Environmental trade-offs of aerostructures

A prospective lifecycle assessment of wing ribs

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by

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Cover image: White aircraft on green strip against cyan background. Design by the author.

TU Delft

Executive summary

Efforts are ongoing to reduce the environmental burdens of the commercial aviation sector. Among these are technological innovations to aircraft structures and materials. Load-bearing structures must be guaranteed to withstand a range of conditions and, to reduce fuel use, they are made to be as light as possible. This lightweighting increasingly involves the use of composite materials. Established composite material systems often use high-strength continuous carbon fibres, embedded in a thermosetting polymer matrix. Thermoplastic polymers are emerging as materials which can enable the reduction of process times, costs, and waste. Furthermore, its waste can be recovered into new products with relative ease.

In this study, a design for a carbon fibre-reinforced thermoplastic (CFRTP) rib made from carbon fibre and polyetherketoneketone (CF/PEKK) was evaluated through a comprehensive lifecycle assessment (LCA). This is a quantitative method of analysing the environmental impacts across a particular product system, isolating it from the wider economy. The research question of this thesis was: “Considering the case study of a CF/PEKK wing rib, how can CFRTP improve the environmental performance of commercial aircraft?” To understand the environmental implications of this material, a variety of factors must be considered. Some hail thermoplastic composites as a gateway to a circular economy for the aviation sector, but how should recycling be accounted for? How does it compare to alternative materials and waste treatment options? Furthermore, the precise lightweighting potential among composites is not yet well understood. This also ties into the energy transition, which has ongoing relevance to production processes, including the production of alternative energy carriers for aviation. This is the first study to consider these aspects across the lifecycle of aviation components.

The CFRTP rib was compared to several hypothetical alternatives: an aluminium alloy rib, a carbon fibre-reinforced thermosetting (CFRTS) rib made using autoclave processing, and a CFRTS rib made using resin transfer moulding. Each alternative was compared for the functional unit of “providing structural support to a single-aisle passenger aircraft over 30 years”. As lifecycle impacts are dominated by mass-induced fuel use, the functional unit was also evaluated when excluding the use phase. These figures are valuable when dealing with uncertainty in component masses, as was the case here.

Scenario analysis was used, creating sets of scenarios which tackle a particular perspective to consider: recyclability (comparing waste treatment options), mass-induced energy demand (comparing impacts of different component masses and use intensities), and alternative energy carriers (comparing fossil kerosene to the introduction of sustainable drop-in fuels based on ReFuelEU Aviation and to a hydrogen-powered scenario). The cradle-to-gate processes were modelled using contemporary data from primary sources, literature, and the ecoinvent database. For the first time, an inventory of environmental flows for the production of PEKK and subsequent products was created. Future processes – the production of alternative energy carriers and the waste treatment at end-of-life – were modelled using a prospective method, transforming the ecoinvent database with the *premise* Python library, such that it follows the nationally determined contributions (NDC) pathway of the REMIND model, with end-of-life in 2050. This is a first for research on aerostructures. Impacts on climate change were assessed using a custom method combining considerations for biogenic carbon, hydrogen emissions, and the altitude of aviation emissions. Other impact categories were assessed using the Environmental Foot-

print method. To interpret the created models and results, a variety of steps was performed, including contribution analyses, break-even analyses of component mass, consistency checks, comparisons to literature, and sensitivity analyses of modelling choices.

The interpretation shows that component mass is the most critical property of aircraft structures, even in scenarios where sustainable energy carriers are used and where the components are used much less intensively than is typically the case. Therefore, the choice between multiple components will always tend towards the lightest alternative. When environmental impacts of other lifecycle phases differ greatly between components, a difference in mass of around 3% would be sufficient to ensure that the lightest component is indeed the most environmentally favourable. This range can not only be seen as a minimum for lightweighting, but also as a maximum for the implementation of low-impact materials. Meaning, a heavier component with less waste, energy demand, etc. could be preferred over a lighter component, as long as it is no more than 3% heavier. Note, however, that this range is a first estimate and that it is small – smaller than the typical manufacturing variability dealt with. Shifting the temporal scope to the future increases the potential mass range.

