paraffinic kerosene (HFS –SIP), Fischer-Tropsch Synthetic Paraffinic Kerosene plus aromatics (FT-SPK/A), Alcohol-to-Jet- Synthetic Paraffinic Kerosene (ATJ-SPK), Catalytic Hydrothermolysis Synthesized Kerosene (CH-SK, or CHJ), Hydroprocessed Hydrocarbons Esters and Fatty Acids Synthetic Paraffinic Kerosene (HHC-SPK or HC-HEFA-SPK).These processes maximum mixing percentage and year of certification are listed in Table 1.

Table 1: Certified processes for the production of biofuels, data from: [12, 17, 18, 15, 18]

| Process | certification year | max % of mixing |
|---|---|---|
| FT-SPK | 2009 | 50 |
| HEFA-SPK | 2011 | 50 |
| HFS–SIP | 2014 | 10 |
| FT-SPK/A | 2015 | 50 |
| ATJ-SPK | 2016 | 50 |
| CH-SK, or CHJ | 2020 | 50 |
| HHC-SPK or HC-HEFA-SPK | 2020 | 10 |

In addition to these certified processes, there are still others in the process of certification. Among the certified processes, the one that currently dominates the aviation biofuels market is the HEFA process [12]. The HEFA process is less complex because it uses the results of biosynthesis carried out by nature, whereas for other processes, organic matter is first destroyed and re-synthesized to meet the required standard. The raw materials for fuel production via HEFA can be found and grown without spending a lot of resources. The hydroprocessing process can be included in oil refineries, which gives it even more advantages, in addition to having greater maturity and yield compared to other processes [19]. The maturity classification of some of the processes mentioned above was presented by *Prussi et al* [12] in two categories: Technology Readiness Level (TRL) and Fuel Readiness Level (FRL), see Table 2. The maximum value of TRL and FRL is 9, which has only been reached by HEFA process.

Table 2: Maturity levels, [12]

| Process | TRL | FRL |
|---|---|---|
| FT-SPK | 6 – 8 | 6 – 7 |
| HEFA-SPK | 9 | 9 |
| HFS–SIP | 7 – 8 | 5 – 7 |
| FT-SPK/A | 6 – 8 | 6 – 7 |
| ATJ-SPK | 7 – 8 | 7 |

### 2.2. Propulsive System

The propulsive system is responsible for providing the aircraft with the necessary force to overcome aerodynamic drag. In conventional aircraft, this force is obtained from to the combustion of fossil fuel inside the engine. The conventional propulsive system has a very low conversion efficiency, in the range between 24 to 50% [20], in addition to emitting a large amount of pollutants into the atmosphere, contributing to climate change.

In addition to the conventional propulsion system, there is also: (1) the fully electric propulsion system, which only uses batteries as a source of energy to power the electric motor; (2) the hybrid-electric propulsion system that uses fuel and batteries as a source of energy to power; and (3) the turbo-electric propulsion system that makes use of the electric motor powered by electricity from a generator, but the power source is the same as the conventional configuration.

Due to the low specific energy density of current batteries, the use of a fully-electric system would be carried out at the expense of loss of performance, namely in terms of range, speed and payload. The application of the fully-electric system is currently applied to VLAs (Very Light Aeroplanes) with MTOW (Maximum Take-Off Weight) not exceeding 750 kg, and UAVs (Unmanned Aerial Vehicles) [21].

In order to reduce the loss of performance and allow the applicability of electric propulsion in larger aircraft, the hybrid electric propulsion system is used, making use of electric motors with high efficiency, and fuels with high specific energy densities.

The electrification problem, in addition to having the specific low energy density barrier, still has other problems that delay its acceptance in the market, namely the fast discharge time, long charging time and thermal instability [20].

The propulsion system applied to the aircraft used in this work will be the hybrid-electric. The hybrid-electric propulsion can be divided into three architectures: (1) hybrid-series; (2) hybrid-parallel; and (3) hybrid series-parallel which is a combination of the previous two. Figures 1 and 2 show how the hybrid series and parallel hybrid architectures are formed.

