Life cycle assessment of a regional hybrid-electric aeroplane

Master's thesis in Industrial Ecology

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Cover: ES-30 flying through the clouds

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Abstract

This thesis presents a life cycle assessment (LCA) of a hybrid electric aeroplane based on the ES-30 currently under development by Heart Aerospace. The thesis and the LCA aim to answer the following questions: (i) How large are the environmental impacts of the hybrid-electric aeroplane?, (ii) Which part of the life cycle has the largest environmental impact?, (iii) Where are the largest uncertainties in the inventory data?, (iv) How would changes in the base-case assumptions alter the overall results of the study?, and (v) Are the environmental impacts different from those of a similar-sized aeroplane with a conventional propulsion system?

The LCA is performed with a cradle-to-grave perspective where the life cycle is divided into production, use phase and end-of-life. The production is modelled with help from published literature, experts at Heart Aerospace and datasets from Ecoinvent 3.9.1. The use phase investigates different flight scenarios concerning flight distance, type of fuel and electricity mixes for charging. The end-of-life only includes dismantling and sorting of materials since the built-in cut-off approach in the Ecoinvent 3.9.1 database was used to conduct the LCA.

The largest uncertainties lie in the aeroplane production since the actual ES-30 is still under development with changes being made to the design and material choices through the duration of this thesis. However, the results of the LCA indicate that the use phase is the dominating phase for all impact categories included in this study. Most of the impacts can be allocated to fuel production and combustion as well as the production and use of batteries. By changing the fuel to alternative aviation fuel, there are reduction potentials in mainly climate change impact and particulate matter formation. Although the future role of alternative aviation fuels is uncertain and may lead to negative impact in other impact categories. Still in the base case with fossil kerosene and Swedish electricity mix, the ES-30 is environmentally beneficial compared to a similar-sized conventional aeroplane. The one impact category where the ES-30 most probably will perform worse than a conventional reference aeroplane is mineral resource scarcity due to the use of rare metals for batteries and power electronics.

Keywords: Life cycle assessment, LCA, Aeroplane, Aviation, Hybrid-electric, Climate change, Lithium-ion battery, Turboprop, Electric motor, Inverter.

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This thesis has been the cherry on top of our academic journey, a very interesting and challenging project straight from the start. We have learned a lot and are very thankful to everyone at Heart Aerospace for all their help with explaining the complexity of developing and building an aeroplane.

Firstly, we would like to send a special thanks to Peter Nelson, General Counsel at Heart Aerospace, for giving us the opportunity to perform our thesis and connecting us with the right people within the organisation. We would also like to thank Edoardo Lena, Electrical Propulsion System Integration Engineer at Heart, who acted as our Technical Advisor during the thesis work and helped us with everything from information regarding alternative aviation fuels to how to navigate the jungle that is Italian culture.

From the Division of Environmental Systems Analysis at Chalmers University of Technology we would like to express our sincere gratitude to our supervisor Anders Nordelöf, Senior Researcher, and our examiner Rickard Arvidsson, Associate Professor. Both have given us unwavering support and advice throughout our work and have shown great excitement and interest in us successfully completing this LCA of a highly complex product.

Magnus Andersson & Emil Inberg
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List of acronyms

Below is the list of acronyms that have been used throughout this thesis listed in alphabetical order:

AAF	Alternative Aviation Fuel
AC	Alternating Current
BESS	Battery Energy Storage System
CF	Characterisation Factor
CFRP	Carbon Fibre Reinforced Plastic
CSI	Crustal Scarcity Indicator
CSP	Crustal Scarcity Potential
DC	Direct Current
DOD	Depth of Discharge
EoL	End-of-Life
EU	European Union
FEP	Freshwater Eutrophication Potential
FFP	Fossil Fuel Potential
FH	Flight Hours
GFRP	Glass Fibre Reinforced Plastic
GHG	Greenhouse Gas
GWP	Global Warming Potential
HEFA	Hydrotreated Esters and Fatty Acids
HV	High-Voltage
ICAO	International Civil Aviation Organization
ISO	International Standards Organisation
LC	Life Cycle
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Inventory Analysis
LIB	Lithium-Ion Battery
LV	Low-Voltage
MCS	Megawatt Charging System
MLG	Main Landing Gear
MRL	Manufacturing Readiness Level
NLG	Nose Landing Gear
NMC	Nickel-Manganese-Cobalt
PAMELA	Process for Advanced Management of End-of-Life Aircraft

Pkm	Passenger kilometer
PM	Particulate Matter
PMFP	Particulate Matter Formation Potential
SAF	Synthetic (Sustainable) Aviation Fuel
SOC	State of Charge
SOH	State of Health
SOP	Surplus Ore Potential
TAP	Terrestrial Acidification Potential
TRL	Technology Readiness Level
UCO	Used Cooking Oil

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Introduction

Emissions from aviation have increased steadily since the beginning of air travel, with some minor decreases during, for instance, the financial crises and the COVID-19 pandemic (Ellerbeck, 2022). Right before the pandemic, carbon emissions from aviation accounted for approximately 2.5 % of global carbon emissions (Ritchie, 2020). Although 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 2050 (Ellerbeck, 2022). To turn this trend, the aviation industry, through the United Nations International Civil Aviation Organization (ICAO), has set up a non-binding target to reach net zero carbon emissions by 2050 (IATA, 2023). This is proposed to be realised through three main areas: implementation of synthetic aviation fuel, streamlining the aviation industry, and focusing on new green technologies (IATA, 2023).

When it comes to new technologies, there are mainly three that are investigated at varying maturity states: hydrogen-powered aircraft using (i) fuel cell electric technologies or (ii) combustion, and (iii) battery-electric propulsion. There are estimates that these technologies could be feasible for flights up to 4 600 km and the development of these technologies could therefore reduce emissions from flying considerably since short-haul flights of 1 500 km or less account for more than 33 % of all emissions from commercial aviation (Rutherford et al., 2019). 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 hydrogen propulsion systems which could potentially replace conventional jet-fuelled aeroplanes (Airbus, 2023). A less established company that still has received attention in sustainable aviation is Heart Aerospace. With their hybrid-electric aeroplane ES-30, which is the main focus in this study, they aim to revolutionise, and de-carbonise air travel (Heart Aerospace AB, 2023a).

1.1 Aim

The aim of this thesis is to assess the environmental performance of a hybrid-electric aeroplane, based on the ES-30, and compare it to similar-sized conventional aeroplanes. Life cycle assessment (LCA) is used to calculate the environmental impacts of production, use and end-of-life of the aeroplane. Specifically, the thesis aims to answer the following questions:

- How large are the environmental impacts of the hybrid-electric aeroplane?
- Which part of the life cycle has the largest environmental impact?
- Where are the largest uncertainties in the inventory data?
- How would changes in the base-case assumptions alter the overall results of the study?
- Are the environmental impacts different from those of a similar-sized aeroplane with a conventional propulsion system?

1.2 Literature review

LCA in the aviation sector is rare, especially for entire aeroplanes, and even rarer for a hybrid-electric aeroplane. However, there are some previous studies that constitute an important background to the present study, some of which can be used to fill data gaps for aeroplanes and their components.

The LCA of an all-electric two-seater aircraft by Arvidsson et al. (2023) is conducted on an actual all-electric aeroplane produced by the Slovenian company Pipistrel. The results of the study indicate that for a long lifetime of 4 000 flight hours, the electric aeroplane has considerable environmental benefits compared to its fossil-fuel-based counterpart (Arvidsson et al., 2023). However, for a shorter lifetime of 700 flight hours, which is the expected life of one battery energy storage system (BESS), the fossil-fuel-based counterpart is preferable from an environmental perspective. In the paper and its supporting information, unit processes for the production of the aircraft are provided, which can be used in other studies as well. Another relevant publication is a prospective life cycle inventory dataset by Thonemann et al. (2023), presenting unit processes both for conventional and hybrid-electric aircraft technologies for modelling the environmental footprint of short-haul flights with an ATR-42 as a reference aircraft. Some unit processes presented by Thonemann et al. (2023) are the production of a turboprop engine, gearbox and nacelles for the aeroplane.

When it comes to LCAs of conventional aeroplanes, Horbath and Chester (2008), Lopes (2010), Lewis and Strømman (2013), and Vivalda (2023) have performed LCAs considering, production, operation and end-of-life (EoL). The study by Lopes (2010) is a process-based LCA that includes an extensive inventory of the material composition of the Airbus A330-200's structure and engines, which is derived from different manuals and expert interviews. Vivalda (2023) also performed a process-based LCA, but on an ATR-42, which is compared to other aeroplanes and also a theoretical hybrid-electric version of the ATR-42. Lewis and Strømman (2013) utilise the models in Lopes (2010) by comparing the process-based LCA to an economic input-output LCA (EIOLCA) approach for different Airbus models. In the study by Horbath and Chester (2008), the EIOLCA method is used to perform an LCA of air and rail travel with models of different aeroplanes. Table 1.1 summarizes the climate impact of the life cycle of some conventional aeroplanes from the mentioned studies, to which results from this study can be compared.

Table 1.1: LCA results regarding climate change for different aeroplane models with the functional unit 1 pkm.

Aeroplane	**LCA approach**	**GHG emissions (g CO_2e/pkm)**	**Source**
ATR-42 300	Process LCA	113	Vivalda, 2023
Airbus A320	EIOLCA	180	Lewis and Strømman, 2013
Airbus A330	EIOLCA	105	Lewis and Strømman, 2013
Airbus A330	Process LCA	130	Lopes, 2010
Airbus A380	EIOLCA	122	Lewis and Strømman, 2013
Boeing 737	EIOLCA & Process LCA	107.5	Horbath and Chester, 2008
Boeing 747	EIOLCA & Process LCA	153	Horbath and Chester, 2008
Embraer 145	EIOLCA & Process LCA	145	Horbath and Chester, 2008

2

Technical background

The following section provides an overview of the aeroplane studied and its subsystems. The components included and their functions are described. The ES-30 is still under development and therefore this section reflects current plans, as well as the author's own assumptions, for components and aircraft systems, which might be subject to change later in the development cycle. Therefore, the actual ES-30 aiming to be type-certified in 2028 might look different from the modelled aeroplane presented in this study.

2.1 Structure

The structure of the ES-30 looks like any turboprop aeroplane on the market, with some slight design changes due to, for instance, the battery packs. Figure 2.1 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 empennage of the aeroplane which consists of the horizontal and vertical tail.

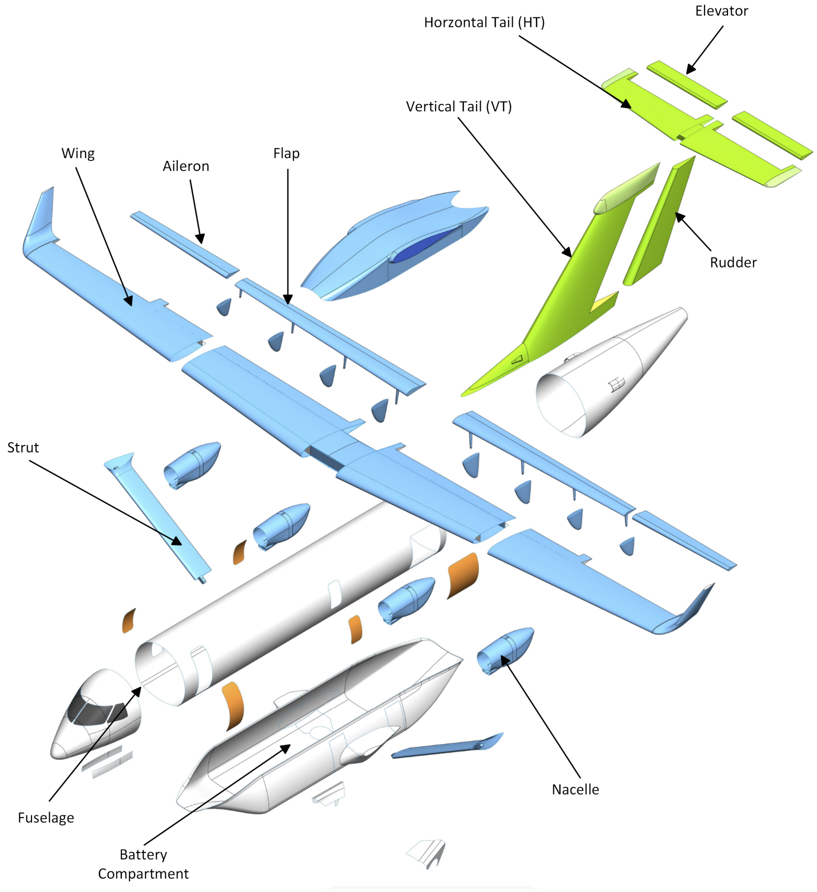


Figure 2.1: Exploded conceptual view of the ES-30 with key components highlighted. Provided by Heart Aerospace with permission, modified by the authors.

2.1.1 Fuselage

The fuselage can be described as the hollow tube of the glider that houses the cockpit, cabin and cargo compartment. Aluminium is the most common material used for the fuselage, but carbon fibre is also a material with benefits for use in the structural parts of an aeroplane (Mouritz, 2012).

2.1.2 Horizontal tail

The horizontal tail is part of the empennage and houses the elevators that control the up-and-down motion of the nose of the aeroplane, also known as pitch. The horizontal tail and the elevators are often dominated by composites due to their light weight, stiffness and tensile strength (Mouritz, 2012).

2.1.3 Main and nose landing gear

The main landing gear (MLG) is situated in the middle of the fuselage and is the part that first touches the ground upon landing. The nose landing gear (NLG) is situated under the cockpit and apart from being used in the landing, it also provides the aeroplane with steering capabilities during the taxi part of the flight. The landing gear consists of a metallic structure and wheels with rubber tyres. The MLG and NLG are considered critical safety components and are exposed to considerable material stress. They are therefore often made of steel due to its high strength (Mouritz, 2012).

2.1.4 Main fairings

Fairings are structures on the aeroplane exterior that only serve the purpose of ensuring a good aerodynamic flow as the aeroplane is in flight and does not hold any critical structural function. The main fairings of the ES-30 are the wing-fuselage fairing (WFF), the belly fairing, sponson, strut to wing fairing as well as the main and nose landing gear doors and landing gear fairings (LGF).

2.1.5 Paint

The painting of the aeroplane is not only for aesthetic reasons but also to protect the aeroplane from corrosion and to improve its aerodynamic properties. Substantial amounts of paint can be required, which makes it an important component to include in this study (IPCM, 2022).

2.1.6 Vertical tail

The vertical tail, sometimes referred to as vertical stabiliser, is also part of the aeroplane's empennage. It houses the rudder, which is used to control the yawing motion of the aeroplane and is commonly made from composites for the same reasons as for the horizontal tail (Mouritz, 2012).

2.1.7 Wing

The wing generates lift for the aeroplane and acts as a structural component. The ailerons that control the roll of the aeroplane and the flaps that control the stall speed are mounted on the trailing edge of the wings. The model created for this study contains the fuel tank and also holds both the electric motors and the conventional turboprop engines in nacelles mounted to the wings. The most common material for the wings is aluminium according to Mouritz (2012).

2.2 Operational systems

The operational systems incorporated into the aeroplane are critical for the safe operation of the ES-30. They are purchased from suppliers with a long history in aviation and no large innovations in terms of material composition are to be expected in these systems according to experts at Heart Aerospace.

2.2.1 Avionics

The word ”avionics” comes from the combination of the words ”aviation” and ”electronics” and constitutes all electronic systems needed for the safe and efficient operation of the aeroplane. Systems included in avionics are, for instance, GPS antennas, weather radar, radio, flight recorders, processing units and monitors to display flight information in the cockpit.

2.2.2 Electrical wiring interconnection system

The electrical wiring interconnection system (EWIS) consists of all wiring needed for the electrical systems onboard the aeroplane, both for high- and low-voltage applications. Its main purpose is to transfer both current and data between different systems.

2.2.3 Environmental control system

The environmental control system (ECS) consists of several systems to regulate the internal environment and protect the aeroplane against the external environment. These systems are the air conditioning with distribution system, fire protection, emergency oxygen system and ice protection system. These subsystems will not differ from those in conventional aeroplanes except for the ice protection system, which in many conventional aeroplanes utilises excess heat in bleed air from the engines, while in the ES-30 there will be an electro-mechanical system that removes ice during flight.

2.2.4 Flight control system

The flight control system (FCS) is the main system used to manoeuvre the aeroplane in flight and on the ground. Subsystems of the FCS are control units to control engines and motors as well as the actuators. The actuators are used to control rudder, elevators, flaps and ailerons. The FCS thereby includes both electrical and mechanical components.

2.2.5 Other electrical systems

Other electrical systems consist of electronics that do not directly influence the navigation or maneuvering capabilities. This includes control units such as the charge control unit (CCU), which controls the charging of the batteries as well as the charge distribution unit (CDU) that distributes the charge to the batteries. Other components in the electrical system are the junction box (which contains safety fuses), low-voltage inverters and converters. These inverters convert current from DC to AC and the converters convert the voltage to the correct voltage suitable for certain components.

2.3 Interior

The main function of the interior of the ES-30 is to provide the pilots and passengers with a comfortable flight experience.

2.3.1 Cockpit instrument panel

The cockpit instrument panel refers only to the framing that holds all the instruments and electronics (such as the avionics and flight control system) in the cockpit.

2.3.2 Flooring

The flooring consists of a carpet with flame-retardant properties and a structure that holds up the floor and runs throughout the cabin as well as into the cockpit and cargo compartment.

2.3.3 Overhead bins

Overhead bins are located in the cabin to provide storage for the passengers' carry-on luggage and onboard equipment used by the cabin attendant.

2.3.4 Seats

The ES-30 will be able to carry 30 passengers with a seat configuration of 10 single seats and 10 double seats. Moreover, the ES-30 will also have two pilot seats, one observer seat in the cockpit and one cabin attendant seat.

2.3.5 Sidewall panel and cabin insulation

The sidewall panel is a panel that covers the inside of the cabin to provide insulation and a comfortable flight environment for the passengers. The cabin insulation blanket is fitted between the sidewall panels and the fuselage to provide thermal and acoustic insulation for the aeroplane.

2.3.6 Other interior components

In the modelling of the interior, supplementary to the subsystems specified above, several additional components are included but modelled generically. These include the wardrobes, lavatory, emergency life jackets, cargo net, cabin pressure bulkheads and the avionics rack.

2.4 Hybrid-electric drivetrain and battery energy storage system

The main function of the ES-30 drivetrain is to provide the thrust to propel the aeroplane from point A to point B. The drivetrain of the ES-30, aiming to be type-certified in 2028, is currently anticipated to be a series hybrid configuration. This configuration uses turbogenerators to generate electricity to drive the electric motors. Due to the lack of publicly available data for this specific configuration, the drivetrain assumed for the model in this study will be a drivetrain with electric motors and turboprop engines separated from each other. This is similar to the configuration presented by Thonemann et al. (2023) and Vivalda (2023). To obtain feasible specifications for the components, and data for the use phase, engineers at Heart Aerospace have been consulted during the modelling process.

2.4.1 Battery energy storage system

The purpose of the battery energy storage system (BESS), is to supply electric motors and other electrical systems with power, and it is located underneath the fuselage. The system needs to be able to deliver enough electricity to complete a mission distance of 200 km without the support from the turboprop engines and have a sufficient lifetime before being replaced. The chemistry of the LIB is assumed to be NMC811, due to the high availability of public data for this type of cell. This does not necessarily mean that it will be the selected cell chemistry for the actual ES-30.

2.4.2 Electric motor

The model of the ES-30 will have two 1.5 MW electric motors located in the inner nacelles with the ability to generate enough thrust for all-electric taxiing, take-off, climb, cruise, descent and landing. The electric motors will be developed internally by Heart Aerospace, potentially in collaboration with one or more partners.

2.4.3 Gearboxes

Both the turboshaft engine and the electric motors require reduction gearboxes to reduce the output speed of the engine, thereby obtaining the required torque for the propeller shaft.

2.4.4 Nacelles

The nacelles contain the turboshaft engines and electric motors of the ES-30 as well as the components connected to them. Both the electric motor and turboshaft engine will have identical nacelles that provide aerodynamic protection from objects such as birds or hail while flying.

2.4.5 Propellers

The propellers will be fitted to the electric motors and turboshaft engines to provide thrust for the aeroplane. The propellers fitted to the electric motors on the inner nacelles will be a bit larger than the propellers fitted to the turboshaft engines on the outer nacelles due to the different specifications of the turboshaft engines and the electric motors.

2.4.6 Power inverter

The power inverters are used to change the DC coming from the batteries to AC to run the electric motors. The power inverters also control the frequency of the current supplied for the motors. Each motor will require 6 power inverters rated at 250 kW each.

2.4.7 Turboprop engine

The model of the ES-30 will have two 1 MW turboprop engines on the outer nacelles to provide extra thrust, which will provide range extension for longer missions. For safety reasons, the turboprop engines will be kept idle during the descent and landing in case of the need for a ”touch-and-go” situation or in the case of being diverted to another airport beyond the all-electric range. A touch-and-go situation is when the pilot goes in for a landing but something is preventing the aeroplane from landing and the pilot touches the ground to then accelerate and take off.

3

Life cycle assessment method

This thesis applies LCA (which is standardised according to ISO 14040:2006) as the method to quantify the environmental impacts of the hybrid-electric aeroplane, This standard outlines four main steps of an LCA: (i) goal and scope definition, (ii) inventory analysis (LCI), (iii) impact assessment (LCIA) and (iv) interpretation (ISO, 2006). These steps are to be conducted in an iterative manner as described in Figure 3.1. For the three last steps (ii), (iii) and (iv), the LCA modelling software openLCA is applied to calculate and interpret the results of the study. Visualisation of the results is done using Microsoft Excel.

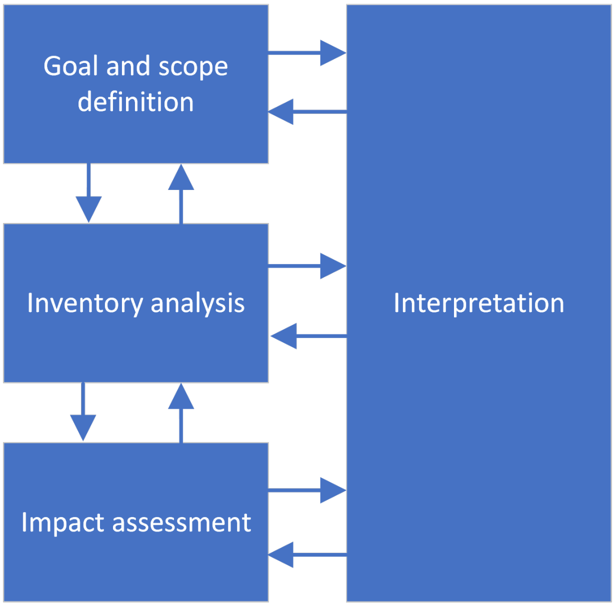


Figure 3.1: LCA methodology according to ISO 14040:2006. Authors' own figure.

3.1 Goal and 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 to. The scope should then define the system boundaries, data quality requirements, functional unit, impact categories, and assessment methods (Baumann and Tillman, 2004).

3.2 Inventory analysis

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

3.3 Life cycle impact assessment

There are several steps in the LCIA. First, the impact categories and indicators to include in the assessment are determined. Second, classification of the results from the inventory is performed, which means that the different inventory flows 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 are 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 performed automatically in LCA software modelling tools such as openLCA which already has LCIA methods implemented (Baumann and Tillman, 2004). The impact categories in focus in this thesis are described in more detail in Sections 3.3.1 - 3.3.3.

3.3.1 Global warming

Global warming caused by humans is mainly the result of the combustion of fossil fuels, which results in the release of greenhouse gases (GHG) into the atmosphere. The most common characterisation factor for global warming is the global warming potential (GWP100), which quantifies the integrated infrared radiative forcing increase of a GHG expressed in kg carbon dioxide equivalents per kg gas emitted (kg CO_2-eq/kg) over a 100 year period (Huijbregts et al., 2016).

3.3.2 Particulate matter

Most vehicles used today are operated by internal combustion engines that result in the formation of particulate matter (Rissman et al., 2013). The impacts of these emissions are predominantly regional or local and can affect human health (Huijbregts et al., 2016; Riley et al., 2021). The chosen midpoint characterisation factor for particulate matter formation potential (PMFP) is expressed in kg primary PM2.5 equivalents per kg particles released (kg PM2.5-eq /kg particles), 2.5 meaning particles with a diameter less than or equal to 2.5 μm (Huijbregts et al., 2016).

3.3.3 Mineral resource scarcity

In most product life cycles, there is a need for abiotic resources such as metals and minerals. It has been argued that these resources exist in nearly infinite amounts on Earth, but their availability depends on the grade of the ore extracted. The grade is the concentration of the required resource in the ore (rock). When the resource is extracted, the overall, global, grade of that resource decreases (Vieira et al., 2017).

This is captured in the midpoint characterisation factor for mineral resource scarcity called the surplus ore potential (SOP), which specifies the extra amount of ore needed to be mined per additional unit of resource extracted (Vieira et al., 2017). The characterisation factor is expressed in kg copper equivalents per kg extracted resource (kg Cu-eq / kg resource) (Huijbregts et al., 2016). The SOP of a resource is often derived from prices on the global market, which is a drawback regarding their temporal reliability since prices vary notably over time (Arvidsson et al., 2020).

There is also an interest in considering the long-term scarcity of resources. In the long-term, prices and other parameters may shift notably and another characterisation factor is therefore also considered in this study. The crustal scarcity indicator (CSI) is based only on average concentrations of resources in the earth's crust. Thus, any time-sensitive parameters, such as prices, are avoided in this indicator. The characterization factors for the CSI are called crustal scarcity potentials (CSP) and are expressed in kg of silicon equivalents per kg of extracted resource (kg Si-eq / kg resource) (Arvidsson et al., 2020).

3.4 Interpretation

Finally, the results of the LCA should be presented comprehensively 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. Another tool that is useful to interpret the results is contribution analysis to find what parts of the life cycle and which processes contribute to which environmental impacts. As a second step in this analysis, the largest contributors can be identified by conducting a dominance analysis. In this LCA, the contribution and dominance analyses are conducted in parallel to the LCIA. Due to the high uncertainty of some data, this study emphasises these interpretation tools to highlight the uncertainties in the study and areas to focus on in future work.

4

Goal and scope definition

This chapter defines the goal of this LCA and what questions it sets out to answer. Furthermore, the scope is defined to set the system boundaries both in terms of geography and time as well as the technical boundaries considered in this LCA.

4.1 Goal

In line with the aim stated in Section 1.1, the goal of this LCA study is to assess the environmental performance of a hybrid-electric aeroplane based on given design data of the ES-30 in combination with existing data in literature and compare the results to the results from a similar-sized conventional aeroplane. The LCA is thereby not completely based on the actual ES-30, but rather a modelled aeroplane similar to the ES-30. The results will therefore not be able to serve as a complete environmental product declaration, nor a complete LCA of the actual ES-30, but serve as a foundation for further data collection and analysis of the life cycle of the actual ES-30, e.g. for upcoming sustainability reporting. The LCA sets out to answer the following questions:

- How large are the environmental impacts of the hybrid-electric aeroplane?
- Which part of the life cycle has the largest environmental impact?
- Where are the largest uncertainties in the inventory data?
- How would changes in the base-case assumptions alter the overall results of the study?
- Are the environmental impacts different from those of a similar-sized aeroplane with a conventional propulsion system?

4.2 Scope

The study is an attributional cradle-to-grave LCA that covers the extraction of raw materials, production of components, transportation, assembly of the aeroplane, use phase and the end-of-life phase. According to Finnveden et al., 2009, an attributional LCA describes the environmentally relevant physical flows to and from a life cycle and its subsystems. The same study describes the other of the two main LCA types, the consequential LCA, which aims to describe how environmentally relevant flows will change after potential decisions have been taken. Another distinction between attributional and consequential is the kind of data used in the inventory.

Marginal data is typically applied in consequential LCA, whereas average data is typically applied in attributional LCA (Finnveden et al., 2009). Being an attributional study, this study thus applies average data. According to Finnveden et al. (2009) and Arvidsson et al. (2018), both types can be used to model future systems. However, in the modelling of the aeroplane, the future life cycle is based on current average data and no future electricity supply mixes or similar is applied.

As the ES-30 is still under development, both the technological- and manufacturing readiness level (TRL and MRL) are low. The LCA is therefore conducted with as much available data from Heart Aerospace as possible, but also complemented with external data to fill data gaps at this early stage in the development process. TRL and MRL are two frameworks to quantify the maturity of a product or system concerning technology or manufacturing on a scale from 1 to 9 (or 10 for MRL), where 1 is the lowest and 9 (or 10) the highest maturity level (Petrovic and Hossain, 2020).

The ES-30 consists of several components with a high TRL (Mankins, 1995) such as electric motors, turboprop engines and LIBs. However, the integration of these components into the overall system of the ES-30 can be argued to define the TRL of the aeroplane. The basic principles of a hybrid-electric aeroplane are observed (TRL 1) in several studies, as described in Section 2, and Heart Aerospace is formulating the technology concepts of the ES-30 (TRL 2). Heart Aerospace has demonstrated experimental proof and concept for the novel electric drivetrain and battery energy storage systems (TRL 3) thereby it can be argued that the ES-30 is at least at TRL 3, as of the writing of this report.

The MRL of the ES-30 is, similar to the TRL, defined by the integration of all the different components. It is not novel to produce an aeroplane and Heart Aerospace does not aim to revolutionise the manufacturing process. However, the company does not have a production plant and hence has not produced a full-scale prototype. The company has identified the manufacturing concepts it will utilise (MRL 2) and is developing a manufacturing proof-of-concept (MRL 3). Therefore, it can be argued that the manufacturing of the ES-30 is at least at MRL 3. It is, however, challenging to pinpoint an exact MRL and TRL of the ES-30 and a complete evaluation lies outside the scope of this study.

4.2.1 Geographical scope

The production of some components and the final assembly of the aeroplane is assumed to take place in Sweden. However, a large fraction of the aeroplane components will be imported from manufacturers all across the world and are therefore modelled with the corresponding electricity supply mixes and transport modes to the assembly location. Furthermore, the operational phase includes flight scenarios in different parts of the world to assess the impacts of electricity supply mixes used by the airlines operating the aeroplane. The fossil fuel and alternative aviation fuel (AAF) are assumed equal irrespective of where the aeroplane operates.

4.2.2 Temporal scope

The temporal scope of the study is set to the expected lifetime of the aeroplane, which is assumed to be 30 years. During this period, the battery energy storage system will have to be replaced a certain number of times and it is therefore relevant to include this in the study when comparing to a conventional aeroplane that does not require such replacements.

4.3 Function and functional unit

The function of the hybrid-electric aeroplane is to transport 30 passengers and their luggage. The main functional unit is therefore set to *1 passenger km (1 pkm),* which is also an industry standard of measuring. Other functional units such as ”1 flight hour” could also be used, but the main purpose of the aeroplane is to transport people and therefore, 1 pkm is most suitable for this study. The aeroplane is evaluated under different sets of flight mission distances, resulting in different ratios of hybrid mode and electric-only mode. Furthermore, some results are relevant to evaluate from the perspective of the entire aeroplane. Therefore, a second functional unit is considered, which is set to *1 aeroplane life cycle.*

4.4 Technical system

Figure 4.1 shows a flowchart describing the technical system under study. The different subsystems, their components and the sources used for modelling them are shown. A more detailed description of the modelling of the different parts of the life cycle will be given in Chapter 5.

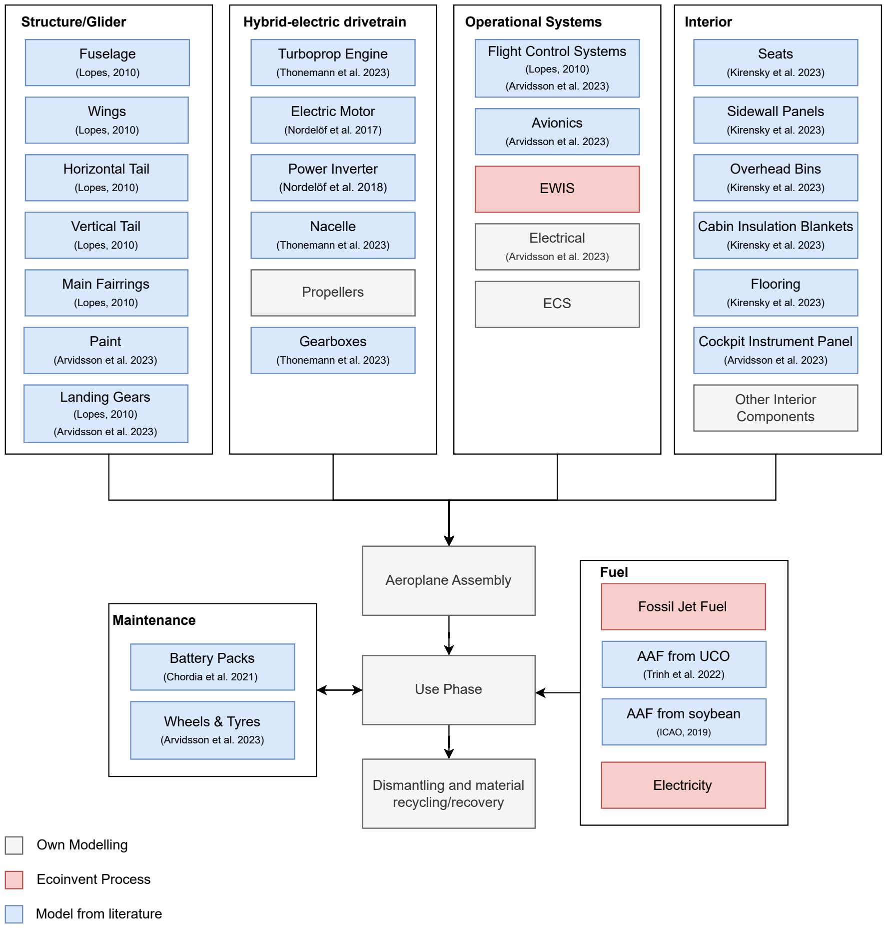


Figure 4.1: Flowchart of the system under study.

4.5 Impact categories

Manufacturers of hybrid-electric aeroplanes often aim to sell a product that is more environmentally benign than the conventional products available today. The largest focus is usually placed on lowering GHG emissions. However, there are several other environmental impacts to consider than solely global warming. This study aims to quantify key impact categories relevant to hybrid-electric aeroplanes.

The ReCiPe 2016 method provides characterisation factors representative for the global scale (Huijbregts et al., 2016). This is suitable, since Heart Aerospace aims to sell the ES-30 on the global market, having received orders and letters of intent from airlines and lessors in Sweden, Europe, North America and the Asia-Pacific region (Heart Aerospace AB, 2023b). Three particularly relevant midpoint impact categories have been selected from the ReCiPe 2016 method: (i) global warming, (ii) particulate matter formation, and (iii) mineral resource scarcity.

Climate change is the most central impact category for this study since an important part of the business model for Heart Aerospace is decarbonizing the aviation sector. Since the aviation sector is generally carbon-intensive, as mentioned in Chapter 1, so it is of high relevance to assess the climate change impact in the case of a hybrid-electric aeroplane. Contrail cirrus, formed when cruising on higher altitudes, account for almost 60 % of the total climate impact from aviation (Lee, 2020). However, Voigt et al. (2021) explain that experiments have shown that the use of alternative aviation fuels can reduce contrail formation substantially. They also emphasize how contrail formation is complex, and they have a short lifespan in the atmosphere, which makes them hard to estimate precisely. According to Bipinchandra (2022), contrails mainly start forming at altitudes above 30 000 ft (9 100 m), which is higher than the cruising altitude of the ES-30 (5 000 m). Therefore, the effects of contrails will not be assessed in this study.

A study by Yim et al., 2015 assessed health impacts stemming from civil aviation emissions and concluded that about 16 000 premature deaths can be attributed to global aviation emissions annually. About 30 % of these could be linked to particulate matter (PM2.5) exposure within 20 km of an airport (Riley et al., 2021). By using electric-hybrid aeroplanes, it is anticipated that these emissions would be and therefore particulate matter formation is assessed.

Mineral resource scarcity is assessed due to the amount of mineral resources required for the production of the hybrid-electric aeroplane (including the battery with its lithium, nickel and cobalt) compared to the mineral resources going into a conventional aeroplane (without a battery used for propulsion). A summary of the chosen impact categories in this LCA is presented in Table 4.1.

Table 4.1: Summary of the selected impact categories.

Impact category	**Impact category indicator**	**CF**	**Unit**
Global warming	Infrared radiative forcing (100-year time horizon)	GWP100	kg CO_2-eq
Mineral resource scarcity, short-term	Surplus ore	SOP	kg Cu-eq
Mineral resource scarcity, long-term	Crustal scarcity indicator (CSI)	CSP	kg Si-eq
Particulate matter	PM2.5 population intake	PMFP	kg PM2.5-eq

4.6 Data acquisition

The modelling of the product system and its related flows is performed using the openLCA software with background data from the Ecoinvent 3.9.1 cut-off database (licence provided by Chalmers University of Technology) regarding, for instance, raw material extraction, refining and electricity production. Within that database, typical current recycled contents in material production datasets are included. Foreground data is obtained from Heart Aerospace as well as from the scientific literature. Most components of the aeroplane will be purchased from suppliers. Heart Aerospace has chosen suppliers for the largest components (by weight) of the aeroplane but not yet for all. Production processes of the largest components are thus modelled using country- or regional-specific data in Ecoinvent on, for instance, electricity, energy and heat inputs. However, if there is a lack of geographically-specific data or if a supplier is not yet chosen for a component by Heart Aerospace, global averages are applied instead. For raw material inputs traded on a global market, global averages will also be used.

4.7 Comparative study

To put the results from this study into context, the results are compared to another study of a similar aeroplane on the market: the ATR-42 with a capacity of 48 passengers (compared to 30 for the ES-30). The ATR-42 is extensively used to fly between regional airports, which is the target market for the ES-30. Vivalda (2023) recently conducted an LCA of the ATR-42 and their results are used for comparability. However, this study has focused on the impact categories climate change, acidification and eutrophication. Therefore, in-depth results from the chosen impact categories are only compared for the climate change impact category. However, all ReCiPe 2016 midpoint impact categories will be calculated, which are available in Appendix D, and thereby both acidification and eutrophication are briefly compared in Section 7.3. The overall assumptions and results from Vivalda (2023) are presented in Tables 4.2 and 4.3, respectively.

Table 4.2: Assumptions from Vivalda (2023).

Passengers per flight	48
Annual flights	1 875
Aeroplane lifetime	20 years
Mission distance	370 km

Table 4.3: Environmental impacts from an ATR-42 according to Vivalda (2023).

Impact category	**Climate change (kg CO_2-eq)**	**Acidification (kg SO_2-eq)**	**Eutrophication (kg NO_x-eq)**
Total impact	7.6E+07	1.4E+05	1.2E+05
use phase	7.6E+07	1.4E+05	1.2E+05
use phase, share of total	99.4 %	98.1 %	98.9 %
Impact per pkm (g)	113	0.21	0.18

The lifetime of the ATR-42 in the above-mentioned study is considered to be 20 years while the lifetime of the ES-30 is assumed to be 30 years. However, when adding 10 years of operational lifetime to the ATR-42, the climate change impact per pkm does not change notably because the operational impact account for 98.9 % of the impact, and this impacts scales linearly with the lifetime (number of pkm). Therefore, 113 g CO_2-eq / pkm is considered to be comparable to the results in this study. There are no other environmental impacts calculated for other mission distances than the 370 km for the ATR-42 available in the study, but in reality, the impacts per pkm would be different for shorter and longer flight distances. This is because the take-off consumes more fuel than the cruise phase of the flight. This means that if the flight is shorter than 370 km, the fuel consumption and its related emissions from the take-off will be spread out over fewer pkm, which increases the CO_2-eq / pkm. The same logic applies the other way around when the flight is longer than 370 km, which would lead to lower CO_2-eq / pkm Rutherford et al., 2019. In order to compare the ATR-42 to the modelled ES-30 in terms of particulate matter emissions, the fuel consumption stated in Vivalda (2023) together with the emission factors stated in Lopes (2010) is used. This gives a value of 90 g PM2.5-eq per pkm, although this value only accounts for the fuel production and combustion.