CFRTP can be a highly advantageous material under the right circumstances. CFRTP scrap could be put to use in creating additional aircraft products. If this brings additional lightweighting benefits, this can play a major role in the environmental performance of CFRTP. However, the potential magnitude of this effect is still unknown, as it requires a component-specific evaluation. If CFRTP scrap is not used in a high-quality application, the benefit of recyclability is relatively minor. Assuming equal mass, impacts of composites are relatively similar. As the demand for primary carbon fibre makes up a majority of impacts when excluding use (typically, around 80% across impact categories), material efficiency and waste treatment become important variables. Interestingly, the mechanical recycling of CFRTP has economic and practical advantages, but it was found here to perform similarly to pyrolysis on an environmental level. Additionally, it was found that care should be taken not to over-value end-of-life recycling: its benefits are limited to a decarbonised future, compared to reducing the production of primary material today. A concern regarding the CFRTP examined here is that the supply chain of PEKK includes carcinogenic and ozone-depleting chemicals, resulting in impacts twice as large when compared to a CFRTS rib manufacturing using RTM. On the other hand, both CFRTP and the RTM rib have advantages compared to the autoclaved CFRTS rib, for which the autoclave consumables form a notable impact. However, the comparison between equal-mass ribs is also sensitive to the manufacturing energy demand, for which data quality is particularly meagre.

In addition to a lack of high-quality inventory data, there are also other limitations to the study. For example, the approach to alternative energy carriers is relatively rudimentary. Additionally, the results indicate that future research should compare a wider range of innovative materials and applications to contextualise more fully the result. Finally, although lightweighting contributes to improving the environmental performance of future aircraft, it must not be confused with reducing the environmental impacts of aviation in aggregate.

Although the environmental performance of aircraft structures is driven by lightweighting, the potential benefits of circular material practises are clear. CFRTP is in an unusual position, where synergy can be created between these two aspects. The pioneering methodology and in-depth analysis of this thesis not only hold value for CFRTP in aviation, but also lay the foundation for broader applications across industries facing the combined challenges of lightweighting and circularity. The developed method has potential to guide sustainable decision-making across various materials, applications, and sectors. As aviation and other industries navigate the intricacies of environmental responsibility, this thesis offers a valuable compass for future exploration.

Preface

Inspiration and input for this thesis came in many forms over the course of several years. This has made it a much more comprehensive work than I thought would be possible. For this I have to thank the Circular Aviation thesis lab of the LDE Centre for Sustainability, its participants and its coordinators. Although not directly involved with the research of this thesis, Ligeia Paletti and her colleagues at the Royal NLR have given me valuable insight into how to evaluate and present environmental analyses in a sector as tricky as aviation. My gratitude of course extends to my supervisors, Irene Fernandez Villegas and Bernhard Steubing, as well as to Thomas de Bruijn from GKN Fokker Aerostructures. Each of them brought a unique perspective to the research, which was valuable and appreciated. There are many more members of the scientific community whose work has made mine possible. They are too numerous to name, but you will find some of them on the pages numbered 81-91.

As this thesis marks a milestone in my academic career, I also want to take the time to acknowledge the friends, family members, and communities with whom I have found inspiration and support over the years. This extends to the VSV 'Leonardo da Vinci' and IESA Shift; to 2.56 and their daily lunch walks; to my colleagues of the FSC and GreenTU; to the people with whom I play games, whether this is in Delft, Amersfoort, Schriek, or elsewhere; to my parents and siblings; and, finally, to Kristie, who is much kinder and smarter than she would let me admit in my thesis preface.

Thomas Arblaster
Delft, September 2023

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Nomenclature

On this page, a number of symbols and abbreviations commonly used in this document is listed.