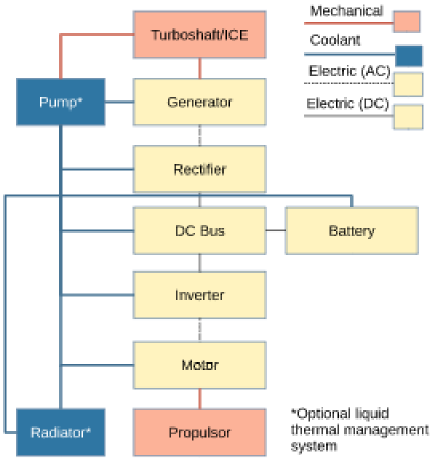

Figure 1: Hybrid serie arquitecture, [11]

The hybrid-series architecture for having the ICE (Internal Combustion Engine) motor mechanically decoupled from the electric motor, its rotation speed is independent of the electric motor, which implies a more simplified control of the ICE motor, which can work at its ideal speed, saving fuel. Mechanical decoupling makes this architecture more flexible than the parallel hybrid. However because of mechanical decoupling, the potential of combining electric and ICEs is not taken advantage of. The system is equipped with three energy conversions, which makes the loss of efficiency greater. And by adding three devices for generating propulsion, the weight of the propulsive system is higher when compared [22, 23].

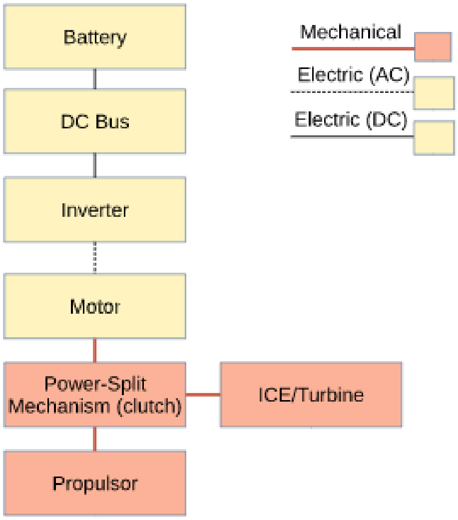

Figure 2: Hybrid parallel arquitecture, [11]

The hybrid-parallel architecture provides a propulsive system and consequently the aircraft weighs less than the series architecture, as it has only two propulsion generation devices. The parallel architecture, having fewer conversions, had greater efficiency than the series. The mechanical coupling between the engines allows the propulsive potential to be harnessed, without the need for highly powerful engines. Mechanical coupling, in turn, will require complex control between them so that they can work at their optimal speeds [22, 24].

### 2.3. Batteries

The battery is an energy storage device, also known as an electrochemical device, which converts electrical energy into chemical energy during the charging process, and subsequently transforms the stored chemical energy into electrical energy for final use.

Currently, the most important rechargeable batteries are: lead acid, lithium ions, nickel metal hydride (NiMH) and nickel-cadmium (NiCd) [25]. Their respective specific energies can be found in Figure 3.

Among the batteries mentioned above, those that are in a process of greater technological maturity are lithium-ion batteries, having their application in several sectors, mainly in the electronics industry.

On the one hand lithium is not toxic, it is light and electropositive, but on the other hand it is highly reactive, which makes it difficult to build battery cells. The solution found was to use com-

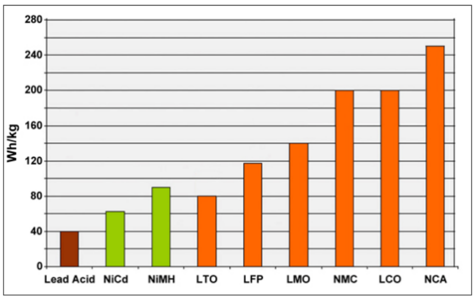

Figure 3: Specific energy of current batteries. Brown: lead-acid, Green: nickel-based batteries, orange: lithium-ion, [26]

pounds that are capable of donating lithium ions [25].

The state of the art of today's batteries allows for electrification of the aviation sector to happen, but only for small aircraft. For civil aviation, the state of the art is still insufficient to meet the fundamental requirements for commercial aviation [11].