4.8 Limitations

One important limitation in this LCA concerns the battery cells used in the aeroplane. The battery LCI data is taken from Chordia et al. (2021), which consider lithium ion batteries with an energy density of 210 - 240 Wh/kg (further specifications are described in section 5.4.1). However, the energy density of the battery in this study is expected to be higher and impacts reported for the batteries in the result chapter of this report relies on the assumption that the material and energy flows reported for cell assembly in Chordia et al. (2021) could be used unaltered on a per kilogram basis, while still representing the more energy dense cells that the aircraft will require. This major assumption is necessary due to battery cell supplier confidentiality.

5

Inventory analysis

The inventory analysis consists of gathering data for the different subsystems of the aeroplane as well as the different phases of its life cycle. Furthermore, the modelling of the different components and scenarios is presented. Unit processes for the modelled components are presented in Appendix A.

5.1 Production of the aeroplane structure

The production of the aeroplane structure is broken down into the production of major structural components, as presented in Sections 5.1.1 - 5.1.4. The glider is produced via conventional production processes and consists mainly of aluminium. The material composition of the different glider components is obtained from the LCA by Lopes, 2010 on an Airbus 330-200. For each component, the composition is then applied to the model of the aeroplane to obtain the weights of each material that goes into each component. The material composition used for the scaling is presented in Figure 5.3.

Table 5.1: Material composition of the aeroplane glider, by weight, derived from Lopes (2010), modified with help from experts at Heart Aerospace to fit the model of the aeroplane.

Subsystem	Material	Share
Fuselage	Aluminium	74 %
	Glass fibre reinforced plastic	1 %
	Miscellaneous	3 %
	Steel	2 %
	Titanium	3 %
	Carbon fibre reinforced plastic	11 %
	Stretched acrylic	3 %
	Cast acrylic	3 %
Horisontal tail	Aluminium	5 %
	Carbon fibre reinforced plastic	92 %
	Glass fibre reinforced plastic	3 %

Table 5.1: Continued - Material composition of the aeroplane glider, by weight, derived from Lopes (2010), modified with help from experts at Heart Aerospace to fit the model of the aeroplane

Subsystem	**Material**	**Share**
Main landing gear	Aluminium	13 %
	Steel	63 %
	Carbon fibre reinforced plastic	5 %
	Titanium	3 %
	Hydraulics oil	2 %
	Rubber	13 %
Main fairings	Aluminium	42 %
	Carbon fibre reinforced plastic	35 %
	Glass fibre reinforced plastic	12 %
	Steel	7 %
	NOMEX HC	4 %
Nose landing gear	Aluminium	16 %
	Steel	58 %
	Carbon fibre reinforced plastic	5 %
	Titanium	3 %
	Hydraulics oil	2 %
	Rubber	16 %
Painting	Polyurethane adhesive	100 %
Vertical tail	Aluminium	3 %
	Carbon fibre reinforced plastic	55 %
	Glass fibre reinforced plastic	42 %
Wing	Aluminium	79 %
	Steel	3 %
	Carbon fibre reinforced plastic	13 %
	Titanium	5 %

5.1.1 Fuselage

The fuselage is mainly produced from aluminium, which matches the material composition described by Lopes (2010). To further adapt the material composition to fit the model of the aeroplane, expert advice from Heart Aerospace was taken into consideration. This leads to a slight refinement of the material composition presented by Lopes (2010) with the addition of cast- and stretched acrylic to account for windows.

5.1.2 Horizontal tail

The horizontal tail is modelled entirely based on the material composition of the Airbus A330-200 (Lopes, 2010), and consists mainly of CFRP and GFRP. The material composition is scaled to fit the target weight for the ES-30 in collaboration with experts at Heart Aerospace.

5.1.3 Main and nose landing gear

The MLG and NLG must withstand a lot of stress and therefore stand out in material composition as they mostly consist of steel. Lopes (2010) provide the material composition of these systems, but the material composition of the tyres and wheels is not specified. The materials of the tyres and wheels are instead taken from Arvidsson et al. (2023). This leads to a slight modification in the total composition of the landing gear systems. With the combined data from both studies, experts at Heart Aerospace verified the material composition of the MLG and NLG. Within the MLG and NLG, there is also hydraulic fluid that constitutes a small share of the total system weight. This fluid is modelled using the Ecoinvent process for lubricating oil.

5.1.4 Main fairings

The main fairings do not provide any structural features and are therefore almost exclusively made of light-weight materials such as aluminium, fibreglass (GFRP), carbon fibre (CFRP) and the very light-weight material NOMEX Honeycomb (HC), which is used to provide structure to the MLG and NLG doors. The material composition of the main fairings in the modelled ES-30 is based on estimations made by a senior weights engineer at Heart Aerospace, differing from Lopes (2010) which uses GFRP and CFRP exclusively for the fairings of the Airbus A330. However, the modelled main fairings also include NOMEX HC and aluminium.

5.1.5 Paint

The painting is modelled based on the study by Arvidsson et al. (2023), where polyurethane is considered as the paint of the aircraft. This is the most common paint used in the aviation industry according to experts at Heart Aerospace. 80 kg of paint is estimated to be required for one modelled aeroplane.

5.1.6 Vertical tail

The vertical tail is modelled in the same manner as the horizontal tail based on the material composition provided by Lopes (2010).

5.1.7 Wing

Much like the fuselage, the wings are mostly produced from aluminium in the model. The material composition of the wings is slightly modified compared to that reported in Lopes (2010) since modern ailerons (hinged flight control surfaces mounted on the wings) are typically made from CFRP. The modelled aeroplane in this study thus has slightly more CFRP and slightly less aluminium compared to the Airbus A330 in Lopes (2010).

5.2 Operational systems

Operational systems are a collection of systems within the aeroplane which are crucial for its operation. The systems contain, for instance, all electrical wiring within the aeroplane (EWIS), the flight controls (FCS), and other electrical components. Table 5.2 provides the composition of the systems and each subsystem is described in the subsequent sections.

Table 5.2: Compositions of the operational system components of the modelled aeroplane.

Subsystem	**Material**	**Share**
Avionics	”Mobile phone” equivalents	52 %
	Aluminium	41 %
	Carbon fibre reinforced plastic	7 %
Environmental control system (ECS)	Climate control system	33%
	Ice protection system	23 %
	Oxygen	3 %
	Fire extinguishing system	16 %
	Thermal management system	25 %
Electrical wiring interconnection system (EWIS)	Cable, unspecified	100 %
Flight control systems (FCS)	Polyethylene terephthalate	6 %
	Electronics production	20 %
	Reinforcing steel	74 %
Other electrical systems	HV-inverters	49 %
	Converters	51 %

5.2.1 Avionics

The avionics of the aeroplane constitute a small fraction of the entire aeroplane’s weight but are a crucial component for the safe navigation of the aeroplane. The system is comprised of the active components, which are the antennas, weather radar, computing, cockpit displays and the plane’s ”black box”. It also includes a passive component, which is the structure that holds the system in place, called an avionics rack. The active components are assumed to have a mass proportional to that of a mobile phone. Therefore, the active components are modelled as mobile phones using the ”consumer electronics, mobile device, smartphone” dataset available in Ecoinvent 3.91. The small share of total weight that these components make up made more detailed modelling of these components unfeasible. The avionics rack is made up of aluminium and CFRP and is modelled using the North American market process for aluminium (primary ingot) and material processing using metal working (average for aluminium product manufacturing) and CFRP (injection moulded). The modelling is based on inventory data presented in Tables S10 and S14 in Arvidsson et al. (2023).

5.2.2 Environmental control system

The environmental control system consisting of the climate control system, ice protection system, oxygen, fire extinguishing system, and thermal management system is modelled generically due to the complexity of these systems and lack of relevant data. A material estimation and material composition were made in collaboration with engineers at Heart Aerospace to model these subsystems. The results of the material estimation are available in Appendix A.4.5 and utilise several Ecoinvent processes such as ”market for air compressor, screw-type compressor, 4kW” for use in the climate control system and ”market for aluminium, cast alloy | aluminium” for the oxygen tanks in the oxygen system.

5.2.3 Electrical wiring interconnection system

The EWIS is assumed to consist of copper cables with a polyethene cover. Its whole weight is therefore modelled using the market process for cable production, unspecified, available in Ecoinvent.

5.2.4 Flight control system

The FCS consists of actuators, control units and sidesticks for pilot control of the system. The actuators are modelled according to Lopes (2010), which uses reinforcing steel as the only input material. The actuators are made to control the rudder, elevators, ailerons and flaps, which means the actuators need to withstand a lot of stress and therefore steel is considered a reasonable material. The control units for the FCS are modelled according to Arvidsson et al. (2023), which used a modified Ecoinvent process ”electronics production, for control units” with the casing of the unit changed from steel to aluminium and the electronics changed to lead-free electronics. The sidesticks comprise a low share of the total system weight and are modelled using the Ecoinvent process ”polyethylene terephthalate, granulate, amorphous”. ”. Polyethylene terephthalate is used due to its strong and rigid material qualities considering the extensive use of a sidestick over its life cycle.

5.2.5 Other electrical systems

The modelling of the junction boxes in the modelled aeroplane is done according to the LCI data available in Arvidsson et al. (2023). However, the junction box on the 2-seat electric plane is modelled with a weight of 0.66 kg which is smaller than the one for the model in this study. Therefore, the junction box is scaled up to the correct weight. The control units for charging and distribution are modelled in the same way as the control units described in Section 5.2.4. The low voltage inverters have a very similar unit weight to the power inverters used in the propulsion system described in Section 5.4.5 and therefore these are scaled to their correct weights and modelled in the same manner. The high-to-low voltage converters are modelled using the Ecoinvent process ”converter production, for electric passenger car”, which is based on a converter with a unit weight of 4.5 kg. This is similar to the unit weight of the converters required for the model in this study (3.15 kg).

5.3 Interior

The interior components are mostly modelled with a material composition provided by Kirensky et al. (2023). The material composition is taken from an Airbus A320 and is then scaled down to fit the target weights for the modelled aeroplane. Table 5.3 lists all interior components and detailed descriptions are provided below.

Table 5.3: Material composition of the different interior components based on Kirensky et al., 2023, modified by the authors in cooperation with experts at Heart Aerospace.

Subsystem	**Material**	**Share**
Avionics Rack	Aluminium	100 %
Bulkheads	Carbon fibre reinforced plastic	100 %
Cabin insulation blanket	Polyethylene terephthalate film	2 %
	Glass fibre reinforced plastic	98 %
Cargo net	Polyester	100 %
Cockpit instrument panel	Carbon fibre reinforced plastic	29 %
	Copper, cathode	52 %
	Ethylene-tetrafluoroethylene	12 %
	Polyethylene terephthalate	7 %
Flooring	Polyethylene	21 %
	Polyethylene terephthalate film	9 %
	Cotton	4 %
	Latex	9 %
	Aluminium	57 %
	Epoxy adhesive	$<$ 1 %
Life jackets	Polyurethane-nylon	81 %
	Aluminium	19 %
Overhead bins	NOMEX HC	9 %
	Glass fibre reinforced plastic	27 %
	Polyvinyl chloride film	8 %
	Aluminium	55 %

Table 5.3: - Continued. Material composition of the different interior components based on Kirensky et al., 2023, modified by the authors in cooperation with experts at Heart Aerospace.

Subsystem	**Material**	**Share**
Seats	Aluminium	36 %
	Polycarbonate	15 %
	Polyurethane foam	13 %
	Polyvinyl chloride film	< 1 %
	Stainless steel	10 %
	Brass	1 %
	Polyethylene terephthalate film	2 %
	Polyurethane adhesive	< 1 %
	Silicone rubber	< 1 %
	Carbon fibre reinforced plastic	11 %
	Synthetic leather	9 %
	Polyamide	3 %
Sidewall panel	NOMEX HC	11 %
	Glass fibre reinforced plastic	33 %
	Polyvinyl chloride film	10 %
	Polyetherimide	47 %
Wardrobe and lavatory	NOMEX HC	9 %
	Glass fibre reinforced plastic	27 %
	Polyvinyl chloride film	8 %
	Aluminium	55 %

5.3.1 Cockpit instrument panel

The cockpit instrument panel is modelled based on Arvidsson et al. (2023) and scaled to fit the target weight of the instrument panel for the modelled aeroplane.

5.3.2 Flooring

The flooring of the Airbus in the study by Kirensky et al. (2023) includes a large aluminium structure for the belly freight compartment, which the modelled aeroplane does not have. However, the total weight of the aluminium for the flooring is deemed reasonable and potential excess aluminium can be assumed to cover underestimations in other interior compartments, such as the lavatory and storage units.

5.3.3 Overhead bins

The modelled aeroplane has overhead bins for passenger luggage. The overhead bins mainly consist of an aluminium structure, composite walls and hatch and are modelled based on Kirensky et al. (2023).

5.3.4 Seats

The seats are modelled with a dataset presented in (Kirensky et al., 2023). The dataset is based on passenger seats from an Airbus A320 with a complete material breakdown of the different components. The material composition was refined with help from interior engineers at Heart Aerospace to obtain a valid model for the seats. The material composition from Kirensky et al. (2023) is also used to model the pilot seats, cabin attendant seat, and the observer seat. These seats require more adjustments to the material composition due to the different design of these seats compared to the passenger seats.

5.3.5 Sidewall panel and cabin insulation

The sidewall panel is modelled with the help of the material composition presented by Kirensky et al. (2023) and is mainly made of composites. By using the target weight of the sidewall panels of the ES-30, a rough estimation is made that 61 m^2 of the sidewall panel would be needed. For the cabin insulation, it is estimated that 26 m^2 would be needed.

5.3.6 Other interior components

To achieve the total target weight of the interior of the modelled aeroplane, some other interior components are modelled generically. These are the pressure bulkheads, which are assumed to be made of CFRP, the cargo net, which is assumed to be made of polyester, and the avionics rack, which is assumed to be made of cast aluminium. Since there is a lack of data on both the lavatory and the storage units (wardrobe) inside the cabin, these are modelled roughly with the same material composition as the overhead bins since they are assumed to be similar in function and structure.

5.4 Production of hybrid-electric drivetrain and battery energy storage system

The production of the hybrid-electric drivetrain is also broken down into its major components, which are the nacelles, propellers, turboshaft engines, gearboxes, electric motors, power inverters, and BESS. See Table 5.4 for the breakdown of the different components.

Table 5.4: Material composition of the different components included in the hybrid-electric drivetrain based on Brown et al. (2005), Nordelöf et al. (2017), Nordelöf et al. (2018), Chordia et al. (2021), and Thonemann et al. (2023).

Subsystem	**Material / components**	**Share**
Battery energy storage system	Battery management system	3 %
	Cells	80 %
	Module and pack (sans cells)	16 %
	HV-connector	< 1 %
Electric motor	Aluminium	32 %
	Copper	8 %
	Ferrosilicon	2 %
	Low-alloy carbon steel	9 %
	Neodynium	1 %
	Stainless steel	1 %
	Unalloyed steel	47 %
Electric motor gearbox	Stainless steel	100 %
Nacelle	Aluminium	15 %
	Carbon fibre reinforced plastic	40 %
	Titanium	45 %
Propeller	Carbon fibre reinforced plastic	100 %
Power inverter	Copper	24 %
	Polypropylene	5 %
	Polyethylene terephthalate	3 %
	Polyurethane resin	2 %
	Aluminium	52 %
	Brass	5 %
	Low-alloy carbon steel	2 %
	Miscellaneous	6 %
Turboshaft engine	Aluminium alloy	13 %
	Titanium aluminide	9 %
	Magnesium alloy	4 %
	Nickel alloy	26 %
	Metal matrix composite	9 %
	Silicon carbide (ceramic matrix composite)	39 %
Turboshaft gearbox	Steel alloy	75 %
	Aluminium alloy	25 %

5.4.1 Battery energy storage system

The battery consists of three main levels of aggregation: (i) the battery cells, (ii) the battery modules and (iii) the battery pack. The battery pack (iii) is what constitutes an entire battery that can be directly incorporated into an application and provide power, the battery modules (ii) consist of several battery cells that are connected in series and/or parallel to achieve the voltage required by the application. The battery cell (i) is the smallest component where the chemistry behind the battery takes place and the actual storage of energy occurs.

The cells used in the modelled aeroplane are assumed to be NMC811 (nickel-manganese-cobalt cathode) cylindrical cells produced in Asia. The cells are thereafter assumed to be assembled into modules and packs in the USA, from where the full battery pack will be delivered to Heart Aerospace. The LCI data is based on a previous study by Chordia et al. (2021), which provides inventory data based on large-scale manufacturing of cylindrical 21700-type NMC811 battery cells in so-called ”gigafactories”, which produces cells at a scale exceeding 1 GWh annual capacity. It is assumed that most battery cells produced in the second half of the 2020s will be produced in such factories. The LCI data from the study by Chordia et al. (2021) is considered relevant for cells with an energy density of 210-240 Wh/kg. The data in Chordia et al. (2021) is altered to include an Asian energy mix to match the country of production. Table 5.5 shows the different cell specifications.

Table 5.5: Battery cell specifications obtained from Chordia et al., 2021.

Cell property	**Specification**
Cell chemistry	NMC811
Cell geometry	Cylindrical
Cell type	21700
Cell energy density	210-240 Wh/kg

To achieve the goal of a 200 km all-electric mission, the energy density of the batteries might need to be higher than the currently, commercially, available cells. It is assumed in this study that the energy density required will be achieved, although there is no LCI data available for future cells. Therefore, it is assumed that future developments in battery cell chemistry will not influence the overall material composition, weight and energy requirements in production of a cell. Thus, the LCI data provided by Chordia et al. (2021) is assumed valid in this study, even though it could be outside of the stated validity range of 210-240 Wh/kg. Chordia et al. (2021) provides LCI results using the reference flow ”kWh”, but using that reference flow in this study could mean that too many cells would be needed to achieve the goals of the ES-30, which could increase the battery weight significantly. Therefore, the LCI data for this model was recalculated to the reference flow ”1 kg of cells”. The full BESS has a total weight of approximately 5 metric tons, which together with the composition described in Table 5.4 gives the total weight of the different battery components. The composition of the BESS components is derived from the composition of the battery pack described in Arvidsson et al. (2023).

Going from cell level to module- and pack level includes further processing and material inputs. The LCI data on these stages of production is based on the article by Arvidsson et al. (2023). It contains LCI data on material inputs for producing batteries, consisting of module and battery pack materials for a small, fully electric aeroplane with a seating capacity of two persons. Although this is substantially smaller than the ES-30, its battery pack will need to withstand similar conditions in terms of G forces, temperature and landing impacts and it is therefore considered a viable source of data. The module and pack data in Arvidsson et al. (2023) is calculated with the reference flow of ”two lithium-ion battery (LIB) packs, in total storing 21 kWh of energy and with a total mass of 118 kg, including 2 kg of battery management system (BMS) equipment”. The cells, BMS and HV-connectors are excluded from the unit process, leaving a reference flow ”1 kg of module and pack components”, which is scaled to the weight of the module and pack using the component composition described in Section 5.4.

Arvidsson et al. (2023) include separate LCI data for the BMS and HV connectors. The BMS is modelled by the authors using the reference flow ”BMS, for 1 LIB pack unit, 4 modules, 1 kg”. This also amounts to 1 kg of BMS that is used in the modelling of the BMS of the model of the aeroplane using the component composition of the BESS. Arvidsson et al. (2023) models HV connectors with the reference flow ”1 HV connector”, which is also used in this study by matching with the number of HV-connectors needed in the energy storage system of the modelled aeroplane.

5.4.2 Electric motor

The production of the electric motors is modelled based on a cradle-to-gate LCI study by Nordelöf et al. (2017), which provided a scalable model of electric motors, including input materials, emissions and waste. This model is intended to be used in the automotive industry and for electric motors with a power output of 20 - 200 kW and a torque output of 48 - 477 Nm (Nordelöf et al., 2017). However, it is considered applicable for aeroplanes too, despite their higher power and torque requirements. For the modelled aeroplane, the intended power output from one electric motor is 1.5 MW, producing 900 Nm of continuous torque. The material composition of the 1.5MW motor can be calculated by setting the model by Nordelöf et al. (2017) to 200 kW, and then the data is extrapolated linearly to 1.5 MW. This results in a motor weighing 442 kg if the casing and end bells (lids of the cylindrical casing) of the motor are excluded, 650 kg if these are included. However, these weights are too high to be used in the aviation industry. To solve this, the model is instead set to a torque of 477 Nm and then extrapolated to 900 Nm, resulting in a motor with a weight of 164 kg including housing and endbells. Internal experts at Heart Aerospace consider this weight close to the actual weight. According to the scalable LCI model, the motor consists of several materials. The largest by weight are aluminium, steel and copper. The motor also consists of rare metals in the permanent magnets, such as dysprosium and neodymium. The motor also needs a reduction gearbox made from cast iron adding a weight of 66 kg.

5.4.3 Nacelle

The nacelles, which provide cover for the electric motors and turboprop engines, are assumed to be the same size for the electric motor, and the turboprop engines. The material composition used to model them is based on the dataset provided by Thonemann et al. (2023) and scaled to fit the target weight provided by Heart Aerospace.

5.4.4 Propeller

The propellers of the aeroplane are modelled to be made of CFRP. The amount of CFRP required is based on the target weight of the propellers provided by engineers at Heart Aerospace.

5.4.5 Power inverter

Similar to the electric motors, the power inverters needed in the drivetrain are based on a previous cradle-to-gate LCI study by Nordelöf et al. (2018), which provides a scalable inventory model of power inverters. This study provides LCI data for inverters within the power range of 20-200 kW and DC voltage range of 250-700 V intended for the automotive industry (Nordelöf et al., 2018). Again, the modelled aeroplane requires higher values (250 kW and 800 V) but the LCI model is still considered applicable and scalable to these requirements, as confirmed with experts at Heart Aerospace. The material composition of the inverters is calculated by setting the model to their maximum ranges and then extrapolating the data to the requirements for the ES-30. This resulted in an inverter weighing 15.6 kg. The model in its current configuration would require a total of 12 power inverters (Heart Aerospace).

5.4.6 Turboprop engine

The turboprop engine is modelled based on the inventory data provided by Thonemann et al. (2023). The materials in that inventory were then presented to engine experts at Heart and deemed applicable for the engines for the model of the aeroplane. However, the specific engine modelled by Thonemann et al. (2023) was deemed too heavy by engineers at Heart Aerospace and therefore an alternative needed to be selected. The turboprop engine investigated during the time of the project weighs 283 kg with a gearbox included. The ratio between engine and gearbox presented by Thonemann et al. (2023) results in a too-heavy gearbox for the selected engine. Therefore, the correlation between shaft horsepower and gearbox weight presented by Brown et al. (2005) is used to estimate the weight of the gearbox needed for the selected engine. For the maximum power requirement of 1 600 shaft horsepower for the selected engine, the weight of the gearbox is estimated to be 68 kg.

5.5 Transportation

Transport of aeroplane components is calculated based on transport distances from known suppliers to Heart Aerospace's assembly plant using distance data obtained from the online shipping calculator sea-distances.org for ocean shipping, Google Maps for road-based transports, and planner.dbcargo.com for shipping by rail. If a supplier is not chosen for a component or system yet, an average transportation by truck within Europe is assumed. Since some supplier relationships are not publicly available information, the transport will be reported as an aggregated sum and only divided according to the mode of transport.

5.6 Assembly plant

The assembly of the aeroplane includes the merging of all components into the finished product. The geographical location of this assembly plant is not yet determined, although Heart Aerospace has signed a letter of intent with the municipality of Halmstad in southwestern Sweden to place its first assembly plant at Halmstad City Airport (Halmstad Kommun, 2023). Therefore, the assembly is assumed to take place at Halmstad City Airport and all components are transported there.

The buildings that Heart Aerospace will need for the assembly of the ES-30 have not been built yet, but there are plans on how much area they will cover. The plant will consist of several hangars similar to the Ecoinvent process ”building construction, hall, steel construction”. All buildings are therefore modelled as this kind of building with a lifetime of 50 years. The environmental burden of the construction of the assembly plant is calculated by dividing the burden between all aeroplanes that are supposed to be delivered during a 50-year period.

There are plans for the assembly line at the plant, but a complete inventory of all the necessary manufacturing equipment is not available. Since there will be no component production at the plant and the various components will only be assembled, it is assumed that no large-scale machinery will be needed. According to the production engineer at Heart Aerospace, there will be a lot of hand tools as well as cranes to lift larger components before assembly. This equipment is assumed to contribute a minor share of the entire environmental impact of the assembly plant and therefore omitted from the LCA.

The electricity needs of the assembly plant are not yet finalised either, but according to the production engineer the majority (> 90 %) of the electricity demand will come from battery charging. Extensive testing of a finished aeroplane is performed and during this testing, the battery will need to be charged 3-4 times before delivery to the customer. Therefore, the electricity demand per assembled aeroplane is calculated as the electricity, in kWh, consumed during 4 test flights according to the typical mission distance of 260 km.

The heating of the facilities in Halmstad will come from the municipal district heating system and is therefore modelled according to the Ecoinvent process ”heat, district or industrial, other than natural gas”. The heat to the plant is expected only to be used for ambient heating of the facilities. The amount of heat needed has not been calculated by Heart Aerospace and is therefore based on average numbers on industrial facilities obtained from the Swedish Energy Agency (Energimyndigheten, 2021). The average numbers are then multiplied by the area of the facilities.

There will also be a need for water, mainly for the cleaning of parts and finished aeroplanes. The amount of water was estimated by the production engineer at Heart Aerospace to be 400 L per aeroplane. During the testing of the finished ES-30, there will also be a need for kerosene during testing of the turboprop engines. The required amount is based on the amount needed for 4 typical regional flights of 260km, similar to the electricity demands.

5.7 Use phase

The use phase of the modelled ES-30 is based on simulations of different use cases developed by Heart Aerospace. These simulations account for electricity and fuel needed for different mission distances as well as energy reserves needed for potential touch-and-go situations or the case of being redirected to another airport. This means that the ES-30 will always have more fuel than necessary to perform a planned mission in case it needs to remain airborne for longer than planned. These simulations are developed by a senior flight science engineer. Since the ES-30 is still in development, the simulations might not be valid for a real-life scenario.

5.7.1 Charging efficiency

The charging efficiency of the batteries affects the electricity requirement of the use phase. There are two ways to charge the ES-30. The first is a normal DC fast charging station used for electric passenger cars. However, given the large capacity of the batteries, these will function as a slower means of charging the ES-30. The charging efficiency of these types of chargers varies between 91 % reported by Genovese et al. (2015) and 98 % according to Özbakir (2018). The second means of charging is through fast charging, which will be needed when a short turn-around time (less than 30 min) is required by the airlines. To manage this, Heart Aerospace intends to use the megawatt charging system (MCS), which can charge at up to 3.75 MW (Manthey, 2023). The MCS is not yet in commercial use but has been tested by the EV-charging manufacturer ABB E-mobility, and the electric truck manufacturer Scania (ABB E-mobility, 2023). The efficiency of the MCS has not been evaluated in scientific literature or by ABB E-mobility but a value of 98 % is used in this study. For simplicity, this charging efficiency is used for both fast- and slow charging of the ES-30. This means that 2 % of the electricity required to charge the aeroplane is lost. These losses are accounted for throughout the life cycle.

5.7.2 Battery capacity loss

Lithium-ion batteries (LIB) lose capacity during their lifetime. Several factors influence a battery's operational lifetime, such as calendar ageing, operating temperature, charging, and overall usage of the battery (Zhang et al., 2021). The most influential in the case of the ES-30 is the charging and usage of the battery. A commercial aeroplane has a high initial investment cost and airliners want to get a return on that investment as soon as possible. Therefore, they strive to keep the aeroplane airborne as often as possible. Because of this, the battery will be used and charged often, which will influence its lifetime negatively. Once the battery reaches a state of health (SOH) of 80 %, meaning that it can only carry 80 % of its initial maximum state of charge, it is no longer considered usable onboard the ES-30 and needs to be replaced.

To estimate the capacity loss of the battery, the estimated depth of discharge (DOD) for different flight profiles is used. This takes into account the average DOD that the battery is exposed to. If the battery is continuously discharged to 80 % DOD, it will lose capacity faster than if discharged to 50 % DOD (Xiong, 2019). However, this does not take into account charging methods, operating temperatures or calendar ageing. In the report by Xiong (2019), they describe the DOD as the "dominant effect" of the cycle life of a LIB. According to another study by Yang et al. (2021), NMC cells that are continuously discharged to more than 65 % DOD will reach 80 % SOH substantially faster. This is the reason for the extended cycle life for the 100 km flight profile compared to the other four flight profiles, described in Section 5.7.6. During the use phase, replacements of new battery packs are needed. Since the ES-30 will be used globally, the destinations of the transports are not possible to predict. To account for these transports in the model, the same distance and mode of transport as for the first battery pack (cells from Asia shipped to the USA for assembly into packs which is then shipped to Sweden) is used throughout the life cycle of the ES-30.

5.7.3 Wheel and tyre changes

The wheels and tyres of passenger aeroplanes are changed several times during an operating year. According to a senior maintenance engineer at Heart Aerospace, they need to be changed every 350 landing for the main landing gear and every 250 landing for the nose landing gear. The difference is that the nose landing gear is used for turning the aeroplane while on the ground. This leads to more stress on these wheels than on the main landing gear wheels. These intervals for tyre- and wheel changes are used in the modelled use phase.

5.7.4 Fuel

The life cycle of the aeroplane is modelled using two different fuel types, standard jet A-1 fuel (kerosene) and AAF, alternative aviation fuels. The production of the kerosene is modelled using a market process available in Ecoinvent for kerosene. The emissions associated with the combustion of kerosene are not available in Ecoinvent, so therefore, kerosene emission factors from Lopes (2010) are applied. AAF can be produced in a variety of ways. The one with the highest technology readiness level (TRL 9) is called HEFA (hydro-processed esters and fatty acids) and this is also the one most readily available on the market (Trinh et al., 2022). The feedstock of HEFA fuel can come from different sources, such as waste products like used cooking oil (UCO) and animal fats, but also primary products such as palm oil, soybean oil and rapeseed oil (EASA, 2022a). In the use phase, it is assumed that the AAF is a HEFA fuel produced from UCO or soybeans. It is assumed that combustion of the HEFA fuel results in the same emissions as the jet A-1 fuel, aside from the CO_2 and CO emissions being non-fossil and that the PM emissions are reduced by 50-97 % as stated by EASA (2022b). The average value of 73.5 % is used in this LCA. The heating value (the amount of energy per unit of weight it contains) of Jet A-1 fuel and the HEFA is assumed to be the same in the study, although Boehm et al. (2022) report a small difference in the heating value for HEFA (1.5 % higher for HEFA). The modelling of the HEFA fuel is conducted using LCI data from the Swedish Environmental Research Institute (IVL) (Trinh et al., 2022). In this study, the UCO is assumed to come from China, which according to IVL is a major exporter of UCO to Europe and North America. In China, the UCO is pre-treated and then shipped to Belgium where the UCO is refined into finished AAF. In the case of the soybean feedstock, an entire life cycle inventory could not be found but the International Civil Aviation Organization has created a model which gives the production-related climate change impact arising from AAF produced from US-grown soybeans using the HEFA pathway ICAO (2019b). The value stated is 39 g CO_2-eq per MJ fuel, this value is used for calculating the climate change impact of AAF from soybeans. Generally, biofuels in the EU are increasingly produced using UCO and animal fats and in the US they are increasingly produced from soybeans (International Energy Agency, 2022). Since the ES-30 is intended for both of these markets, AAF produced from UCO and soybeans is interesting to consider.

5.7.5 Utilisation

For flight analysis, Heart Aerospace is using three utilisation profiles of the aeroplane. These are (i) low utilisation, (ii) average utilisation and (iii) high utilisation. The utilisation profiles and their specifications are presented further in Table 5.6. In this study, only the average utilisation is considered in the use phase since otherwise, too many scenarios would obscure the analysis and its interpretation.

Table 5.6: Utilisation profiles of the ES-30.

Specifications	Low utilisation	Average utilisation	High utilisation
Annual flight hours	1 200 FH	1 785 FH	2 100 FH
Slow charging	70 %	50 %	40 %
Fast charging	30 %	50 %	60 %

5.7.6 Mission profile

As with any hybrid-electric transportation mode, the distance travelled has a large influence on the electricity and fuel consumption. In the aviation industry, this is referred to as the ”mission distance”, defined as the distance travelled from point A to B. The life-cycle consumption is also dependent on the number of flight hours throughout the aeroplanes’ lifetime, which is described in the before-mentioned utilisation profiles. Five different mission distance profiles are described in the below sections. The assumptions for all mission profiles are described in Table 5.7.

Table 5.7: Assumptions on all mission profiles.

Days flying per year (#)	350
Passengers per flight (#)	30
ES-30 lifetime (years)	30
Charging efficiency, slow (%)	98
Charging efficiency, fast (%)	98
MLG wheel and tyre changes (landings)	350
NLG wheel and tyre changes (landings)	250

In the profiles, it is assumed that the aeroplane will have a constant mission distance on all flights throughout its lifetime (no switch between shorter and longer distances). Aside from the fuel and electricity consumption, battery depletion and replacements as well as tyre and wheel changes are accounted for. The passengers per flight are assumed to remain constant at 30 passengers, whereas in reality, it is uncommon for an airline to have a load factor of 100 %. During the years before the COVID-19 pandemic, the average load factor for an airline was about 80 % (Statista, 2022). However, for reasons of comparability to other studies, a 100 % load factor is assumed in this LCA.

5.7.6.1 Typical mission

The ”typical mission” of the ES-30 is calculated by Heart Aerospace and estimated to be 260 km. This distance together with the average utilisation profile from Table 5.6 is considered to be the base-case in this LCA. The specifications for a typical mission flight are presented in Table 5.8.

Table 5.8: Typical mission specifications.

Mission distance	260 km
Electricity consumption per flight	954 kWh
DOD per flight	73.5 %
Fuel consumption per flight	79 kg
Flights to battery at 80 % SOH	2500

Combining the average utilisation profile in Table 5.6, the assumptions on all mission profiles in Table 5.7 and the specifications from the typical mission profile in Table 5.8 results in several metrics for the typical mission case, presented in Table 5.9.

Table 5.9: Typical mission data.

Utilisation profile	**Average**
Annual flight hours (FH)	1785
Flights per day (#)	5.0
Yearly flights (#)	1750
Annual el. cons. (MWh)	1669
El cons. inc. inefficiency (MWh)	1703
Annual fuel cons. (kg)	139 003
Years to BESS 80 % SOH (#)	1.43
Annual BESS consumption (#)	0.70
Slow charging	50 %
Fast charging	50 %
Annual distance travelled (km)	4.55E+05
Annual passenger km travelled (pkm)	1.37E+07
LC distance travelled (km)	1.37E+07
LC passenger km travelled (pkm)	4.10E+08
Annual MLG wheel and tyres change (#)	5.0
Annual NLG wheel and tyres change (#)	7.0

5.7.6.2 Fjord-hopper

This utilisation case is described as the ”fjord-hopper” case, taken from one of the cases for which the ES-30 is marketed. In the Norwegian fjords, it is common to travel in small turboprop aeroplanes over smaller bodies of water that would have taken a much longer time to drive around. This case considers 100 km missions throughout the ES-30 lifetime. The specifications for a 100 km flight are presented in Table 5.10.

Table 5.10: Fjord-hopper mission specifications.

Mission distance	100 km
Electricity consumption per flight	555 kWh
DOD per flight	39 %
Fuel consumption per flight	17 kg
Flights to battery at 80 % SOH	4000

Combining the utilisation profiles in Table 5.6, the assumptions on all mission profiles in Table 5.7 and the specifications from the fjord-hopper mission profile in Table 5.10 results in several metrics for the ”fjord-hopper” mission case, presented in Table 5.11.

Table 5.11: Fjord-hopper mission data.

Utilisation profile	**Average**
Annual flight hours (FH)	1785
Flights per day (#)	12.0
Yearly flights (#)	4200
Annual el. cons. (MWh)	2332
El cons. inc. inefficiency (MWh)	2379
Annual fuel cons. (kg)	70 363
Years to BESS 80 % SOH (#)	0.95
Annual BESS consumption (#)	1.05
Slow charging	50 %
Fast charging	50 %
Annual distance travelled (km)	4.20E+05
Annual passenger km travelled (pkm)	1.26E+07
LC distance travelled (km)	1.26E+07
LC passenger km travelled (pkm)	3.78E+08
Annual MLG wheel and tyres change (#)	12.0
Annual NLG wheel and tyres change (#)	16.8

5.7.6.3 Regular regional

The ”regular regional” case of the ES-30 uses a mission distance of 200 km for all missions during the aeroplane’s lifetime. This flight profile utilises the battery of the aeroplane to its maximum. The specifications for a regular regional flight are presented in Table 5.12.

Table 5.12: Regular regional mission specifications.

Mission distance	200 km
Electricity consumption per flight	954 kWh
DOD per flight	73.5 %
Fuel consumption per flight	17 kg
Flights to battery at 80 % SOH	2500

Combining the utilisation profiles in Table 5.6, the assumptions on all mission profiles in Table 5.7 and the specifications from the regular regional mission profile in Table 5.12 results in several metrics for the regular regional mission case, presented in Table 5.13.

Table 5.13: Regular regional mission data.

Utilisation profile	**Average**
Annual flight hours (FH)	1785
Flights per day (#)	7.0
Yearly flights (#)	2450
Annual el. cons. (MWh)	2339
El cons. inc. inefficiency (MWh)	2386
Annual fuel cons. (kg)	41 045
Years to BESS 80 % SOH (#)	1,02
Annual BESS consumption (#)	0.98
Slow charging	50 %
Fast charging	50 %
Annual distance travelled (km)	4,90E+05
Annual passenger km travelled (pkm)	1,47E+07
LC distance travelled (km)	1,47E+07
LC passenger km travelled (pkm)	4,41E+08
Annual MLG wheel and tyres change (#)	7.0
Annual NLG wheel and tyres change (#)	9.8

5.7.6.4 Long regional

The ”long regional” case of the ES-30 uses a mission distance of 400 km for all missions during the aeroplane’s lifetime. This case results in a higher fuel consumption than the three previously mentioned mission cases since the battery of the aeroplane is set to perform an all-electric flight of a maximum of 200 km. The specifications for a long regional flight are presented in Table 5.14.

Table 5.14: Long regional mission specifications.

Mission distance	400 km
Electricity consumption per flight	955 kWh
DOD per flight	73.5 %
Fuel consumption per flight	217 kg
Flights to battery at 80 % SOH	2500

Combining the utilisation profiles in Table 5.6, the assumptions on all mission profiles in Table 5.7 and the specifications from the long regional mission profile in Table 5.14 results in several metrics for the long regional mission case, presented in Table 5.15.

Table 5.15: Long regional mission data.