Abbreviation	Definition
(P)EF	(Product) Environmental Footprint
AIC	Aviation-induced cloudiness
AFP	Automated fibre placement
ALCA	Attributional lifecycle assessment
ATL	Automated tape laying
CF	Carbon fibre
CFF	Carbon Footprint Formula
CFRP	Carbon fibre-reinforced polymer
CFRTP	Carbon fibre-reinforced thermoplastic polymer
CFRTS	Carbon fibre-reinforced thermoset polymer
CLCA	Consequential lifecycle assessment
GWP	Global warming potential
IAM	Integrated assessment model
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organization for Standardization
LCA	Lifecycle assessment
LCI	Lifecycle inventory
LCIA	Lifecycle impact assessment
NDC	Nationally determined contribution
PEEK	Polyetheretherketone
PEKK	Polyetherketoneketone
RTM	Resin transfer moulding
SAF	Sustainable aviation fuel
SDF	Scenario difference file
SRQ	Sub research question
SSP	Shared Socio-economic Pathway
AlLi	Aluminium-lithium
CO_2	Carbon dioxide
H_2	Molecular hydrogen
H_2O	Water
HCl	Hydrogen chloride
NO_x	Nitrogen oxides
SO_x	Sulphur oxides

I

Introduction

1
Problem situation

This chapter introduces two trends affecting the environmental sustainability of aerostructures: the shift in materials towards (thermoplastic) composites and the transition towards alternative aviation fuels. Next, the case study for this thesis is introduced, which builds on the work of Stefanidi [1]. Finally, this chapter provides an overview of the thesis outline.

1.1. Problem statement

From environmental and financial perspectives, there is a desire to minimise the fuel consumption of aviation. This has led to a focus on lightweighting and materials with a high specific strength [2]. Specialised metal alloys have played a dominant role here, but also high-strength fibres – particularly, carbon fibre (CF) – have emerged as suitable material. Fibres are embedded in a polymer matrix, creating carbon fibre-reinforced polymers (CFRP). For various reasons, thermosetting polymers (TS) are the dominant matrix material for CFRP (distinguished here as CFRTS). However, increasingly, thermoplastic polymers (TP) emerge as preferred material (distinguished here as CFRTP), due to manufacturing advantages such as weldability, decreased processing times, improved automation, and the possibility to reprocess manufacturing off-cuts [3]. Because of such advantages, there is a growing industrial and academic interest in composite manufacturing with high-performance thermoplastic matrices, such as polyphenylene sulfide (PPS) [4] or polyaryletherketone (PEAK) materials polyetherketoneketone (PEKK) [1] and polyetheretherketone (PEEK) [5]. Increasingly, projects emerge to tackle metal alloy parts which were unappealing to replace using conventional composite manufacturing processes. These projects instead explore novel out-of-autoclave thermoplastic composite processes. Examples include spars and ribs by Daher [6, 7] and the case study of this thesis: a rib by GKN Aerospace (see Section 1.2).

At the same time that manufacturing shares of CFRP – and particularly, of CFRTP – are growing to improve the fuel efficiency of aircraft, aviation fuel is experiencing a transition of its own. The exploitation of fossil fuels such as kerosene contribute to the ongoing climate crisis [8], and one avenue to reduce this impact is to shift to renewable fuels. Drop-in sustainable aviation fuels (SAF) are compatible with current aircraft technology, while non-drop-in energy carriers, such as molecular hydrogen (H_2) and chemical batteries, require adapting aircraft propulsion systems, on-board storage, infrastructure, etc.

accordingly [9, 10]. Possible production pathways for alternative liquid fuels are varied, from biomass-derived fuels, to power-to-liquid fuels (also known as electro-fuels or e-fuels), which are synthesised from building blocks extracted from air and water, but which require high electricity inputs [11]. This energy transition is tightly linked to the decarbonisation of society's energy systems at large [12].

