PLANNING REPORT

Life Cycle Assessment of a Hybrid Electric Aeroplane

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1 Introduction

Emissions from the aviation industry has been, with some minor setbacks during for instance the financial crises and the Covid-19 pandemic, increasing steadily since the beginning of air travel (Ellerbeck, 2022). Right before the pandemic carbon emissions from aviation accounted for around 2.5% of the worlds total carbon emissions (Ritchie, 2020), and though this figure might not seem very high at first glance, there are predictions that the demand for flying will continue to increase and could potentially cause the greenhouse gas emissions from aviation to triple by the year of 2050 (Ellerbeck, 2022). To combat this, the aviation industry, through the United Nations International Civil Aviation Organization (ICAO), has set up a target to reach net zero carbon emissions by the year 2050 (Ellerbeck, 2022). This is proposed to become a reality through three main focus areas: implementation of sustainable aviation fuel, streamlining the aviation industry, and focusing on new green technologies (Ellerbeck, 2022).

When it comes to new technologies there are mainly three that are investigated in various maturity states; hydrogen-powered aircraft using (i) fuel cell electric technologies or (ii) combustion, and (iii) battery-electric propulsion. There are estimates claiming that these technologies could be feasible for flights of up to 2500 nautical miles and development of these technologies could therefore have the potential to lower the emissions from flying considerably since short-haul flights of 600 nautical miles or less accounts for more than 17% of all airline emissions (Ellerbeck, 2022). The large aeroplane producer Airbus is pursuing hydrogen propulsion and aims to develop "the world's first hydrogen-powered commercial aeroplane" (Airbus, 2023). With their "ZEROe" project, they investigate various configurations of a hydrogen propulsion which could potentially replace conventional jet fueled aeroplanes (Airbus, 2023). A company that might not be as well established as Airbus, but still has drawn a lot of attention and made great progress in sustainable aviation, is Heart Aerospace. With their small commercial aeroplane ES-30, which will be the main focus in this study, they aim to revolutionise air travel with an hybrid electric drive-train with a reserve turbo generator that can serve as a range extender (Heart Aerospace, 2023). This will deliver a fully electric range of up to 200km and 400km with the help of the reserve turbo generator.

1.1 Aeroplane Structure

This section aims to provide some background information of the structure of an aeroplane and important terminology that will be used throughout the report. The ES-30 will structure wise look like any turboprop aeroplane on the market, with some slight design changes due to, for instance, the battery pack. Figure 1 shows an exploded view of the aeroplane's structure and highlights some of its key components. The blue parts all make up the wing structure, the white parts the fuselage and the green parts the tail of the aeroplane. When it comes to the drive-train there are different approaches to construct a hybrid-electric drive-train.

Section 1.1.1 and 1.1.2 will describe two common system architectures of an hybrid-electric drive-train.