Utilisation profile	**Average**
Annual flight hours (FH)	1785
Flights per day (#)	4.0
Yearly flights (#)	1400
Annual el. cons. (MWh)	1335
El cons. inc. inefficiency (MWh)	1449
Annual fuel cons. (kg)	304 291
Years to BESS 80 % SOH (#)	2.28
Annual BESS consumption (#)	0.44
Slow charging	50 %
Fast charging	50 %
Annual distance travelled (km)	5.60E+05
Annual passenger km travelled (pkm)	1.68E+07
LC distance travelled (km)	1.68E+07
LC passenger km travelled (pkm)	5.04E+08
Annual MLG wheel and tyres change (#)	4.0
Annual NLG wheel and tyres change (#)	5.6

5.7.6.5 X-long regional

The ”X-long regional” case of the ES-30 uses a mission distance of 600 km for all missions during the aeroplane’s lifetime. This case will result in the highest fuel consumption per flight of all mission profiles since the battery of the ES-30 is scaled to perform an all-electric flight of a maximum of 200 km. The specifications for an X-long regional flight are presented in Table 5.16.

Table 5.16: X-Long regional mission specifications.

Mission distance	600 km
Electricity consumption per flight	954 kWh
DOD per flight	73.5 %
Fuel consumption per flight	405 kg
Flights to battery at 80 % SOH	2500

Combining the utilisation profiles in Table 5.6, the assumptions on all mission profiles in Table 5.7 and the specifications from the X-long regional mission profile in Table 5.16 results in several metrics for the X-long regional mission case, presented in Table 5.17.

Table 5.17: X-Long regional mission data.

Utilisation profile	**Average**
Annual flight hours (FH)	1785
Flights per day (#)	2.0
Yearly flights (#)	700
Annual el. cons. (MWh)	668
El cons. inc. inefficiency (MWh)	681
Annual fuel cons. (kg)	283 643
Years to BESS 80 % SOH (#)	3.57
Annual BESS consumption (#)	0.28
Slow charging	50 %
Fast charging	50 %
Annual distance travelled (km)	4.20E+05
Annual passenger km travelled (pkm)	1.26E+07
LC distance travelled (km)	1.26E+07
LC passenger km travelled (pkm)	3.78E+08
Annual MLG wheel and tyres change (#)	2.0
Annual NLG wheel and tyres change (#)	2.8

5.8 End-of-life

Decommissioning of aeroplanes has historically consisted of airfield storage, or storage in e.g., desserts outside of the EU (European Comission, n.d.). To combat this growing problem, Airbus coordinated the Process for Advanced Management of End of Life of Aircraft (PAMELA) in the early 2000s to initiate a recycling program, which showed that up to 85 % of an aeroplane's components could be recycled (European Comission, n.d.).

Today, many aeroplane carriers are focusing on appropriate EoL processes for retired aeroplanes (ICAO, 2019a). According to ICAO (International Civil Aviation Organisation), an ideal process for the EoL process is broken down into a series of steps. The first step includes dismantling the aeroplane to salvage its valuable components that can return to the aviation market. After the components relevant for reuse have been removed, other components that might have value for other markets and applications are removed from the aeroplane. The remaining parts of the aeroplane are considered waste and the last steps include sorting recyclable waste, and waste that will go to disposal and landfilling (ICAO, 2019a). Development of aeroplane recycling has proven successful and today about 85-95 % of the weight of a retired aeroplane is re-used or recycled (ICAO, 2019a).

In this study, the cut-off approach is applied, meaning that material inputs to the aeroplane are assumed to contain some recycled content according to market processes for that specific material. The aeroplane is assumed to be dismantled and the materials sorted into the corresponding market process for waste/scrap handling and thereafter assumed to exit the technical system. All electrical components, such as the electric motor and power inverter are sorted into the ”market for shredder fraction after manual dismantling of used electronic product | shredder fraction after manual dismantling of used electronic product | Cutoff, U - GLO”. The turboshaft engines are also included in this market process due to their complex alloys and material mixes. For a detailed division of the materials after the disassembly of the aeroplane, see Appendix A.7.

5.9 Background modelling

A couple of custom material processes are created to better meet the requirements of the materials going into the production of the aeroplane. Much of the aluminium used goes into the fuselage and wings where sheets of aluminium are the main component. Therefore, a custom aluminium process is introduced by combining the ”aluminium wrought alloy”, ”metal working average for aluminium product manufacturing” and ”sheet rolling aluminium” processes in Ecoinvent. For aluminium components not made out of sheet aluminium, a suitable aluminium alloy and processing process is selected.

For steel, ”chromium steel 18/8” is assumed due to the high requirements for strength and resistance to corrosion. The process ”metal working average for chromium steel product manufacturing” is added to account for machining and metalworking on the steel components.

Composite, lightweight, materials are often used in aircraft production, and one material that is assumed to be used in the modelled aeroplane is ”NOMEX HC”, which is a nonmetallic honeycomb core material made from aramid fibre paper. There is no included process of NOMEX HC-production in Ecoinvent and therefore a custom process was created based on the material composition presented in Campos (2023).

6

Impact assessment

In this section, the results from the LCIA are presented. Tables 6.2, 6.7, 6.12 and 6.15 show the contributions of each phase of the modelled aeroplane's life cycle. The base-case scenario is a typical mission distance of 260 km, 1 750 annual flights, 30 passengers per flight, 30-year lifetime, using fossil jet fuel (kerosene), Swedish electricity supply mix and battery cells produced in Asia. All batteries that will be used through the life cycle are included in the use phase of the aeroplane, even though one BESS is mounted to the aeroplane during original assembly. The BESS is thus considered a consumable in the same manner as jet fuel. The same rationale is applied to the wheels and tyres of the landing gear, which are included in the "maintenance" during the use phase. Table 6.1 provides results independent of impact categories but can preferably be read in conjunction with the impact assessment to compare the different impact categories. The total battery energy storage systems needed are decreasing with increasing flight distances since increased distance leads to a decreased total number of flights an airline can achieve per day. This means the batteries are cycled less and therefore their longevity is increased and hence need to be replaced less often. The total number of pkm per flight profile is dependent on the flight distance and how many flights can be achieved per day; the maximum is achieved in the 400 km flight profile.

Table 6.1: Total number of BESS and pkm over life cycle.

Flight profile	**Total BESS (#)**	**Total pkm**
100 km	31.5	3.78E+08
200 km	29.4	4.41E+08
260 km	21	4.10E+08
400 km	16.8	5.04E+08
600 km	8.4	3.78E+08

6.1 Global warming

Table 6.2 presents the results of the total global warming potential, highlighting the contributions of the production, use phase and EoL of the base-case scenario.

Table 6.2: Climate change impact of 1 modelled aeroplane life cycle, base-case scenario.

Phase	System	kg CO_2-eq	Share
Production	Structure	1.85E+05	0.80 %
	Drivetrain	9.66E+04	0.41 %
	Operational systems	2.99E+04	0.13 %
	Interior	1.66E+04	0.07 %
	Assembly	4.22E+03	0.02 %
	Transports	2.37E+03	0.01 %
	Total contribution	3.35E+05	1.44 %
Use	Kerosene	1.68E+07	72.24 %
	Electricity consumption	1.90E+06	8.14 %
	BESS replacements	2.51E+06	10.76 %
	Maintenance	1.72E+06	7.40 %
	Total contribution	2.30E+07	98.54 %
End-of-Life	Total contribution	5.21E+03	0.02 %
Total	Modelled aeroplane	2.33E+07	100.00 %

The distribution of climate impact per phase varies little between the different flight profiles, as can be seen in Figure 6.1. The largest differences lie within the use phase for the different profiles, which are further discussed in Section 6.1.2

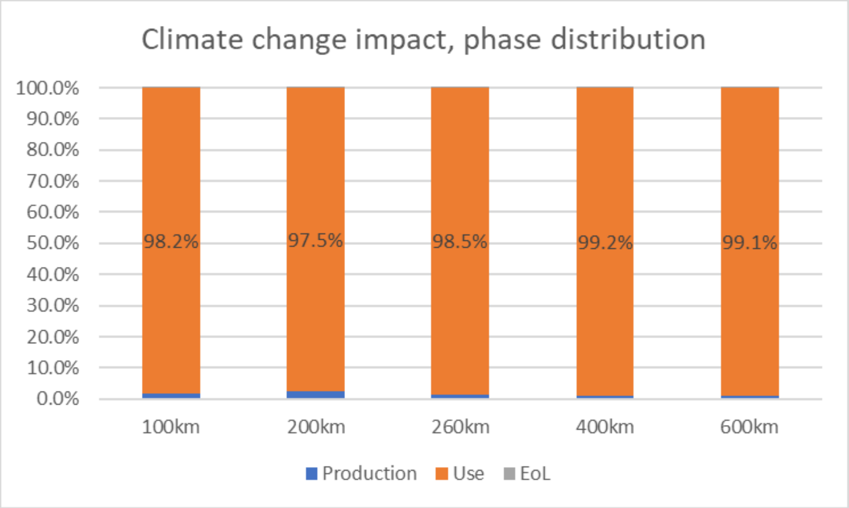


Figure 6.1: Climate change impact phase distribution.

The climate change impact scaled per pkm differs notably between the different flight profiles, as can be seen in Figure 6.2. The climate impact per pkm for a comparative aeroplane, the ATR-42, is also added for comparison (Vivalda, 2023).

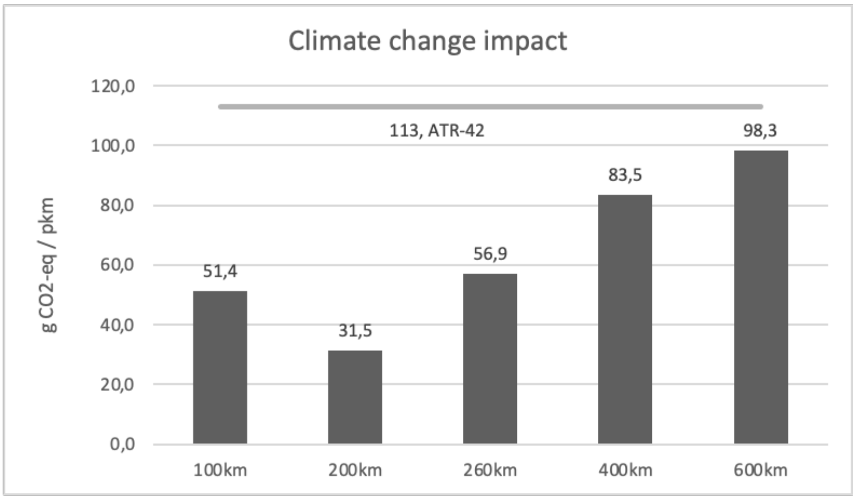


Figure 6.2: Climate change impact per pkm.

As can be seen in Figure 6.2 the 200 km mission profile has the lowest climate change impact. The reason for the 100 km being higher is due to the fuel being burnt while keeping the turboprop engines in idle during descent and landing. The 100 km mission profile leads to a higher number of yearly flights, which then leads to more fuel being burnt and more BESS replacements during the life cycle. For the mission profiles beyond 200 km (260 km, 400 km and 600 km) we see a more linear increase of the impact that can solely be connected to the increase of fuel consumption for these mission profiles.

6.1.1 Production

Although the production phase constitutes a small share of the total climate change impact of the modelled aeroplane, it is interesting to look deeper into the production phase and what systems and components contribute more or less to the impact. Figure 6.3 provides more detailed information. The production phase of the model is not affected by the flight distance profile.

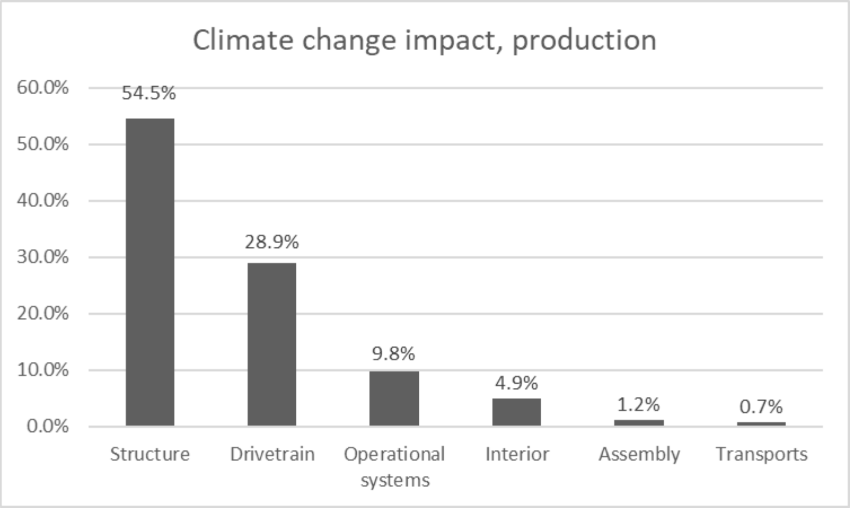


Figure 6.3: Climate change impact, production components distribution.

As seen in Figure 6.3, the three largest contributors to climate change in the production phase are the aeroplane structure, drivetrain and operational systems such as the avionics, flight control system and EWIS. These are in turn comprised of several components and their individual environmental impact is further described in Appendix B. These three major contributors are also the largest by weight which is the main reason for why they contribute to the highest impact.

6.1.2 Use phase

The use phase is the largest contributor to climate change and differs between the flight profiles. As seen in Figure 6.4 the total impact per aeroplane life time is generally larger when the model is propelled with more jet fuel than electricity. However, following that logic, the 100 km profile should result in a lower impact than the 200 km profile, which is not the case. The reason for this is that the 100 km profile achieves more flights during the life cycle and that the usage time per flight of the turboprops is the same for both profiles, resulting in more jet fuel being consumed for the 100 km profile. The reason for this is that both the 100 km and 200 km profiles need to keep the turboprops in idle during landing (and none of them needs to keep them running during cruise) and because the 100 km profile will achieve more flights per day, this results in a higher fuel consumption. This higher fuel consumption is then distributed over fewer pkm (see Table 6.1). The 400 km and 600 km mission profiles also stand out from the trend. The reason for the 600 km profile resulting in a lower total impact per aeroplane lifetime is due to the low usage of batteries compared to the 400 km profile, as can be seen in Table 6.1.

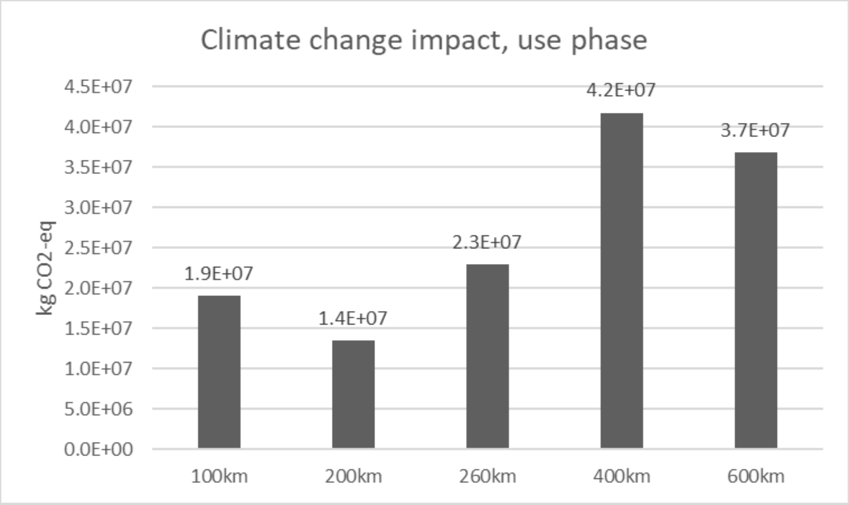


Figure 6.4: Total use phase impact comparison between flight profiles, per aeroplane life cycle.

The climate change impact distribution within the use phase of the different flight profiles is also shifting depending on how much fuel is being consumed and how often the batteries need to be replaced. The distribution of climate impacts for the flight profiles is described in Figure 6.5.

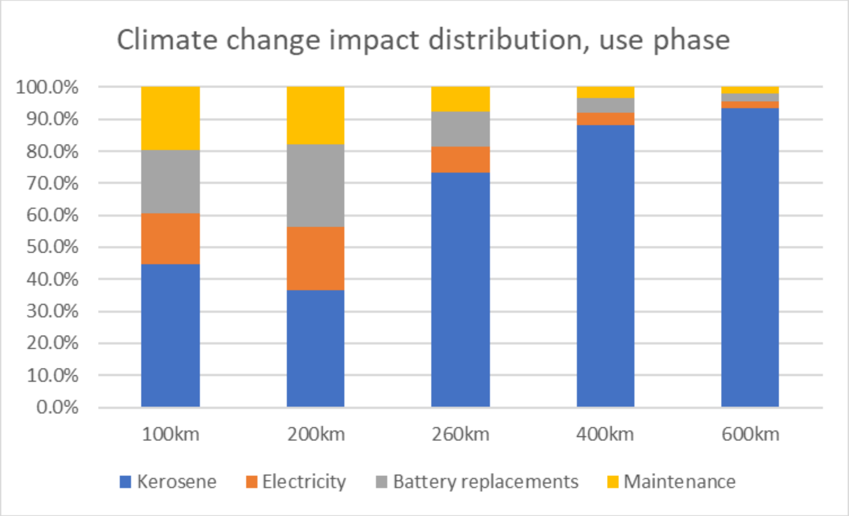


Figure 6.5: Distribution of use phase climate change impact in the different flight profiles.

The share of the climate impact originating from the production of the batteries varies between flight mission profiles, from 25 % to less than 5 % of the total use phase climate impact. The components in the BESS that contribute the most to the impact are the battery cells as can be seen in Table 6.3. The total climate impact from all BESS needed in the typical mission case (260 km) is presented in more detail in Table 6.4. The largest contributor for all mission cases is the kerosene (production plus combustion), whose individual contributions are presented in Table 6.5 and the total required BESS are presented in Table 6.2.

Table 6.3: Climate change impact, 1 BESS.

	Component	**kg CO_2-eq**	**Share**
BESS	Cells	8.33E+04	75.53 %
	Pack & module	1.56E+04	14.13 %
	BMS	1.12E+04	10.19 %
	High-voltage connectors	1.75E+02	0.16 %
	Total contribution	1.10E+05	100.00 %

Table 6.4: 260 km climate change impact, total BESS per aeroplane life cycle.

	Component	**kg CO_2-eq**	**Share**
Batteries	BESS	2.32E+06	92.35 %
	Recycling of used BESS	1.61E+05	6.41 %
	Transports	3.12E+04	1.24 %
	Total contribution	2.51E+06	100.00 %

Table 6.5: 260 km climate change impact, kerosene production and combustion per aeroplane life cycle.

	Component	**kg CO_2-eq**	**Share**
Kerosene	Combustion	1.32E+07	78.27 %
	Production	3.66E+06	21.73 %
	Total contribution	1.68E+07	100.00 %

6.1.3 End-of-life

The climate change impact from the end-of-life treatment of the modelled aeroplane constitutes a small fraction of the total impact. The distribution of the impacts is presented in Table 6.6. Plastics and electronics are the dominating categories and almost all of the impact comes from incineration. For the other categories, the amount that is incinerated is either small, or the waste treatment process includes more material recovery and land-filling.

Table 6.6: Climate change impact EoL treatment of 1 aeroplane.

	Material	**kg CO_2-eq**	**Share**
EoL	Plastics	2.86E+03	54.84 %
	Electronics	2.18E+03	41.88 %
	Aluminium	7.63E+01	1.46 %
	Textile	4.47E+01	0.86 %
	Mineral oil	3.52E+01	0.68 %
	Steel	1.23E+01	0.24 %
	Rubber	2.27E+00	0.04 %
	Total contribution	5.21E+03	100.00 %

6.2 Particulate matter

This section presents the results of the particulate matter formation. The total results of the particulate matter formation are presented in Table 6.7.

Table 6.7: Particulate matter formation impact of 1 modelled aeroplane life cycle, base-case scenario.

Phase	**System**	**kg PM2.5-eq**	**Share**
Production	Structure	3.55E+02	1.39 %
	Drivetrain	1.86E+02	0.73 %
	Operational systems	1.34E+02	0.53 %
	Interior	3.13E+01	0.12 %
	Assembly	6.17E+00	0.02 %
	Transports	5.65E+00	0.02 %
	Total contribution	7.18E+02	2.82 %
Use	Kerosene	1.20E+04	47.35 %
	Electricity consumption	2.65E+03	10.40 %
	BESS replacements	7.17E+03	28.16 %
	Maintenance	2.87E+03	11.26 %
	Total contribution	2.47E+04	97.17 %
End-of-Life	Total contribution	1.01E+00	<0.01 %
Total	Modelled aeroplane	2.54E+04	100.00 %

Again, similarly to the climate change impact, the distribution of impact per phase varies little and the use phase holds the largest share of impact which can be seen in Figure 6.6.

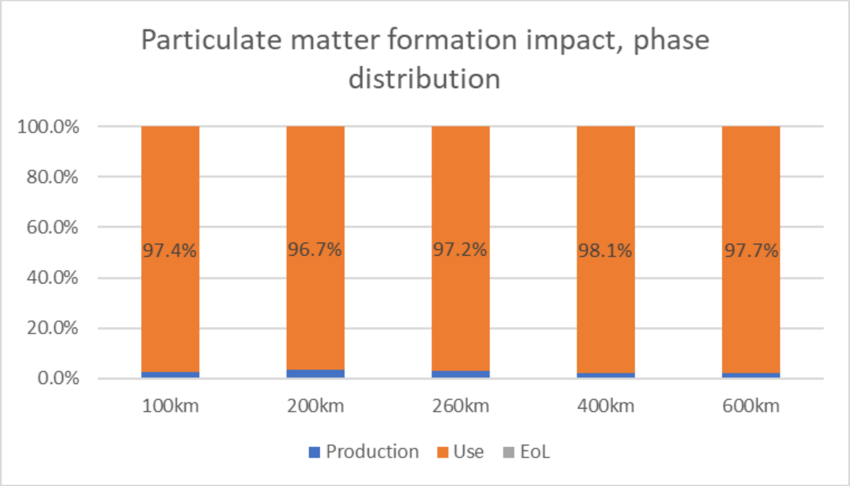


Figure 6.6: Particulate matter formation impact, phase distribution.

When studying the PM formation normalised to the functional unit per passenger km in Figure 6.7, it is clear that it follows a similar trend as the climate change impact. This can also be explained by the fact that the 100 km case consumes more fuel and batteries compared to the 200 km case during its lifetime due to a higher number of yearly flights, as described in Section 6.1.2. A comparative value for the ATR-42, is in Figure 6.7.

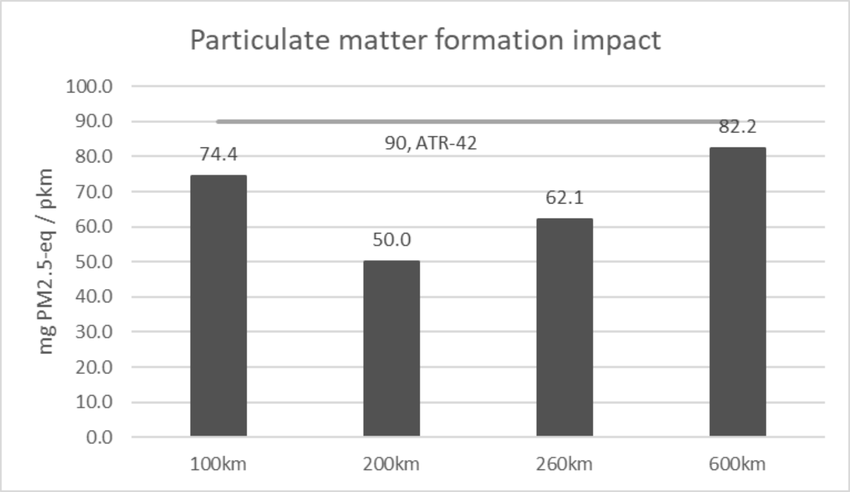


Figure 6.7: Particulate matter formation impact per passenger km.

6.2.1 Production

The distribution of impact from the different components of the production phase is presented in this section. Figure 6.8 displays the distribution. The three main contributors are the same as in the climate change impact and the reason is that these components also are the largest by weight.

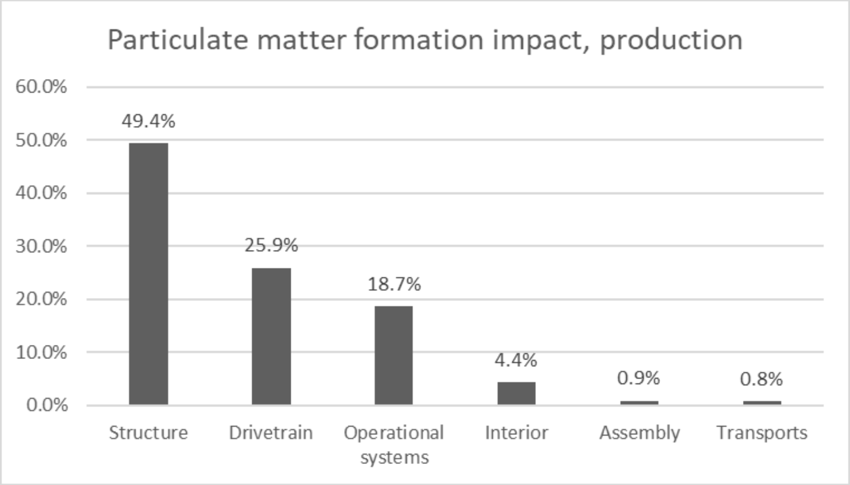


Figure 6.8: Particulate matter formation impact, production component distribution.

6.2.2 Use

The use phase is the largest contributor to particulate matter formation but its quantity differs between flight profiles. As seen in Figure 6.9, the total impact is larger when the modelled aeroplane utilises its turboprop engines more for propulsion than when it is propelled using its electric motor. However, the 100 km and 600 km mission profiles break the trend, just as in the case of climate change. The reasons for this is described in Section 6.1.2.

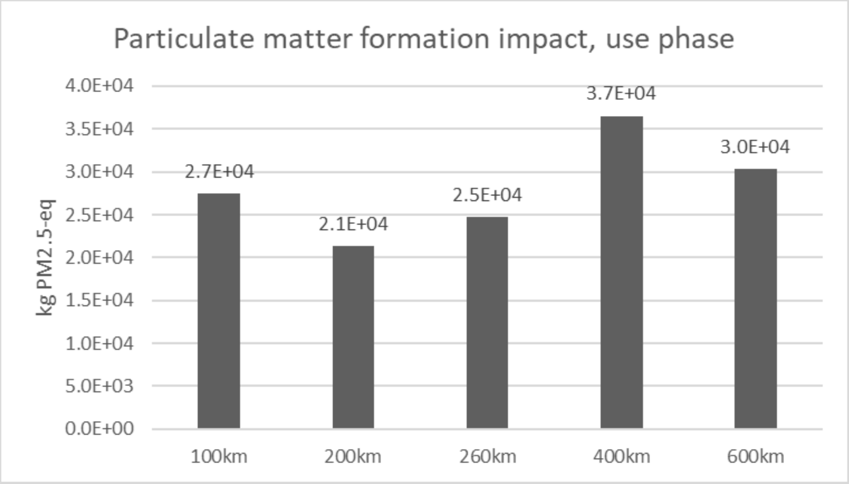


Figure 6.9: Total use phase comparison between flight profiles, particulate matter formation impact per aeroplane life cycle.

The use phase is the largest contributor to particulate matter but its distribution is different depending on the flight profile. The distribution for the flight profiles is presented in Figure 6.10.

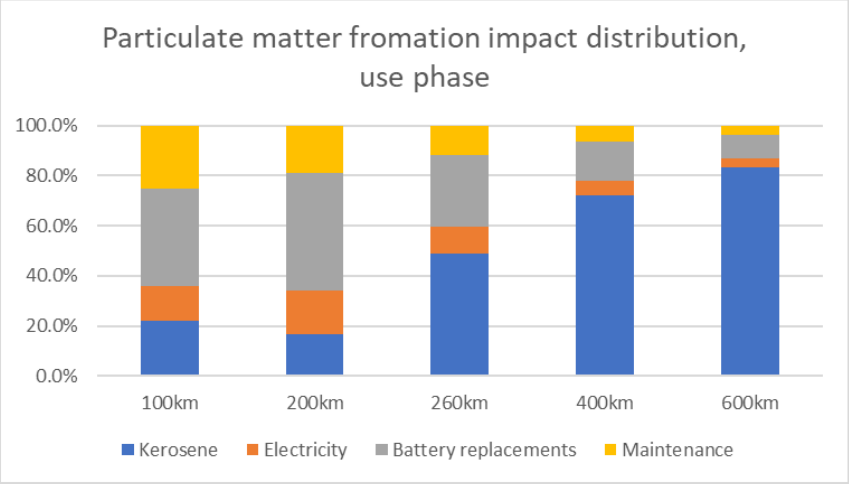


Figure 6.10: Distribution of particulate matter formation impact, in the different flight profiles.

The share of impact originating from the batteries is the dominating share for the 100 km and 200 km mission profiles, which can be seen in Figure 6.10. The component in the batteries that contribute most to the impact are the battery cells, which can be seen in Table 6.8. The total impact from all batteries needed in the typical mission case (260 km) is presented in more detail in Table 6.9. The largest contributor to the impact of the other three profiles is the kerosene production and combustion, presented in Table 6.10. Particulate matter emissions are different from climate change emissions since its impact is highly dependent on where the emissions happen. Since this study does not include high altitude effects, impacts on human health is the main impacts studied in this category. In the case of the three longest mission profiles, the emissions largely take place during the cruise phase of the flight when the turboprops are used, meaning that the risk of exposure to living organisms is low. For all mission profiles, the turboprops will be in idle during landing, leading to a higher risk of exposure to people working or living close to airports. For the 100 km and 200 km mission profiles, the particulate matter formation mainly happen during the production of the battery cells. These impacts may have a higher risk of exposure to workers in the raw material supply chain and in the cell production supply chain as well as to communities close to these operations.

Table 6.8: Particulate matter formation impact, 1 BESS.

	Component	**kg PM2.5-eq**	**Share**
BESS	Cells	2.50E+02	78.83 %
	Pack & module	3.25E+01	10.23 %
	BMS	3.20E+01	10.08 %
	High-voltage connectors	2.73E+00	0.86 %
	Total contribution	3.17E+02	100.00 %

Table 6.9: 260 km particulate matter formation impact, total BESS per aeroplane life cycle.

	Component	**kg PM2.5-eq**	**Share**
Batteries	BESS	6.67E+03	93.03 %
	Recycling of used batteries	3.47E+02	4.85 %
	Transports	1.52E+02	2.13 %
	Total contribution	7.17E+03	100.00 %

Table 6.10: 260 km particulate matter formation impact kerosene production and combustion, per aeroplane life cycle.

	Component	**kg PM2.5-eq**	**Share**
Kerosene	Combustion	7.39E+03	61.34 %
	Production	4.66E+03	38.66 %
	Total contribution	1.20E+04	100.00 %

6.2.3 End-of-life

The impact related to the EoL of the modelled aeroplane is described in Table 6.11. The distribution of the impact is similar to the climate change case which also can be explained by the incineration of waste plastics and electronics.

Table 6.11: Particulate matter formation impact from EoL treatment of the modelled aeroplane.

	Material	**kg PM2.5-eq**	**Share**
EoL	Plastics	4.66E-01	46.11 %
	Electronics	3.63E-01	35.92 %
	Aluminium	1.34E-01	13.22 %
	Textile	2.60E-02	2.57 %
	Mineral oil	1.15E-03	0.11 %
	Steel	2.08E-02	2.05 %
	Rubber	6.52E-05	<0.01 %
	Total contribution	1.01E+00	100.00 %

6.3 Mineral resource scarcity, SOP

This section presents the results of the total mineral resource scarcity impact from the life cycle of the modelled aeroplane and highlights all phases of the life cycle. Mineral resource scarcity is described using two different characterisation factors, both surplus ore potential (SOP) and crustal scarcity indicator (CSI), which is presented in the subsequent Section 6.4.

Table 6.12: Mineral resource scarcity impact (SOP) of the modelled aeroplane, base-case scenario, per aeroplane life cycle.

Phase	**System**	**kg Cu-eq**	**Share**
Production	Structure	2.55E+03	0.28 %
	Drivetrain	2.29E+04	2.52 %
	Operational systems	2.12E+03	0.23 %
	Interior	6.11E+02	0.07 %
	Assembly	2.63E+02	0.03 %
	Transports	3.35E+01	<0.01 %
	Total contribution	2.84E+04	3.13 %
Use	Kerosene	7.27E+04	8.01 %
	Electricity consumption	6.47E+04	7.12 %
	BESS replacements	7.20E+05	79.34 %
	Maintenance	2.17E+04	2.39 %
	Total contribution	8.80E+05	96.87 %
End-of-life	Total contribution	9.87E+00	<0.01 %
Total	Modelled aeroplane	9.08E+05	100.00 %

Similar to the climate change impact, the distribution of impact per phase varies little between the different flight profiles as can be seen in Figure 6.11. As in the climate change impact, the largest differences between the flight profiles lie within the use phase which is further presented in section 6.3.2.

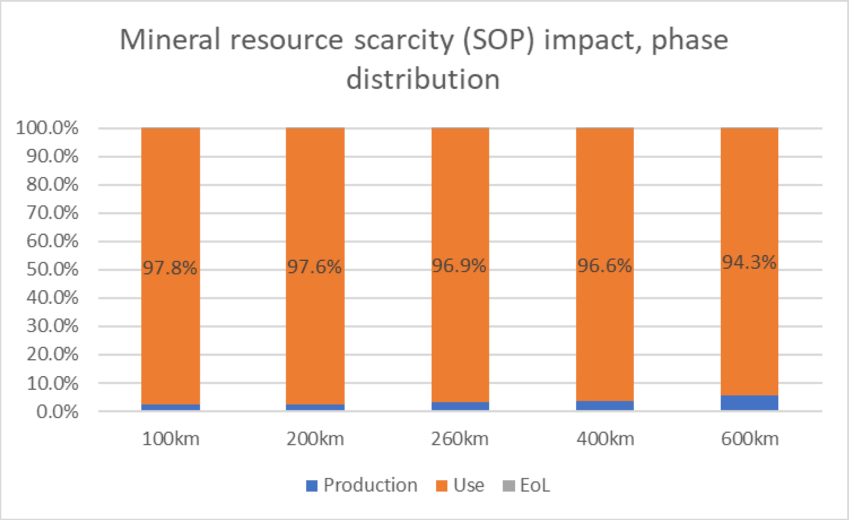


Figure 6.11: Mineral resource scarcity impact, phase distribution.

The mineral resource scarcity impact normalised per passenger km differs a lot between the different flight profiles as can be seen in Figure 6.12. The same Figure also describes the relationship between the minerals that influence the impact. The extended results from the SOP are available in Appendix, Section B.1.

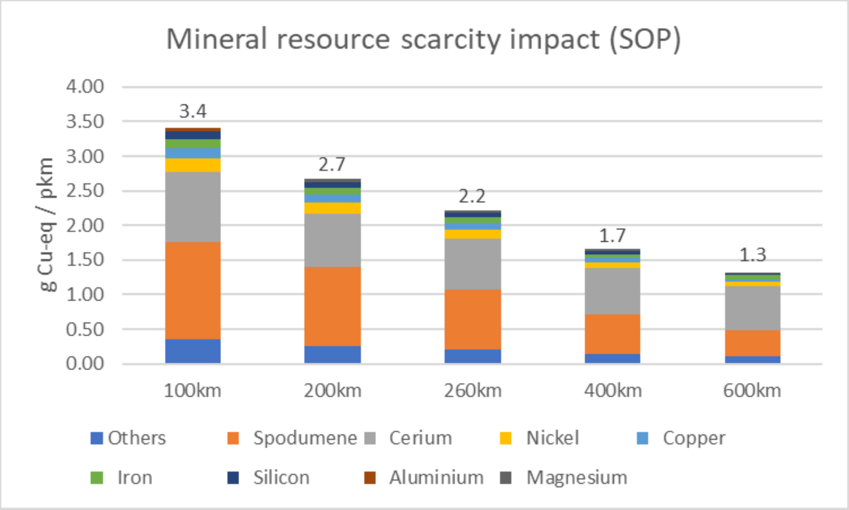


Figure 6.12: Mineral resource scarcity impact (SOP) per passenger km.

6.3.1 Production

The production phase is a relatively small share of the total impact, but it is larger for resource scarcity than for the climate impact. The different components of the modelled aeroplane and its associated mineral resource scarcity impact share are presented in Figure 6.13. The drivetrain is the largest contributor to mineral resource scarcity. One major explanation is the neodymium which is an important part of the permanent magnets in the electric motors. Although it only amounts to 3.8 kg of material per aeroplane, it accounts for 73 % of the total mineral resource scarcity (SOP) potential arising from the production.

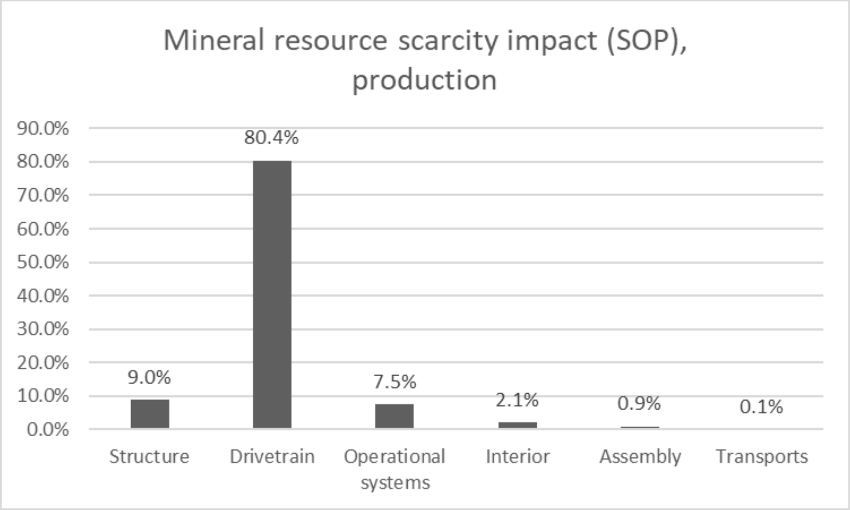


Figure 6.13: Mineral resource scarcity impact (SOP), production components distribution.

6.3.2 Use

The use phase is the largest contributor to mineral resource scarcity, but its quantity differs between flight profiles. As shown in Figure 6.14, the total impacts are larger when the modelled aeroplane utilises its batteries more for propulsion and will therefore need to have them replaced more often, compared to when it is propelled using its conventional turboprop engines.

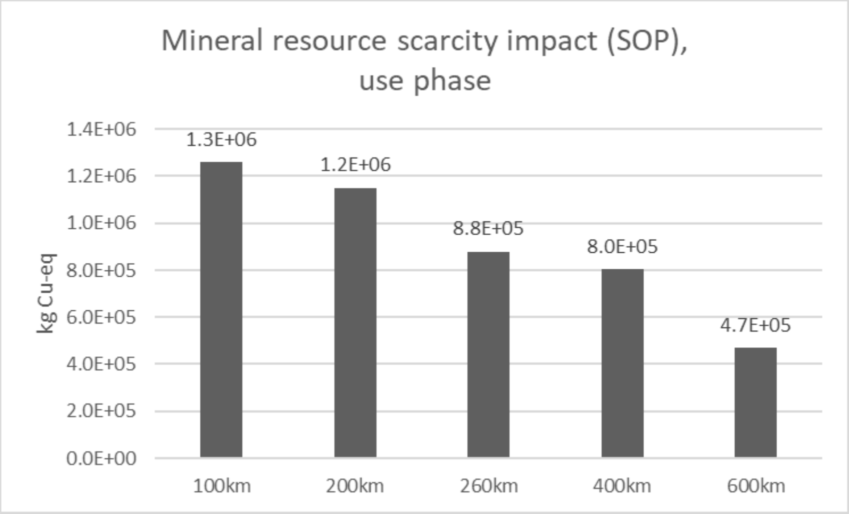


Figure 6.14: Use phase comparison between flight profiles (SOP), per aeroplane life cycle.