These developments are promising, but understanding their effects on environmental sustainability is not straightforward. Mass-induced energy demand takes centre stage when comparing environmental impacts of aerostructures [13–15]. However, through the energy transition and the transition from metal alloys to composites (and within composites, from thermosetting matrix materials to thermoplastics), two topics of interest emerge.

Firstly, it becomes important to understand the environmental impacts of manufacturing, and later, decommissioning, CFRTP components. As energy carriers become more sustainable, these lifecycle phases are expected to take up a larger portion of the whole [16]. Additionally, when comparing several carbon fibre composites, mass differences might be negligible, bringing other lifecycle stages to the foreground. In this context, analyses should also consider the growing interest in, and opportunities for, circular solutions to waste. How such solutions are accounted for could be significant in determining whether one material is desirable over another [16].

Secondly, aircraft often have a lifespan of over 20 years [17, 18]. The case study examined here is designed for a 30-year lifespan [1]. This means that an aircraft entering service today could still be flying in 2050, using the fuel produced at that time. However, the impact of future energy carriers is still uncertain [12, 19].

These two topics create grey areas when aiming to improve environmental performance, i.e., to minimise the environmental impacts associated with a particular aircraft component. Lifecycle assessment (LCA) is a method of quantifying the environmental impacts of a product or service [20]. Its ability to consider a product across its entire lifecycle, from cradle to grave, in combination with the databases, tools, discussion, examples, etc. which support its practitioners (see, e.g., Wernet et al. [21], Steubing et al. [22], Rupcic et al. [23], and Sacchi et al. [24]) make this method a good match to evaluating the environmental impacts of aerostructures. To explore how this thesis can contribute to illuminating the environmental trade-offs of aerostructures from a lifecycle perspective, a literature review is performed in Chapter 2. This reveals knowledge gaps which inform the research question, presented in Chapter 3.

1.2. Case study component: wing rib

The design of aerostructures must interact with the trinity of material properties, manufacturing, and structural performance. This means that a difference in material also results in differences in manufacturing method and the waste created, for example. This should be accounted for when drawing a comparison between alternatives [25]. Here, this is done by basing the evaluation on a case study: a carbon fibre/polyetherketoneketone (CF/PEKK) wing rib developed by GKN Aerospace. This is a state-of-the-art project which demonstrates out-of-autoclave thermoplastic processing. This component is described in Section 1.2.1, with the alternatives to which it is compared being described in Section 1.2.2.

1.2.1. Description of component

Figure 1.1 shows three specimens of the component in question. The web of the rib is around 0.90 m-by-0.24 m and strengthened by several stiffening elements [26]. Notice that there are flanges at the base of the rib, but not the top. The rib has a mass of 2.1 kg [1].

The wing rib is formed from continuous CF/PEKK prepreg (where the fibres are "pre-impregnated" with the matrix material, as opposed to combining fibres and matrix through another mechanism). After forming the rib, it is consolidated in a heated press [1]. A diagram of this process is presented in Figure 1.3(a). As discussed in Section 1.1, hot press consolidation has several advantages over the more established composite manufacturing method, which uses an autoclave to cure thermosetting material. Autoclave processing will be explained in more detail as one of the alternatives in Section 1.2.2. One of the advantages of CFRTP is that the matrix polymer chains can be made mobile again, allowing waste to be reprocessed into a new component. GKN Aerospace has participated in demonstrating this technology, which is illustrated in Figure 1.2. Parts created from reprocessed CFRTP scrap can offer lightweighting when replacing metal alloy components.

Figure 1.1: Photograph of three identical CF/PEKK ribs by GKN Aerospace. This rib serves as case study for this thesis. Image obtained via Mason [26].

1.2.2. Description of alternatives

Evaluating the CFRTP rib on its own would provide insight into the relative impacts of various lifecycle activities, but little insight would be gained into how the component performs as a whole. To gain such insight, the component is compared against reasonable alternatives.