Advances in materials for the cathode, anode and electrolyte can double the specific energy of lithium ions, thus reaching, in 15 and 30 years, a specific energy of at most between 400 and 450 Wh/kg, respectively [27].

Solutions have been studied and tested in laboratories in order to develop batteries with an energy capacity similar to fossil fuels, and that are economically and ecologically viable. Some examples of these batteries in development are: lithium-air (Li-air), lithium-metal, lithium in solid state, lithium-sulfur (Li-S), sodium ions (Na-ion), Aluminum-air (Al – air), magnesium-air (Mg – air), Zinc-air (Zn – air), and flow batteries [28, 29].

### 2.3.1 Lithium-sulfur (Li-S) batteries

Sulfur has a high specific capacity, 1625 mAh/g, which allows it to have a high theoretical specific energy, ranging from 2000 to 2600 Wh/kg [29, 30]. Because of the additional weight of the battery components, this theoretical energy is not achieved, and only a small part of this theoretical value can be used.

Sulfur for being a non-toxic chemical component, because it exists in large quantities in nature and has an affordable price, presents itself as one of the battery technologies to be promising in the not too distant future.

During the chemical reaction between lithium and sulfur, in addition to the formation of $Li_2S$, substances such as $Li_2S_8$, $Li_2S_6$, $Li_2S_4$ are also formed, which are soluble in most organic electrolyte solutions. This phenomenon can lead to the loss of sulfur from the electrode, which leads to a loss of capacity after each cycle [30].

With the improvement of the battery components, it is possible to achieve specific energies varying between 500 to 600 Wh/kg and 800 to 950 Wh/kg in 2030 and 2050, respectively [27].

### 2.3.2 Lithium-air batteries

Lithium-air batteries are also known as lithium-oxygen batteries (Li-air / $O_2$). It is one of the batteries to be designed for the not too distant future. The high capacity of the battery cells, 3861.3 mAh/g [31], allows it to have a specific theoretical energy ranging from 3000 to 3500 Wh/kg [29, 32].

Currently the technology is limited by the number of life cycles, since the battery capacity decreases after 50 cycles of charge and discharge [31].

According to NASA if the development of $(Li-air/O_2)$ cell technology happens as expected, forecasts for 10 and 25 years from now point to specific energies ranging from 600 to 700 Wh/kg and 1200 to 1400 Wh/kg respectively [27].

Both Li-S and $(Li-air/O_2)$ batteries will be employed in this work to provide part of the energy to be used in the hybrid-electric propulsive system, with specific energies of 500 and 1200 Wh/kg respectively for the 2030 and 2050 forecasts respectively.

## 3. Implementation

### 3.1. Hybrid-eletric propulsive system

The hybrid electric propulsion system, which is a different concept from the conventional one, is obtained based on the conventional propulsion system. From the conventional methodology, it is possible to obtain some parameters that will serve as the basis for the new concept. With the application of the conventional propulsive system, it is possible to estimate the weight of the aircraft before take-off, and through the design point, it is possible to determine the power/thrust of the engine, and the wing area of the aircraft. These parameters may not be the same for the new conceptual design, but these values serve as a reference. For the case of this project, the weight of the aircraft and its geometry will be kept constant.

The methodology developed and applied in this work is described in Figure 4, where $W_{to}$ is the weight of the aircraft before take-off, $W_{fuel}$ is the total weight of the fuel needed for the flight, $W_{bat}$ the weight of the batteries, $AEW$ is the available empty weight, $REW$ is the required empty weight, P and T the power and thrust of the engine respectively, $E$ and $e$ the specific energy and energy respectively, $\phi$ the degree of energy hybridization, and $R$ the range.