The distribution of resource scarcity impact within the use phase is different depending on the flight distance profile. The distribution of the flight profiles is presented in Figure 6.15.

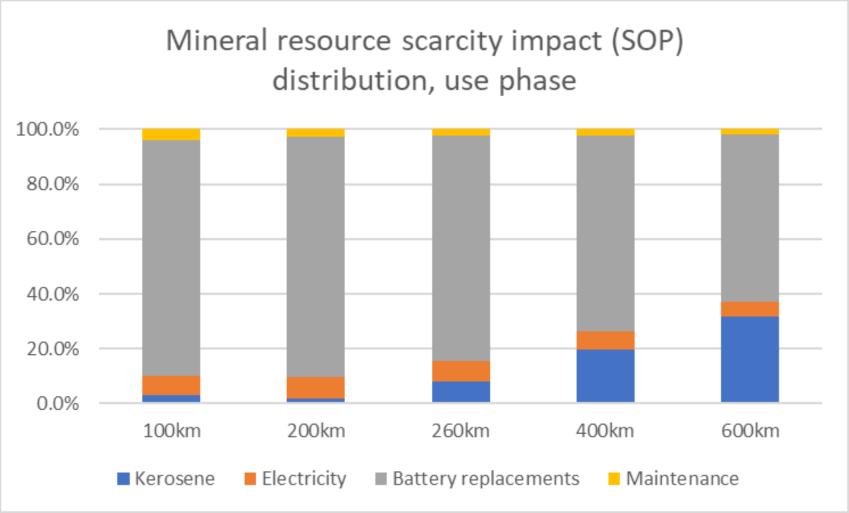


Figure 6.15: Distribution of mineral resource scarcity impact (SOP) in the different flight profiles.

The share of impact originating from the batteries is the dominating share for all mission profiles which can be seen in Figure 6.15. The components in the batteries that contribute most to the impact are the battery cells which can be seen in Table 6.13.

Table 6.13: Mineral resource depletion impact (SOP), 1 BESS.

	Component	kg Cu-eq	Share
BESS	Cells	9.64E+05	96.72 %
	Pack & module	1.02E+04	1.02 %
	BMS	2.15E+04	2.16 %
	High-voltage connectors	1.07E+03	0.11 %
	Total contribution	9.97E+05	100.00 %

6.3.3 End-of-life

The impact related to the EoL treatment of the modelled aeroplane is described in Table 6.14 and it shows that rubber, plastics and electronics are the main contributors since these materials mainly goes to incineration or landfill compared to for instance steel and aluminium which have high recycling rates and therefore a low impact in this case.

Table 6.14: Mineral resource depletion impact (SOP) EoL treatment of modelled aeroplane.

	Material	kg Cu-eq	Share
EoL	Plastics	2.78E+00	28.15 %
	Electronics	2.74E+00	27.75 %
	Aluminium	1.68E-01	1.71 %
	Textile	2.36E-02	0.24 %
	Mineral oil	2.24E-01	2.28 %
	Steel	1.65E-03	0.17 %
	Rubber	3,93E+00	39.86 %
	Total contribution	9.87E+00	100.00 %

6.4 Mineral resource scarcity, CSI

This section presents the results of the mineral resource scarcity impact but instead calculated using the CSI. This results in slightly different impact distributions compared to the SOP.

Table 6.15: Mineral resource scarcity impact (CSI) of the modelled aeroplane, base-case scenario, per aeroplane life cycle.

Phase	**System**	**kg Si-eq**	**Share**
Production	Structure	1.80E+07	0.54 %
	Drivetrain	1.80E+07	0.54 %
	Operational systems	3.18E+07	0.96 %
	Interior	2.64E+06	0.08 %
	Assembly	5.46E+05	0.02 %
	Transports	1.75E+05	<0.01 %
	Total contribution	7.11E+07	2.15 %
Use	Kerosene	1.04E+09	31.36 %
	Electricity consumption	3.39E+08	10.26 %
	BESS replacements	1.71E+09	51.82 %
	Maintenance	1.46E+08	4.41 %
	Total contribution	3.23E+09	97.85 %
End-of-Life	Total contribution	3.75E+04	<0.01 %
Total	Modelled aeroplane	3.31E+09	100.00 %

Again, similarly to the climate change impact, the distribution of impact per phase varies little and the use phase holds the largest share of impact as can be seen in Figure 6.16.

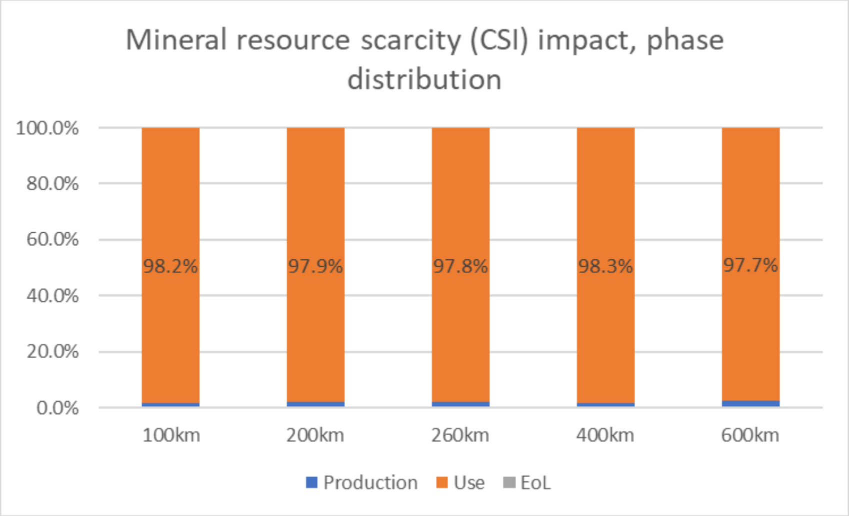


Figure 6.16: Mineral resource scarcity impact (CSI), phase distribution.

The mineral resource scarcity impact based on the CSI normalised per passenger km results in smaller differences between the flight profiles as compared to the SOP which is presented in Figure 6.17. The distribution between the different minerals is also visible in the same Figure. The extended results from the CSI are available in Appendix, Section B.2.

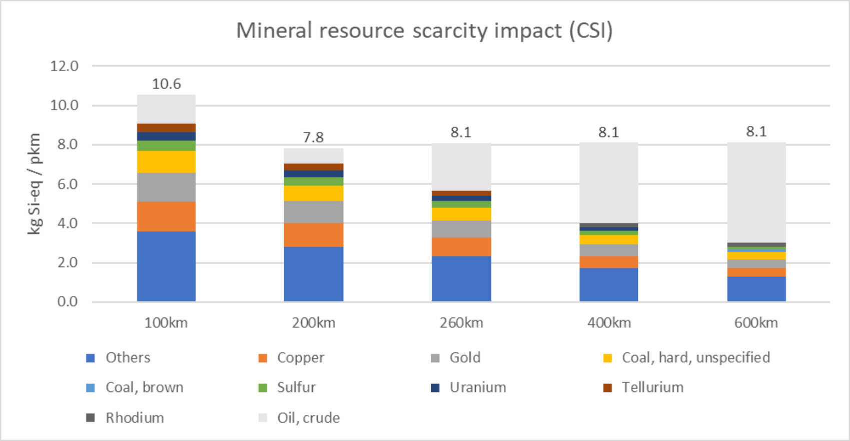


Figure 6.17: Mineral resource scarcity impact (CSI) per pkm.

When studying Figure 6.17, it shows little difference between the mission profiles except for the 100 km profile which is higher than the rest. This can be explained by the high BESS consumption as well as a quite high fuel consumption normalised by fewer pkm than for the other cases. The 100 km profile has the largest share of minerals categorised as ”others”. This category includes battery minerals such as molybdenum, nickel and the lithium-rich mineral spodumene.

6.4.1 Production

As with the previously-mentioned impact categories, the production phase is a smaller share of the total impact. When calculated using the CSI, the distribution within the production phase is more distributed among the different components as compared to the SOP as can be seen in Figure 6.18. The operational systems account for the highest impact, which is mainly connected to copper for the electric wires and other rare metals used in the inverters and junction boxes. For the structure, the use of aluminium is the main contributor to its impact on the CSP. For the drivetrain, the rare metals used for the inverters along with the complex alloys used in the turboshaft engines contribute the most.

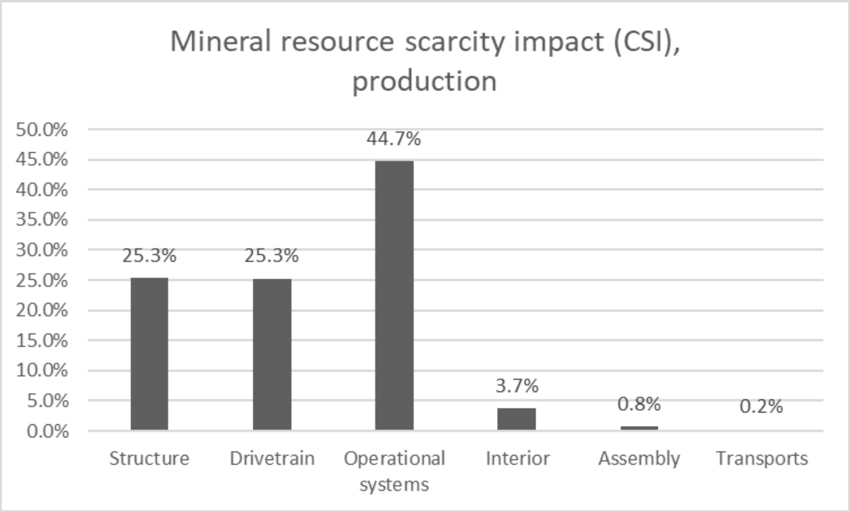


Figure 6.18: Mineral resource scarcity impact (CSI), production component distribution.

6.4.2 Use phase

The use phase is the largest contributor to mineral resource scarcity, but its quantity differs between flight profiles. As shown in Figure 6.19, the total impacts are larger when the modelled aeroplane utilises its batteries more for propulsion than when it is propelled using its conventional turboprop engines. Again, the 400 km flight profile does not follow the same trend. The reason for this is that it consumes a significantly higher quantity of batteries than the 600 km flight profile (as can be seen in Table 6.1) and has a high fuel consumption.

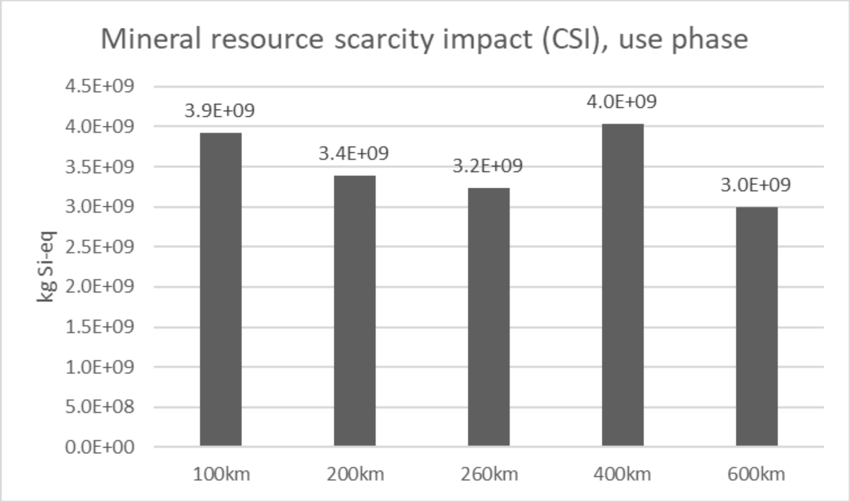


Figure 6.19: Use-phase comparison between flight profiles (CSI), per aeroplane life cycle.

The use phase is the largest contributor to mineral resource scarcity but its distribution is different depending on the flight profile. The distribution for the flight profiles is presented in Figure 6.20.

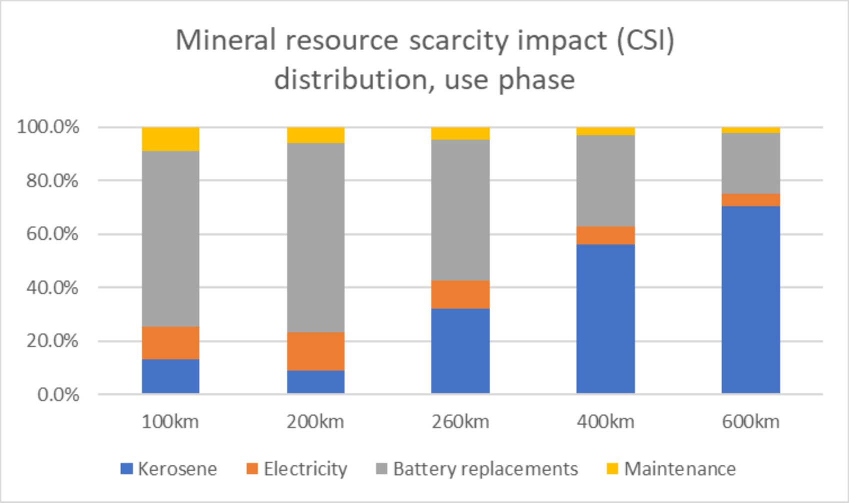


Figure 6.20: Distribution of mineral resource scarcity impact (CSI), in the different flight profiles.

The share of impact originating from the batteries is the dominating share for the three shorter mission profiles, which can be seen in Figure 6.20. The elements in the batteries that contribute most to the impact are the battery cells, which can be seen in Table 6.16. The main contributors in the cell supply chain are nickel sulfate followed by cobalt and lithium hydroxide. The BMS also accounts for almost a third of the total impact of the BESS where the gold used in the circuit boards is a main contributor.

Table 6.16: Mineral resource depletion impact (CSI), 1 BESS.

	Component	**kg Si-eq**	**Share**
BESS	Cells	5.38E+07	67.44 %
	Pack & module	2.10E+06	2.63 %
	BMS	2.32E+07	29.11 %
	High-voltage connectors	6.56E+05	0.82 %
	Total contribution	7.97E+07	100.00 %

6.4.3 End-of-life

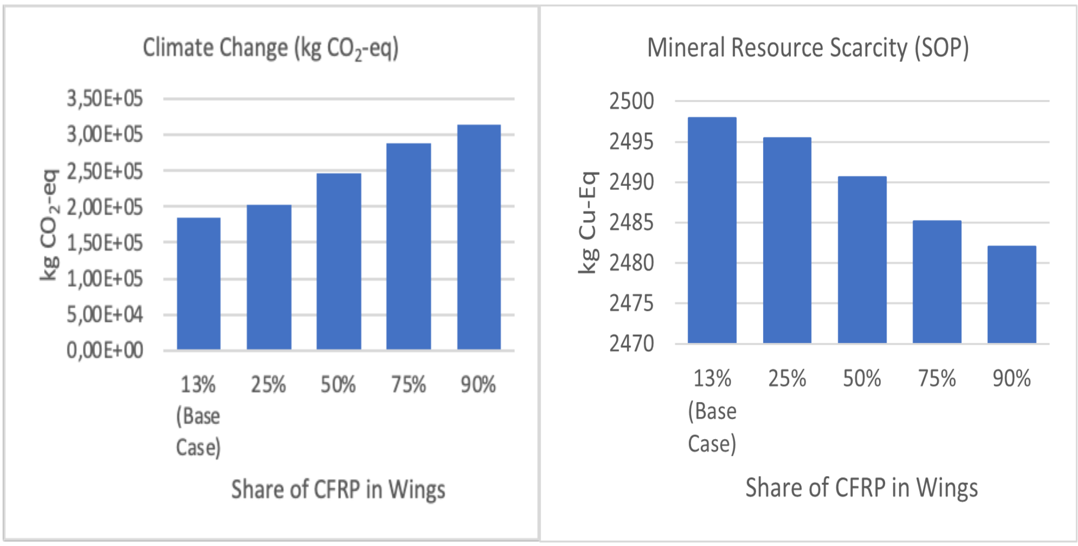
The impact related to the EoL of the modelled aeroplane is shown in Table 6.17 and it shows the three largest contributors being electronics, aluminium and plastics. The market process for shredding electronics in Ecoinvent involves large amounts of electricity from the global electricity mix which has a high CSI impact. The reason for plastics being a high contributor is the same as described in Section 6.14. Aluminium has a high impact since the market process in Ecoinvent for scrap aluminium involves municipal incineration of scrap aluminium meaning it is not recycled.

Table 6.17: Mineral resource depletion impact (CSI) EoL treatment of the modelled aeroplane.

	Material	kg Si-eq	Share
EoL	Plastics	7.99E+03	21.29 %
	Electronics	1.81E+04	48.22 %
	Aluminium	9.16E+03	24.41 %
	Textile	4.87E+02	1.30 %
	Mineral oil	6.37E+01	0.17 %
	Steel	1.72E+03	4.60 %
	Rubber	3.86E+00	0.01 %
	Total contribution	3.75E+04	100.00 %

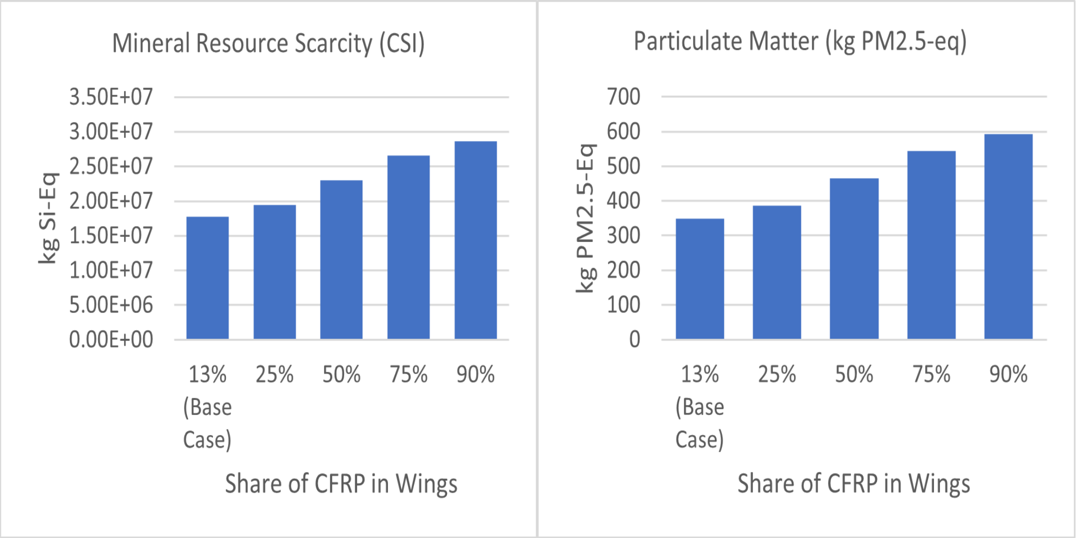
6.4.4 CFRP in wings

Some aeroplanes on the market today are being built with a higher share of CFRP in the structure, mainly when it comes to the wings. Since the ES-30 is planned to follow a conventional aeroplane structure, it is interesting to analyse how changing the share of CFRP in the wings would alter the results compared to the base case. Results for this scenario are presented in Figure 6.21. The results only present the change in impact categories on a component level and not on the overall result of the entire life cycle. Over the entire life cycle, the difference would not be noticeable due to the dominance of the use phase.



(a) (b)

Figure 6.21: Sensitivity analysis for various amounts of CFRP in the wings on the production impact (Continues on next page).



(c) **(d)**

Figure 6.21: Sensitivity analysis for various amounts of CFRP in the wings on the production impact.

7

Interpretation

7.1 Sensitivity analysis

To assess the sensitivity of the LCA, a sensitivity analysis was conducted where it was investigated how changing the electricity supply mix for charging of the aeroplane would alter the results.

It would also have been interesting to investigate the implementation of CFRP in the wings further since it also could alter the performance during the use phase, which was not considered for the results presented in Section 6.4.4 due to lack of data on this. Therefore, a sensitivity analysis regarding the use phase impacts of increased share of CFRP in the wings could not be performed in the time frame of this study.

7.1.1 Electricity mix

Within the use phase of the modelled aeroplane, a significant part of the climate impact can be attributed to the generation of electricity, which is needed to charge the onboard batteries on the 100 km and 200 km flight profiles. The electricity used in the base-case (260 km) is based on the current Swedish electricity supply mix. Considering that the Swedish electricity supply mix has a very low carbon intensity compared to the present-day European and global average, it is interesting to look into how the climate change impact would differ when using another electricity supply mix. Figure 7.1 presents results for two new electricity supply mixes and their impact on the total CO_2-eq per pkm as well as the original Swedish electricity supply mix. A comparison with the ATR-42 using fossil jet fuel is also added to Figure 7.1. The electricity supply mixes and their respective Ecoinvent processes are presented in Table 7.1.

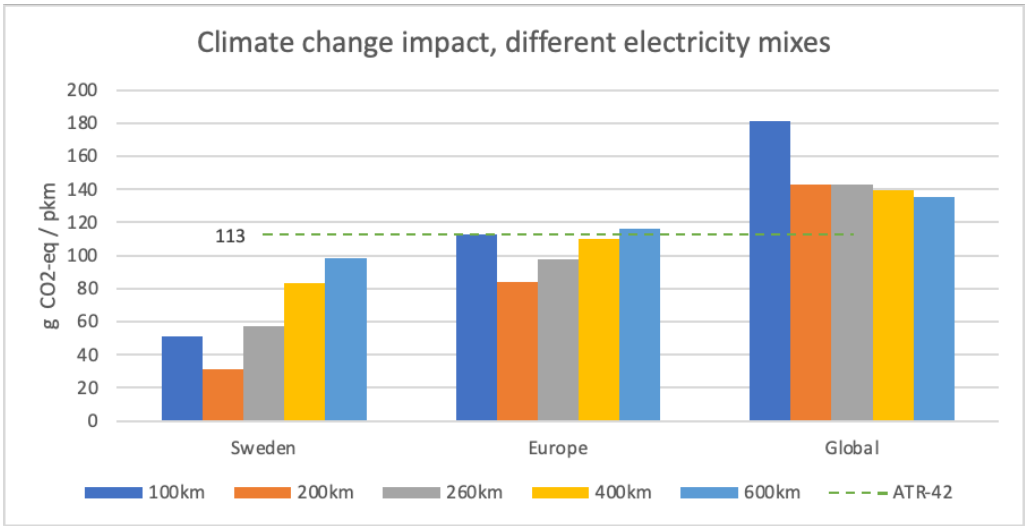


Figure 7.1: Climate change impact per pkm, different electricity supply mixes.

Table 7.1: Electricity supply mixes and the used processes from Ecoinvent.

Region	**Ecoinvent process**
Sweden	market for electricity, medium voltage | electricity, medium voltage | Cutoff, U - SE
Europe	market group for electricity, medium voltage | electricity, medium voltage | Cutoff, U - Europe without Switzerland
Global	market group for electricity, medium voltage | electricity, medium voltage | Cutoff, U - GLO

7.2 Scenario analysis

As previously mentioned, the ES-30 is planned to be type-certified in 2028. Since there are a few years until then, and with the ambitious sustainability goals for the aviation sector in mind, it is interesting to investigate some possible future scenarios that could reduce the impact results further. The first scenario concerns future fuel scenarios where the use of AAF is standardised and used broadly in the aviation sector with up to 100 % compared to the max blending rate of 50 % today. The other scenario concerns battery technology, which is advancing at a rapid pace. In this study, a potential future cycle life which is not feasible with today's technology will be studied. The opposite is also investigated, to show the potential impacts if the battery performs worse than assumed in this study. The difference in climate change impact between producing the batteries in Asia / USA compared to Sweden is also analysed.

7.2.1 Fuel variation

Since there is a large share of the climate change impact which originates from the fuel consumption of the modelled aeroplane it is interesting to look into how the impact on climate change would change if the fuel is exchanged from a fossil-based fuel to a renewable fuel. In this scenario, 100 % of the fuel is made from used cooking oil (UCO) or soybeans through the HEFA pathway. The results are presented in Figure 7.2 together with comparisons from the fossil fuel. Using the UCO will result in a reduction of CO_2-eq of 78 % per passenger km. The reduction using soybeans is 58 %. Using AAF instead of fossil kerosene in the ATR-42 study by Vivalda (2023) resulted in a climate change impact per pkm of 26 g CO_2-eq using UCO and 49 g CO_2-eq using soybeans as feedstock by applying the same percentage reductions on fuel production and combustion.

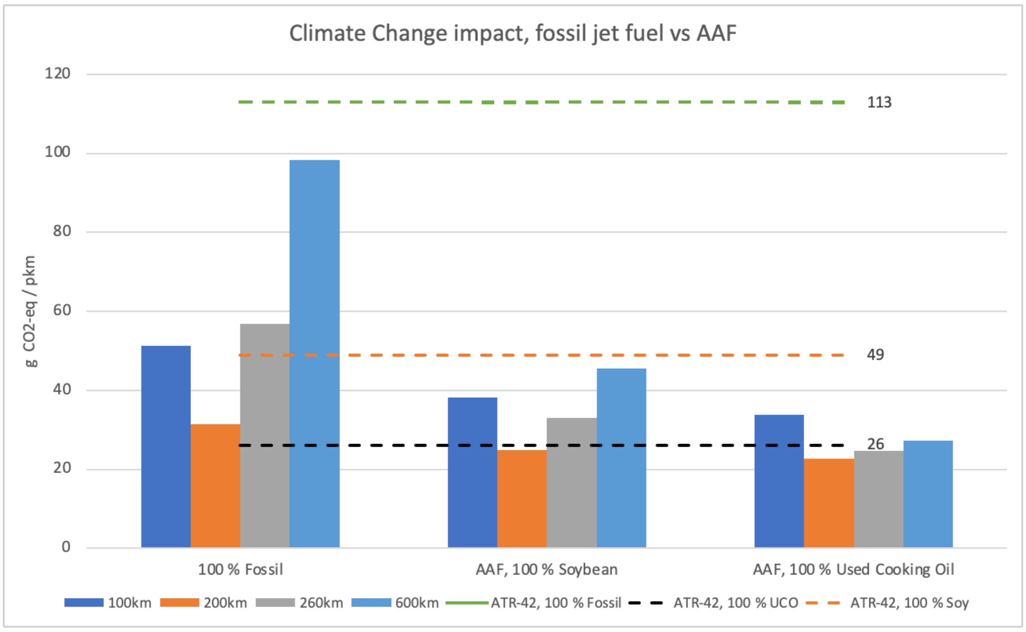


Figure 7.2: Climate change impact per pkm using fossil jet fuel and AAFs, compared to the base case scenario.

The total climate change impact throughout the life cycle is significantly reduced when using AAF instead of fossil kerosene, as presented in Figure 7.3. Total climate change impact for the ATR-42 using fossil kerosene as well as the two AAFs are available in Appendix C, Table C.3.

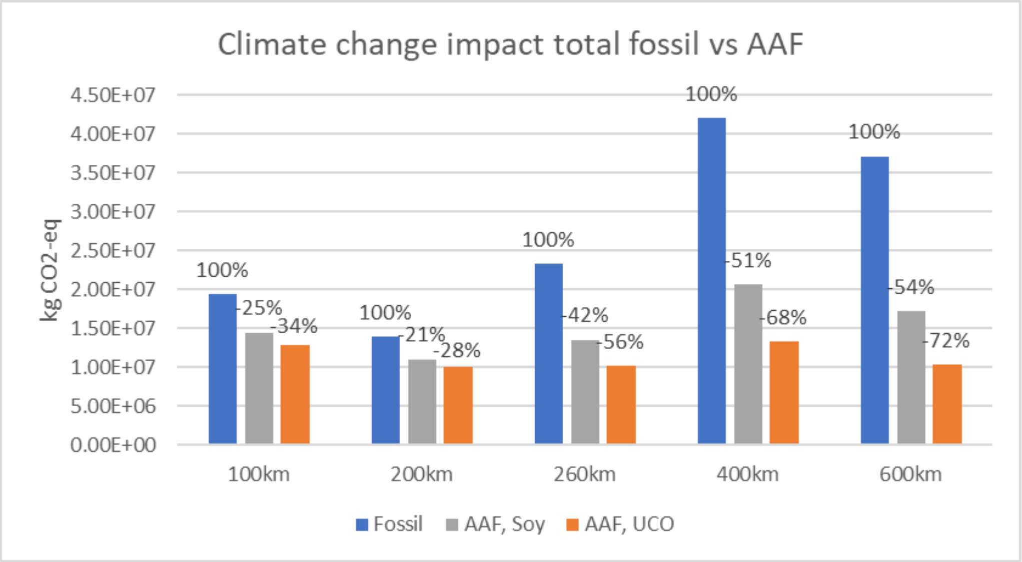


Figure 7.3: Total life cycle climate change impact fossil fuel vs AAFs, for all flight profiles.

The fuel is also a large contributor to particulate matter emissions in the 260, 400 and 600 km flight profiles. According to EASA (2022b) the emissions of particulate matter in the combustion of AAF can be reduced by 50-90 % compared to fossil fuels. It is therefore interesting to look into how this may change when using AAF instead of fossil jet fuel. In the scenario, the reduction of particulate matter emissions in the combustion of AAF was set to 73.5 %. The results from this scenario are presented in Figure 7.4. In the fossil case, the driving force of PM2.5-eq was the increase of fuel being burnt during the life cycle but for the AAF case, the driving force is the batteries being consumed and the longer the flight distance is, the fewer batteries are consumed. This is because the use of the batteries is decreased when increasing the mission distance. This results in a reduction of particulate matter formation impact of up to 37 % using AAF in the 600km flight profile. If the UCO feedstock did not need to be transported from China to Europe, which is the case in the study by Trinh et al. (2022) the potential PM2.5-eq reduction for the 600km flight profile is 51 %. The environmental impacts for all ReCiPe 2016 midpoint impact categories as well as the CSI for the modelled aeroplane using AAF from UCO are presented in Appendix D, Tables D.6 to D.10.

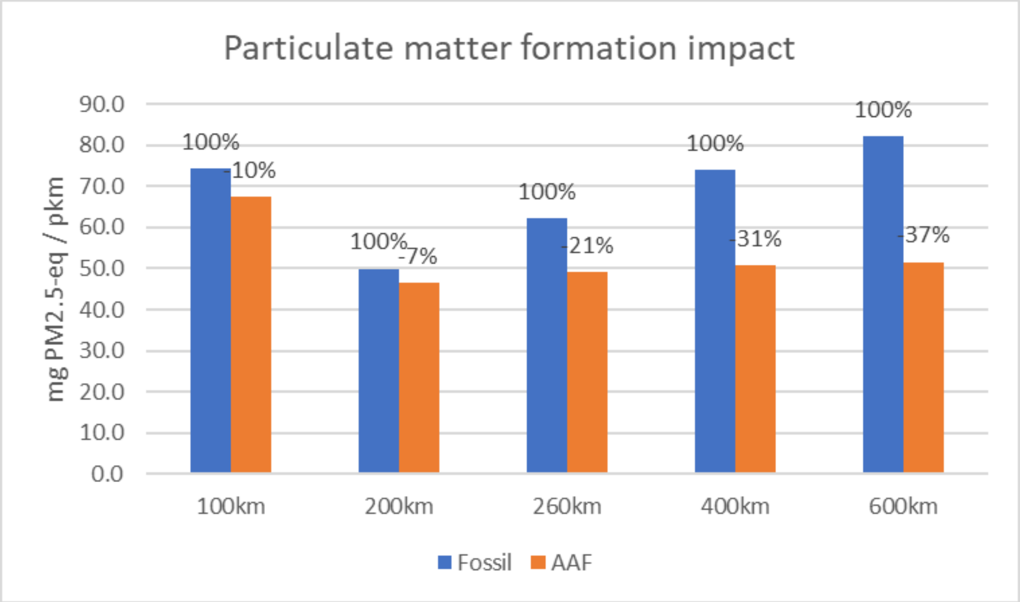


Figure 7.4: Total particulate matter formation impact per passenger km fossil vs AAF.

7.2.2 Battery performance

In the 100km and 200km flight distance profiles, the batteries are a major part of the climate change impact and in all flight distance profiles, they are a large part of the mineral resource scarcity impact both concerning SOP and CSP. Therefore, three scenarios were considered to investigate how they would change when (i) choosing a different country of production and (ii) changing the battery longevity. The third (iii) scenario involves assigning a different environmental burden to the batteries when in the use phase since a battery with 80 % SOH still can hold a significant economic value and thereby be reused in other applications.

In this first altered battery scenario, the country of production for the batteries was changed to Sweden. Instead of the battery cells being produced in Asia and then shipped to the US where they were assembled into modules and packs, both these processes happen in the north of Sweden. This means that the transport distances and electricity supply mixes are affected. This resulted in the climate change impact decreasing by 30 % per BESS produced. However, this did not have a notable impact on the total impact per pkm as can be seen in Figure 7.5. For this scenario, the Swedish electricity supply mix is being used for all steps of cell, module and pack manufacturing and assembly. However, the processes for raw material processing and extraction are still according to Chordia et al. (2021) since these materials are assumed to be purchased on the global market.

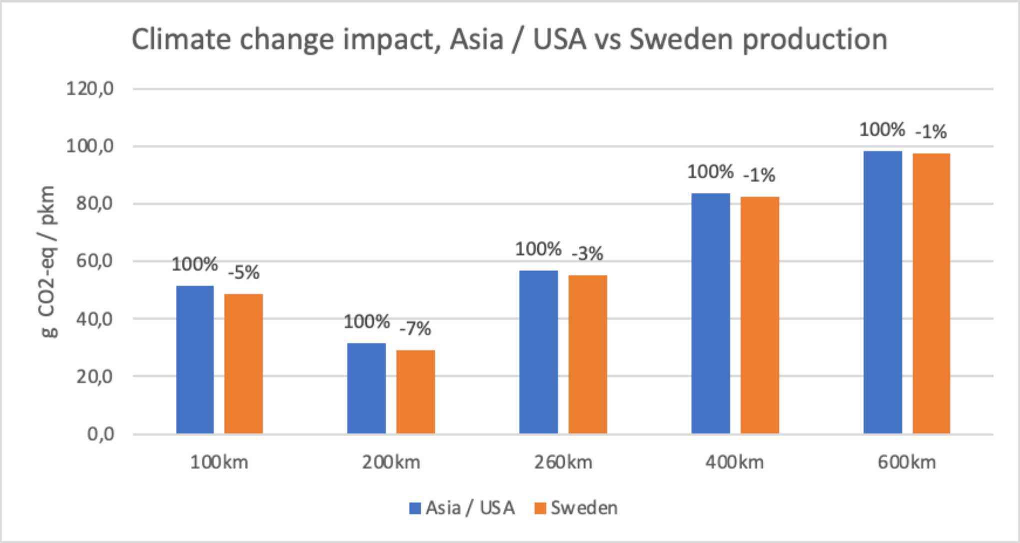
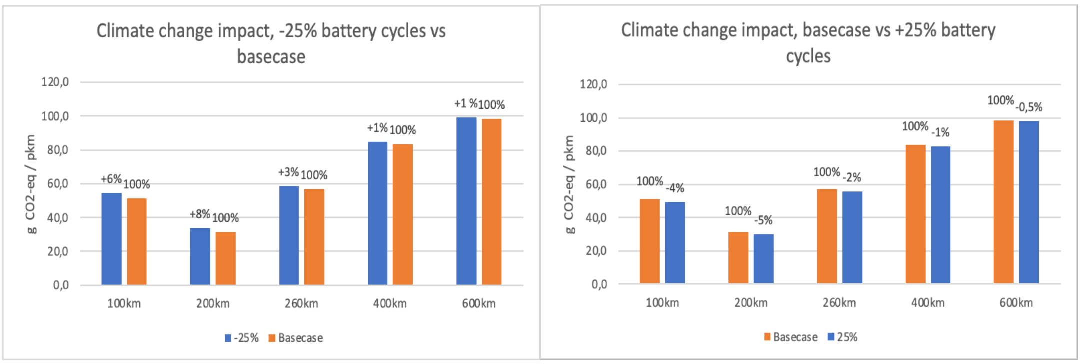


Figure 7.5: Climate change impact per passenger km with batteries produced in Asia / USA vs in Sweden.

The second scenario that is interesting to look into is the longevity of the battery cells, increasing or decreasing the number of cycles which the battery can deliver before reaching 80 % SOH will determine how many batteries are required during the LC of the ES-30. Future batteries may have further increased performance than the ones assumed in this study on a number of measurements such as increased energy density, increased resistance to temperature changes and overall longevity. These performance increases may arise from improvements to current cell chemistries or the introduction of new chemistries. However, in this scenario, the material composition of the battery cells remains constant according to Chordia et al. (2021). The opposite case is that the battery performance is lower than assumed in this LCA and due to that the number of cycles until reaching 80 % SOH is fewer. To simulate both cases in a scenario the number of cycles until reaching 80 % SOH were increased and decreased by 25 %. The impact on total climate change impact per passenger km along with the base-case are presented in Figure 7.6.



(a)

(b)

Figure 7.6: Climate change impact per pkm with +/- 25 % battery cycles.

The impact on climate change per passenger km did not change notably, but these changes in the cycle life of the batteries also affect the SOP and CSP because of the use of fewer batteries throughout the life cycle. The results are presented in Figure 7.7 and the results are far more considerable for these impact categories than for the climate change impact. In the most battery-intensive flight profiles the SOP per pkm could increase by 28 % and decrease by 17 %. A similar pattern is also visible in the CSI per pkm.

(a) **(b)**

(c) **(d)**

Figure 7.7: Mineral resource scarcity impact (SOP, a-b & CSP, c-d) per passenger km with +/- 25 % battery cycles.

In this third battery scenario, the environmental burden of the batteries from the use phase is manually reduced. The logic behind this is that the batteries in reality might have a second or even third life after their first life in the ES-30 since the batteries are at 80 % SOH when removed and therefore might be usable in other applications, instead of being recycled after first use. Second-life of the batteries might be within automotive applications such as buses or lorries which, compared to the aviation industry, have lower requirements for power. Third-life applications could be within backup or peak-shaving electricity storage. Finding an allocation procedure for the allocation of environmental burdens between the first and second (and possibly third) lives is not trivial and an easy-to-use manner of doing this has not been found in any previous research. As an example; if the allocation of burden would be 70 % to the first life (in the modelled aeroplane) and 30 % in the second life, the overall results for climate change impact would be mathematically equivalent to the results in Figure 7.5, where the change of production country reduced the climate impact per battery by 30 % and total CO_2-eq per pkm by 1 % to 7 %. An allocation higher than 30 % for the second life would be considered unreasonable since the battery is manufactured in the first place to be in the aeroplane. This same allocation could be done for the other impact categories as well and result in a greater decrease, the results of this scenario for all impact categories are presented in Table 7.2.

Table 7.2: Reductions from 70 % allocation of BESS environmental impacts to the aeroplane life cycle, per pkm.