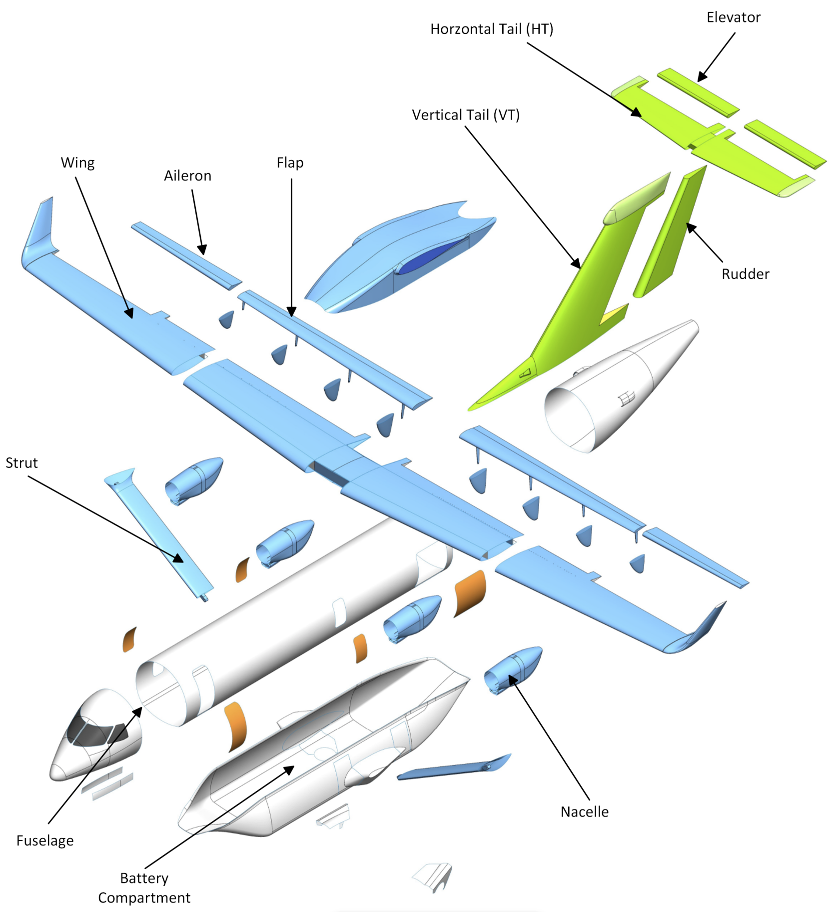

Figure 1: Exploded conceptual view of the ES-30 with key components highlighted. Provided by Heart Aerospace with permission with permission, modified by the authors.

1.1.1 Series Hybrid System

There are several architectures discussed in the literature concerning the design of the energy-storage and propulsion systems of an hybrid electric aeroplane. One of them is the series hybrid architecture, depicted in Figure 2. In this system, there are no mechanical connections between the combustion engine and the propellers - the only function of the combustion engine is to generate electricity, which in turn either charges the on-board batteries or drive the electric motors (Rendón et al., 2021). Thanks to the combustion engine not being mechanically coupled to the propellers, it can constantly run at optimal performance concerning power and speed and overall enables a simple system design (Rendón et al., 2021). One drawback of the series hybrid system is that the energy conversion efficiency from liquid energy carriers to electric energy is lower as compared to the engine directly providing mechanical energy to the propeller (Rendón et al., 2021). Another drawback is that the electric motors need to supply the entire propulsion system with power which will require large and heavy motors (Rendón et al., 2021).

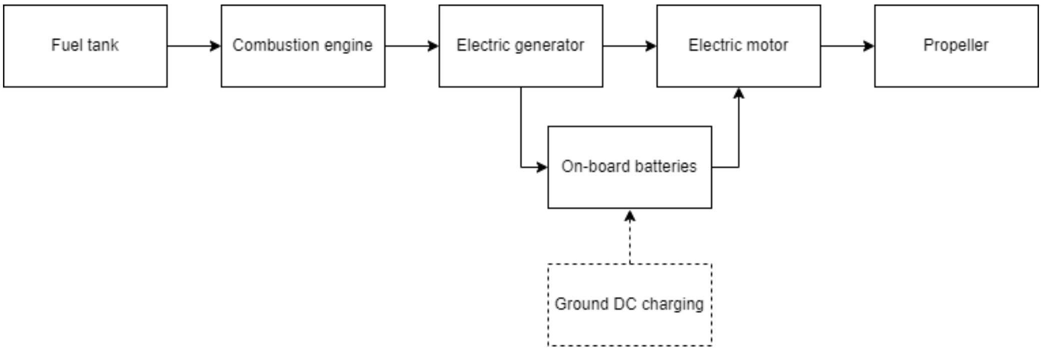

Figure 2: Aeroplane series hybrid architecture. Authors' own figure.

1.1.2 Parallel Hybrid System

The parallel hybrid architecture is depicted in Figure 3. In this system, there is a mechanical coupling both between the combustion engine and electric motor to the propeller of the aeroplane (Rendón et al., 2021). This gives the aeroplane the possibility of generating propulsion from either the electric motor, the combustion engine or both sources simultaneously (Rendón et al., 2021). It is also possible to charge the on-board batteries using the combustion engine, by running the engine that in turn drives the electric motor which acts as a generator (Rendón et al., 2021). One of the main advantages of the parallel hybrid is that there is not as much energy losses during the conversion from liquid fuel to mechanical energy as there is from adding the step of converting the mechanical energy to electricity through a generator (Rendón et al., 2021). Since this setting eliminates the need for an electric generator and adds the ability for propulsion from dual sources, the electric motor and combustion engine can be designed smaller, which gives an overall decrease in weight (Rendón et al., 2021). However, there is a need for extra weight in the form of the mechanical coupling system and the complexity of the propulsion system is increased (Rendón et al., 2021).