When the conventional methodology is applied, values are obtained for some variables that are im-

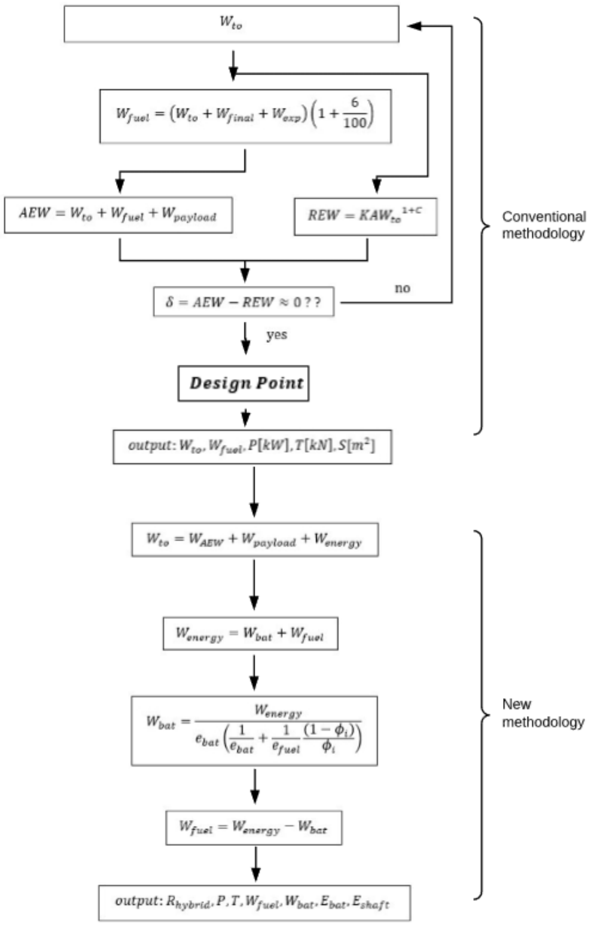

Figure 4: Methodology for the design of an aircraft

portant for the implementation of the new methodology, such as the cases of $W_{to}$ and $W_{AEW}$ that remain constant in the new methodology. The weight of the propulsion system is distributed between fuels and batteries. The weight of the batteries is related to the weight of the propulsion system ($W_{energy}$), taking into account the degree of energy hybridization ($\phi$) and the specific energies of the power generation sources. Knowing the weight of the batteries, we automatically know the weight of the fuels, and based on these two variables it is possible to determine the energy spent in each of the phases of the flight, and consequently the power or the strength of the engine. Based on the masses and energies spent during the trip and the applied hybridization, the aircraft's range is determined.

## 3.2. Life Cycle assessment

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

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

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

### 3.2.1 Goal and scope definition

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

The application will be made taking into account the steps from the cradle to the grave, and also from the cradle to the end of production (cradle to gate), see Figure 5.

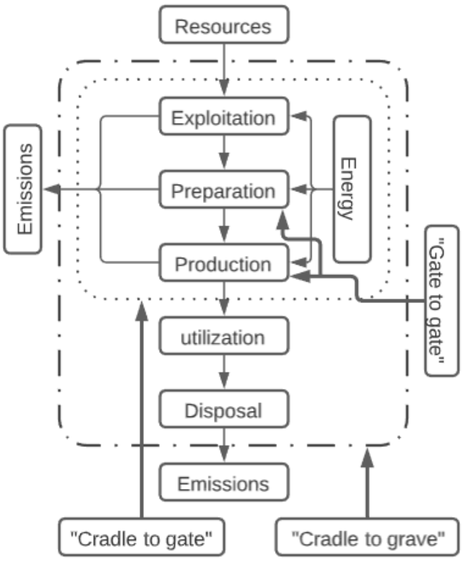

Figure 5: Definition of system boundaries for products. Based on [33].

For the sake of uniformity and standardization, in order to facilitate the understanding of the results obtained from the application of the LCA tool, the functional units will be as follows: $kg$ for mass and $kW.h$ for energy.

Table 3: Some Midpoints and Endpoints from Recipe

| Midpoints | Endpoints |
|---|---|
| Ozone depletion | Hh |
| Particulate matter formation | |
| Acidification | Eq |
| Eutrophication | |
| Depletion of metals and minerals | R |
| Depletion of fossil fuel | |
| Climate Change | Hh, Eq |
| Water scarity | Hh, Eq, R |

### 3.2.2 Invetory Analysis

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

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

### 3.2.3 Impact category

This is characterized by the classification and characterization of the environmental impacts caused by the product or service. In this phase, the inputs and outputs listed in the previous phase are distributed and quantified by impact categories.