Flight Profile	**Percentage reduction per pkm**			
	CO_2-eq	**CU-eq**	**Si-eq**	**PM2.5-eq**
100km	-5 %	-25 %	-19 %	-19 %
200km	-7 %	-26 %	-21 %	-14 %
260km	-3 %	-24 %	-16 %	-8 %
400km	-1 %	-21 %	-10 %	-5 %
600km	-1 %	-17 %	-7 %	-3 %

7.3 Discussion of results

For mineral resource scarcity, when studying the results for SOP in Figure 6.12, it follows a linear trend downward for increasing mission distances. This seems reasonable due to the reduction in batteries consumed over the life cycle for the longer mission profiles. This is also visible in the Figure 6.12 where the mineral ”spodumene” is the mineral which is decreasing the most. Spodumene is rich in lithium and is connected to the production of LIBs. Cerium is also present in all of the mission profiles and is connected to oil refining.

When instead looking at the CSI, the mission profiles do not differ substantially from each other except for the 100 km profile, which is higher than the other profiles. However, this is when looking at the total impact per pkm. The CSI take into account the average carbon content in the earth’s crust, which the SOP does not. It is thereby not a fair comparison between the indicators. If one were to disregard the impact of crude oil in Figure 6.17, the trend of both CSI and SOP is very simila: Both indicators decrease with longer flight distance profiles.

Particulate matter follows the same trend as global warming where the 100km mission profile has a higher impact due to the fuel required for keeping the turboprops in idle during descent and landing. From the 200 km mission profile and onwards the development follows a linear increasing trend per pkm. Although the impacts follow the same trend, the environmental impacts from particulate matter emissions are very dependent on where they occur, which is different from GHGs.

The results of climate change impact are similar to the results described in Lopes (2010) and Vivalda (2023), where the majority of CO_2-eq can be attributed to the use phase of the aeroplane. This would not be the case if the batteries were not considered consumables but added into the production phase of the modelled aeroplane.

SOP and CSI have not been analysed in any of the previous LCAs on conventional aeroplanes. Therefore, it is difficult to compare the results from this study with a conventional aeroplane. However, it is suspected that the mineral resource scarcity impact category would differ between the ES-30 and a conventional aeroplane due to the batteries and their rare metals such as lithium and cobalt. To confirm this suspicion, a check was performed where the two electric motors and their power electronics were replaced with two extra turboprop engines in the model of the aeroplane. This confirmed that the SOP is much higher (3-4 times higher) for the production of the hybrid-electric aeroplane. For CSI however, there is almost no difference between the two aeroplanes due to the operational systems being the main contributor for that indicator.

It was studied how changing the share of CFRP in the wings to see how that would affect the impact results in the production phase. For all impact categories, the trend is increased impact for increasing the amount of CFRP except for the SOP where a downward trend was observed. The CSI includes characterisation factors for both aluminium and carbon with the characterisation factor for carbon being much higher than for aluminium which might explain this result. The SOP has a CF for aluminium but none for carbon, which might explain why the SOP decreases due to the increased use of CFRP. For climate change and particulate matter, the increasing trend due to increased CFRP in the wings seems reasonable since carbon fibre is energy-intensive to produce and with limited recyclability, thus aluminium should perform better in these impact categories. However, this only covers the production impacts, which have been proven to have a very small total impact throughout the life cycle of the aeroplane. Therefore, the impacts of using CFRP or aluminium in the wing production could be considered negligible when looking at the entire life cycle. However, if the change of the total weight of the aeroplane due to increased CFRP would be considered it would most likely alter the results for the use phase as well and could then no longer be considered negligible. However, the weight change is not considered in this study.

The study by Vivalda (2023) included results from the impact categories acidification and eutrophication, which are presented in Section 4.7. To increase the comparability between this study and the ATR-42 study, these impact categories are briefly discussed. The results from the modelled base-case are fully presented in Appendix D. Table 7.3 presents the comparison of the two impact categories TAP and FEP. The results for the ATR-42 are based on a 20-year life cycle while the modelled aeroplane is based on 30 years. It is therefore clear that the modelled aeroplane has a lower impact on both these impact categories. This is due to the modelled aeroplane requiring less liquid fuel.

Table 7.3: Comparison between ATR-42 (20-year LC) and the modelled aeroplane (30-year LC), acidification and eutrophication.

Unit	**Acidification, SO_2-eq**		**Eutrophication, P-eq**	
	ATR-42	**Model**	**ATR-42**	**Model**
Total impact (kg)	1.38E+05	6.78E+04	1.18E+05	3.52E+03
Per pkm (g)	2.07E-01	1.66E-01	1.78E-01	8.60E-03

7.3.1 Sensitivity analysis discussion

In the sensitivity analysis the electricity used for charging the aeroplane during its use phase was changed. Two different electricity supply mixes, aside from the Swedish one, were analysed which would represent the electricity supply mixes that could be used if the ES-30 would enter operation today. For the global electricity supply mix, with more non-renewable energy sources, the climate change impact was higher than for the ATR-42. No future electricity supply mixes have been analysed in this LCA. However, several institutions and countries have set up targets to increase their shares of renewable electricity. A directive from the EU, which entered into force in November 2023, sets a binding target to increase its share of renewables in the electricity mix from 23 % in 2022 to 42.5 % in 2030 (European Commission, 2023). In the US, a target of 80 % by 2030 has been announced by the White House (Mai, 2023). Considering these commitments from two major aviation markets and the assumed aeroplane lifetime of 30 years, there is a good chance that the climate impact from the ES-30 will be lower in these markets compared to current electricity supply mixes, assuming these targets are achieved.

7.3.2 Scenario analysis discussion

In the scenario analysis, two scenarios were investigated. In the fuel scenario, where the fossil kerosene was exchanged with AAF there is a large potential to decrease the climate change impact further. However, the AAF that was used is based on UCO which has a very limited supply. In a study by Brazilian agriculture consultancy firm Agroicone, the maximum potential feedstock of UCO in Brazil amounted to 5.4 % of the total jet A1 consumption in Brazil. The same study also concluded that the demand for AAF would compete with the demand for bio-diesel which could hinder the potential of AAF in Brazil (Moreira et al., 2020). In another study by the ICCT (International Council on Clean Transportation) the estimated available feedstock of FOGs (Fats Oils and Greases) in 2030 in the EU for AAF amounted to 1.9 % of the total 2030 EU jet A1 consumption (O'Malley et al., 2021). The FOG includes UCO, animal fats and other oils such as tall oil. The same study also concluded that 62 % of all UCO used for biofuel production in the EU today are imported, mainly from Asia. The study by the ICCT presents that the total AAF, from various feedstocks and through various production pathways, supplied in the EU in 2030 could amount to 5.5 % of total 2030 jet A1 fuel consumption. Concerning the two above studies, it can be concluded that AAF cannot supply the aviation industry with the whole demand for jet fuel in 2030. Thus, the feasibility of AAF is highly uncertain and assumptions of 100 % or even 50 % AAF in the tank of the ES-30 or the ATR-42 are very unrealistic since the limited demand would result in high prices and thereby high ticket prices which could not compete on the market. However, the target in the EU of 6 % AAF in the aviation fuel mix in 2030 is more realistic (The European Parliament, 2023). There are also other feedstocks than UCO and animal fats which can be used to produce AAF using the HEFA pathway, such as primary rapeseed oil, soybean oil and palm oil. However, using a primary feedstock is problematic since the need for fuel could compete with the need for food in the future (Trinh et al., 2022).

AAF produced from soybeans was also considered in one scenario, but complete LCI data was not found. Therefore other impacts than climate change could not be evaluated. The use of soybeans will have other environmental impacts as well, such as land use change, acidification and eutrophication, which Zortea et al. (2018) report. According to their study, the climate change emissions from soybean cultivation in Brazil could be up to 150 % larger if effects from land use change are accounted for. This is not accounted for in the scenario described in Section 7.2.1 (which considered soybeans from the USA).

In the scenario analysis concerning the battery of the modelled aeroplane, it was concluded that the climate change impact stemming from the battery production could be decreased by changing the country of production. However, the total impact per pkm would not be significantly reduced. The scenario involving increasing the number of cycles the batteries can deliver had large implications on the mineral resource scarcity impact. This is not surprising, since the battery is a large part of the total impact in this impact category and by increasing the longevity, fewer batteries are needed. Another discussion point is the potential allocation of the environmental burden of the battery since there is a potential value of the batteries when they still hold 80 % SOH.

7.4 General discussion

As mentioned earlier in this study, obtaining relevant and detailed data has been problematic in some cases. This has led to the model of the aeroplane being detailed for some systems, and less detailed for others. However, the results of this study for the production of the aeroplane correlate well with other studies that have shown that the production phase of an aeroplane accounts for a small fraction of the total impact over its life cycle. The main contributing phase is the use where the combustion and linked fuel production, as well as the battery replacements, also coupled to their production emissions, are included and account for the majority of impacts. Therefore, it can be assumed that refining the model of the production phase would not change the outcome of this LCA substantially. For the model in this study, the current dominating technology for fuel, namely fossil jet fuel, has been used as the base scenario. Assumptions have been made that the battery cell energy density required by Heart Aerospace will be technically possible. The impacts stemming from the batteries are thereby uncertain since the precise battery cell technology that will be used is not yet determined.

Another important aspect to emphasise once more is the fact that the ES-30 is still under development, and therefore there has been no finished product to perform this LCA on. The entire model is based on the target weights of the aeroplane and its subsystems along with calculations provided by Heart Aerospace on flight scenarios for different drivetrain configurations. The chosen drivetrain configuration with two electric motors and two turboprop engines is one of many different concepts investigated by Heart Aerospace and was at the time this thesis was conducted, the one with the most publicly available data to perform the LCA on. The ES-30, aiming to be type-certified in 2028, may therefore look different from the model in this thesis. However, the results from this study indicate the impacts that the ES-30 might have and key factors that influence the result.

8

Conclusion

The results of this study indicate that there is a great reduction potential for climate change when operating a hybrid electric aeroplane with fossil kerosene and Swedish electricity compared to a conventional aeroplane only propelled by kerosene.

As seen in previous studies, the use phase is the dominant part of the life cycle for all the investigated impact categories (94-99 %), assuming that the batteries are assigned to the use phase. This makes it crucial to operate the ES-30 using fuels and electricity with a low environmental impact. The results show the importance of charging the ES-30 with electricity from renewable sources.

The largest uncertainty in this study can be connected to the assumption that the energy density of the battery cells will be high enough to travel 200 km while still having the same material composition and performance as current NMC811 LIBs, described in Chordia et al. (2021). This is highly uncertain since the batteries used in the ES-30 in 2028 might have a different battery cell chemistry, utilising other materials. These future cells can have a higher or lower environmental impact per kg of battery cells. The performance of future batteries can impact the longevity, weight, charging efficiency as well as other parameters which in this study is connected to the NMC811 cell chemistry. There are also uncertainties in the use phase, aside from the batteries, since electricity and fuel consumption are based on simulations and not data from actual operations. However, there is a large potential to eliminate these uncertainties once the aeroplane is airborne.

The results from the study indicate that some key changes in the base-case assumptions have the potential to alter the overall results of this study. Increasing the share of CFRP in the wings will increase the impacts from production in all impact categories except for the surplus ore potential (SOP). However, the impacts on the use phase from changing the share of CFRP in the wings have not been included in this study. As mentioned, charging the aeroplane with renewable electricity will be essential to obtain the environmental benefits from a hybrid-electric aeroplane. Using fossil-based electricity can lead to the hybrid-electric aeroplane performing worse than a conventional aeroplane. AAFs have the potential to reduce the climate change impact and particulate matter emissions of the aeroplane. However, these fuels are in different stages of maturity and the future will tell which part they will play in aviation.

Since the comparative studies found on conventional aeroplanes did not include indicators for short- and long-term mineral resource scarcity, it is hard to compare them to this study. However, when looking at the production of the modelled hybrid-electric drivetrain and a conventional drivetrain it was clear that the short-term resource scarcity impact is much higher for the modelled hybrid-electric aeroplane. This is due to the materials needed to produce the electric motors and power electronics. If including the battery use, it will be even higher. There is a clear trade-off between a reduction in the emissions-based impact categories (climate change and particulate matter) and an increase in the resource-based impact categories (SOP and CSI). The long-term mineral resource scarcity impact from the production of the hybrid-electric aeroplane and the conventional aeroplane is almost identical, where copper is the largest contributor which is very similar for both configurations.

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A

Appendix

Here, the unit processes for the modelling of the aeroplane are presented. The flows are categorized as product flows (P), waste (W), or emissions (E).

A.1 Custom materials production

Table A.1: Custom process for producing aluminium sheets used in, for instance, the fuselage and wings.

Input	**Amount**	**Unit**	**Type**	**Dataset/source for upstream flow provider**
aluminium, wrought alloy	1.0	kg	P	market for aluminium, wrought alloy | aluminium, wrought alloy | Cutoff, U - GLO
metal working, average for aluminum product manufacturing	1.0	kg	P	market for metal working, average for aluminium product manufacturing | metal working, average for aluminium product manufacturing | Cutoff, U - GLO
sheet rolling, aluminium	1.0	kg	P	market for sheet rolling, aluminium | sheet rolling, aluminium | Cutoff, U - GLO
Output				
Custom Aluminium	1.0	kg	P	

Table A.2: Custom process for producing steel used in the production of the aeroplane.

Input	**Amount**	**Unit**	**Type**	**Dataset/source for upstream flow provider**
metal working, average for chromium steel product manufacturing	1.0	kg	P	market for metal working, average for chromium steel product manufacturing | metal working, average for chromium steel product manufacturing | Cutoff, U - GLO
sheet rolling, chromium steel	1.0	kg	P	market for sheet rolling, chromium steel | sheet rolling, chromium steel | Cutoff, U - GLO
steel, chromium steel 18/8	1.0	kg	P	market for steel, chromium steel 18/8 | steel, chromium steel 18/8 | Cutoff, U - GLO
Output				
Custom Steel	1.0	kg	P	

Table A.3: Unit process for producing NOMEX HC.

Input	**Amount**	**Unit**	**Type**	**Dataset/source for upstream flow provider**
nylon 6-6	0.84615	kg	P	market for nylon 6-6 | nylon 6-6 | Cutoff, U - RER
phenolic resin	0.15385	kg	P	market for phenolic resin | phenolic resin | Cutoff, U - RER
Output	Amount	Unit	Type	Dataset/source for upstream flow provider
NOMEX HC	1.0	kg	P	

A.2 Glider production

Table A.4: Unit process for the assembly of the glider.

Input	Amount	Unit	Type	Dataset/source for upstream flow provider
Fuselage	1.0	Item(s)	P	See Table A.5
HT	1.0	Item(s)	P	See Table A.9
Main Fairings	1.0	Item(s)	P	See Table A.11
MLG	1.0	Item(s)	P	See Table A.7
NLG	1.0	Item(s)	P	See Table A.8
VT	1.0	Item(s)	P	See Table A.10
Wing	1.0	Item(s)	P	See Table A.6
polyurethane adhesive	80.0	kg	P	market for polyurethane adhesive | polyurethane adhesive | Cutoff, U - GLO
Output	Amount	Unit	Type	Dataset/source for upstream flow provider
Stucture Production	1.0	Item(s)	P	

A.2.1 Fuselage

Table A.5: Unit process for the production of the fuselage.

Input	Amount	Unit	Type	Dataset/source for upstream flow provider
carbon fibre reinforced plastic, injection moulded	98.0	kg	P	market for carbon fibre reinforced plastic, injection moulded | carbon fibre reinforced plastic, injection moulded | Cutoff, U - GLO
Custom Aluminium	1570.0	kg	P	See Table A.1
Custom Steel	20.0	kg	P	See Table A.2
glass fibre reinforced plastic, polyamide, injection moulded	20.0	kg	P	market for glass fibre reinforced plastic, polyamide, injection moulded | glass fibre reinforced plastic, polyamide, injection moulded | Cutoff, U - GLO
polymethyl methacrylate, sheet	118.0	kg	P	market for polymethyl methacrylate, sheet | polymethyl methacrylate, sheet | Cutoff, U - GLO
titanium, triple-melt	59.0	kg	P	market for titanium, triple-melt | titanium, triple-melt | Cutoff, U - GLO
Output	Amount	Unit	Type	Dataset/source for upstream flow provider
Fuselage	1.0	Item(s)	P	

A.2.2 Wings

Table A.6: Unit process for the production of the wings.

Input	Amount	Unit	Type	Dataset/source for upstream flow provider
carbon fibre reinforced plastic, injection moulded	337.0	kg	P	market for carbon fibre reinforced plastic, injection moulded | carbon fibre reinforced plastic, injection moulded | Cutoff, U - GLO
Custom Aluminium	2061.0	kg	P	See Table A.1
Custom Steel	69.0	kg	P	See Table A.2
titanium, triple-melt	131.0	kg	P	market for titanium, triple-melt | titanium, triple-melt | Cutoff, U - GLO
Output	Amount	Unit	Type	Dataset/source for upstream flow provider
Wing	1.0	Item(s)	P	

A.2.3 Main landing gear

Table A.7: Unit process for the production of the main landing gear.

Input	**Amount**	**Unit**	**Type**	**Dataset/source for upstream flow provider**
aluminium, cast alloy	88.0	kg	P	market for aluminium, cast alloy | aluminium, cast alloy | Cut-off, U - GLO
carbon fibre reinforced plastic, injection moulded	34.0	kg	P	market for carbon fibre reinforced plastic, injection moulded | carbon fibre reinforced plastic, injection moulded | Cutoff, U - GLO
Custom Steel	417.0	kg	P	See Table A.2
lubricating oil	11.0	kg	P	market for lubricating oil | lubricating oil | Cutoff, U - RER
synthetic rubber	87.0	kg	P	market for synthetic rubber | synthetic rubber | Cutoff, U - GLO
titanium, triple-melt	23.0	kg	P	market for titanium, triple-melt | titanium, triple-melt | Cut-off, U - GLO
Output	Amount	Unit	Type	Dataset/source for upstream flow provider
MLG	1.0	Item(s)	P	

A.2.4 Nose landing gear

Table A.8: Unit process for the production of the nose landing gear.

Input	**Amount**	**Unit**	**Type**	**Dataset/source for upstream flow provider**
aluminium, cast alloy	18.0	kg	P	market for aluminium, cast alloy | aluminium, cast alloy | Cut-off, U - GLO
carbon fibre reinforced plastic, injection moulded	5.0	kg	P	market for carbon fibre reinforced plastic, injection moulded | carbon fibre reinforced plastic, injection moulded | Cutoff, U - GLO
Custom Steel	68.0	kg	P	See Table A.2
lubricating oil	2.0	kg	P	market for lubricating oil | lubricating oil | Cutoff, U - RER
synthetic rubber	19.0	kg	P	market for synthetic rubber | synthetic rubber | Cutoff, U - GLO
titanium, triple-melt	4.0	kg	P	market for titanium, triple-melt | titanium, triple-melt | Cut-off, U - GLO
Output	Amount	Unit	Type	Dataset/source for upstream flow provider
NLG	1.0	Item(s)	P	

A.2.5 Horizontal tail

Table A.9: Unit process for the production of the horiztonal tail.

Input	**Amount**	**Unit**	**Type**	**Dataset/source for upstream flow provider**
carbon fibre reinforced plastic, injection moulded	259.0	kg	P	market for carbon fibre reinforced plastic, injection moulded | carbon fibre reinforced plastic, injection moulded | Cutoff, U - GLO
Custom Aluminium	14.0	kg	P	See Table A.1
glass fibre reinforced plastic, polyamide, injection moulded	8.0	kg	P	market for glass fibre reinforced plastic, polyamide, injection moulded | glass fibre reinforced plastic, polyamide, injection moulded | Cutoff, U - GLO
Output	Amount	Unit	Type	Dataset/source for upstream flow provider
HT	1.0	Item(s)	P	

A.2.6 Vertical tail

Table A.10: Unit process for the production of the vertical tail.

Input	**Amount**	**Unit**	**Type**	**Dataset/source for upstream flow provider**
carbon fibre reinforced plastic, injection moulded	162.0	kg	P	market for carbon fibre reinforced plastic, injection moulded | carbon fibre reinforced plastic, injection moulded | Cutoff, U - GLO
Custom Aluminium	10.0	kg	P	See Table A.1
glass fibre reinforced plastic, polyamide, injection moulded	123.0	kg	P	market for glass fibre reinforced plastic, polyamide, injection moulded | glass fibre reinforced plastic, polyamide, injection moulded | Cutoff, U - GLO
Output	Amount	Unit	Type	Dataset/source for upstream flow provider
VT	1.0	Item(s)	P	

A.2.7 Main fairings

Table A.11: Unit process for the production of the main farings.

Input	**Amount**	**Unit**	**Type**	**Dataset/source for upstream flow provider**
carbon fibre reinforced plastic, injection moulded	147.0	kg	P	carbon fibre reinforced plastic, injection moulded | carbon fibre reinforced plastic, injection moulded | Cutoff, U - GLO
Custom Aluminium	176.0	kg	P	See Table A.1
Custom Steel	29.0	kg	P	See Table A.2
glass fibre reinforced plastic, polyamide, injection moulded	50.0	kg	P	market for glass fibre reinforced plastic, polyamide, injection moulded | glass fibre reinforced plastic, polyamide, injection moulded | Cutoff, U - GLO
NOMEX HC	17.0	kg	P	See Table A.3
Output	Amount	Unit	P	Dataset/source for upstream flow provider
Main Fairings	1.0	Item(s)	P	

A.3 Drivetrain

Table A.12: Unit process for the assembly of the drivetrain.

Input	**Amount**	**Unit**	**Type**	**Dataset/source for upstream flow provider**
Turboprop Engine Assembled	2.0	Item(s)	P	See Table A.13
Electric motor 900nm	2.0	Item(s)	P	See Table A.17
EM Propeller	2.0	Item(s)	P	market for carbon fibre reinforced plastic, injection moulded | carbon fibre reinforced plastic, injection moulded | Cutoff, U - GLO
Gearbox, Electric motor 900nm	2.0	Item(s)	P	See Table
Nacelle	4.0	Item(s)	P	See Table A.15
Power Inverter	187.2	kg	P	See Table A.16
Turboprop propeller 1x	2.0	Item(s)	P	See Table A.18
Fuel System	1	Item(s)	P	See Table A.20
Output	Amount	Unit	Type	Dataset/source for upstream flow provider
Drivetrain	1.0	Item(s)	P	

A.3.1 Turboshaft engine

Table A.13: Unit process for the production of the turboshaft engine.

Input	**Amount**	**Unit**	**Type**	**Dataset/source for upstream flow provider**
aluminium alloy, metal matrix composite	20.0	kg	P	market for aluminium alloy, metal matrix composite | aluminium alloy, metal matrix composite | Cutoff, U - GLO
aluminium, wrought alloy	27.0	kg	P	market for aluminium, wrought alloy | aluminium, wrought alloy | Cutoff, U - GLO
diesel	182.0	kg	P	market for diesel | diesel | Cutoff, U - Europe without Switzerland
electricity, medium voltage	8604.0	kWh	P	market group for electricity, medium voltage | electricity, medium voltage | Cutoff, U - Europe without Switzerland
heat, from steam, in chemical industry	1078.0	kWh	P	market for heat, from steam, in chemical industry | heat, from steam, in chemical industry | Cutoff, U - RER
iron-nickel-chromium alloy	57.0	kg	P	market for iron-nickel-chromium alloy | iron-nickel-chromium alloy | Cutoff, U - GLO
kerosene	394.0	kg	P	market for kerosene | kerosene | Cutoff, U - Europe without Switzerland
magnesium-alloy, AZ91, diecast	9.0	kg	P	market for magnesium-alloy, AZ91, diecast | magnesium-alloy, AZ91, diecast | Cutoff, U - GLO
natural gas, burned in gas turbine	8652.0	kWh	P	market for natural gas, burned in gas turbine | natural gas, burned in gas turbine | Cutoff, U - GLO
silicon carbide	84.0	kg	P	market for silicon carbide | silicon carbide | Cutoff, U - GLO
tap water	21000.0	kg	P	market for tap water | tap water | Cutoff, U - Europe without Switzerland
titanium, triple-melt	18.0	kg	P	market for titanium, triple-melt | titanium, triple-melt | Cutoff, U - GLO
Output	Amount	Unit	Type	Dataset/source for upstream flow provider
Carbon dioxide, fossil	3840.0	kg	E	
inert waste, for final disposal	477.0	kg	W	market for inert waste, for final disposal | inert waste, for final disposal | Cutoff, U - RoW
Nitrogen oxides	1.5	kg	E	
Sulfur oxides	0.1	kg	E	
Turboprop Enginr	1.0	Item(s)	P	
VOC, volatile organic compounds	7.0	kg	E	
Waste water	20000.0	kg	W	

A.3.2 Turboshaft gearbox

Table A.14: Unit process for the production of the gearbox for the turboshaft engine.

Input	**Amount**	**Unit**	**Type**	**Dataset/source for upstream flow provider**
aluminium alloy, AlMg3	17.0	kg	P	market for aluminium alloy, AlMg3 | aluminium alloy, AlMg3 | Cutoff, U - GLO
diesel	57.0	kg	P	market for diesel | diesel | Cutoff, U - Europe without Switzerland
electricity, medium voltage	2722.0	kWh	P	market group for electricity, medium voltage | electricity, medium voltage | Cutoff, U - Europe without Switzerland
heat, from steam, in chemical industry	342.0	kWh	P	market for heat, from steam, in chemical industry | heat, from steam, in chemical industry | Cutoff, U - RER
kerosene	125.0	kg	P	market for kerosene | kerosene | Cutoff, U - Europe without Switzerland
natural gas, burned in gas turbine	2737.0	kWh	P	market for natural gas, burned in gas turbine | natural gas, burned in gas turbine | Cutoff, U - GLO
steel, low-alloyed	51.0	kg	P	market for steel, low-alloyed | steel, low-alloyed | Cutoff, U - GLO
tap water	6400.0	kg	P	market for tap water | tap water | Cutoff, U - Europe without Switzerland
Output	Amount	Unit	Type	Dataset/source for upstream flow provider
Carbon dioxide	1215.0	kg	E	
Gearbox, Turboprop Engine	1.0	Item(s)	P	
inert waste, for final disposal	151.0	kg	W	
Nitrogen oxides	0.5	kg	E	
Sulfur oxides	0.03	kg	E	
VOC, volatile organic compounds	2.0	kg	E	
Waste water	6400.0	kg	W	

A.3.3 Nacelle

Table A.15: Unit process for the production of the nacelle.

Input	**Amount**	**Unit**	**Type**	**Dataset/source for upstream flow provider**
carbon fibre reinforced plastic, injection moulded	39.0	kg	P	market for carbon fibre reinforced plastic, injection moulded | carbon fibre reinforced plastic, injection moulded | Cutoff, U - GLO
Custom Aluminium	15.0	kg	P	See Table A.1
titanium, triple-melt	44.0	kg	P	market for titanium, triple-melt | titanium, triple-melt | Cutoff, U - GLO
Output	Amount	Unit	Type	Dataset/source for upstream flow provider
Nacelle	1.0	Item(s)	P	

A.3.4 Power inverter

Table A.16: Unit process for the production of the power inverter.

Input	**Amount**	**Unit**	**Type**	**Dataset/source for upstream flow provider**
thio-carbamate-compound	1.5	g	P	market for thio-carbamate-compound | thio-carbamate-compound | Cutoff, U - GLO
acetone, liquid	4.5	g	P	market for acetone, liquid | acetone, liquid | Cutoff, U - RER
acrylic binder, with water, in 54 % solution state	2.2	g	P	market for acrylic binder, with water, in 54 % solution state | acrylic binder, with water, in 54 % solution state | Cutoff, U - RER
acrylic dispersion, with water, in 58 % solution state	0.55	g	P	market for acrylic dispersion, with water, in 58 % solution | acrylic dispersion, with water, in 58 % solution state | Cutoff, U - RER
adipic acid	7.0	mg	P	market for adipic acid | adipic acid | Cutoff, U - GLO
alkyd resin, long oil, without solvent, in 70 % white spirit solution state	148.0	g	P	market for alkyd resin, long oil, without solvent, in 70 % white spirit solution state | alkyd resin, long oil, without solvent, in 70 % white spirit solution state | Cutoff, U - RER
aluminium oxide, metallurgical	0.03	kg	P	market for aluminium oxide, metallurgical | aluminium oxide, metallurgical | Cutoff, U - IAI Area, EU27 & EFTA
aluminium oxide, metallurgical	15.0	g	P	market for aluminium oxide, metallurgical | aluminium oxide, metallurgical | Cutoff, U - IAI Area, EU27 & EFTA
aluminium scrap, new	2.0	g	P	market for aluminium scrap, new | aluminium scrap, new | Cutoff, U - RER
aluminium, primary, ingot	8.99	kg	P	market for aluminium, primary, ingot | aluminium, primary, ingot | Cutoff, U - IAI Area, EU27 & EFTA
antimony	7.7	g	P	market for antimony | antimony | Cutoff, U - GLO
benzaldehyde	0.3	g	P	market for benzaldehyde | benzaldehyde | Cutoff, U - RER
brass	1.04	kg	P	market for brass | brass | Cutoff, U - RoW
brass removed by turning, primarily dressing, computer numerical controlled	0.19	kg	P	market for brass removed by turning, primarily dressing, computer numerical controlled | brass removed by turning, primarily dressing, computer numerical controlled | Cutoff, U - GLO
butyl acetate	0.5	kg	P	market for butyl acetate | butyl acetate | Cutoff, U - RER
capacitor, auxilliaries and energy use	2.04	kg	P	market for capacitor, auxilliaries and energy use | capacitor, auxilliaries and energy use | Cutoff, U - GLO
capacitor, electrolyte type, < 2cm height	6.5	g	P	market for capacitor, electrolyte type, < 2cm height | capacitor, electrolyte type, < 2cm height | Cutoff, U - GLO
capacitor, for surface-mounting	4.1	g	P	market for capacitor, for surface-mounting | capacitor, for surface-mounting | Cutoff, U - GLO
capacitor, tantalum-, for through-hole mounting	2.2	g	P	market for capacitor, tantalum-, for through-hole mounting | capacitor, tantalum-, for through-hole mounting | Cutoff, U - GLO
casting, brass	1.03	kg	P	market for casting, brass | casting, brass | Cutoff, U - GLO
chemical, organic	7.0	g	P	market for chemical, organic | chemical, organic | Cutoff, U - GLO

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Table A.16: Unit process for the production of the power inverter. (Continued)

Input	Amount	Unit	Type	Dataset/source for upstream flow provider
chlorine, gaseous	8.0	g	P	market for chlorine, gaseous | chlorine, gaseous | Cutoff, U - RER
copper, anode	3.74	kg	P	market for copper, anode | copper, anode | Cutoff, U - GLO
diode, glass-, for surface-mounting	4.3	g	P	market for diode, glass-, for surface-mounting | diode, glass-, for surface-mounting | Cutoff, U - GLO
dipropylene glycol monomethyl ether	4.9	g	P	market for dipropylene glycol monomethyl ether | dipropylene glycol monomethyl ether | Cutoff, U - RER
electric connector, peripheral component interconnect buss	49.0	g	P	market for electric connector, peripheral component interconnect buss | electric connector, peripheral component interconnect buss | Cutoff, U - GLO
electric connector, wire clamp	22.8	g	P	market for electric connector, wire clamp | electric connector, wire clamp | Cutoff, U - GLO
electricity, medium voltage	1.02	kWh	P	market group for electricity, medium voltage | electricity, medium voltage | Cutoff, U - Europe without Switzerland
electricity, medium voltage	5.89	kWh	P	market group for electricity, medium voltage | electricity, medium voltage | Cutoff, U - Europe without Switzerland
electricity, medium voltage	6.75	kWh	P	market group for electricity, medium voltage | electricity, medium voltage | Cutoff, U - Europe without Switzerland
electricity, medium voltage	0.81	kWh	P	market group for electricity, medium voltage | electricity, medium voltage | Cutoff, U - Europe without Switzerland
electricity, medium voltage, aluminium industry	24.06	kWh	P	market for electricity, medium voltage, aluminium industry | electricity, medium voltage, aluminium industry | Cutoff, U - IAI Area, EU27 & EFTA
extrusion, co-extrusion	0.0	kg	P	market for extrusion, co-extrusion | extrusion, co-extrusion | Cutoff, U - GLO
extrusion, co-extrusion	0.031	kg	P	market for extrusion, co-extrusion | extrusion, co-extrusion | Cutoff, U - GLO
extrusion, plastic pipes	0.035	kg	P	market for extrusion, plastic pipes | extrusion, plastic pipes | Cutoff, U - GLO
extrusion, plastic pipes	0.002	kg	P	market for extrusion, plastic pipes | extrusion, plastic pipes | Cutoff, U - GLO
glass fibre reinforced plastic, polyester resin, hand lay-up	64.0	g	P	market for glass fibre reinforced plastic, polyester resin, hand lay-up | glass fibre reinforced plastic, polyester resin, hand lay-up | Cutoff, U - GLO
glycerine	2.7	g	P	market for glycerine | glycerine | Cutoff, U - RER
gold, unrefined	0.29	g	P	market for gold, unrefined | gold, unrefined | Cutoff, U - GLO
heat, district or industrial, natural gas	91.6	MJ	P	market for heat, district or industrial, natural gas | heat, district or industrial, natural gas | Cutoff, U - Europe without Switzerland
hot rolling, steel	0.43	kg	P	market for hot rolling, steel | hot rolling, steel | Cutoff, U - GLO
hydrochloric acid, without water, in 30 % solution state	9.2	g	P	market for hydrochloric acid, without water, in 30 % solution state | hydrochloric acid, without water, in 30 % solution state | Cutoff, U - RER
inductor, low value multilayer chip	18.0	mg	P	market for inductor, low value multilayer chip | inductor, low value multilayer chip | Cutoff, U - GLO
inductor, miniature radio frequency chip	385.0	mg	P	market for inductor, miniature radio frequency chip | inductor, miniature radio frequency chip | Cutoff, U - GLO
inductor, ring core choke type	5.7	g	P	market for inductor, ring core choke type | inductor, ring core choke type | Cutoff, U - GLO
injection moulding	0.23	kg	P	market for injection moulding | injection moulding | Cutoff, U - GLO
injection moulding	0.009	kg	P	market for injection moulding | injection moulding | Cutoff, U - GLO
integrated circuit, logic type	10.2	g	P	market for integrated circuit, logic type | integrated circuit, logic type | Cutoff, U - GLO
integrated circuit, memory type	36.0	mg	P	market for integrated circuit, memory type | integrated circuit, memory type | Cutoff, U - GLO
isohexane	3.0	g	P	market for isohexane | isohexane | Cutoff, U - GLO
isopropanol	22.8	g	P	market for isopropanol | isopropanol | Cutoff, U - RER
laminating service, foil, with acrylic binder	0.71	m2	P	market for laminating service, foil, with acrylic binder | laminating service, foil, with acrylic binder | Cutoff, U - GLO

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Table A.16: Unit process for the production of the power inverter. (Continued)

Input	Amount	Unit	Type	Dataset/source for upstream flow provider
light emitting diode	20.0	mg	P	market for light emitting diode | light emitting diode | Cutoff, U - GLO
lubricating oil	170.0	g	P	market for lubricating oil | lubricating oil | Cutoff, U - RER
metal working, average for chromium steel product manufacturing	0.43	kg	P	market for metal working, average for chromium steel product manufacturing | metal working, average for chromium steel product manufacturing | Cutoff, U - GLO
metal working, average for copper product manufacturing	3.12	kg	P	market for metal working, average for copper product manufacturing | metal working, average for copper product manufacturing | Cutoff, U - GLO
methylene diphenyl diisocyanate	68.0	g	P	market for methylene diphenyl diisocyanate | methylene diphenyl diisocyanate | Cutoff, U - RER
monoethanolamine	0.74	g	P	market for monoethanolamine | monoethanolamine | Cutoff, U - GLO
naphtha	136.0	g	P	market for naphtha | naphtha | Cutoff, U - RER
naphtha	178.0	g	P	market for naphtha | naphtha | Cutoff, U - RER
nickel, class 1	27.0	g	P	market for nickel, class 1 | nickel, class 1 | Cutoff, U - GLO
nitric acid, without water, in 50 % solution state	17.0	g	P	market for nitric acid, without water, in 50 % solution state | nitric acid, without water, in 50 % solution state | Cutoff, U - RER w/o RU
nitrogen, liquid	6.62	kg	P	market for nitrogen, liquid | nitrogen, liquid | Cutoff, U - RER
nylon 6, glass-filled	11.0	g	P	market for nylon 6, glass-filled | nylon 6, glass-filled | Cutoff, U - RER
polycarbonate	18.0	g	P	market for polycarbonate | polycarbonate | Cutoff, U - GLO
polyethylene terephthalate, granulate, amorphous	388.0	g	P	market for polyethylene terephthalate, granulate, amorphous | polyethylene terephthalate, granulate, amorphous | Cutoff, U - GLO
polyethylene terephthalate, granulate, bottle grade	31.0	g	P	market for polyethylene terephthalate, granulate, bottle grade | polyethylene terephthalate, granulate, bottle grade | Cutoff, U - GLO
polyol	226.0	g	P	market for polyol | polyol | Cutoff, U - RER
polyphenylene sulfide	153.0	g	P	market for polyphenylene sulfide | polyphenylene sulfide | Cutoff, U - GLO
polypropylene, granulate	596.0	g	P	market for polypropylene, granulate | polypropylene, granulate | Cutoff, U - GLO
potassium carbonate	20.0	g	P	market for potassium carbonate | potassium carbonate | Cutoff, U - GLO
potassium hydroxide	20.0	g	P	market for potassium hydroxide | potassium hydroxide | Cutoff, U - GLO
printed wiring board, for surface mounting, Pb free surface	2.2	dm2	P	market for printed wiring board, for surface mounting, Pb free surface | printed wiring board, for surface mounting, Pb free surface | Cutoff, U - GLO
resistor, surface-mounted	1.3	g	P	market for resistor, surface-mounted | resistor, surface-mounted | Cutoff, U - GLO
section bar rolling, steel	0.43	kg	P	market for section bar rolling, steel | section bar rolling, steel | Cutoff, U - GLO
sheet rolling, copper	3.12	kg	P	market for sheet rolling, copper | sheet rolling, copper | Cutoff, U - GLO
silicone product	0.6	g	P	market for silicone product | silicone product | Cutoff, U - RER
silicone product	35.0	g	P	market for silicone product | silicone product | Cutoff, U - RER
silicone product	3.0	g	P	market for silicone product | silicone product | Cutoff, U - RER
silicone product	149.0	g	P	market for silicone product | silicone product | Cutoff, U - RER
sodium hydroxide, without water, in 50 % solution state	11.0	g	P	market for sodium hydroxide, without water, in 50 % solution state | sodium hydroxide, without water, in 50 % solution state | Cutoff, U - GLO
sodium sulfate, anhydrite	0.0	g	P	market for sodium sulfate, anhydrite | sodium sulfate, anhydrite | Cutoff, U - RER
solder, bar, Sn95.5Ag3.9Cu0.6, for electronics industry	0.31	g	P	market for solder, bar, Sn95.5Ag3.9Cu0.6, for electronics industry | solder, bar, Sn95.5Ag3.9Cu0.6, for electronics industry | Cutoff, U - GLO
solder, paste, Sn95.5Ag3.9Cu0.6, for electronics industry	99.0	g	P	market for solder, paste, Sn95.5Ag3.9Cu0.6, for electronics industry | solder, paste, Sn95.5Ag3.9Cu0.6, for electronics industry | Cutoff, U - GLO

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Table A.16: Unit process for the production of the power inverter. (Continued)

Input	**Amount**	**Unit**	**Type**	**Dataset/source for upstream flow provider**
steel, low-alloyed	0.43	kg	P	market for steel, low-alloyed | steel, low-alloyed | Cutoff, U - GLO
sulfuric acid	19.0	g	P	market for sulfuric acid | sulfuric acid | Cutoff, U - RER
switch, toggle type	300.0	mg	P	market for switch, toggle type | switch, toggle type | Cutoff, U - GLO
tap water	3.3	kg	P	market for tap water | tap water | Cutoff, U - Europe without Switzerland
tin	75.0	g	P	market for tin | tin | Cutoff, U - GLO
transformer, low voltage use	30.0	g	P	market for transformer, low voltage use | transformer, low voltage use | Cutoff, U - GLO
transistor, surface-mounted	1.8	g	P	market for transistor, surface-mounted | transistor, surface-mounted | Cutoff, U - GLO
wafer, fabricated, for integrated circuit	11.1	cm2	P	market for wafer, fabricated, for integrated circuit | wafer, fabricated, for integrated circuit | Cutoff, U - GLO
water, deionised	25.9	kg	P	market for water, deionised | water, deionised | Cutoff, U - Europe without Switzerland
water, deionised	126.0	mg	P	market for water, deionised | water, deionised | Cutoff, U - Europe without Switzerland
water, ultrapure	19.0	g	P	market for water, ultrapure | water, ultrapure | Cutoff, U - RER
wire drawing, copper	0.11	kg	P	market for wire drawing, copper | wire drawing, copper | Cutoff, U - GLO
zinc	154.0	g	P	market for zinc | zinc | Cutoff, U - GLO
zinc oxide	3.0	g	P	market for zinc oxide | zinc oxide | Cutoff, U - GLO
Output				
Aluminium III	3.4	g	E	
Ammonia, SE	0.11	g	E	
Carbon dioxide	1.2	g	E	
Carbon monoxide, fossil	0.77	g	E	
Cyanide	0.016	mg	E	
Cyanide	0.65	mg	E	
Ethanol	3.0	g	E	
hazardous waste, for incineration	5.9	g	W	market for hazardous waste, for incineration | hazardous waste, for incineration | Cutoff, U - Europe without Switzerland
hazardous waste, for incineration	5.3	g	W	market for hazardous waste, for incineration | hazardous waste, for incineration | Cutoff, U - Europe without Switzerland
hazardous waste, for incineration	1.5	g	W	market for hazardous waste, for incineration | hazardous waste, for incineration | Cutoff, U - Europe without Switzerland
Nickel II	1.1	mg	E	
Nickel, ion	0.4	mg	E	
NMVOC, non-methane volatile organic compounds	148.3	g	E	
Power Inverter	15.6	kg	P	
scrap aluminium	428.0	g	W	market for scrap aluminium | scrap aluminium | Cutoff, U - Europe without Switzerland
spent solvent mixture	1.3	g	W	market for spent solvent mixture | spent solvent mixture | Cutoff, U - Europe without Switzerland
spent solvent mixture	0.085	kg	W	market for spent solvent mixture | spent solvent mixture | Cutoff, U - Europe without Switzerland
spent solvent mixture	5.7	g	W	market for spent solvent mixture | spent solvent mixture | Cutoff, U - Europe without Switzerland
waste aluminium	0.51	kg	W	market for waste aluminium | waste aluminium | Cutoff, U - GLO
waste mineral oil	178.0	g	W	market for waste mineral oil | waste mineral oil | Cutoff, U - Europe without Switzerland
waste plastic, mixture	0.0	g	W	market group for waste plastic, mixture | waste plastic, mixture | Cutoff, U - Europe without Switzerland

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Table A.16: Unit process for the production of the power inverter. (Continued)

Input	Amount	Unit	Type	Dataset/source for upstream flow provider
wastewater, average	25.4	dm3	W	market for wastewater, average | wastewater, average | Cutoff, U - Europe without Switzerland
Zinc, ion	0.0052	mg	E	

A.3.5 Electric motor production

Table A.17: Unit process for the production of the electric motor.