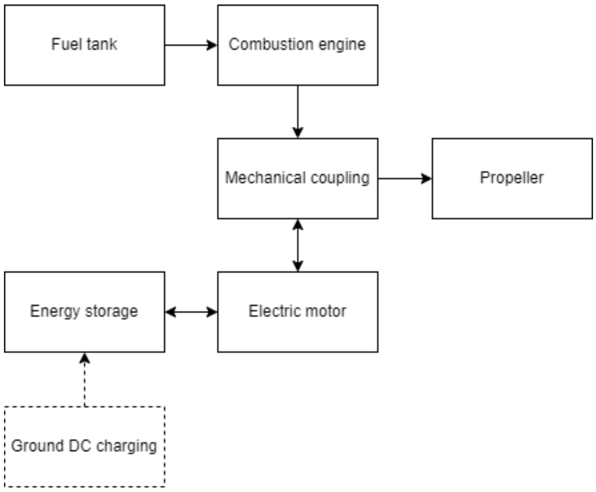

Figure 3: Aeroplane parallel hybrid architecture. Authors' own figure.

1.1.3 Hybrid Architecture Comparison

An overall comparison of the two hybrid systems is summarised in Table 1. As shown in the table, both systems come with advantages and disadvantages and there is no clear best alternative. A multitude of factors, such as mission length, aeroplane regulations, market needs and overall sustainability performance will influence an aeroplane manufacturer in their choice of hybrid architecture.

Table 1: Series versus parallel hybrid architecture (Rendón et al., 2021).

Series	**Parallel**
+ Simple propulsion system	- Sophisticated propulsion system
- Larger electric motor	+ Smaller electric motor
+ Optimised ICE operation	- Suboptimal ICE operation
- Electric generator required	+ No electric generator required
+ Two independent energy sources	- Energy sources closely coupled

1.2 Aim & Research Questions

The aim of this thesis is to assess the potential environmental impacts of a hybrid-electric passenger aeroplane that is set to enter the market in the end of the 2020s. The particular aeroplane under study, the ES-30, will have a capacity to accommodate 30 passengers, two pilots and one flight attendant as well as their respective luggage. To assess the environmental impacts, an attributional cradle-to-grave life cycle assessment (LCA) of the aeroplane will be conducted. By using this approach, all parts of the aeroplane life cycle will be considered, including the extraction of raw-materials, product manufacturing, use and waste management at the end-of-life of the aeroplane. The attributional LCA method accounts for the linear environmental impacts stemming from the physical inputs and outputs of a systems life cycle (Finnveden et al., 2009). The results from this study will be compared to the environmental impacts from a similar aeroplane with a traditional non-electric drive-train to understand if and how the environmental impacts differ between the two aeroplanes. The comparable aeroplane will be similar in size and capacity, but with a longer operating range compared to the ES-30 since it is not hybrid-electric. The following research questions will be investigated in the thesis:

- What are the environmental impacts of the hybrid-electric aeroplane?
- Which parts of the life cycle have the largest impact?
- What components of the aeroplane have the largest impact?
- Does the environmental impacts from a non-electric drive-train aeroplane differ from a hybrid-electric one?

1.3 Limitations of the thesis

Since the type of aeroplane studied in this thesis does not yet exist, there will be limitations on the availability of data from all stages of the product life cycle. This will therefore require the use of data from a variety of sources, such as simulations, interviews with experts in the field, potential suppliers, LCA databases and results from similar life cycle assessments. The LCA database Ecoinvent will be used, but comes with limitations, such as the availability of data relevant for the future concerning, e.g., energy mixes, resulting in a limited temporal accuracy.

1.4 Assumptions

Since there are several limitations on the availability of data, there will be a need for assumptions in the study. Since the exact propulsion components and specific suppliers are not yet determined, there will be a lack of specific data. This means that in the modelling of the system, many of the components might be modelled by scaling up existing, well specified components from, for instance, the automotive industry. A key assumption concerns the choice of hybrid architecture, the design of the propulsion system which for the aeroplane under study it is not yet determined. The focus of this study will be on a series hybrid architecture (as described in section 1.1.1) since the modelling of flight data, such as fuel consumption and efficiencies, are substantially easier given the lower complexity of that system.

2 Method

In the following chapter, the method applied in the study is presented. The section will also explain the rationale behind its application to this particular study.

2.1 Literature Review

Due to the complicated nature of performing an LCA of an entire aeroplane where a lot of parameters are unknown or uncertain, a literature review will be conducted as a first step. This to investigate the existence of similar work that could be useful to fill data gaps. Furthermore, it could be of interest to investigate reports of, for instance, fuel consumption of traditional aeroplanes of similar size as the investigated model to be able to create scenarios on how the hybrid electric aeroplane will perform in its use phase.