The CFRTP rib would replace an aluminium alloy rib [1]. Stefanidi [1] discusses the machining of aluminium 7075, a high-performance aluminium alloy which has zinc as primary alloying element. Machining entails starting from a solid block and removing material until the desired shape remains. This method generates a lot of scrap, but is used to ensure that the desired crystal structure – initially obtained through heat treatment – is maintained. The redesign to CFRTP includes changes to the wing architecture, reducing the number of ribs. There is therefore no direct aluminium alloy equivalent to the CFRTP rib examined here. Because of this, a hypothetical aluminium alloy rib is created, assumed to be compatible with this new airframe architecture.

Curing prepreg CF/epoxy in an autoclave is the incumbent composite manufacturing method for high-performance aerostructures. A hypothetical set-up of a CF/epoxy rib in an autoclave is shown in Figure 1.3(c). This method includes numerous consumables and is generally thought of as energy intensive, as the autoclave applies heat and pressure over several hours. However, few measurements

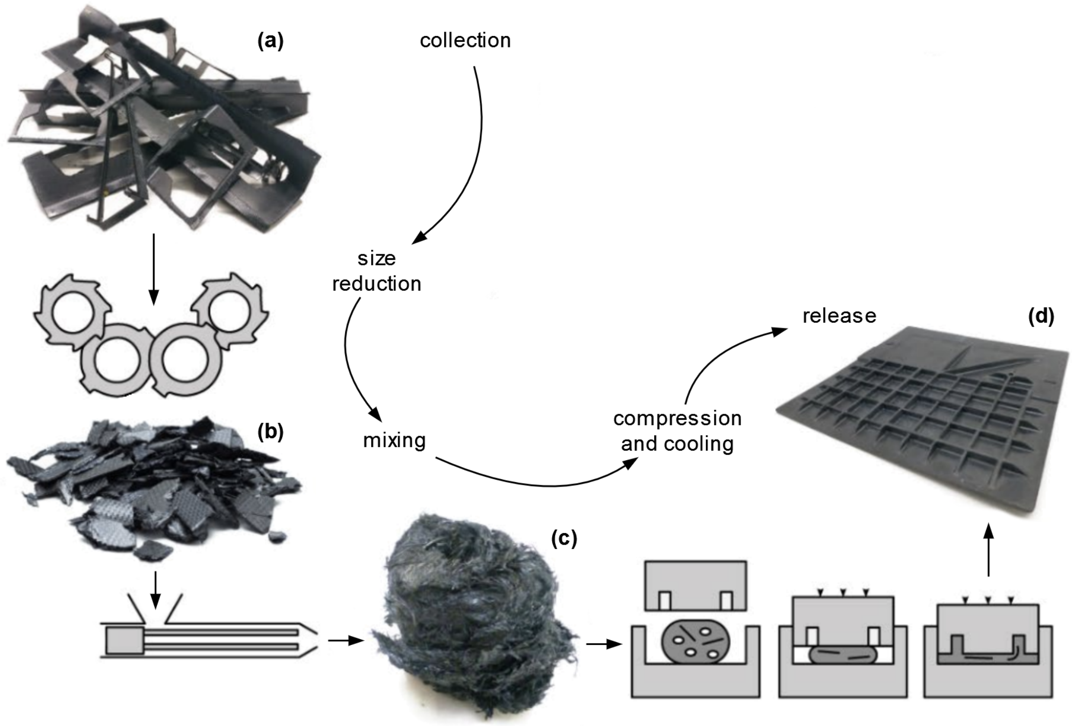

Figure 1.2: Diagram of process steps to convert **(a)** CFRTP trims into **(b)** shredded flakes, which are heated and mixed into **(c)** molten and mixed dough, and subsequently pressed into **(d)** a moulded part. The waste material in this example is similar to the CFRTP manufacturing waste generated in this case study. Diagram adapted from images obtained via TPAC [27].

are available to accurately quantify the energy demand. Another promising composite manufacturing method is resin transfer moulding (RTM). This process is depicted in Figure 1.3(b) and involves pre-forming the fibre architecture of the rib before injecting it with the thermosetting matrix material. This process can be advantageous over the use of an autoclave, as it avoids the handling challenges associated with prepreg composite fabric, while also reducing processing times. These two methods are interesting alternatives to compare CFRTP to and were also evaluated by Stefanidi [1]. However, little data is available on these processes, both from primary sources and literature. Over the course of this study, several assumptions are made in order to perform a complete and consistent assessment.