Input	Amount	Unit	Type	Dataset/source for upstream flow provider
alkyd resin, long oil, without solvent, in 70 % white spirit solution state	528.3	g	P	market for alkyd resin, long oil, without solvent, in 70 % white spirit solution state | alkyd resin, long oil, without solvent, in 70 % white spirit solution state | Cutoff, U - RER
aluminium, cast alloy	57.9	kg	P	market for aluminium, cast alloy | aluminium, cast alloy | Cutoff, U - GLO
anode, graphite, for Li-ion battery	0.4	kg	P	market for anode, graphite, for Li-ion battery | anode, graphite, for Li-ion battery | Cutoff, U - CN
argon, liquid	96.2	g	P	market for argon, liquid | argon, liquid | Cutoff, U - RER
boron carbide	71.7	g	P	market for boron carbide | boron carbide | Cutoff, U - GLO
copper, cathode	14.3	kg	P	market for copper, cathode | copper, cathode | Cutoff, U - GLO
dysprosium oxide	218.9	g	P	market for dysprosium oxide | dysprosium oxide | Cutoff, U - GLO
electricity, medium voltage	366.6	kWh	P	market group for electricity, medium voltage | electricity, medium voltage | Cutoff, U - Europe without Switzerland
epoxy resin, liquid	1000.0	g	P	market for epoxy resin, liquid | epoxy resin, liquid | Cutoff, U - RER
extrusion, plastic film	1.3	kg	P	market for extrusion, plastic film | extrusion, plastic film | Cutoff, U - GLO
extrusion, plastic pipes	0.1	kg	P	market for extrusion, plastic pipes | extrusion, plastic pipes | Cutoff, U - GLO
ferrosilicon	3.5	kg	P	market for ferrosilicon | ferrosilicon | Cutoff, U - GLO
glass fibre	13.2	g	P	market for glass fibre | glass fibre | Cutoff, U - GLO
heat, central or small-scale, natural gas	1390.5	MJ	P	market group for heat, central or small-scale, natural gas | heat, central or small-scale, natural gas | Cutoff, U - RER
hot rolling, steel	184.8	kg	P	market for hot rolling, steel | hot rolling, steel | Cutoff, U - GLO
hydrogen, liquid	2.8	kg	P	market for hydrogen, liquid | hydrogen, liquid | Cutoff, U - RER
injection moulding	0.6	kg	P	market for injection moulding | injection moulding | Cutoff, U - GLO
liquefied petroleum gas	1773.6	g	P	market for liquefied petroleum gas | liquefied petroleum gas | Cutoff, U - Europe without Switzerland
lithium fluoride	15.1	g	P	market for lithium fluoride | lithium fluoride | Cutoff, U - GLO
lubricating oil	1134.0	g	P	market for lubricating oil | lubricating oil | Cutoff, U - RER
metal working, average for copper product manufacturing	0.2	kg	P	market for metal working, average for copper product manufacturing | metal working, average for copper product manufacturing | Cutoff, U - GLO
metal working, average for steel product manufacturing	35.2	kg	P	market for metal working, average for steel product manufacturing | metal working, average for steel product manufacturing | Cutoff, U - GLO
methyl methacrylate	209.4	g	P	market for methyl methacrylate | methyl methacrylate | Cutoff, U - RER
naphtha	486.8	g	P	market for naphtha | naphtha | Cutoff, U - RER
naphtha	1273.6	g	P	market for naphtha | naphtha | Cutoff, U - RER
neodymium oxide	1.9	kg	P	market for neodymium oxide | neodymium oxide | Cutoff, U - GLO
nickel, class 1	50.9	g	P	market for nickel, class 1 | nickel, class 1 | Cutoff, U - GLO
nylon 6	27.0	g	P	market for nylon 6 | nylon 6 | Cutoff, U - RER

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Table A.17: Unit process for the production of the electric motor. (Continued)

Input	**Amount**	**Unit**	**Type**	**Dataset/source for upstream flow provider**
phenolic resin	147.2	g	P	market for phenolic resin | phenolic resin | Cutoff, U - RER
polyester resin, unsaturated	639.6	g	P	market for polyester resin, unsaturated | polyester resin, unsaturated | Cutoff, U - RER
polyethylene terephthalate, granulate, bottle grade	539.6	g	P	market for polyethylene terephthalate, granulate, bottle grade | polyethylene terephthalate, granulate, bottle grade | Cutoff, U - GLO
polyethylene terephthalate, granulate, bottle grade	262.3	g	P	market for polyethylene terephthalate, granulate, bottle grade | polyethylene terephthalate, granulate, bottle grade | Cutoff, U - GLO
propylene glycol, liquid	5.9	kg	P	market for propylene glycol, liquid | propylene glycol, liquid | Cutoff, U - RER
quicklime, milled, packed	184.9	g	P	market for quicklime, milled, packed | quicklime, milled, packed | Cutoff, U - RER
section bar rolling, steel	35.2	kg	P	market for section bar rolling, steel | section bar rolling, steel | Cutoff, U - GLO
sheet rolling, chromium steel	4.5	kg	P	market for sheet rolling, chromium steel | sheet rolling, chromium steel | Cutoff, U - GLO
sheet rolling, copper	0.2	kg	P	market for sheet rolling, copper | sheet rolling, copper | Cutoff, U - GLO
silica sand	49.1	g	P	market for silica sand | silica sand | Cutoff, U - GLO
silica sand	317.0	g	P	market for silica sand | silica sand | Cutoff, U - GLO
silicone product	52.8	g	P	market for silicone product | silicone product | Cutoff, U - RER
silicone product	7.5	g	P	market for silicone product | silicone product | Cutoff, U - RER
sodium hydroxide, without water, in 50 % solution state	5.7	g	P	market for sodium hydroxide, without water, in 50 % solution state | sodium hydroxide, without water, in 50 % solution state | Cutoff, U - GLO
steel, chromium steel 18/8	1.9	kg	P	market for steel, chromium steel 18/8 | steel, chromium steel 18/8 | Cutoff, U - GLO
steel, low-alloyed	14.8	kg	P	market for steel, low-alloyed | steel, low-alloyed | Cutoff, U - GLO
steel, unalloyed	168.9	kg	P	market for steel, unalloyed | steel, unalloyed | Cutoff, U - GLO
sulfuric acid	2837.7	g	P	market for sulfuric acid | sulfuric acid | Cutoff, U - RER
tap water	85.5	kg	P	market for tap water | tap water | Cutoff, U - Europe without Switzerland
tin plating, pieces	0.0	m2	P	market for tin plating, pieces | tin plating, pieces | Cutoff, U - GLO
wire drawing, copper	34.0	kg	P	market for wire drawing, copper | wire drawing, copper | Cutoff, U - GLO
xylene	341.5	g	P	market for xylene | xylene | Cutoff, U - RER
zinc coat, coils	0.1	m2	P	market for zinc coat, coils | zinc coat, coils | Cutoff, U - GLO
Output	Amount	Unit	Type	Dataset/source for upstream flow provider
Aluminium III	20.75	g	E	
Carbon dioxide	6.92	kg	E	
Electric motor 1nm	900	Item(s)	P	
hazardous waste, for incineration	1481.13	g	W	market for hazardous waste, for incineration | hazardous waste, for incineration | Cutoff, U - RoW
Hydrocarbons, aliphatic, unsaturated	50.94	g	E	
Hydrogen fluoride	9.43	g	E	
iron scrap, unsorted	943.40	g	P	market for iron scrap, unsorted | iron scrap, unsorted | Cutoff, U - GLO
Nickel II	20.75	mg	E	
Nickel, ion	24.53	mg	E	
Nitrogen oxides	14.72	g	E	
NMVOC, non-methane volatile organic compounds	541.51	g	E	
Particulates, > 2.5 um, and < 10um	7.55	g	E	

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Table A.17: Unit process for the production of the electric motor. (Continued)

Input	Amount	Unit	Type	Dataset/source for upstream flow provider
scrap aluminium	2.30	kg	W	market for scrap aluminium | scrap aluminium | Cutoff, U - RoW
scrap copper	213.21	g	W	market for scrap copper | scrap copper | Cutoff, U - RoW
scrap steel	91.51	kg	W	market for scrap steel | scrap steel | Cutoff, U - RoW
sludge, NaCl electrolysis	141.51	g	W	market for sludge, NaCl electrolysis | sludge, NaCl electrolysis | Cutoff, U - GLO
spent antifreezer liquid	5.94	kg	W	treatment of spent antifreezer liquid, hazardous waste incineration | spent antifreezer liquid | Cutoff, U - CH
Sulfur dioxide	8.87	g	E	
waste aluminium	3.25	kg	W	market for waste aluminium | waste aluminium | Cutoff, U - GLO

A.3.6 Propellers

A.3.6.1 Turboshaft propeller

Table A.18: Unit process for the production of the propeller for the turboshaft engines.

Input	Amount	Unit	Type	Dataset/source for upstream flow provider
carbon fibre reinforced plastic, injection moulded	81.1	kg	P	market for carbon fibre reinforced plastic, injection moulded | carbon fibre reinforced plastic, injection moulded | Cutoff, U - GLO
Output	Amount	Unit	Type	Dataset/source for upstream flow provider
Turboprop propeller 1x	1.0	Item(s)	P	

A.3.6.2 Electric motor propeller

Table A.19: Unit process for the production of the propeller for the electric motors.

Input	Amount	Unit	Type	Dataset/source for upstream flow provider
carbon fibre reinforced plastic, injection moulded	120.0	kg	P	market for carbon fibre reinforced plastic, injection moulded | carbon fibre reinforced plastic, injection moulded | Cutoff, U - GLO
Output	Amount	Unit	Type	Dataset/source for upstream flow provider
Electric Motor Propeller 1x	1.0	Item(s)	P	

A.3.7 Fuel system

Table A.20: Unit process for the production of the fuel system.

Input	Amount	Unit	Type	Dataset/source for upstream flow provider
Coolant pump 1x0.66kg	40.0	Item(s)	P	Arvidsson et al., 2023
Electronic control units Acc. Pipistrell	7.44	kg	P	electronics production, for control units | electronics, for control units | Cutoff, U (Modified according to Arvidsson et al., 2023)
metal working, average for chromium steel product manufacturing	51.0	kg	P	market for metal working, average for chromium steel product manufacturing | metal working, average for chromium steel product manufacturing | Cutoff, U - GLO
steel, chromium steel 18/8	51.0	kg	P	market for steel, chromium steel 18/8 | steel, chromium steel 18/8 | Cutoff, U - GLO
synthetic rubber	25.0	kg	P	market for synthetic rubber | synthetic rubber | Cutoff, U - GLO
Output	Amount	Unit	Type	Dataset/source for upstream flow provider
Fuel system	1.0	Item(s)	P	

A.3.8 Battery energy storage system

Table A.21: Unit process for the production of 1 battery energy storage system.

Input	**Amount**	**Unit**	**Type**	**Dataset/source for upstream flow provider**
BMS	161.0	kg	P	See Table A.22
HV Connector	85.0	Item(s)	P	See Table A.26
Pack & module production (1kg pack & module)	809.0	kg	P	See Table A.27
Battery cells	4004.0	kg	P	Datasets reported in Chordia et al. (2021), altered using an Asian electricity mix in cell production
Output	Amount	Unit	Type	Dataset/source for upstream flow provider
1 battery energy storage system	1.0	Item(s)	P	

A.3.8.1 Battery management system (BMS)

Table A.22: Unit process for the production of 1 kg battery management system (BMS).

Input	**Amount**	**Unit**	**Type**	**Dataset/source for upstream flow provider**
BMS, HV-system	0.41	kg	P	See Table A.23
LV-system for BMS	0.38	kg	P	See Table A.24
Logic boards for BMS	0.2	kg	P	See Table A.25
Output	Amount	Unit	Type	Dataset/source for upstream flow provider
Battery management system	1.0	kg	P	

A.3.8.2 BMS, HV-system

Table A.23: Unit process for the production of 1 kg HV-system for BMS.

Input	**Amount**	**Unit**	**Type**	**Dataset/source for upstream flow provider**
aluminium, wrought alloy	0.12	kg	P	market for aluminium, wrought alloy | aluminium, wrought alloy | Cutoff, U - GLO
cable, ribbon cable, 20-pin, with plugs	0.45	kg	P	market for cable, ribbon cable, 20-pin, with plugs | cable, ribbon cable, 20-pin, with plugs | Cutoff, U - GLO
copper, cathode	0.27	kg	P	market for copper, cathode | copper, cathode | Cutoff, U - GLO
injection moulding	0.13	kg	P	market for injection moulding | injection moulding | Cutoff, U - GLO
metal working, average for metal product manufacturing	0.41	kg	P	market for metal working, average for metal product manufacturing | metal working, average for metal product manufacturing | Cutoff, U - GLO
nylon 6-6	0.044	kg	P	market for nylon 6-6 | nylon 6-6 | Cutoff, U - RoW
polyethylene terephthalate, granulate, amorphous	0.057	kg	P	market for polyethylene terephthalate, granulate, amorphous | polyethylene terephthalate, granulate, amorphous | Cutoff, U - GLO
polyphenylene sulfide	0.032	kg	P	market for polyphenylene sulfide | polyphenylene sulfide | Cutoff, U - GLO
steel, low-alloyed, hot rolled	0.0014	kg	P	market for steel, low-alloyed, hot rolled | steel, low-alloyed, hot rolled | Cutoff, U - GLO
synthetic rubber	0.0036	kg	P	market for synthetic rubber | synthetic rubber | Cutoff, U - GLO
tin	0.016	kg	P	market for tin | tin | Cutoff, U - GLO
Output	Amount	Unit	Type	Dataset/source for upstream flow provider
HV-system for BMS	1.0	kg	P	

A.3.8.3 BMS, LV-system

Table A.24: Unit process for the production of 1 kg LV-system for BMS.

Input	**Amount**	**Unit**	**Type**	**Dataset/source for upstream flow provider**
electronic component, passive, unspecified	0.97	kg	P	market for electronic component, passive, unspecified | electronic component, passive, unspecified | Cutoff, U - GLO
injection moulding	0.029	kg	P	market for injection moulding | injection moulding | Cutoff, U - GLO
nylon 6-6	0.029	kg	P	market for nylon 6-6 | nylon 6-6 | Cutoff, U - RoW
Output	Amount	Unit	Type	Dataset/source for upstream flow provider
LV-system for BMS	1.0	kg	P	

A.3.8.4 BMS, logicboards

Table A.25: Unit process for the production of the BMS logic board

Input	**Amount**	**Unit**	**Type**	**Dataset/source for upstream flow provider**
thio-carbamate-compound	8.3	g	P	market for thio-carbamate-compound | thio-carbamate-compound | Cutoff, U - GLO
adipic acid	0.08	g	P	market for adipic acid | adipic acid | Cutoff, U - GLO
benzaldehyde	1.4	g	P	market for benzaldehyde | benzaldehyde | Cutoff, U - RoW
butyl acetate	2.9	g	P	market for butyl acetate | butyl acetate | Cutoff, U - RoW
capacitor, electrolyte type, < 2cm height	64.9	g	P	market for capacitor, electrolyte type, < 2cm height | capacitor, electrolyte type, < 2cm height | Cutoff, U - GLO
capacitor, for surface-mounting	33.3	g	P	market for capacitor, for surface-mounting | capacitor, for surface-mounting | Cutoff, U - GLO
diode, glass-, for surface-mounting	9.5	g	P	market for diode, glass-, for surface-mounting | diode, glass-, for surface-mounting | Cutoff, U - GLO
dipropylene glycol monomethyl ether	7.8	g	P	market for dipropylene glycol monomethyl ether | dipropylene glycol monomethyl ether | Cutoff, U - RoW
electric connector, wire clamp	162.0	g	P	market for electric connector, wire clamp | electric connector, wire clamp | Cutoff, U - GLO
electric connector, wire clamp	84.0	g	P	market for electric connector, wire clamp | electric connector, wire clamp | Cutoff, U - GLO
electricity, medium voltage	0.61	kWh	P	market group for electricity, medium voltage | electricity, medium voltage | Cutoff, U - GLO
electricity, medium voltage	5.41	kWh	P	market group for electricity, medium voltage | electricity, medium voltage | Cutoff, U - GLO
inductor, low value multilayer chip	0.3	g	P	market for inductor, low value multilayer chip | inductor, low value multilayer chip | Cutoff, U - GLO
inductor, miniature radio frequency chip	6.1	g	P	market for inductor, miniature radio frequency chip | inductor, miniature radio frequency chip | Cutoff, U - GLO
inductor, ring core choke type	100.0	g	P	market for inductor, ring core choke type | inductor, ring core choke type | Cutoff, U - GLO
integrated circuit, logic type	114.0	g	P	market for integrated circuit, logic type | integrated circuit, logic type | Cutoff, U - GLO
integrated circuit, memory type	0.6	g	P	market for integrated circuit, memory type | integrated circuit, memory type | Cutoff, U - GLO
isohexane	15.1	g	P	market for isohexane | isohexane | Cutoff, U - GLO
light emitting diode	0.2	g	P	market for light emitting diode | light emitting diode | Cutoff, U - GLO
monoethanolamine	1.2	g	P	market for monoethanolamine | monoethanolamine | Cutoff, U - GLO
nitrogen, liquid	0.19	kg	P	market for nitrogen, liquid | nitrogen, liquid | Cutoff, U - RoW
nitrogen, liquid	7.61	kg	P	market for nitrogen, liquid | nitrogen, liquid | Cutoff, U - RoW
printed wiring board, for surface mounting, Pb free surface	11.9	dm2	P	market for printed wiring board, for surface mounting, Pb free surface | printed wiring board, for surface mounting, Pb free surface | Cutoff, U - GLO
resistor, surface-mounted	5.3	g	P	market for resistor, surface-mounted | resistor, surface-mounted | Cutoff, U - GLO

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Table A.25: Unit process for the production of the BMS logic board (Continued)

Input	**Amount**	**Unit**	**Type**	**Dataset/source for upstream flow provider**
solder, bar, Sn95.5Ag3.9Cu0.6, for electronics industry	3.7	g	P	market for solder, bar, Sn95.5Ag3.9Cu0.6, for electronics industry | solder, bar, Sn95.5Ag3.9Cu0.6, for electronics industry | Cutoff, U - GLO
solder, paste, Sn95.5Ag3.9Cu0.6, for electronics industry	11.2	g	P	market for solder, paste, Sn95.5Ag3.9Cu0.6, for electronics industry | solder, paste, Sn95.5Ag3.9Cu0.6, for electronics industry | Cutoff, U - GLO
switch, toggle type	5.3	g	P	market for switch, toggle type | switch, toggle type | Cutoff, U - GLO
transistor, surface-mounted	9.5	g	P	market for transistor, surface-mounted | transistor, surface-mounted | Cutoff, U - GLO
water, deionised	1.5	g	P	market for water, deionised | water, deionised | Cutoff, U - RoW
water, deionised	38.9	g	P	market for water, deionised | water, deionised | Cutoff, U - RoW
Output	Amount	Unit	Type	Dataset/source for upstream flow provider
electronics scrap from control units	12.0	g	W	market for electronics scrap from control units | electronics scrap from control units | Cutoff, U - GLO
Ethanol	0.47	g	E	
hazardous waste, for incineration	0.4	g	W	market for hazardous waste, for incineration | hazardous waste, for incineration | Cutoff, U - RoW
NMVOC, non-methane volatile organic compounds	18.6	g	E	
spent solvent mixture	9.0	g	W	market for spent solvent mixture | spent solvent mixture | Cutoff, U - RoW
Logicboards for BMS	1.0	kg	P	

A.3.8.5 HV-connector

Table A.26: Unit process for the production of 1 HV-connector.

Input	**Amount**	**Unit**	**Type**	**Dataset/source for upstream flow provider**
copper, cathode	295.0	g	P	market for copper, cathode | copper, cathode | Cutoff, U - GLO
injection moulding	11.0	g	P	market for injection moulding | injection moulding | Cutoff, U - GLO
metal working, average for copper product manufacturing	295.0	g	P	market for metal working, average for copper product manufacturing | metal working, average for copper product manufacturing | Cutoff, U - GLO
polyethylene, high density, granulate	11.0	g	P	market for polyethylene, high density, granulate | polyethylene, high density, granulate | Cutoff, U - GLO
sheet rolling, copper	295.0	g	P	market for sheet rolling, copper | sheet rolling, copper | Cutoff, U - GLO
Output	Amount	Unit	Type	Dataset/source for upstream flow provider
1 HV-connector	1.0	Item(s)	P	

A.3.8.6 Pack and module production

Table A.27: Unit process for production of 1 kg of pack and module for the battery energy storage system

Input	**Amount**	**Unit**	**Type**	**Dataset/source for upstream flow provider**
aluminium, wrought alloy	0.71	kg	P	market for aluminium, wrought alloy | aluminium, wrought alloy | Cutoff, U - GLO
copper, cathode	0.009	kg	P	market for copper, cathode | copper, cathode | Cutoff, U - GLO
electricity, medium voltage	0.002	kWh	P	market group for electricity, medium voltage | electricity, medium voltage | Cutoff, U - US
electronic component factory	6.67E-10	Item(s)	P	market for electronic component factory | electronic component factory | Cutoff, U - GLO
ethylene glycol	0.076	kg	P	market for ethylene glycol | ethylene glycol | Cutoff, U - GLO
impact extrusion of aluminium, 1 stroke	0.53	kg	P	market for impact extrusion of aluminium, 1 stroke | impact extrusion of aluminium, 1 stroke | Cutoff, U - GLO
injection moulding	0.021	kg	P	market for injection moulding | injection moulding | Cutoff, U - GLO
metal working factory	2.4E-9	Item(s)	P	market for metal working factory | metal working factory | Cutoff, U - GLO
metal working, average for aluminium product manufacturing	0.20	kg	P	market for metal working, average for aluminium product manufacturing | metal working, average for aluminium product manufacturing | Cutoff, U - GLO
metal working, average for chromium steel product manufacturing	0.03	kg	P	market for metal working, average for chromium steel product manufacturing | metal working, average for chromium steel product manufacturing | Cutoff, U - GLO
metal working, average for copper product manufacturing	0.01	kg	P	market for metal working, average for copper product manufacturing | metal working, average for copper product manufacturing | Cutoff, U - GLO
polyethylene, high density, granulate	0.02	kg	P	market for polyethylene, high density, granulate | polyethylene, high density, granulate | Cutoff, U - GLO
sheet rolling, aluminium	0.71	kg	P	market for sheet rolling, aluminium | sheet rolling, aluminium | Cutoff, U - GLO
sheet rolling, chromium steel	0.032	kg	P	market for sheet rolling, chromium steel | sheet rolling, chromium steel | Cutoff, U - GLO
sheet rolling, copper	0.009	kg	P	market for sheet rolling, copper | sheet rolling, copper | Cutoff, U - GLO
steel, chromium steel 18/8, hot rolled	0.032	kg	P	market for steel, chromium steel 18/8, hot rolled | steel, chromium steel 18/8, hot rolled | Cutoff, U - GLO
tap water	0.076	kg	P	market group for tap water | tap water | Cutoff, U - GLO
Output	Amount	Unit	Type	Provider
Pack & Module production for 1KG Pack&Modules	1.0	kg	P	

A.4 Systems

A.4.1 Avionics

Table A.28: Unit process for the production of the avionics.

Input	**Amount**	**Unit**	**Type**	**Dataset/source for upstream flow provider**
aluminium, primary, ingot	33.0	kg	P	market for aluminium, primary, ingot | aluminium, primary, ingot | Cutoff, U - IAI Area, North America
carbon fibre reinforced plastic, injection moulded	6.0	kg	P	market for carbon fibre reinforced plastic, injection moulded | carbon fibre reinforced plastic, injection moulded | Cutoff, U - GLO
consumer electronics, mobile device, smartphone	256.0	Item(s)	P	market for consumer electronics, mobile device, smartphone | consumer electronics, mobile device, smartphone | Cutoff, U - GLO
metal working, average for aluminium product manufacturing	33.0	kg	P	market for metal working, average for aluminium product manufacturing | metal working, average for aluminium product manufacturing | Cutoff, U - GLO
Output	Amount	Unit	Type	Dataset/source for upstream flow provider
Avionics production	1.0	Item(s)	P	

A.4.2 Flight control system

Table A.29: Unit process for the production of the flight control system.

Input	Amount	Unit	Type	Dataset/source for upstream flow provider
casting, steel, lost-wax	156.0	kg	P	market for casting, steel, lost-wax | casting, steel, lost-wax | Cutoff, U - GLO
Electronic control units Acc. Pipistrell	42.0	kg	P	electronics production, for control units Acc. Pipistrell - RoW
injection moulding	14.0	kg	P	market for injection moulding | injection moulding | Cutoff, U - GLO
polyethylene terephthalate, granulate, amorphous	14.0	kg	P	market for polyethylene terephthalate, granulate, amorphous | polyethylene terephthalate, granulate, amorphous | Cutoff, U - GLO
reinforcing steel	156.0	kg	P	market for reinforcing steel | reinforcing steel | Cutoff, U - GLO
Output	Amount	Unit	Type	Dataset/source for upstream flow provider
FCS	1.0	Item(s)	P	

A.4.3 Electrical

Table A.30: Unit process for the production of the electrical system.

Input	Amount	Unit	Type	Dataset/source for upstream flow provider
Electronic control units Acc. Pipistrell	14.15	kg	P	electronics production, for control units Acc. Pipistrell - RoW
Junction box	171.53	Item(s)	P	Junction box
LV Converters	20.0	Item(s)	P	LV Converters 20x
LV Inverters	4.0	Item(s)	P	LV Inverters 4x
Output	Amount	Unit	Type	Dataset/source for upstream flow provider
Electrical category	1.0	Item(s)	P	

A.4.4 Electrical wiring interconnection system

Table A.31: Unit process for the production of the EWIS.

Input	Amount	Unit	Type	Dataset/source for upstream flow provider
cable, unspecified	730.0	kg	P	market for cable, unspecified | cable, unspecified | Cutoff, U - GLO
Output	Amount	Unit	Type	Dataset/source for upstream flow provider
EWIS	1.0	Item(s)	P	

A.4.5 Environmental control system

A.4.5.1 Climate control system

Table A.32: Unit process for the production of the climate control system.

Input	**Amount**	**Unit**	**Type**	**Dataset/source for upstream flow provider**
air compressor, screw-type compressor, 4kW	0.47	Item(s)	P	market for air compressor, screw-type compressor, 4kW | air compressor, screw-type compressor, 4kW | Cutoff, U - GLO
air filter, decentralized unit, 180-250 m3/h	56.0	Item(s)	P	market for air filter, decentralized unit, 180-250 m3/h | air filter, decentralized unit, 180-250 m3/h | Cutoff, U - GLO
aluminium, cast alloy	24.8	kg	P	market for aluminium, cast alloy | aluminium, cast alloy | Cutoff, U - GLO
Electronic control units Acc. Pipistrell	0.32	kg	P	electronics production, for control units Acc. Pipistrell - RoW
glass fibre reinforced plastic, polyamide, injection moulded	35.4	kg	P	market for glass fibre reinforced plastic, polyamide, injection moulded | glass fibre reinforced plastic, polyamide, injection moulded | Cutoff, U - GLO
metal working, average for chromium steel product manufacturing	19.16	kg	P	market for metal working, average for chromium steel product manufacturing | metal working, average for chromium steel product manufacturing | Cutoff, U - GLO
polycarbonate	2.8	kg	P	market for polycarbonate | polycarbonate | Cutoff, U - GLO
steel, chromium steel 18/8	19.16	kg	P	market for steel, chromium steel 18/8 | steel, chromium steel 18/8 | Cutoff, U - GLO
Output	Amount	Unit	P	Dataset/source for upstream flow provider
Climate Control System	1.0	Item(s)	P	

A.4.5.2 Fire extinguisher system

Table A.33: Unit process for the production of the fire extinguisher system.

Input	**Amount**	**Unit**	**Type**	**Dataset/source for upstream flow provider**
aluminium, cast alloy	32.64516	kg	P	market for aluminium, cast alloy | aluminium, cast alloy | Cutoff, U - GLO
monoammonium phosphate	44.35484	kg	P	market for monoammonium phosphate | monoammonium phosphate | Cutoff, U - RER
polycarbonate	3.0	kg	P	market for polycarbonate | polycarbonate | Cutoff, U - GLO
Output	Amount	Unit	P	Dataset/source for upstream flow provider
Firex	1.0	Item(s)	P	

A.4.5.3 Ice protection system

Table A.34: Unit process for the production of the ice protection system.

Input	**Amount**	**Unit**	**Type**	**Dataset/source for upstream flow provider**
aluminium, cast alloy	46.8	kg	P	market for aluminium, cast alloy | aluminium, cast alloy | Cutoff, U - GLO
metal working, average for chromium steel product manufacturing	46.8	kg	P	market for metal working, average for chromium steel product manufacturing | metal working, average for chromium steel product manufacturing | Cutoff, U - GLO
polycarbonate	12.0	kg	P	market for polycarbonate | polycarbonate | Cutoff, U - GLO
steel, chromium steel 18/8	46.8	kg	P	market for steel, chromium steel 18/8 | steel, chromium steel 18/8 | Cutoff, U - GLO
synthetic rubber	12.0	kg	P	market for synthetic rubber | synthetic rubber | Cutoff, U - GLO
Output	Amount	Unit	Type	Dataset/source for upstream flow provider
IPS	1.0	Item(s)	P	

A.4.5.4 Oxygen system

Table A.35: Unit process for the production of the oxygen system.

Input	Amount	Unit	Type	Dataset/source for upstream flow provider
aluminium, cast alloy	11.4	kg	P	market for aluminium, cast alloy | aluminium, cast alloy | Cut-off, U - GLO
extrusion, plastic pipes	0.8	kg	P	market for extrusion, plastic pipes | extrusion, plastic pipes | Cutoff, U - GLO
metal working, average for chromium steel product manufacturing	0.5	kg	P	market for metal working, average for chromium steel product manufacturing | metal working, average for chromium steel product manufacturing | Cutoff, U - GLO
polycarbonate	1.209	kg	P	market for polycarbonate | polycarbonate | Cutoff, U - GLO
steel, chromium steel 18/8	0.5	kg	P	market for steel, chromium steel 18/8 | steel, chromium steel 18/8 | Cutoff, U - GLO
Output	Amount	Unit	P	Dataset/source for upstream flow provider
Oxygen system	1.0	Item(s)	P	

A.4.5.5 Thermal management system

Table A.36: Unit process for the production of the thermal management system.

Input	Amount	Unit	Type	Dataset/source for upstream flow provider
aluminium, wrought alloy	52.393	kg	P	market for aluminium, wrought alloy | aluminium, wrought alloy | Cutoff, U - GLO
Coolant pump 1x0.66kg	25.0	Item(s)	P	Arvidsson et al., 2023
ethylene glycol	58.876	kg	P	market for ethylene glycol | ethylene glycol | Cutoff, U - GLO
Output	Amount	Unit	Type	Dataset/source for upstream flow provider
TMS	1.0	Item(s)	P	

A.5 Interior

Table A.37: Unit process for the assembly of the interior.

Input	Amount	Unit	Type	Dataset/source for upstream flow provider
Assebled Seat Single Pax	10.0	Item(s)	P	See Table A.38
Assembled Seat CAS	1.0	Item(s)	P	See Table A.42
Assembled Seat Double Pax	10.0	Item(s)	P	See Table A.39
Assembled Seat OS	1.0	Item(s)	P	See Table A.41
Assembled Seat Pilot	2.0	Item(s)	P	See Table A.40
Avionics rack, cabin	1.0	Item(s)	P	See Table A.49
Bulkheads	1.0	Item(s)	P	See Table A.46
Cabin Insulation Blanket	25.0	m2	P	See Table A.47
Cargo net	1.0	Item(s)	P	See Table A.50
Carpet	16.0	m2	P	See Table A.43
Emergency (life-jackets)	1.0	Item(s)	P	See Table A.51
Instrument panel (Chockpit side and centre console)	1.0	Item(s)	P	See Table A.44
Overhead Bin	3.3	Item(s)	P	See Table A.45
Sidewall Panel	60.0	m2	P	See Table A.48
Output	Amount	Unit	Type	Dataset/source for upstream flow provider
Interior	1.0	Item(s)	P	

A.5.1 Seats

A.5.1.1 Single passenger seat

Table A.38: Unit process for the production of the single passenger seat.

Input	**Amount**	**Unit**	**Type**	**Dataset/source for upstream flow provider**
aluminium, cast alloy	2.628	kg	P	market for aluminium, cast alloy | aluminium, cast alloy | Cutoff, U - GLO
casting, steel, lost-wax	0.788	kg	P	market for casting, steel, lost-wax | casting, steel, lost-wax | Cutoff, U - GLO
polycarbonate	1.240	kg	P	market for polycarbonate | polycarbonate | Cutoff, U - GLO
polyvinylfluoride, film	0.012	kg	P	market for polyvinylfluoride, film | polyvinylfluoride, film | Cutoff, U - GLO
Cotton Upholstery	0.696	kg	P	(Arvidsson et al., 2023) and (Sandin et al., 2019)
nylon 6	0.204	kg	P	market for nylon 6 | nylon 6 | Cutoff, U - RoW
packaging film, low density polyethylene	0.182	kg	P	market for packaging film, low density polyethylene | packaging film, low density polyethylene | Cutoff, U - GLO
polyurethane, flexible foam, flame retardant	1.020	kg	P	market for polyurethane, flexible foam, flame retardant | polyurethane, flexible foam, flame retardant | Cutoff, U - GLO
brass	0.096	kg	P	market for brass | brass | Cutoff, U - RoW
silicone product	0.004	kg	P	market for silicone product | silicone product | Cutoff, U - RER
carbon fibre reinforced plastic, injection moulded	1.133	kg	P	market for carbon fibre reinforced plastic, injection moulded | carbon fibre reinforced plastic, injection moulded | Cutoff, U - GLO
Output	Amount	Unit	Type	Dataset/source for upstream flow provider
Single Passenger Seat	1	Item(s)	P	

A.5.1.2 Double passenger seat

Table A.39: Unit process for the production of the double passenger seat.

Input	**Amount**	**Unit**	**Type**	**Dataset/source for upstream flow provider**
aluminium, cast alloy	4.60	kg	P	market for aluminium, cast alloy | aluminium, cast alloy | Cutoff, U - GLO
casting, steel, lost-wax	1.38	kg	P	market for casting, steel, lost-wax | casting, steel, lost-wax | Cutoff, U - GLO
polycarbonate	2.17	kg	P	market for polycarbonate | polycarbonate | Cutoff, U - GLO
polyvinylfluoride, film	0.02	kg	P	market for polyvinylfluoride, film | polyvinylfluoride, film | Cutoff, U - GLO
Cotton Upholstery	1.22	kg	P	(Arvidsson et al., 2023) and (Sandin et al., 2019)
nylon 6	0.36	kg	P	market for nylon 6 | nylon 6 | Cutoff, U - RoW
packaging film, low density polyethylene	0.32	kg	P	market for packaging film, low density polyethylene | packaging film, low density polyethylene | Cutoff, U - GLO
polyurethane, flexible foam, flame retardant	1.78	kg	P	market for polyurethane, flexible foam, flame retardant | polyurethane, flexible foam, flame retardant | Cutoff, U - GLO
brass	0.17	kg	P	market for brass | brass | Cutoff, U - RoW
silicone product	0.01	kg	P	market for silicone product | silicone product | Cutoff, U - RER
carbon fibre reinforced plastic, injection moulded	1.98	kg	P	market for carbon fibre reinforced plastic, injection moulded | carbon fibre reinforced plastic, injection moulded | Cutoff, U - GLO
Output	Amount	Unit	Type	Dataset/source for upstream flow provider
Double Passenger Seat	1	Item(s)	P	

A.5.1.3 Pilot seat

Table A.40: Unit process for the production of the pilot seat.