2.2 Life Cycle Assessment

This thesis will apply LCA as a method to quantify the environmental impacts of a hybrid-electric aeroplane, which is standardised according to ISO 14040:2006. This standard outlines four main steps of an LCA: (i) goal and scope definition, (ii) inventory analysis, (iii) impact assessment and (iv) interpretation (ISO, 2006). These steps are to be conducted in an iterative manner as described in Figure 4. For the three last steps (ii), (iii) and (iv), the LCA modelling software openLCA will be applied to calculate and interpret the results of the study. Visualisation of the results will be done with the help of Microsoft Excel.

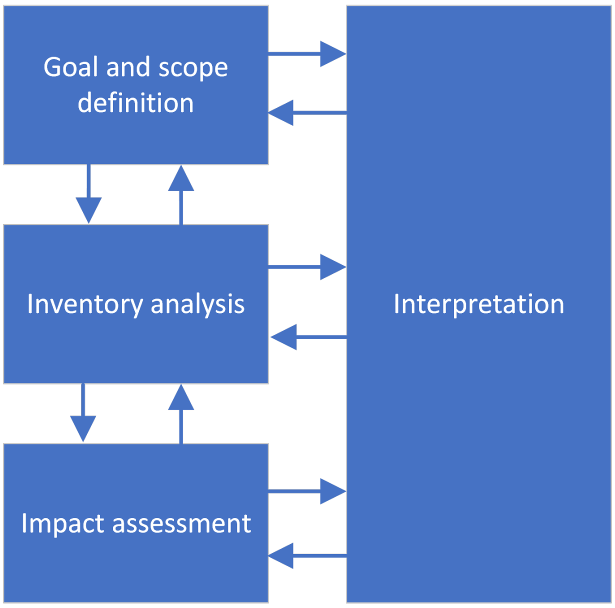

Figure 4: LCA methodology according to ISO 14040:2006. Authors' own figure.

2.2.1 Goal & Scope Definition

The first step of the LCA methodology is to define the goal and scope of the study. This means to clearly define what the objective of the study is, the questions to answer, and who the study will be of interest for. The scope should then define the system boundaries, data quality requirements, functional unit, impact categories, impact assessment method. (Baumann and Tillman, 2004).

2.2.2 Inventory Analysis

The inventory analysis will consist of determining the different flows of mass, energy and emissions within the system (product flows) as well as flows that leave and enter the system (elementary flows). A flow chart will be drawn to provide an overview of the system and its product flows. This will likely be the most time-consuming part of the study since it will require a lot of data collection from different sources, potential allocation between coproducts, and estimations due to uncertain data (Baumann and Tillman, 2004).

2.2.3 Life Cycle Impact Assessment

There are several steps within the LCIA. First, the impact categories and indicators to include in the assessment are determined. Second, classification of the results from the inventory is done, which means that the different inventory parameters are assigned to appropriate impact categories. Some parameters from the inventory may belong to more than one impact category. Third, the substances from the inventory is characterised to determine how much they contribute to each impact category. The contribution to each impact category is quantified to disclose how large the environmental impact is for a specific amount of elementary flow. Practically, the classification and characterisation steps are usually preformed automatically in LCA software modelling tools such as openLCA that already has LCIA methods implemented (Baumann and Tillman, 2004). In this thesis, selected impact categories from ReCiPe 2016 will be considered Huijbregts et al., 2016.

2.2.4 Interpretation

Finally, the results of the LCA should be presented in a comprehensive way and interpreted (Baumann and Tillman, 2004). To further evaluate the results, uncertainty analysis and sensitivity analysis are tools that can be applied to test the robustness of the results. Due to the high uncertainty of certain data, this study will put emphasis on these interpretation tools in order to be able to highlight the uncertainties in the study and areas to focus on in future work to combat them.

3 Schedule

In Figure 5, the initial time plan of the study is presented in a Gantt chart. This schedule may be subject to change if some steps prove to take more/less time than initially anticipated.

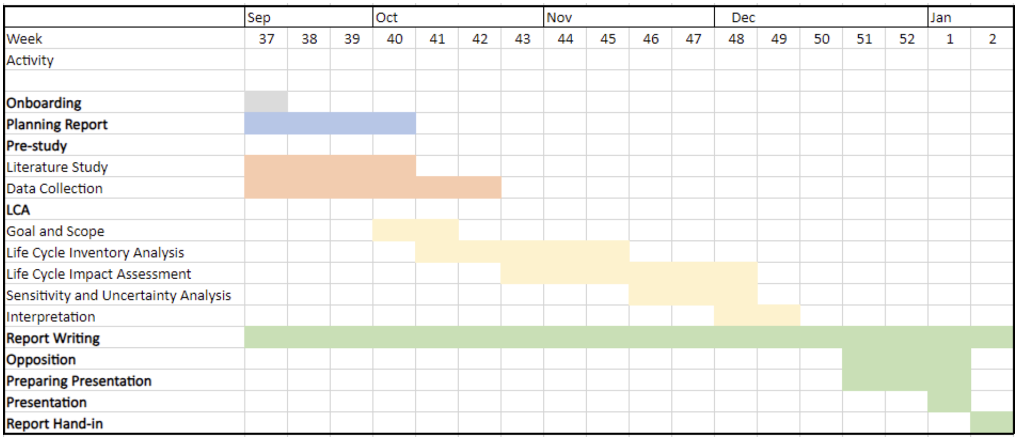

Figure 5: Study time plan.