The application of LCA is made using suitable methods for this. The main difference between these methods is related to the impact categories. Examples of some of these methods are: Eco-indicator 99, EPS 2000, IMPACT 2002+, EDIP 2003, ReCiPe, ILCD 2011 Midpoint, Product Environmental Footprint, among others.

The method to be applied in this dissertation for the assessment of impacts will be ReCiPe.

ReCiPe is a method that covers the environmental impacts of the midpoint and endpoint levels. Midpoint levels encompass all the impact categories in detail, while the endpoint levels regroups the impacts listed in the midpoint levels in 3 impact categories: Human health (Hh), Ecosystem quality (Eq) and Resources (Rs). Examples of some categories at midipoint and endpoint level can be seen in Table 3.

There are three scenarios or perspectives within the ReCiPe method. The first is the individualistic perspective, which is based on short-term interests, approximately 20 years; the second is the hierarchical perspective based on scientific consensus, the evaluation is made considering a period of approximately 100 years, and finally the egalitarian perspective, the interest in the result is over the long term, approximately 1000 years [34]. For the application and obtaining of the emission results caused by the processes that are part of a product's useful life, the hierarchical perspective will be used.

### 3.2.4 Interpretation

The interpretation phase is used to analyze the results obtained in the previous phase, taking into account the initial objective, in order to reach conclusions and determine the limitations and recommendations regarding the application of the study tool, the life cycle assessment.

## 4. Results

The 4 chapter is divided into two parts of the income statement.

The results demonstration of the first part is related to the application of the methodology to obtain hybrid-electric aircraft.

The second has to do with the life cycle analysis of the components that provide energy to the aircraft.

### 4.1. Hybrid-electric aircraft

Based on the results obtained from the application of the conventional methodology, namely the maximum weight before take-off, the total mass of fuels during the route, and among others, the new methodology was applied to design hybrid-electric aircraft.

### 4.1.1 Cirrus SR22T hybrid-electric aircraft

Hybridization is a factor that is linked to loss of performance in some of the parameters, and performance gain in others. In the case of this aircraft, hybridization was achieved at the expense of reducing a passenger for both scenarios, 2030 and 205. This means that higher degrees of hybridization can be achieved, and consequently a reduction in greenhouse gas emissions ( See Figure 6, and 7).

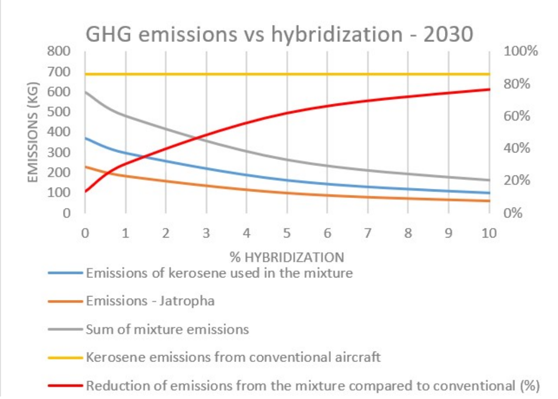

Figure 6: Variation of GHG emissions in relation to hybridization

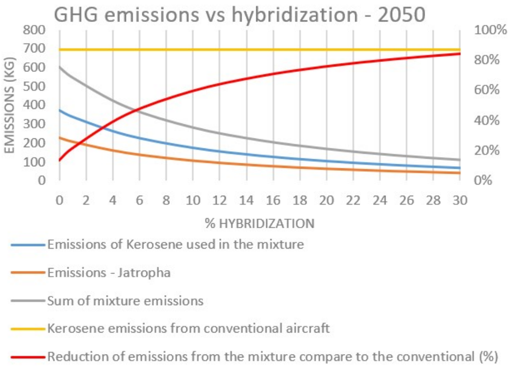

Figure 7: Variation of GHG emissions in relation to hybridization

In order to have a better relationship between the fuel saved, the range, and the number of passengers, 10 % and 25 % hybridization was chosen for the years 2030 and 2050, respectively. This application causes fuel reduction compared to the reference aircraft to be 47 % and 55 % for the years 2030 and 2050, respectively.