Input	Amount	Unit	Type	Dataset/source for upstream flow provider
aluminium, cast alloy	9.351	kg	P	market for aluminium, cast alloy | aluminium, cast alloy | Cutoff, U - GLO
casting, steel, lost-wax	1.969	kg	P	market for casting, steel, lost-wax | casting, steel, lost-wax | Cutoff, U - GLO
polycarbonate	2.305	kg	P	market for polycarbonate | polycarbonate | Cutoff, U - GLO
polyvinylfluoride, film	0.031	kg	P	market for polyvinylfluoride, film | polyvinylfluoride, film | Cutoff, U - GLO
Cotton Upholstery	1.741	kg	P	(Arvidsson et al., 2023) and (Sandin et al., 2019)
nylon 6	0.510	kg	P	market for nylon 6 | nylon 6 | Cutoff, U - RoW
packaging film, low density polyethylene	0.454	kg	P	market for packaging film, low density polyethylene | packaging film, low density polyethylene | Cutoff, U - GLO
polyurethane, flexible foam, flame retardant	2.549	kg	P	market for polyurethane, flexible foam, flame retardant | polyurethane, flexible foam, flame retardant | Cutoff, U - GLO
brass	0.241	kg	P	market for brass | brass | Cutoff, U - RoW
silicone product	0.011	kg	P	market for silicone product | silicone product | Cutoff, U - RER
polyurethane, rigid foam	0.808	kg	P	market for polyurethane, rigid foam | polyurethane, rigid foam | Cutoff, U - RER
polyurethane adhesive	0.036	kg	P	market for polyurethane adhesive | polyurethane adhesive | Cutoff, U - GLO
Output	Amount	Unit	Type	Dataset/source for upstream flow provider
Pilot Seat	1	Item(s)	P	

A.5.1.4 Observer seat

Table A.41: Unit process for the production of the observer seat.

Input	Amount	Unit	Type	Dataset/source for upstream flow provider
aluminium, cast alloy	5.052	kg	P	market for aluminium, cast alloy | aluminium, cast alloy | Cutoff, U - GLO
casting, steel, lost-wax	0.990	kg	P	market for casting, steel, lost-wax | casting, steel, lost-wax | Cutoff, U - GLO
polycarbonate	1.150	kg	P	market for polycarbonate | polycarbonate | Cutoff, U - GLO
polyvinylfluoride, film	0.008	kg	P	market for polyvinylfluoride, film | polyvinylfluoride, film | Cutoff, U - GLO
Cotton Upholstery	0.870	kg	P	(Arvidsson et al., 2023) and (Sandin et al., 2019)
nylon 6	0.255	kg	P	market for nylon 6 | nylon 6 | Cutoff, U - RoW
packaging film, low density polyethylene	0.227	kg	P	market for packaging film, low density polyethylene | packaging film, low density polyethylene | Cutoff, U - GLO
polyurethane, flexible foam, flame retardant	1.275	kg	P	market for polyurethane, flexible foam, flame retardant | polyurethane, flexible foam, flame retardant | Cutoff, U - GLO
brass	0.120	kg	P	market for brass | brass | Cutoff, U - RoW
silicone product	0.005	kg	P	market for silicone product | silicone product | Cutoff, U - RER
polyurethane, rigid foam	0.029	kg	P	market for polyurethane, rigid foam | polyurethane, rigid foam | Cutoff, U - RER
polyurethane adhesive	0.018	kg	P	market for polyurethane adhesive | polyurethane adhesive | Cutoff, U - GLO
Output	Amount	Unit	Type	Dataset/source for upstream flow provider
Observer Seat	1	Item(s)	P	

A.5.1.5 Cabin attendant aeat

Table A.42: Unit process for the production of the cabin attendant seat.

Input	Amount	Unit	Type	Dataset/source for upstream flow provider
aluminium, cast alloy	4.547	kg	P	market for aluminium, cast alloy | aluminium, cast alloy | Cutoff, U - GLO
casting, steel, lost-wax	0.891	kg	P	market for casting, steel, lost-wax | casting, steel, lost-wax | Cutoff, U - GLO
polycarbonate	1.035	kg	P	market for polycarbonate | polycarbonate | Cutoff, U - GLO
polyvinylfluoride, film	0.007	kg	P	market for polyvinylfluoride, film | polyvinylfluoride, film | Cutoff, U - GLO
Cotton Upholstery	0.783	kg	P	(Arvidsson et al., 2023) and (Sandin et al., 2019)
nylon 6	0.229	kg	P	market for nylon 6 | nylon 6 | Cutoff, U - RoW
packaging film, low density polyethylene	0.204	kg	P	market for packaging film, low density polyethylene | packaging film, low density polyethylene | Cutoff, U - GLO
polyurethane, flexible foam, flame retardant	1.147	kg	P	market for polyurethane, flexible foam, flame retardant | polyurethane, flexible foam, flame retardant | Cutoff, U - GLO
brass	0.108	kg	P	market for brass | brass | Cutoff, U - RoW
silicone product	0.005	kg	P	market for silicone product | silicone product | Cutoff, U - RER
polyurethane, rigid foam	0.026	kg	P	market for polyurethane, rigid foam | polyurethane, rigid foam | Cutoff, U - RER
polyurethane adhesive	0.016	kg	P	market for polyurethane adhesive | polyurethane adhesive | Cutoff, U - GLO
Output	Amount	Unit	Type	Dataset/source for upstream flow provider
Cabin Attendant Seat	1	Item(s)	P	

A.5.2 Flooring

Table A.43: Unit process for the production of the flooring.

Input	Amount	Unit	Type	Dataset/source for upstream flow provider
aluminium, cast alloy	1.852	kg	P	market for aluminium, cast alloy | aluminium, cast alloy | Cutoff, U - GLO
epoxy resin, liquid	0.014	kg	P	market for epoxy resin, liquid | epoxy resin, liquid | Cutoff, U - RER
latex	0.28	kg	P	market for latex | latex | Cutoff, U - RER
nylon 6	0.7	kg	P	market for nylon 6 | nylon 6 | Cutoff, U - RER
packaging film, low density polyethylene	0.28	kg	P	market for packaging film, low density polyethylene | packaging film, low density polyethylene | Cutoff, U - GLO
textile, woven cotton	0.14	kg	P	market for textile, woven cotton | textile, woven cotton | Cutoff, U - GLO
Output	Amount	Unit	Type	Dataset/source for upstream flow provider
Carpet	1.0	m2	P	

A.5.3 Cockpit instrument panel

Table A.44: Unit process for the production of the cockpit instrument panel.

Input	Amount	Unit	Type	Dataset/source for upstream flow provider
carbon fibre reinforced plastic, injection moulded	14.3	kg	P	market for carbon fibre reinforced plastic, injection moulded | carbon fibre reinforced plastic, injection moulded | Cutoff, U - GLO
copper, cathode	25.3	kg	P	market for copper, cathode | copper, cathode | Cutoff, U - GLO
Ethylen-tetrafluorethylen	5.9	kg	P	Arvidsson et al., 2023
injection moulding	9.3	kg	P	market for injection moulding | injection moulding | Cutoff, U - GLO
metal working, average for copper product manufacturing	25.3	kg	P	metal working, average for copper product manufacturing | metal working, average for copper product manufacturing | Cutoff, U - RoW
polyethylene terephthalate, granulate, amorphous	3.4	kg	P	market for polyethylene terephthalate, granulate, amorphous | polyethylene terephthalate, granulate, amorphous | Cutoff, U - GLO
Output	Amount	Unit	Type	Dataset/source for upstream flow provider
Instrument panel (Chockpit side and centre console)	1.0	Item(s)	P	

A.5.4 Overhead bins

Table A.45: Unit process for the production of the overhead bins.

Input	**Amount**	**Unit**	**Type**	**Dataset/source for upstream flow provider**
aluminium, cast alloy	12.113	kg	P	market for aluminium, cast alloy | aluminium, cast alloy | Cutoff, U - GLO
carbon fibre reinforced plastic, injection moulded	2.027	kg	P	market for carbon fibre reinforced plastic, injection moulded | carbon fibre reinforced plastic, injection moulded | Cutoff, U - GLO
glass fibre reinforced plastic, polyamide, injection moulded	6.031	kg	P	market for glass fibre reinforced plastic, polyamide, injection moulded | glass fibre reinforced plastic, polyamide, injection moulded | Cutoff, U - GLO
polyvinylfluoride, film	1.829	kg	P	market for polyvinylfluoride, film | polyvinylfluoride, film | Cutoff, U - GLO
Output	Amount	Unit	Type	Dataset/source for upstream flow provider
Overhead Bin	1.0	Item(s)	P	

A.5.5 Bulkheads

Table A.46: Unit process for the production of the bulkheads.

Input	**Amount**	**Unit**	**Type**	**Dataset/source for upstream flow provider**
carbon fibre reinforced plastic, injection moulded	36.0	kg	P	market for carbon fibre reinforced plastic, injection moulded | carbon fibre reinforced plastic, injection moulded | Cutoff, U - GLO
Output	Amount	Unit	Type	Dataset/source for upstream flow provider
Bulkheads	1.0	Item(s)	P	

A.5.6 Cabin insulation blankets

Table A.47: Unit process for the production of the cabin insulation blankets.

Input	**Amount**	**Unit**	**Type**	**Dataset/source for upstream flow provider**
glass fibre reinforced plastic, polyester resin, hand lay-up	2.225	kg	P	market for glass fibre reinforced plastic, polyester resin, hand lay-up | glass fibre reinforced plastic, polyester resin, hand lay-up | Cutoff, U - GLO
packaging film, low density polyethylene	0.05	kg	P	market for packaging film, low density polyethylene | packaging film, low density polyethylene | Cutoff, U - GLO
Output	Amount	Unit	Type	Dataset/source for upstream flow provider
Cabin Insulation Blanket	1.0	m2	P	

A.5.7 Sidewall panels

Table A.48: Unit process for the production of the sidewall panels.

Input	**Amount**	**Unit**	**Type**	**Dataset/source for upstream flow provider**
carbon fibre reinforced plastic, injection moulded	0.420	kg	P	market for carbon fibre reinforced plastic, injection moulded | carbon fibre reinforced plastic, injection moulded | Cutoff, U - GLO
glass fibre reinforced plastic, polyamide, injection moulded	3.035	kg	P	market for glass fibre reinforced plastic, polyamide, injection moulded | glass fibre reinforced plastic, polyamide, injection moulded | Cutoff, U - GLO
polyvinylfluoride, film	0.379	kg	P	market for polyvinylfluoride, film | polyvinylfluoride, film | Cutoff, U - GLO
Output	Amount	Unit	Type	Dataset/source for upstream flow provider
Sidewall Panel	1.0	m2	P	

A.5.8 Avionics rack

Table A.49: Unit process for the production of the avionics rack.

Input	**Amount**	**Unit**	**Type**	**Dataset/source for upstream flow provider**
aluminium, cast alloy	21.7	kg	P	market for aluminium, cast alloy | aluminium, cast alloy | Cut-off, U - GLO
Output	Amount	Unit	Type	Dataset/source for upstream flow provider
Avionics rack, cabin	1.0	Item(s)	P	

A.5.9 Cargo net

Table A.50: Unit process for the production of the cargo net.

Input	**Amount**	**Unit**	**Type**	**Dataset/source for upstream flow provider**
textile, nonwoven polyester	15.3	kg	P	market for textile, nonwoven polyester | textile, nonwoven polyester | Cutoff, U - GLO
Output	Amount	Unit	Type	Dataset/source for upstream flow provider
Cargo net	1.0	Item(s)	P	

A.5.10 Life jackets

Table A.51: Unit process for the production of the life jackets.

Input	**Amount**	**Unit**	**Type**	**Dataset/source for upstream flow provider**
aluminium, cast alloy	3.0	kg	P	market for aluminium, cast alloy | aluminium, cast alloy | Cut-off, U - GLO
nylon 6	15.0	kg	P	market for nylon 6 | nylon 6 | Cutoff, U - RER
Output	Amount	Unit	Type	Dataset/source for upstream flow provider
Emergency (life-jackets)	1.0	Item(s)	P	

A.6 Aeroplane assembly

Table A.52: Unit process for the assembly of the aeroplane.

Input	**Amount**	**Unit**	**Type**	**Dataset/source for upstream flow provider**
Annual electricity needs	1/120	Item(s)	P	Annual electricity needs
Annual Heating needs	1/120	Item(s)	P	Annual Heating needs
Drivetrain	1.0	Item(s)	P	Table A.12
Interior	1.0	Item(s)	P	Table A.37
Stucture	1.0	Item(s)	P	Table A.4
Systems	1.0	Item(s)	P	Table A.28-A.36
Halmstad Assembly plant	1/6000	P	Item(s)	Halmstad Assembly plant
Output	Amount	Unit	P	Dataset/source for upstream flow provider
Assembled aeroplane	1.0	Item(s)	P	

A.7 End-of-Life

Table A.53: Unit process for the EoL process for the aeroplane.

Input	**Amount**	**Unit**	**Type**	**Provider**
Discarded aeroplane	1.0	Item(s)	W	
Output	Amount	Unit	Type	Provider
scrap aluminium	3963.6	kg	W	market for scrap aluminium | scrap aluminium | Cutoff, U - Europe without Switzerland
scrap steel	1255.8	kg	W	market for scrap steel | scrap steel | Cutoff, U - Europe without Switzerland
shredder fraction after manual dismantling of used electronic product	2267.4	kg	W	market for shredder fraction after manual dismantling of used electronic product | shredder fraction after manual dismantling of used electronic product | Cutoff, U - GLO
waste mineral oil	15.5	kg	W	market for waste mineral oil | waste mineral oil | Cutoff, U - Europe without Switzerland
waste plastic, mixture	2063.3	kg	W	market group for waste plastic, mixture | waste plastic, mixture | Cutoff, U - Europe without Switzerland
waste rubber, unspecified	107.3	kg	W	market for waste rubber, unspecified | waste rubber, unspecified | Cutoff, U - Europe without Switzerland
waste textile, soiled	57.2	kg	W	market for waste textile, soiled | waste textile, soiled | Cutoff, U - RoW

B

LCIA results

In this appendix, the results from the LCIA are presented for the three impact categories, climate change, mineral resource scarcity and particulate matter. The transports are all accumulated together and not reported per component since this could reveal non-disclosed partners of Heart Aerospace.

Table B.1: Environmental impact production phase of the aeroplane.

	Component	**kg CO_2-eq**	**kg Cu-Eq**	**kg Si-Eq**	**kg PM2.5-Eq**
Production	Structure	1.85E+05	2.55E+03	1.80E+07	3.55E+02
	Drivetrain	9.66E+04	2.29E+04	1.80E+07	1.86E+02
	Systems	2.99E+04	6.11E+02	3.18E+07	1.34E+02
	Interior	1.66E+04	2.63E+02	2.64E+06	3.13E+01
	Assembly	4.22E+03	3.35E+01	5.46E+05	6.17E+00
	Transports	2.37E+03	2.84E+04	1.75E+05	5.65E+00
	Total Contribution	3.35E+05	2.84E+04	7.11E+07	7.18E+02

Table B.2: Environmental impact from structure of the aeroplane.

	Component	**kg CO_2-eq**	**kg Cu-Eq**	**kg Si-Eq**	**kg PM2.5-Eq**
Structure	Wing Production	7.52E+04	1.11E+03	7.28E+06	1.44E+02
	Fuselage	4.65E+04	7.27E+02	4.40E+06	8.85E+01
	HT	2.24E+04	7.88E+01	1.89E+06	4.16E+01
	Main Fairings	1.67E+04	1.17E+02	1.46E+06	3.11E+01
	VT	1.51E+04	5.14E+01	1.26E+06	2.72E+01
	MLG	7.77E+03	3.90E+02	1.38E+06	1.88E+01
	NLG	1.23E+03	6.41E+01	2.23E+05	3.00E+00
	Paint	4.26E+02	6.12E+00	1.14E+05	6.69E-01
	Total Contribution	1.85E+05	2.55E+03	1.80E+07	3.55E+02

Table B.3: Environmental impact from drivetrain of the aeroplane.

	Component	**kg CO_2-eq**	**kg Cu-Eq**	**kg Si-Eq**	**kg PM2.5-Eq**
Drivetrain	Turboprop engines	3.16E+04	5.30E+02	4.40E+06	4.69E+01
	Turboprop propellers	1.38E+04	4.67E+01	1.16E+06	2.57E+01
	Electric motors	3.28E+03	2.13E+04	1.45E+06	9.26E+00
	EM propellers	2.04E+04	6.86E+01	1.72E+06	3.80E+01
	Nacelles	2.35E+04	2.47E+02	5.63E+06	1.77E+01
	Power Inverters	3.93E+03	5.38E+02	2.76E+06	4.46E+01
	Fuel system	1.64E+03	9.45E+01	8.33E+05	4.06E+00
	Total Contribution	9.78E+04	2.28E+04	1.80E+07	1.86E+02

Table B.4: Environmental impact from systems of the aeroplane.

	Component	**kg CO_2-eq**	**kg Cu-Eq**	**kg Si-Eq**	**kg PM2.5-Eq**
Systems	Avionics	1.12E+04	2.86E+02	2.44E+06	2.17E+01
	Flight control system	8.04E+03	4.81E+02	4.16E+06	1.76E+01
	EWIS	4.48E+03	8.95E+02	1.62E+	6.73E+01
	Other electrical	6.17E+03	3.06E+02	8.04E+06	1.90E+01
	ECS	3.36E+03	1.51E+02	9.12E+05	8.35E+00
	Total Contribution	3.32E+04	2.12E+03	3.18E+07	1.34E+02

Table B.5: Environmental impact from the interior of the aeroplane.

	Component	**kg CO_2-eq**	**kg Cu-Eq**	**kg Si-Eq**	**kg PM2.5-Eq**
Interior	Seats	4.72E+03	6.53E+01	6.10E+05	9.01E+00
	Panels	4.28E+03	2.95E+02	3.44E+05	6.42E+00
	Bulkheads	3.14E+03	1.06E+01	2.65E+05	5.84E+00
	Cockpit inst. panel	2.31E+03	1.43E+02	1.15E+06	6.72E+00
	Overhead bins	1.13E+03	8.43E+01	1.08E+05	1.93E+00
	Flooring	3.45E+02	3.71E+00	3.53E+04	5.24E-01
	Cabin insulation	2.28E+02	3.90E+00	8.80E+04	3.55E-01
	Emergency	1.69E+02	3.69E-01	1.10E+04	1.52E-01
	Avionics rack	1.29E+02	2.42E+00	1.73E+04	2.47E-01
	Cargo net	9.36E+01	1.70E+00	1.09E+04	1.42E-01
	Total Contribution	1.66E+04	6.11E+02	2.64E+06	3.13E+01

Table B.6: Environmental impact from assembly of the aeroplane.

	Component	**kg CO_2-eq**	**kg Cu-Eq**	**kg Si-Eq**	**kg PM2.5-Eq**
Assembly	Assembly plant	2.77E+03	2.52E+02	4.37E+05	5.01E+00
	Kerosene, for testing	1.28E+03	5.54E+00	7.90E+04	9.18E-01
	Electricity	1.69E+02	5.75E+00	3.02E+04	2.35E-01
	Tap water	1.69E+02	1.39E-02	1.54E+01	2.06E-04
	Total Contribution	4.22E+03	2.63E+02	5.46E+05	6.17E+00

Table B.7: Environmental impact from transports of aeroplane parts.

	Component	**kg CO_2-eq**	**kg Cu-Eq**	**kg Si-Eq**	**kg PM2.5-Eq**
Transports	Lorry	1.10E+03	2.04E+01	9.56E+04	1.06E+00
	Container ship	6.44E+02	8.52E+00	3.98E+04	3.84E+00
	Aeroplane	5.40E+02	2.38E+00	3.38E+04	4.36E-01
	Bulk ship	4.82E+01	7.54E-01	3.05E+03	2.61E-01
	Train	3.49E+01	1.44E+00	3.22E+03	6.22E-02
	Total Contribution	2.37E+03	3.35E+01	1.75E+05	5.65E+00

Table B.8: Environmental impact from, typical mission case of the aeroplane.

	Component	**kg CO_2-eq**	**kg Cu-Eq**	**kg Si-Eq**	**kg PM2.5-Eq**
Use-phase	Kerosene	1.68E+07	7.27E+04	1.04E+09	1.20E+04
	Electricity	1.90E+06	6.47E+04	3.39E+08	2.65E+03
	Battery replacements	2.39E+06	7.20E+05	1.71E+09	7.17E+03
	Maintenance	1.72E+06	2.17E+04	1.46E+08	2.87E+03
	Total Contribution	2.28E+07	8.80E+05	3.23E+09	2.47E+04

Table B.9: Environmental impact for kerosene, typical mission case of the aeroplane.

	Component	kg CO_2-eq	kg Cu-Eq	kg Si-Eq	kg PM2.5-Eq
Kerosene	Combustion	1.32E+07	0.00E+00	0.00E+00	7.39E+03
	Production	3.66E+06	7.27E+04	1.04E+09	4.66E+03
	Total Contribution	1.68E+07	7.27E+04	1.04E+09	1.20E+04

Table B.10: Environmental impact for electricity, typical mission case of the aeroplane.

	Component	kg CO_2-eq	kg Cu-Eq	kg Si-Eq	kg PM2.5-Eq
Electricity	Battery consumption	1.32E+07	6.34E+04	3.33E+08	2.59E+03
	Charging inefficiency	3.66E+06	1.29E+03	6.79E+06	5.29E+01
	Total Contribution	1.90E+06	6.47E+04	3.39E+08	2.65E+03

Table B.11: Environmental impact, battery packs, typical mission case of the aeroplane.

	Component	kg CO_2-eq	kg Cu-Eq	kg Si-Eq	kg PM2.5-Eq
Batteries	Battery packs	2.32E+06	7.12E+05	1.67E+09	6.67E+03
	Recycling, batteries	1.61E+05	8.10E+03	3.67E+07	3.47E+02
	Transports	3.12E+04	4.50E+02	2.11E+06	1.52E+02
	Total Contribution	2.51E+06	7.20E+05	1.71E+09	7.17E+03

Table B.12: Environmental impact maintenance, typical mission case of the aeroplane.

	Component	kg CO_2-eq	kg Cu-Eq	kg Si-Eq	kg PM2.5-Eq
Maintenance	MLG wheel & tyre	1.27E+06	1.65E+04	1.11E+08	2.18E+03
	NLG wheel & tyre	3.98E+05	5.18E+03	3.48E+07	6.83E+02
	EoL treatment	5.42E+04	3.90E+01	1.00E+05	1.68E+00
	Total Contribution	1.72E+06	2.17E+04	1.46E+08	2.87E+03

Table B.13: Environmental impact for EoL treatment of the aeroplane.

	Component	kg CO_2-eq	kg Cu-Eq	kg Si-Eq	kg PM2.5-Eq
EoL	Plastics	2.86E+03	2.78E+00	7.99E+03	4.66E-01
	Electronics	2.18E+03	2.74E+00	1.81E+04	3.63E-01
	Aluminium	7.63E+01	3.93E+00	3.86E+00	6.52E-05
	Textile	4.47E+01	1.68E-01	9.16E+03	1.34E-01
	Mineral oil	3.52E+01	2.36E-02	4.87E+02	2.60E-02
	Steel	1.23E+01	2.24E-01	6.37E+01	1.15E-03
	Rubber	2.27E+00	1.65E-03	1.72E+03	2.08E-02
	Total Contribution	5.21E+03	9.87E+00	3.75E+04	1.01E+00

B.1 Inventory analysis from mineral resource scarcity (SOP)

Table B.14: 260 km flight profile - Impact analysis, mineral resource scarcity (SOP), results < 1% impact is excluded

Name	**Inventory result**	**Unit**	**CF**	**Unit**	**LCIA result**	**Unit**	**Share**
Total SOP impact					9.08E+05	kg Cu-Eq	100 %
Spodumene	73530.02	kg	4.86	kg Cu-Eq/kg	3.57E+05	kg Cu-Eq	39%
Cerium	25.61	kg	11800	kg Cu-Eq/kg	3.02E+05	kg Cu-Eq	33%
Nickel	17828.98	kg	2.89	kg Cu-Eq/kg	5.15E+04	kg Cu-Eq	6%
Copper	38836.63	kg	1	kg Cu-Eq/kg	3.88E+04	kg Cu-Eq	4%
Iron	529372.30	kg	0.0619	kg Cu-Eq/kg	3.28E+04	kg Cu-Eq	4%
Silicon	66461.35	kg	0.428	kg Cu-Eq/kg	2.84E+04	kg Cu-Eq	3%
Magnesium	17262.98	kg	0.79	kg Cu-Eq/kg	1.36E+04	kg Cu-Eq	2%
Uranium	510.11	kg	25.2	kg Cu-Eq/kg	1.29E+04	kg Cu-Eq	1%
Aluminium	67533.48	kg	0.169	kg Cu-Eq/kg	1.14E+04	kg Cu-Eq	1%
Molybdenum	300.18	kg	29.2	kg Cu-Eq/kg	8.77E+03	kg Cu-Eq	1%
Cobalt	1224.58	kg	6.57	kg Cu-Eq/kg	8.05E+03	kg Cu-Eq	1%
Lithium	1294.85	kg	4.86	kg Cu-Eq/kg	6.29E+03	kg Cu-Eq	1%
Gold	1.66	kg	3730	kg Cu-Eq/kg	6.19E+03	kg Cu-Eq	1%
Graphite	24567.61	kg	0.192	kg Cu-Eq/kg	4.72E+03	kg Cu-Eq	1%

Table B.15: 100 km flight profile - Impact analysis, mineral resource scarcity (SOP), results < 1% impact is excluded

Name	**Inventory result**	**Unit**	**CF**	**Unit**	**LCIA result**	**Unit**	**Share**
Total SOP impact					1.29E+06	kg Cu-Eq	100%
Spodumene	110291.54	kg	4.86	kg Cu-Eq/kg	5.36E+05	kg Cu-Eq	42%
Cerium	32.13	kg	11800	kg Cu-Eq/kg	3.79E+05	kg Cu-Eq	29%
Nickel	26159.40	kg	2.89	kg Cu-Eq/kg	7.56E+04	kg Cu-Eq	6%
Copper	57525.56	kg	1	kg Cu-Eq/kg	5.75E+04	kg Cu-Eq	4%
Iron	735251.14	kg	0.0619	kg Cu-Eq/kg	4.55E+04	kg Cu-Eq	4%
Silicon	100061.62	kg	0.428	kg Cu-Eq/kg	4.28E+04	kg Cu-Eq	3%
Aluminium	123061.50	kg	0.169	kg Cu-Eq/kg	2.08E+04	kg Cu-Eq	2%
Magnesium	25846.13	kg	0.79	kg Cu-Eq/kg	2.04E+04	kg Cu-Eq	2%
Uranium	716.37	kg	25.2	kg Cu-Eq/kg	1.81E+04	kg Cu-Eq	1%
Molybdenum	433.95	kg	29.2	kg Cu-Eq/kg	1.27E+04	kg Cu-Eq	1%
Cobalt	1834.08	kg	6.57	kg Cu-Eq/kg	1.20E+04	kg Cu-Eq	1%
Lithium	1942.23	kg	4.86	kg Cu-Eq/kg	9.44E+03	kg Cu-Eq	1%
Hafnium	96.58	kg	96.7	kg Cu-Eq/kg	9.34E+03	kg Cu-Eq	1%
Gold	2.46	kg	3730	kg Cu-Eq/kg	9.19E+03	kg Cu-Eq	1%
Titanium	9532.17	kg	0.879	kg Cu-Eq/kg	8.38E+03	kg Cu-Eq	1%
Graphite	36869.89	kg	0.192	kg Cu-Eq/kg	7.08E+03	kg Cu-Eq	1%

Table B.16: 200 km flight profile - Impact analysis, mineral resource scarcity (SOP), results < 1% impact is excluded

Name	**Inventory result**	**Unit**	**CF**	**Unit**	**LCIA result**	**Unit**	**Share**
Total SOP impact					1.18E+06	kg Cu-Eq	100%
Spodumene	102938.97	kg	4.86	kg Cu-Eq/kg	5.00E+05	kg Cu-Eq	42%
Cerium	28.90	kg	11800	kg Cu-Eq/kg	3.41E+05	kg Cu-Eq	29%
Nickel	24420.00	kg	2.89	kg Cu-Eq/kg	7.06E+04	kg Cu-Eq	6%
Copper	53839.50	kg	1	kg Cu-Eq/kg	5.38E+04	kg Cu-Eq	5%
Iron	672265.48	kg	0.0619	kg Cu-Eq/kg	4.16E+04	kg Cu-Eq	4%
Silicon	92893.99	kg	0.428	kg Cu-Eq/kg	3.98E+04	kg Cu-Eq	3%
Magnesium	24109.41	kg	0.79	kg Cu-Eq/kg	1.90E+04	kg Cu-Eq	2%
Uranium	713.11	kg	25.2	kg Cu-Eq/kg	1.80E+04	kg Cu-Eq	2%

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Table B.16: 200 km flight profile - Impact analysis, mineral resource scarcity (SOP), results < 1% impact is excluded (Continued)

Name	Inventory result	Unit	CF	Unit	LCIA result	Unit	Share
Aluminium	92251.29	kg	0.169	kg Cu-Eq/kg	1.56E+04	kg Cu-Eq	1%
Molybdenum	408.48	kg	29.2	kg Cu-Eq/kg	1.19E+04	kg Cu-Eq	1%
Cobalt	1711.91	kg	6.57	kg Cu-Eq/kg	1.12E+04	kg Cu-Eq	1%
Lithium	1812.75	kg	4.86	kg Cu-Eq/kg	8.81E+03	kg Cu-Eq	1%
Gold	2.30	kg	3730	kg Cu-Eq/kg	8.58E+03	kg Cu-Eq	1%
Graphite	34388.34	kg	0.192	kg Cu-Eq/kg	6.60E+03	kg Cu-Eq	1%

Table B.17: 400 km flight profile - Impact analysis, mineral resource scarcity (SOP), results < 1% impact is excluded

Name	Inventory result	Unit	CF	Unit	LCIA result	Unit	Share
Total SOP impact					8.33E+05	kg Cu-Eq	100%
Cerium	28.62	kg	11800	kg Cu-Eq/kg	3.38E+05	kg Cu-Eq	41%
Spodumene	58826.08	kg	4.86	kg Cu-Eq/kg	2.86E+05	kg Cu-Eq	34%
Nickel	14863.38	kg	2.89	kg Cu-Eq/kg	4.30E+04	kg Cu-Eq	5%
Copper	31524.67	kg	1	kg Cu-Eq/kg	3.15E+04	kg Cu-Eq	4%
Iron	508488.99	kg	0.0619	kg Cu-Eq/kg	3.15E+04	kg Cu-Eq	4%
Silicon	53317.15	kg	0.428	kg Cu-Eq/kg	2.28E+04	kg Cu-Eq	3%
Magnesium	13871.79	kg	0.79	kg Cu-Eq/kg	1.10E+04	kg Cu-Eq	1%
Uranium	409.74	kg	25.2	kg Cu-Eq/kg	1.03E+04	kg Cu-Eq	1%
Aluminium	55519.00	kg	0.169	kg Cu-Eq/kg	9.38E+03	kg Cu-Eq	1%
Molybdenum	250.20	kg	29.2	kg Cu-Eq/kg	7.31E+03	kg Cu-Eq	1%
Cobalt	982.12	kg	6.57	kg Cu-Eq/kg	6.45E+03	kg Cu-Eq	1%
Lithium	1035.90	kg	4.86	kg Cu-Eq/kg	5.03E+03	kg Cu-Eq	1%
Gold	1.35	kg	3730	kg Cu-Eq/kg	5.02E+03	kg Cu-Eq	1%

Table B.18: 600 km flight profile - Impact analysis, mineral resource scarcity (SOP), results < 1% impact is excluded

Name	Inventory result	Unit	CF	Unit	LCIA result	Unit	Share
Total SOP impact					5.00E+05	kg Cu-Eq	100%
Cerium	20.58	kg	11800	kg Cu-Eq/kg	2.43E+05	kg Cu-Eq	49%
Spodumene	29416.59	kg	4.86	kg Cu-Eq/kg	1.43E+05	kg Cu-Eq	29%
Nickel	7937.99	kg	2.89	kg Cu-Eq/kg	2.29E+04	kg Cu-Eq	5%
Iron	314121.93	kg	0.0619	kg Cu-Eq/kg	1.94E+04	kg Cu-Eq	4%
Copper	16333.43	kg	1	kg Cu-Eq/kg	1.63E+04	kg Cu-Eq	3%
Silicon	26811.42	kg	0.428	kg Cu-Eq/kg	1.15E+04	kg Cu-Eq	2%
Magnesium	6992.94	kg	0.79	kg Cu-Eq/kg	5.52E+03	kg Cu-Eq	1%
Uranium	206.34	kg	25.2	kg Cu-Eq/kg	5.20E+03	kg Cu-Eq	1%
Aluminium	30455.56	kg	0.169	kg Cu-Eq/kg	5.15E+03	kg Cu-Eq	1%
Molybdenum	137.74	kg	29.2	kg Cu-Eq/kg	4.02E+03	kg Cu-Eq	1%
Cobalt	493.58	kg	6.57	kg Cu-Eq/kg	3.24E+03	kg Cu-Eq	1%
Gold	0.70	kg	3730	kg Cu-Eq/kg	2.62E+03	kg Cu-Eq	1%
Lithium	518.00	kg	4.86	kg Cu-Eq/kg	2.52E+03	kg Cu-Eq	1%

B.2 Inventory analysis from mineral resource scarcity (CSI)

Table B.19: 260 km flight profile - Impact analysis, mineral resource scarcity (CSI), results < 1% impact is excluded

Name	**Inventory result**	**Unit**	**CF**	**Unit**	**LCIA result**	**Unit**	**Share**
Total CSI impact					3.31E+09	kg Si-Eq	100%
Oil, crude	4929397.74	kg	200	kg Si-Eq/kg	9.86E+08	kg Si-Eq	30%
Copper	38836.63	kg	10000	kg Si-Eq/kg	3.88E+08	kg Si-Eq	12%
Gold	1.66	kg	2.20E+08	kg Si-Eq/kg	3.65E+08	kg Si-Eq	11%
Coal, hard, unspecified	1480905.199	kg	180	kg Si-Eq/kg	2.67E+08	kg Si-Eq	8%
Sulfur	189120.36	kg	700	kg Si-Eq/kg	1.32E+08	kg Si-Eq	4%
Uranium	510.11	kg	220000	kg Si-Eq/kg	1.12E+08	kg Si-Eq	3%
Tellurium	1.88	kg	5.70E+07	kg Si-Eq/kg	1.07E+08	kg Si-Eq	3%
Molybdenum	300.18	kg	350000	kg Si-Eq/kg	1.05E+08	kg Si-Eq	3%
Sodium chloride	138380.32	kg	730	kg Si-Eq/kg	1.01E+08	kg Si-Eq	3%
Coal, brown	570788.36	kg	170	kg Si-Eq/kg	9.70E+07	kg Si-Eq	3%
Nickel	17828.98	kg	4800	kg Si-Eq/kg	8.56E+07	kg Si-Eq	3%
Rhodium	1.72E-02	kg	4.70E+09	kg Si-Eq/kg	8.06E+07	kg Si-Eq	2%
Silver	15.53	kg	5100000	kg Si-Eq/kg	7.92E+07	kg Si-Eq	2%
Selenium	23.67	kg	2200000	kg Si-Eq/kg	5.21E+07	kg Si-Eq	2%
Spodumene	73530.02	kg	670	kg Si-Eq/kg	4.93E+07	kg Si-Eq	1%
Rhenium	3.12E-02	kg	1.50E+09	kg Si-Eq/kg	4.68E+07	kg Si-Eq	1%
Palladium	0.17	kg	1.90E+08	kg Si-Eq/kg	3.22E+07	kg Si-Eq	1%
Barium	37791.56	kg	620	kg Si-Eq/kg	2.34E+07	kg Si-Eq	1%
Platinum	0.12	kg	1.90E+08	kg Si-Eq/kg	2.33E+07	kg Si-Eq	1%
Lithium	1294.85	kg	1.80E+04	kg Si-Eq/kg	2.33E+07	kg Si-Eq	1%
Tin	121.24	kg	170000	kg Si-Eq/kg	2.06E+07	kg Si-Eq	1%
Lead	725.10	kg	26000	kg Si-Eq/kg	1.89E+07	kg Si-Eq	1%

Table B.20: 100 km flight profile - Impact analysis, mineral resource scarcity (CSI), results < 1% impact is excluded

Name	**Inventory result**	**Unit**	**CF**	**Unit**	**LCIA result**	**Unit**	**Share**
Total CSI impact					3.99E+09	kg Si-Eq	100%
Copper	57525.56	kg	10000	kg Si-Eq/kg	5.75E+08	kg Si-Eq	14%
Oil, crude	2829835.25	kg	200	kg Si-Eq/kg	5.66E+08	kg Si-Eq	14%
Gold	2.46	kg	2.20E+08	kg Si-Eq/kg	5.42E+08	kg Si-Eq	14%
Coal, hard, unspecified	2431612.56	kg	180	kg Si-Eq/kg	4.38E+08	kg Si-Eq	11%
Sulfur	283247.39	kg	700	kg Si-Eq/kg	1.98E+08	kg Si-Eq	5%
Uranium	716.37	kg	220000	kg Si-Eq/kg	1.58E+08	kg Si-Eq	4%
Tellurium	2.72	kg	5.70E+07	kg Si-Eq/kg	1.55E+08	kg Si-Eq	4%
Coal, brown	909765.09	kg	170	kg Si-Eq/kg	1.55E+08	kg Si-Eq	4%
Sodium chloride	209982.26	kg	730	kg Si-Eq/kg	1.53E+08	kg Si-Eq	4%
Molybdenum	433.95	kg	350000	kg Si-Eq/kg	1.52E+08	kg Si-Eq	4%
Nickel	26159.40	kg	4800	kg Si-Eq/kg	1.26E+08	kg Si-Eq	3%
Silver	22.92	kg	5100000	kg Si-Eq/kg	1.17E+08	kg Si-Eq	3%
Rhodium	0.02	kg	4.70E+09	kg Si-Eq/kg	9.29E+07	kg Si-Eq	2%
Selenium	34.31	kg	2200000	kg Si-Eq/kg	7.55E+07	kg Si-Eq	2%
Spodumene	110291.54	kg	670	kg Si-Eq/kg	7.39E+07	kg Si-Eq	2%
Rhenium	0.05	kg	1.50E+09	kg Si-Eq/kg	6.77E+07	kg Si-Eq	2%
Palladium	0.22	kg	1.90E+08	kg Si-Eq/kg	4.22E+07	kg Si-Eq	1%
Lithium	1942.23	kg	18000	kg Si-Eq/kg	3.50E+07	kg Si-Eq	1%
Tin	178.07	kg	170000	kg Si-Eq/kg	3.03E+07	kg Si-Eq	1%
Lead	1078.96	kg	26000	kg Si-Eq/kg	2.81E+07	kg Si-Eq	1%
Platinum	0.14	kg	1.90E+08	kg Si-Eq/kg	2.63E+07	kg Si-Eq	1%
Tantalum	51.36	kg	400000	kg Si-Eq/kg	2.05E+07	kg Si-Eq	1%

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Table B.20: 100 km flight profile - Impact analysis, mineral resource scarcity (CSI), results < 1% impact is excluded (Continued)

Name	Inventory result	Unit	CF	Unit	LCIA result	Unit	Share
Gangue	7306197.81	kg	2.8	kg Si-Eq/kg	2.05E+07	kg Si-Eq	1%
Cobalt	1834.08	kg	11000	kg Si-Eq/kg	2.02E+07	kg Si-Eq	1%