1.3. Thesis outline

Beyond this chapter, Chapter 2 provides a review of the state of the art in scientific literature. Based on this review, knowledge gaps are identified. These inform the research questions, shown in Chapter 3. These research questions will be answered using a prospective lifecycle assessment approach, which is introduced in Chapter 4, before diving in with Part II, where each phase of the LCA is reported. This reporting also involves extensive supporting information in Appendix A through Appendix H. The results of the LCA are discussed in Chapter 10, which leads to the research questions being answered. The relevance of these answers becomes clear in Chapter 11, which discusses the limitations of the study, how the results can be generalised, and what to take away for future research. Finally, the thesis is concluded in Chapter 12.

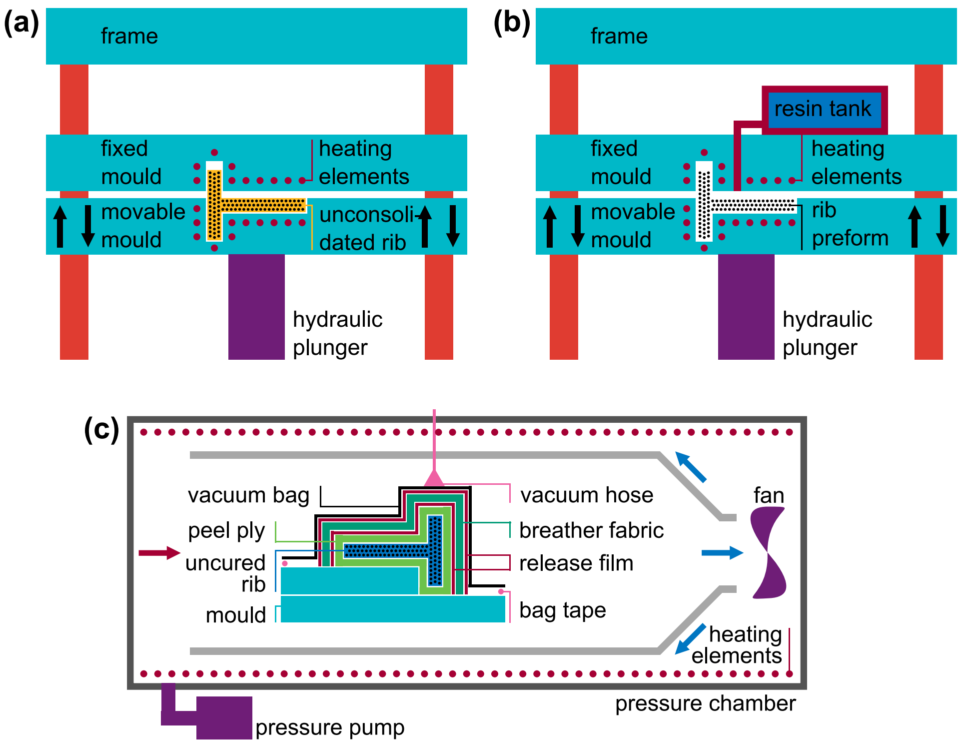

Figure 1.3: Simplified diagrams of possible composite manufacturing processes, depicting **(a)** hot press consolidation; **(b)** resin transfer moulding (RTM); and **(c)** autoclave processing. This visual representation is informed and inspired by Lunetto et al. [28]. Note: diagram elements are not to scale.