### 4.1.2 A320neo hybrid-electric aircraft

The Airbus A320neo is a large, long-range aircraft. Hybridization of this aircraft to an acceptable degree is a difficult requirement to meet due to current battery technologies and even those projected 30 years from now are still of low energy density to meet the energy demand required for a large aircraft.

The choice of the degree of hybridization to be applied was made taking into account the losses in the number of passengers, the range, and the fuel savings. Figures 8 and 9, show the relationship between the variables in question, for the 2030 scenario.

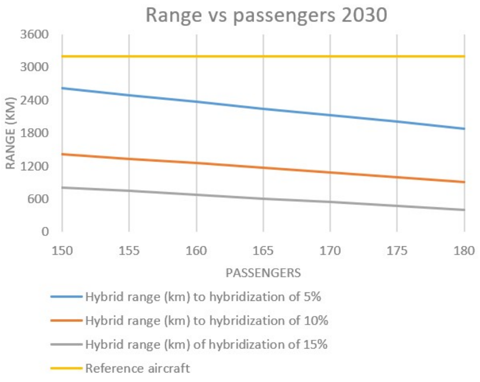

Figure 8: Range variation concerning the number of passengers, taking hybridization into account

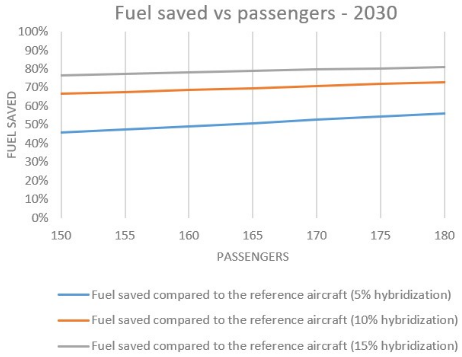

Figure 9: Variation of fuel-saving concerning the number of passengers, taking hybridization into account

By analyzing the relationship between performance, it was concluded that the best relationship between the number of passengers, reach and fuel savings are achieved with 5 % and 150 passengers for the year 2030, and 10 % and 165 passengers for the year 2050. This choice allows the fuel saved to be in the proportion of 45 % and 47 % for the years 2030 and 2050, respectively.

### 4.2. Life Cycle assessment

The life cycle assessment was applied to batteries, biofuel, and fossil fuel. They were subjected to three analyzes, emphasizing comparisons with each other in order to better study the ecological viability of alternative systems that have been proposed with the aim of reducing emissions caused by the aviation sector.

The first analysis takes into account only fossil fuel and biofuel in order to study which would be the best option from an environmental point of view.

The second analysis is done in order to study the emission behavior of the battery cells. And finally, the last analysis is a study of all components and their quantification in terms of emissions.

The summary of emissions in proportions for the 2030 scenario year can be found in Table ref conclusion.

Table 4: Life cycle assessment. Proportional emissions

| | A320neo - 2030 | | |
|---|---|---|---|
| | Bat 5093 kWh | Q | J |
| C-Ga (%) | 0.73 | 62 | 37.27 |
| C-Gr (%) | 8.00 | 54.57 | 37.43 |
| | SR22T - 2030 | | |
| | Bat 74 kWh | Q | J |
| C-Ga (%) | 1.53 | 61.45 | 37.02 |
| C-Gr (%) | 18.62 | 50.14 | 31.21 |

Emissions from fossil fuel were more important, mainly due to the impact category, resources, since large amounts of resources are needed to be able to extract fossil fuel from its habitat. On the other hand, biofuels showed a higher proportion of emissions in the human health category, mainly due to the emissions of particulate materials being emitted in more than double the proportion of biofuel compared to fossil fuel.

## 5. Conclusions

The first part of the study showed that if battery technologies evolve as expected, such that in 2030 and 2050 we have batteries with capacities identical to the one used in this work, then civil aviation electrification will be an alternative to be implemented in the future not too far.

The results of the application of life cycle assessment imply that batteries and biofuels generally emit fewer pollutants than fossil fuel. But it must be borne in mind that emissions from battery disposal have not been accounted for and that there is also a great need to adapt the propulsion system to work with biofuels, in order to reduce particulate matter emissions.

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