Table B.21: 200 km flight profile - Impact analysis, mineral resource scarcity (CSI), results < 1% impact is excluded

Name	Inventory result	Unit	CF	Unit	LCIA result	Unit	Share
Total CSI impact					3.46E+09	kg Si-Eq	100%
Copper	53839.50	kg	10000	kg Si-Eq/kg	5.38E+08	kg Si-Eq	16%
Gold	2.30	kg	2.20E+08	kg Si-Eq/kg	5.06E+08	kg Si-Eq	15%
Oil, crude	1760567.53	kg	200	kg Si-Eq/kg	3.52E+08	kg Si-Eq	10%
Coal, hard, unspecified	1909868.99	kg	180	kg Si-Eq/kg	3.44E+08	kg Si-Eq	10%
Sulfur	264382.22	kg	700	kg Si-Eq/kg	1.85E+08	kg Si-Eq	5%
Uranium	713.11	kg	220000	kg Si-Eq/kg	1.57E+08	kg Si-Eq	5%
Tellurium	2.56	kg	5.70E+07	kg Si-Eq/kg	1.46E+08	kg Si-Eq	4%
Molybdenum	408.48	kg	350000	kg Si-Eq/kg	1.43E+08	kg Si-Eq	4%
Sodium chloride	188491.38	kg	730	kg Si-Eq/kg	1.38E+08	kg Si-Eq	4%
Coal, brown	759873.77	kg	170	kg Si-Eq/kg	1.29E+08	kg Si-Eq	4%
Nickel	24420.00	kg	4800	kg Si-Eq/kg	1.17E+08	kg Si-Eq	3%
Silver	21.35	kg	5100000	kg Si-Eq/kg	1.09E+08	kg Si-Eq	3%
Rhodium	0.02	kg	4.70E+09	kg Si-Eq/kg	8.17E+07	kg Si-Eq	2%
Selenium	32.31	kg	2200000	kg Si-Eq/kg	7.11E+07	kg Si-Eq	2%
Spodumene	102938.98	kg	670	kg Si-Eq/kg	6.90E+07	kg Si-Eq	2%
Rhenium	0.04	kg	1.50E+09	kg Si-Eq/kg	6.38E+07	kg Si-Eq	2%
Palladium	0.20	kg	1.90E+08	kg Si-Eq/kg	3.84E+07	kg Si-Eq	1%
Lithium	1812.75	kg	18000	kg Si-Eq/kg	3.26E+07	kg Si-Eq	1%
Tin	166.34	kg	170000	kg Si-Eq/kg	2.83E+07	kg Si-Eq	1%
Lead	973.07	kg	26000	kg Si-Eq/kg	2.53E+07	kg Si-Eq	1%
Platinum	0.12	kg	1.90E+08	kg Si-Eq/kg	2.31E+07	kg Si-Eq	1%
Tantalum	47.93	kg	400000	kg Si-Eq/kg	1.92E+07	kg Si-Eq	1%
Cobalt	1711.90	kg	11000	kg Si-Eq/kg	1.88E+07	kg Si-Eq	1%
Gangue	6346450.8	kg	2.8	kg Si-Eq/kg	1.78E+07	kg Si-Eq	1%
Chromium	8253.11	kg	2100	kg Si-Eq/kg	1.73E+07	kg Si-Eq	1%

Table B.22: 400 km flight profile - Impact analysis, mineral resource scarcity (CSI), results < 1% impact is excluded

Name	Inventory result	Unit	CF	Unit	LCIA result	Unit	Share
Total CSI impact					4.10E+09	kg Si-Eq	100%
Oil, crude	1.04E+07	kg	200	kg Si-Eq/kg	2.08E+09	kg Si-Eq	51%
Copper	31524.67	kg	10000	kg Si-Eq/kg	3.15E+08	kg Si-Eq	8%
Gold	1.35	kg	2.20E+08	kg Si-Eq/kg	2.96E+08	kg Si-Eq	7%
Coal, hard, unspecified	1363875.55	kg	180	kg Si-Eq/kg	2.45E+08	kg Si-Eq	6%
Sulfur	151669.30	kg	7.00E+02	kg Si-Eq/kg	1.06E+08	kg Si-Eq	3%
Rhodium	0.022	kg	4.70E+09	kg Si-Eq/kg	1.03E+08	kg Si-Eq	3%
Uranium	409.74	kg	220000	kg Si-Eq/kg	9.01E+07	kg Si-Eq	2%
Tellurium	1.55	kg	5.70E+07	kg Si-Eq/kg	8.86E+07	kg Si-Eq	2%
Molybdenum	250.20	kg	350000	kg Si-Eq/kg	8.76E+07	kg Si-Eq	2%
Coal, brown	500079.69	kg	170	kg Si-Eq/kg	8.50E+07	kg Si-Eq	2%
Sodium chloride	116284.70	kg	730	kg Si-Eq/kg	8.49E+07	kg Si-Eq	2%
Nickel	14863.38	kg	4800	kg Si-Eq/kg	7.13E+07	kg Si-Eq	2%

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Table B.22: 400 km flight profile - Impact analysis, mineral resource scarcity (CSI), results < 1% impact is excluded (Continued)

Name	**Inventory result**	**Unit**	**CF**	**Unit**	**LCIA result**	**Unit**	**Share**
Silver	12.75	kg	5100000	kg Si-Eq/kg	6.50E+07	kg Si-Eq	2%
Barium	76096.61	kg	620	kg Si-Eq/kg	4.72E+07	kg Si-Eq	1%
Selenium	19.61	kg	2200000	kg Si-Eq/kg	4.31E+07	kg Si-Eq	1%
Spodumene	58826.08	kg	6.70E+02	kg Si-Eq/kg	3.94E+07	kg Si-Eq	1%
Rhenium	0.03	kg	1.50E+09	kg Si-Eq/kg	3.88E+07	kg Si-Eq	1%
Palladium	0.18	kg	1.90E+08	kg Si-Eq/kg	3.41E+07	kg Si-Eq	1%
Platinum	0.16	kg	1.90E+08	kg Si-Eq/kg	3.06E+07	kg Si-Eq	1%

Table B.23: 600 km flight profile - Impact analysis, mineral resource scarcity (CSI), results < 1% impact is excluded

Name	**Inventory result**	**Unit**	**CF**	**Unit**	**LCIA result**	**Unit**	**Share**
Total CSI impact					3.07E+09	kg Si-Eq	100%
Oil, crude	9606031.69	kg	200	kg Si-Eq/kg	1.92E+09	kg Si-Eq	63%
Copper	16333.43	kg	10000	kg Si-Eq/kg	1.63E+08	kg Si-Eq	5%
Gold	0.70	kg	2.20E+08	kg Si-Eq/kg	1.54E+08	kg Si-Eq	5%
Coal, hard, unspecified	835918.75	kg	180	kg Si-Eq/kg	1.50E+08	kg Si-Eq	5%
Rhodium	0.02	kg	4.70E+09	kg Si-Eq/kg	7.85E+07	kg Si-Eq	3%
Sulfur	76225.33	kg	700	kg Si-Eq/kg	5.34E+07	kg Si-Eq	2%
Coal, brown	286908.68	kg	170	kg Si-Eq/kg	4.88E+07	kg Si-Eq	2%
Tellurium	0.85	kg	5.70E+07	kg Si-Eq/kg	4.84E+07	kg Si-Eq	2%
Molybdenum	137.74	kg	350000	kg Si-Eq/kg	4.82E+07	kg Si-Eq	2%
Sodium chloride	63161.29	kg	730	kg Si-Eq/kg	4.61E+07	kg Si-Eq	2%
Uranium	206.34	kg	220000	kg Si-Eq/kg	4.54E+07	kg Si-Eq	1%
Barium	69353.56	kg	620	kg Si-Eq/kg	4.30E+07	kg Si-Eq	1%
Nickel	7937.99	kg	4800	kg Si-Eq/kg	3.81E+07	kg Si-Eq	1%
Silver	6.81	kg	5100000	kg Si-Eq/kg	3.47E+07	kg Si-Eq	1%
Selenium	10.72	kg	2200000	kg Si-Eq/kg	2.36E+07	kg Si-Eq	1%
Platinum	0.12	kg	1.90E+08	kg Si-Eq/kg	2.36E+07	kg Si-Eq	1%
Palladium	0.12	kg	1.90E+08	kg Si-Eq/kg	2.29E+07	kg Si-Eq	1%
Rhenium	0.01	kg	1.50E+09	kg Si-Eq/kg	2.12E+07	kg Si-Eq	1%
Spodumene	29416.59	kg	670	kg Si-Eq/kg	1.97E+07	kg Si-Eq	1%

C

Results from sensitivity & scenario analysis

In this chapter the extended results for the sensitivity and scenario analyses are presented.

C.1 Electricity

Table C.1: Climate change impact g CO2-eq / pkm for different electricity mixes.

Flight Profile	**Electricity mix**				
	Renewable	**Sweden**	**Europe**	**USA**	**Global**
100km	46.9	51.4	112.7	134.9	181.0
200km	27.6	31.5	84.2	103.3	142.9
260km	53.9	56.9	97.5	112.1	142.6
400km	81.6	83.5	109.9	119.4	139.2
600km	97.0	98.3	115.8	122.2	135.4

C.2 Fuel

Table C.2: Climate change impact g CO2-eq / pkm for different fuels.

Flight Profile	**Fuel & ATR-42 comparison**					
	Fossil	**AAF, Soy**	**AAF, UCO**	**ATR-42, Soy**	**ATR-42, UCO**	**ATR-42, Fossil**
100km	51.37	38.27	33.75	49	26	113
200km	31.52	24.97	22.71	49	26	113
260km	56.92	33.04	24.79	49	26	113
400km	83.54	41.05	26.38	49	26	113
600km	98.28	45.48	27.24	49	26	113

Table C.3: Total climate change impact kg CO_2-eq for different fuels.

Flight Profile	Fuel & ATR-42 comparison					
	Fossil	AAF, Soy	AAF, UCO	ATR-42, Soy	ATR-42, UCO	ATR-42, Fossil
100km	1.94E+07	1.45E+07	1.28E+07	1.14E+08	4.80E+07	2.50E+07
200km	1.39E+07	1.10E+07	1.00E+07	1.14E+08	4.80E+07	2.50E+07
260km	2.33E+07	1.35E+07	1.01E+07	1.14E+08	4.80E+07	2.50E+07
400km	4.21E+07	2.07E+07	1.33E+07	1.14E+08	4.80E+07	2.50E+07
600km	3.72E+07	1.72E+07	1.03E+07	1.14E+08	4.80E+07	2.50E+07

Table C.4: Particulate matter impact mg PM2.5-eq / pkm for fossil kerosene and AAF, using UCO transported from China.

Flight profile	Fossil	AAF	Reduction
100km	74.45	67.33	-10 %
200km	49.95	46.40	-7 %
260km	62.13	49.14	-21 %
400km	73.87	50.75	-31 %
600km	82.25	51.61	-37 %

Table C.5: Particulate matter impact mg PM2.5-eq / pkm for fossil kerosene and AAF, using UCO from Europe (Excluding shipping from China).

Flight profile	Fossil	AAF	Reduction
100km	74.45	64.48	-13%
200km	49.95	44.97	-10%
260km	62.13	43.95	-29%
400km	73.87	41.52	-44%
600km	82.25	40.13	-51%

C.3 Battery energy storage system (BESS)

Table C.6: Climate change impact g CO2-eq / pkm using two different countries of battery production.

Flight profile	Taiwan / USA	Sweden	Reduction
100km	51.4	48.6	-5 %
200km	31.5	29.3	-7 %
260km	56.9	55.2	-3 %
400km	83.5	82.4	-1 %
600km	98.3	97.5	-1 %

Table C.7: Climate change impact g CO2-eq / pkm for different battery longevity.

textbfFlight profile	**-25 %**	**Basecase**	+25 %
100km	54.4	51.4	49.5
200km	34.0	31.5	30.0
260km	58.8	56.9	55.8
400km	84.8	83.5	82.8
600km	99.1	98.3	97.8

Table C.8: Mineral resource scarcity impact (SOP) g Cu-eq / pkm for different battery longevity.

textbfFlight profile	**-25 %**	**Basecase**	+25 %
100km	4.35	3.41	2.84
200km	3.43	2.67	2.22
260km	2.80	2.22	1.87
400km	2.03	1.65	1.43
600km	1.57	1.32	1.17

Table C.9: Mineral resource scarcity impact (CSP) kg Si-eq / pkm for different battery longevity.

Flight profile	**-25 %**	**Basecase**	+25 %
100km	12.77	10.55	9.23
200km	9.61	7.83	6.77
260km	9.44	8.07	7.26
400km	9.02	8.13	7.60
600km	8.70	8.11	7.76

D

Extended LCIA results

In this appendix, the LCIA results for all ReCiPe 2016 midpoint impact categories as well as the crustal scarcity indicator results are presented, first using 100 % fossil fuels and Swedish electricity and in Section D.0.1 the results from using 100 % AAF from UCO and Swedish electricity.

Table D.1: Total impact results and per passenger km with the modelled ES-30 typical mission of 260 km using 100 % fossil kerosene and Swedish electricity mix.

Impact category	**Reference unit**	**Total**	**Per pkm**
acidification: terrestrial - terrestrial acidification potential (TAP)	kg SO2-Eq	6.78E+04	1.66E-04
climate change - global warming potential (GWP100)	kg CO2-Eq	2.33E+07	5.69E-02
ecotoxicity: freshwater - freshwater ecotoxicity potential (FETP)	kg 1,4-DCB-Eq	1.12E+06	2.74E-03
ecotoxicity: marine - marine ecotoxicity potential (METP)	kg 1,4-DCB-Eq	1.47E+06	3.58E-03
ecotoxicity: terrestrial - terrestrial ecotoxicity potential (TETP)	kg 1,4-DCB-Eq	9.54E+07	2.33E-01
energy resources: non-renewable, fossil - fossil fuel potential (FFP)	kg oil-Eq	6.54E+06	1.60E-02
eutrophication: freshwater - freshwater eutrophication potential (FEP)	kg P-Eq	3.52E+03	8.60E-06
eutrophication: marine - marine eutrophication potential (MEP)	kg N-Eq	1.16E+03	2.82E-06
human toxicity: carcinogenic - human toxicity potential (HTPc)	kg 1,4-DCB-Eq	9.14E+05	2.23E-03
human toxicity: non-carcinogenic - human toxicity potential (HTPnc)	kg 1,4-DCB-Eq	2.06E+07	5.03E-02
ionising radiation - ionising radiation potential (IRP)	kBq Co-60-Eq	1.58E+07	3.86E-02
land use - agricultural land occupation (LOP)	m2*a crop-Eq	7.96E+05	1.94E-03
material resources: metals/minerals - surplus ore potential (SOP)	kg Cu-Eq	9.08E+05	2.22E-03
ozone depletion - ozone depletion potential (ODPinfinite)	kg CFC-11-Eq	6.87E+00	1.68E-08
particulate matter formation - particulate matter formation potential (PMFP)	kg PM2.5-Eq	2.55E+04	6.24E-05
photochemical oxidant formation: human health - photochemical oxidant formation potential: humans (HOFP)	kg NOx-Eq	8.76E+04	2.14E-04
photochemical oxidant formation: terrestrial ecosystems - photochemical oxidant formation potential: ecosystems (EOFP)	kg NOx-Eq	9.08E+04	2.22E-04
water use - water consumption potential (WCP)	m3	3.64E+05	8.89E-04
crustal scarcity indicator (CSP)	kg Si-Eq	3.31E+09	8.07E+00

Table D.2: Total impact results and per passenger km with the modelled ES-30 fjord-hopper mission of 100 km using 100 % fossil kerosene and Swedish electricity mix.

Impact category	**Reference unit**	**Total**	**Per pkm**
acidification: terrestrial - terrestrial acidification potential (TAP)	kg SO2-Eq	6.78E+04	1.79E-04
climate change - global warming potential (GWP100)	kg CO2-Eq	1.94E+07	5.14E-02
ecotoxicity: freshwater - freshwater ecotoxicity potential (FETP)	kg 1,4-DCB-Eq	1.65E+06	4.36E-03
ecotoxicity: marine - marine ecotoxicity potential (METP)	kg 1,4-DCB-Eq	2.14E+06	5.66E-03
ecotoxicity: terrestrial - terrestrial ecotoxicity potential (TETP)	kg 1,4-DCB-Eq	1.33E+08	3.51E-01
energy resources: non-renewable, fossil - fossil fuel potential (FFP)	kg oil-Eq	5.14E+06	1.36E-02
eutrophication: freshwater - freshwater eutrophication potential (FEP)	kg P-Eq	5.49E+03	1.45E-05
eutrophication: marine - marine eutrophication potential (MEP)	kg N-Eq	1.54E+03	4.09E-06
human toxicity: carcinogenic - human toxicity potential (HTPc)	kg 1,4-DCB-Eq	1.32E+06	3.48E-03
human toxicity: non-carcinogenic - human toxicity potential (HTPnc)	kg 1,4-DCB-Eq	3.06E+07	8.10E-02
ionising radiation - ionising radiation potential (IRP)	kBq Co-60-Eq	2.22E+07	5.87E-02
land use - agricultural land occupation (LOP)	m2*a crop-Eq	1.11E+06	2.93E-03
material resources: metals/minerals - surplus ore potential (SOP)	kg Cu-Eq	1.29E+06	3.41E-03
ozone depletion - ozone depletion potential (ODPinfinite)	kg CFC-11-Eq	9.45E+00	2.50E-08
particulate matter formation - particulate matter formation potential (PMFP)	kg PM2.5-Eq	2.82E+04	7.46E-05
photochemical oxidant formation: human health - photochemical oxidant formation potential: humans (HOFP)	kg NOx-Eq	6.43E+04	1.70E-04
photochemical oxidant formation: terrestrial ecosystems - photochemical oxidant formation potential: ecosystems (EOFP)	kg NOx-Eq	6.72E+04	1.78E-04
water use - water consumption potential (WCP)	m3	5.19E+05	1.37E-03
crustal scarcity indicator (CSI)	kg Si-Eq	3.99E+09	1.06E+01

Table D.3: Total impact results and per passenger km with the modelled ES-30 regular regional mission of 200 km using 100 % fossil kerosene and Swedish electricity mix.

Impact category	**Reference unit**	**Total**	**Per pkm**
acidification: terrestrial - terrestrial acidification potential (TAP)	kg SO2-Eq	5.29E+04	1.20E-04
climate change - global warming potential (GWP100)	kg CO2-Eq	1.39E+07	3.15E-02
ecotoxicity: freshwater - freshwater ecotoxicity potential (FETP)	kg 1,4-DCB-Eq	1.51E+06	3.43E-03
ecotoxicity: marine - marine ecotoxicity potential (METP)	kg 1,4-DCB-Eq	1.96E+06	4.45E-03
ecotoxicity: terrestrial - terrestrial ecotoxicity potential (TETP)	kg 1,4-DCB-Eq	1.23E+08	2.80E-01
energy resources: non-renewable, fossil - fossil fuel potential (FFP)	kg oil-Eq	3.57E+06	8.09E-03
eutrophication: freshwater - freshwater eutrophication potential (FEP)	kg P-Eq	4.67E+03	1.06E-05
eutrophication: marine - marine eutrophication potential (MEP)	kg N-Eq	1.26E+03	2.86E-06
human toxicity: carcinogenic - human toxicity potential (HTPc)	kg 1,4-DCB-Eq	1.12E+06	2.53E-03
human toxicity: non-carcinogenic - human toxicity potential (HTPnc)	kg 1,4-DCB-Eq	2.74E+07	6.21E-02
ionising radiation - ionising radiation potential (IRP)	kBq Co-60-Eq	2.21E+07	5.01E-02
land use - agricultural land occupation (LOP)	m2*a crop-Eq	1.08E+06	2.44E-03
material resources: metals/minerals - surplus ore potential (SOP)	kg Cu-Eq	1.18E+06	2.67E-03
ozone depletion - ozone depletion potential (ODPinfinite)	kg CFC-11-Eq	8.61E+00	1.95E-08
particulate matter formation - particulate matter formation potential (PMFP)	kg PM2.5-Eq	2.21E+04	5.00E-05
photochemical oxidant formation: human health - photochemical oxidant formation potential: humans (HOFP)	kg NOx-Eq	4.45E+04	1.01E-04
photochemical oxidant formation: terrestrial ecosystems - photochemical oxidant formation potential: ecosystems (EOFP)	kg NOx-Eq	4.65E+04	1.05E-04
water use - water consumption potential (WCP)	m3	4.96E+05	1.13E-03
crustal scarcity indicator (CSI)	kg Si-Eq	3.46E+09	7.83E+00

Table D.4: Total impact results and per passenger km with the modelled ES-30 long regional mission of 400 km using 100 % fossil kerosene and Swedish electricity mix.

Impact category	**Reference unit**	**Total**	**Per pkm**
acidification: terrestrial - terrestrial acidification potential (TAP)	kg SO2-Eq	1.07E+05	2.11E-04
climate change - global warming potential (GWP100)	kg CO2-Eq	4.21E+07	8.35E-02
ecotoxicity: freshwater - freshwater ecotoxicity potential (FETP)	kg 1,4-DCB-Eq	9.58E+05	1.90E-03
ecotoxicity: marine - marine ecotoxicity potential (METP)	kg 1,4-DCB-Eq	1.27E+06	2.51E-03
ecotoxicity: terrestrial - terrestrial ecotoxicity potential (TETP)	kg 1,4-DCB-Eq	8.82E+07	1.75E-01
energy resources: non-renewable, fossil - fossil fuel potential (FFP)	kg oil-Eq	1.22E+07	2.43E-02
eutrophication: freshwater - freshwater eutrophication potential (FEP)	kg P-Eq	3.10E+03	6.15E-06
eutrophication: marine - marine eutrophication potential (MEP)	kg N-Eq	1.37E+03	2.71E-06
human toxicity: carcinogenic - human toxicity potential (HTPc)	kg 1,4-DCB-Eq	9.23E+05	1.83E-03
human toxicity: non-carcinogenic - human toxicity potential (HTPnc)	kg 1,4-DCB-Eq	1.81E+07	3.58E-02
ionising radiation - ionising radiation potential (IRP)	kBq Co-60-Eq	1.27E+07	2.52E-02
land use - agricultural land occupation (LOP)	m2*a crop-Eq	6.84E+05	1.36E-03
material resources: metals/minerals - surplus ore potential (SOP)	kg Cu-Eq	8.33E+05	1.65E-03
ozone depletion - ozone depletion potential (ODPinfinite)	kg CFC-11-Eq	6.73E+00	1.34E-08
particulate matter formation - particulate matter formation potential (PMFP)	kg PM2.5-Eq	3.75E+04	7.43E-05
photochemical oxidant formation: human health - photochemical oxidant formation potential: humans (HOFP)	kg NOx-Eq	1.68E+05	3.33E-04
photochemical oxidant formation: terrestrial ecosystems - photochemical oxidant formation potential: ecosystems (EOFP)	kg NOx-Eq	1.74E+05	3.45E-04
water use - water consumption potential (WCP)	m3	3.07E+05	6.09E-04
crustal scarcity indicator (CSI)	kg Si-Eq	4.10E+09	8.13E+00

Table D.5: Total impact results and per passenger km with the modelled ES-30 X-long regional mission of 600 km using 100 % fossil kerosene and Swedish electricity mix.

Impact category	**Reference unit**	**Total**	**Per pkm**
acidification: terrestrial - terrestrial acidification potential (TAP)	kg SO2-Eq	8.95E+04	2.37E-04
climate change - global warming potential (GWP100)	kg CO2-Eq	3.72E+07	9.83E-02
ecotoxicity: freshwater - freshwater ecotoxicity potential (FETP)	kg 1,4-DCB-Eq	5.38E+05	1.42E-03
ecotoxicity: marine - marine ecotoxicity potential (METP)	kg 1,4-DCB-Eq	7.22E+05	1.91E-03
ecotoxicity: terrestrial - terrestrial ecotoxicity potential (TETP)	kg 1,4-DCB-Eq	5.35E+07	1.42E-01
energy resources: non-renewable, fossil - fossil fuel potential (FFP)	kg oil-Eq	1.09E+07	2.89E-02
eutrophication: freshwater - freshwater eutrophication potential (FEP)	kg P-Eq	1.80E+03	4.75E-06
eutrophication: marine - marine eutrophication potential (MEP)	kg N-Eq	9.91E+02	2.62E-06
human toxicity: carcinogenic - human toxicity potential (HTPc)	kg 1,4-DCB-Eq	6.10E+05	1.61E-03
human toxicity: non-carcinogenic - human toxicity potential (HTPnc)	kg 1,4-DCB-Eq	1.04E+07	2.75E-02
ionising radiation - ionising radiation potential (IRP)	kBq Co-60-Eq	6.39E+06	1.69E-02
land use - agricultural land occupation (LOP)	m2*a crop-Eq	3.77E+05	9.99E-04
material resources: metals/minerals - surplus ore potential (SOP)	kg Cu-Eq	5.00E+05	1.32E-03
ozone depletion - ozone depletion potential (ODPinfinite)	kg CFC-11-Eq	4.25E+00	1.13E-08
particulate matter formation - particulate matter formation potential (PMFP)	kg PM2.5-Eq	3.06E+04	8.09E-05
photochemical oxidant formation: human health - photochemical oxidant formation potential: humans (HOFP)	kg NOx-Eq	1.51E+05	3.99E-04
photochemical oxidant formation: terrestrial ecosystems - photochemical oxidant formation potential: ecosystems (EOFP)	kg NOx-Eq	1.56E+05	4.13E-04
water use - water consumption potential (WCP)	m3	1.65E+05	4.37E-04
crustal scarcity indicator (CSI)	kg Si-Eq	3.07E+09	8.11E+00

D.0.1 AAF from UCO

Table D.6: Total impact results and per passenger km with the modelled ES-30 typical mission of 260 km using 100 % AAF from UCO and Swedish electricity mix.

Impact category	**Reference unit**	**Total**	**Per pkm**	**Change from fossil**
acidification: terrestrial - terrestrial acidification potential (TAP)	kg SO2-Eq	6.94E+04	1.70E-04	2 %
climate change - global warming potential (GWP100)	kg CO2-Eq	1.01E+07	2.48E-02	-56 %
ecotoxicity: freshwater - freshwater ecotoxicity potential (FETP)	kg 1,4-DCB-Eq	1.13E+06	2.76E-03	1 %
ecotoxicity: marine - marine ecotoxicity potential (METP)	kg 1,4-DCB-Eq	1.47E+06	3.59E-03	0 %
ecotoxicity: terrestrial - terrestrial ecotoxicity potential (TETP)	kg 1,4-DCB-Eq	9.70E+07	2.37E-01	2 %
energy resources: non-renewable, fossil - fossil fuel potential (FFP)	kg oil-Eq	3.11E+06	7.60E-03	-52 %
eutrophication: freshwater - freshwater eutrophication potential (FEP)	kg P-Eq	3.74E+03	9.13E-06	6 %
eutrophication: marine - marine eutrophication potential (MEP)	kg N-Eq	9.33E+02	2.28E-06	-19 %
human toxicity: carcinogenic - human toxicity potential (HTPc)	kg 1,4-DCB-Eq	9.12E+05	2.23E-03	0 %
human toxicity: non-carcinogenic - human toxicity potential (HTPnc)	kg 1,4-DCB-Eq	2.07E+07	5.05E-02	0 %
ionising radiation - ionising radiation potential (IRP)	kBq Co-60-Eq	1.59E+07	3.88E-02	1 %
land use - agricultural land occupation (LOP)	m2*a crop-Eq	8.06E+05	1.97E-03	1 %
material resources: metals/minerals - surplus ore potential (SOP)	kg Cu-Eq	8.64E+05	2.11E-03	-5 %
ozone depletion - ozone depletion potential (ODPinfinite)	kg CFC-11-Eq	6.70E+00	1.64E-08	-2 %
particulate matter formation - particulate matter formation potential (PMFP)	kg PM2.5-Eq	2.02E+04	4.93E-05	-21 %
photochemical oxidant formation: human health - photochemical oxidant formation potential: humans (HOFP)	kg NOx-Eq	8.72E+04	2.13E-04	0 %
photochemical oxidant formation: terrestrial ecosystems - photochemical oxidant formation potential: ecosystems (EOFP)	kg NOx-Eq	8.88E+04	2.17E-04	-2 %
water use - water consumption potential (WCP)	m3	3.66E+05	8.95E-04	1 %
crustal scarcity indicator (CSP)	kg Si-Eq	2.56E+09	6.24E+00	-23 %

Table D.7: Total impact results and per passenger km with the modelled ES-30 fjord-hopper mission of 100 km using 100 % AAF from UCO and Swedish electricity mix.

Impact category	**Reference unit**	**Total**	**Per pkm**	**Change from fossil**
acidification: terrestrial - terrestrial acidification potential (TAP)	kg SO2-Eq	6.87E+04	1.82E-04	1 %
climate change - global warming potential (GWP100)	kg CO2-Eq	1.28E+07	3.37E-02	-34 %
ecotoxicity: freshwater - freshwater ecotoxicity potential (FETP)	kg 1,4-DCB-Eq	1.65E+06	4.36E-03	0 %
ecotoxicity: marine - marine ecotoxicity potential (METP)	kg 1,4-DCB-Eq	2.14E+06	5.67E-03	0 %
ecotoxicity: terrestrial - terrestrial ecotoxicity potential (TETP)	kg 1,4-DCB-Eq	1.34E+08	3.54E-01	1 %
energy resources: non-renewable, fossil - fossil fuel potential (FFP)	kg oil-Eq	3.40E+06	9.00E-03	-34 %
eutrophication: freshwater - freshwater eutrophication potential (FEP)	kg P-Eq	5.60E+03	1.48E-05	2 %
eutrophication: marine - marine eutrophication potential (MEP)	kg N-Eq	1.43E+03	3.79E-06	-7 %
human toxicity: carcinogenic - human toxicity potential (HTPc)	kg 1,4-DCB-Eq	1.32E+06	3.48E-03	0 %
human toxicity: non-carcinogenic - human toxicity potential (HTPnc)	kg 1,4-DCB-Eq	3.07E+07	8.11E-02	0 %
ionising radiation - ionising radiation potential (IRP)	kBq Co-60-Eq	2.22E+07	5.88E-02	0 %
land use - agricultural land occupation (LOP)	m2*a crop-Eq	1.11E+06	2.95E-03	0 %
material resources: metals/minerals - surplus ore potential (SOP)	kg Cu-Eq	1.27E+06	3.35E-03	-2 %
ozone depletion - ozone depletion potential (ODPinfinite)	kg CFC-11-Eq	9.37E+00	2.48E-08	-1 %
particulate matter formation - particulate matter formation potential (PMFP)	kg PM2.5-Eq	2.54E+04	6.71E-05	-10 %
photochemical oxidant formation: human health - photochemical oxidant formation potential: humans (HOFP)	kg NOx-Eq	6.41E+04	1.70E-04	0 %
photochemical oxidant formation: terrestrial ecosystems - photochemical oxidant formation potential: ecosystems (EOFP)	kg NOx-Eq	6.62E+04	1.75E-04	-1 %
water use - water consumption potential (WCP)	m3	5.20E+05	1.38E-03	0 %
crustal scarcity indicator (CSP)	kg Si-Eq	3.61E+09	9.55E+00	-10 %

Table D.8: Total impact results and per passenger km with the modelled ES-30 regular regional mission of 200 km using 100 % AAF from UCO and Swedish electricity mix.

Impact category	**Reference unit**	**Total**	**Per pkm**	**Change from fossil**
acidification: terrestrial - terrestrial acidification potential (TAP)	kg SO2-Eq	5.34E+04	1.21E-04	1 %
climate change - global warming potential (GWP100)	kg CO2-Eq	1.00E+07	2.27E-02	-28 %
ecotoxicity: freshwater - freshwater ecotoxicity potential (FETP)	kg 1,4-DCB-Eq	1.52E+06	3.44E-03	0 %
ecotoxicity: marine - marine ecotoxicity potential (METP)	kg 1,4-DCB-Eq	1.96E+06	4.45E-03	0 %
ecotoxicity: terrestrial - terrestrial ecotoxicity potential (TETP)	kg 1,4-DCB-Eq	1.24E+08	2.81E-01	0 %
energy resources: non-renewable, fossil - fossil fuel potential (FFP)	kg oil-Eq	2.56E+06	5.80E-03	-28 %
eutrophication: freshwater - freshwater eutrophication potential (FEP)	kg P-Eq	4.74E+03	1.07E-05	1 %
eutrophication: marine - marine eutrophication potential (MEP)	kg N-Eq	1.20E+03	2.71E-06	-5 %
human toxicity: carcinogenic - human toxicity potential (HTPc)	kg 1,4-DCB-Eq	1.12E+06	2.53E-03	0 %
human toxicity: non-carcinogenic - human toxicity potential (HTPnc)	kg 1,4-DCB-Eq	2.74E+07	6.22E-02	0 %
ionising radiation - ionising radiation potential (IRP)	kBq Co-60-Eq	2.21E+07	5.02E-02	0 %
land use - agricultural land occupation (LOP)	m2*a crop-Eq	1.08E+06	2.45E-03	0 %
material resources: metals/minerals - surplus ore potential (SOP)	kg Cu-Eq	1.17E+06	2.65E-03	-1 %
ozone depletion - ozone depletion potential (ODPinfinite)	kg CFC-11-Eq	8.56E+00	1.94E-08	-1 %
particulate matter formation - particulate matter formation potential (PMFP)	kg PM2.5-Eq	2.05E+04	4.65E-05	-7 %
photochemical oxidant formation: human health - photochemical oxidant formation potential: humans (HOFP)	kg NOx-Eq	4.44E+04	1.01E-04	0 %
photochemical oxidant formation: terrestrial ecosystems - photochemical oxidant formation potential: ecosystems (EOFP)	kg NOx-Eq	4.59E+04	1.04E-04	-1 %
water use - water consumption potential (WCP)	m3	4.97E+05	1.13E-03	0 %
crustal scarcity indicator (CSP)	kg Si-Eq	3.23E+09	7.33E+00	-6 %

Table D.9: Total impact results and per passenger km with the modelled ES-30 long regional mission of 400 km using 100 % AAF from UCO and Swedish electricity mix.

Impact category	**Reference unit**	**Total**	**Per pkm**	**Change from fossil**
acidification: terrestrial - terrestrial acidification potential (TAP)	kg SO2-Eq	1.10E+05	2.18E-04	3 %
climate change - global warming potential (GWP100)	kg CO2-Eq	1.33E+07	2.64E-02	-68 %
ecotoxicity: freshwater - freshwater ecotoxicity potential (FETP)	kg 1,4-DCB-Eq	9.71E+05	1.93E-03	1 %
ecotoxicity: marine - marine ecotoxicity potential (METP)	kg 1,4-DCB-Eq	1.27E+06	2.52E-03	0 %
ecotoxicity: terrestrial - terrestrial ecotoxicity potential (TETP)	kg 1,4-DCB-Eq	9.17E+07	1.82E-01	4 %
energy resources: non-renewable, fossil - fossil fuel potential (FFP)	kg oil-Eq	4.73E+06	9.39E-03	-61 %
eutrophication: freshwater - freshwater eutrophication potential (FEP)	kg P-Eq	3.58E+03	7.10E-06	15 %
eutrophication: marine - marine eutrophication potential (MEP)	kg N-Eq	8.80E+02	1.75E-06	-36 %
human toxicity: carcinogenic - human toxicity potential (HTPc)	kg 1,4-DCB-Eq	9.19E+05	1.82E-03	0 %
human toxicity: non-carcinogenic - human toxicity potential (HTPnc)	kg 1,4-DCB-Eq	1.82E+07	3.62E-02	1 %
ionising radiation - ionising radiation potential (IRP)	kBq Co-60-Eq	1.29E+07	2.56E-02	2 %
land use - agricultural land occupation (LOP)	m2*a crop-Eq	7.07E+05	1.40E-03	3 %
material resources: metals/minerals - surplus ore potential (SOP)	kg Cu-Eq	7.38E+05	1.46E-03	-11 %
ozone depletion - ozone depletion potential (ODPinfinite)	kg CFC-11-Eq	6.36E+00	1.26E-08	-6 %
particulate matter formation - particulate matter formation potential (PMFP)	kg PM2.5-Eq	2.58E+04	5.13E-05	-31 %
photochemical oxidant formation: human health - photochemical oxidant formation potential: humans (HOFP)	kg NOx-Eq	1.67E+05	3.32E-04	0 %
photochemical oxidant formation: terrestrial ecosystems - photochemical oxidant formation potential: ecosystems (EOFP)	kg NOx-Eq	1.69E+05	3.36E-04	-2 %
water use - water consumption potential (WCP)	m3	3.13E+05	6.20E-04	2 %
crustal scarcity indicator (CSP)	kg Si-Eq	2.46E+09	4.88E+00	-40 %

Table D.10: Total impact results and per passenger km with the modelled ES-30 X-long regional mission of 600 km using 100 % AAF from UCO and Swedish electricity mix.

Impact category	Reference unit	Total	Per pkm	Change from fossil
acidification: terrestrial - terrestrial acidification potential (TAP)	kg SO2-Eq	9.28E+04	2.46E-04	4 %
climate change - global warming potential (GWP100)	kg CO2-Eq	1.03E+07	2.72E-02	-72 %
ecotoxicity: freshwater - freshwater ecotoxicity potential (FETP)	kg 1,4-DCB-Eq	5.50E+05	1.46E-03	2 %
ecotoxicity: marine - marine ecotoxicity potential (METP)	kg 1,4-DCB-Eq	7.27E+05	1.92E-03	1 %
ecotoxicity: terrestrial - terrestrial ecotoxicity potential (TETP)	kg 1,4-DCB-Eq	5.67E+07	1.50E-01	6 %
energy resources: non-renewable, fossil - fossil fuel potential (FFP)	kg oil-Eq	3.92E+06	1.04E-02	-64 %
eutrophication: freshwater - freshwater eutrophication potential (FEP)	kg P-Eq	2.24E+03	5.93E-06	25 %
eutrophication: marine - marine eutrophication potential (MEP)	kg N-Eq	5.38E+02	1.42E-06	-46 %
human toxicity: carcinogenic - human toxicity potential (HTPc)	kg 1,4-DCB-Eq	6.07E+05	1.60E-03	-1 %
human toxicity: non-carcinogenic - human toxicity potential (HTPnc)	kg 1,4-DCB-Eq	1.05E+07	2.79E-02	1 %
ionising radiation - ionising radiation potential (IRP)	kBq Co-60-Eq	6.61E+06	1.75E-02	3 %
land use - agricultural land occupation (LOP)	m2*a crop-Eq	3.99E+05	1.06E-03	6 %
material resources: metals/minerals - surplus ore potential (SOP)	kg Cu-Eq	4.11E+05	1.09E-03	-18 %
ozone depletion - ozone depletion potential (ODPinfinite)	kg CFC-11-Eq	3.91E+00	1.03E-08	-8 %
particulate matter formation - particulate matter formation potential (PMFP)	kg PM2.5-Eq	1.93E+04	5.10E-05	-37 %
photochemical oxidant formation: human health - photochemical oxidant formation potential: humans (HOFP)	kg NOx-Eq	1.50E+05	3.97E-04	0 %
photochemical oxidant formation: terrestrial ecosystems - photochemical oxidant formation potential: ecosystems (EOFP)	kg NOx-Eq	1.52E+05	4.02E-04	-3 %
water use - water consumption potential (WCP)	m3	1.70E+05	4.51E-04	3 %
crustal scarcity indicator (CSP)	kg Si-Eq	1.54E+09	4.07E+00	-50 %

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