4 Sustainable Development

In 2015, the members of the United Nations adopted the ”Sustainable Development Goals”, which are 17 goals that should ensure sustainable development through global partnership between countries (United Nations, 2022). The International Civil Aviation Organization, which is a specialized agency within the UN, links to 15 out of the 17 goals in their strategic objectives, which they aim to work directly with in different ways (ICAO, 2019). Figure 6 shows the SDGs linked to the strategic objectives of the ICAO.

Figure 6: The UN SDGs connected to the ICAO’s strategic objectives.

4.1 Environmental Aspects

There are initiatives in the aviation industry as a whole, but also from individual companies, to reduce the environmental impact of air travel. As previously mentioned, the aviation sector stands for approximately 2.5% of the world’s total carbon emissions, but is expected to increase even further as demand for air travel increases (Ellerbeck, 2022).

Heart Aerospace is, through their ES-30, trying to combat this with hybrid electric propulsion system that have the potential to obtain an emission reduction of over 50% per seat compared to a similar sized conventional turboprop aeroplane, and over 90% reduction if sustainable aviation fuel (SAF) is being used (Heart Aerospace, 2023). The all-electric landing and take-off also contributes to drastically reduced noise and local emissions. However, a large part of the aviation industry’s contribution to anthropogenic climate change comes from atmospheric emissions during cruise through the creation of contrails, which are very complex to analyse (Lee, 2020). This makes the operational phase highly relevant to study even for the case of the ES-30.

In the supplier code of conduct by Heart Aerospace, much emphasis is also put on close collaboration with suppliers and the sustainability in the entire supply chain. Demand is being put on, for instance, waste handling, resource efficiency and suppliers being able to provide accurate data to preform LCA in order to measure the environmental impacts throughout the supply chain (Heart Aerospace, 2022).

4.2 Ethical and Societal Aspects

Air traffic is an important piece of infrastructure in several regions of the world today. It allows for transport of people and goods to and from sparsely populated areas with insufficient or no ground-based transport infrastructure. Small regional aeroplanes connect people in small island nations, across mountain ranges and fjords across the globe. However, in 2018, before the Covid-19 pandemic, it is estimated that only 11% of global population travelled by air and that at most 4% flew internationally (Gössling and Humpe, 2020). This share of the global population is also heavily skewed toward higher-income countries, as seen in Table 2, where one can find that individuals from high-income countries fly substantially more than people from the low, lower-middle, and upper-middle income countries (Gössling and Humpe, 2020). One can therefore argue that as of today, air travel is primarily a luxury for the richer part of the world. However, the largest growth of air travel is projected to happen in lower-income parts of the world, such as Africa, Asia-Pacific, the Middle-East and Latin America. All of which are projected to have an annual growth rate of over 5% until 2050 (Gössling and Humpe, 2020). Denying these regions of the world the development of air travel due to environmental concerns while the richer parts of the world have been flying for decades is not ethically defensible. Therefore, it is crucial that this develops as sustainably as possible. To curb emissions from air travel but not limit air traffic growth in developing regions of the world, there is a need for, among other initiatives, cleaner technologies.

Table 2: Flying individuals based on global income group (Gössling and Humpe, 2020).

Income group	Population (million)	Passengers (million)	Passengers per capita of population	Flying population (%)
Low income	705	23	0,03	0,7
Lower middle	3 023	454	0,15	3
Upper middle	2 656	1 313	0,49	10
High income	1 210	2 442	2,02	40

Heart Aerospace is not only determined to develop a regional hybrid-electric aeroplane causing less emissions than a conventional aeroplane but also at a lower cost (Heart Aerospace, 2023). The main parts of the lower cost comes from the lower price of electricity as compared to jet fuel, lower maintenance of the electric motors as well as increasing costs for airlines related to carbon taxes in some regions of the world (Heart Aerospace, 2023). This could contribute to lowering the economic barriers of air travel in developing regions of the world, making air travel accessible to a larger part of the global population.

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