2
Literature review

A literature study report [29] was written in preparation of this thesis. This chapter provides a brief overview of the relevant literature, which can be divided into lifecycle assessment literature (Section 2.1) and other literature on the environmental impacts of aviation (Section 2.2). Next, the identified knowledge gaps are summarised.

2.1. Lifecycle assessment literature

Lifecycle assessment (LCA) is a standardised framework of quantitative sustainability assessment. The framework itself will be defined in Section 4.1. This method has developed considerably over the past decades and there are several studies which demonstrate how it can be applied to aviation products. Several of these are summarised in the literature study report [29], but since this report was completed, the reviews of Rupcic et al. [23] and Keiser et al. [30] were published, which each provide a complete, expert assessment of aviation LCA, as well as how LCA studies on this topic can be improved. The following sections will provide a brief overview of the state of the art, focusing first on material aspects such as manufacturing and recycling, and then on aspects related to flight itself, being mass-induced energy use and related impacts.

2.1.1. Manufacturing, servicing, and recycling of (composite) aerostructures

Several studies have previously been published which comparatively assess aluminium alloy and composite aviation components (see, e.g., Timmis et al. [14], Markatos and Pantelakis [16], and Scelsi et al. [31]). These come to the conclusion that, since a switch to a composite design is paired with substantial lightweighting, savings relating to fuel demand can vastly outweigh any differences in other lifecycle phases. Similar conclusions have been made when comparing metal alluminium alloys, for example by comparing subtractive and additive manufacturing (see, e.g., Huang et al. [13] and Mami et al. [32]). Composite components have also been compared to each other: Van Grootel et al. [33] point out the role of manufacturing variability has on mass-induced emissions and Vidal et al. [34] demonstrate that bio-based composites can offer an advantage over traditional materials when the new component also results in lightweighting. Bio-composites are a growing field of research, but fall beyond the scope of this thesis.

The cradle-to-gate phase of aerostructures (or of components using similar materials, such as in the automotive sector) has furthermore been analysed in studies such as those of Ogugua, Sinke, and Dransfeld [4], Paris et al. [35], Duflou et al. [36], Forcellese et al. [37], Witik et al. [38], and Hohmann et al. [39]. Although several of these studies report their methods and results in detail, there are large knowledge gaps in quantifying the environmental impacts of aerospace materials [23, 30]. Not only the materials themselves, but also important aspects of manufacturing activities often lack resolution [30]. One of these aspects is the buy-to-fly ratio – the material which enters the manufacturing phase compared to the material which is part of the final product. This can be a highly relevant metric in the analysis of components (see, e.g., Scelsi et al. [31] and Paris et al. [35]), however, manufacturing waste is often ignored (see, e.g., Cox, Jemiolo, and Mutel [15]).

After manufacturing, aircraft products are inspected, assembled, and serviced – which can include inspections, repairs, and replacements. These activities are overwhelmingly cut off during LCA studies. One example of a study which does consider repair is Vidal et al. [34], based on the repair procedure of their case study. Largely, the data required to model these activities is simply not available, although Keiser et al. [30] point out developments in this area. A phase which has received more attention – although it is also operating under limited data availability – is the end-of-life phase. Particularly popular are the emerging technologies which can enable composite recycling (see, e.g., Tapper et al. [40], Bachmann, Hidalgo, and Bricout [41], Pillain et al. [42], and Witik et al. [43]). On this topic, Stelzer et al. [44] conclude that the environmental benefits of applying mechanically recycled CFRTP can outweigh the lightweighting benefits of primary CFRTP in an automotive setting. The question of recyclability and potential environmental credits is of interest to aviation as well. However, how to account for the creation of recyclates in LCA is a long-enduring topic of discussion (see, e.g., Brander and Wylie [45]), which this thesis also engages in (see Section 6.1.2).

2.1.2. Operations: mass-induced energy demand and resulting emissions

As introduced in Section 2.1.1, several studies have included the effect of lightweighting on the use phase, representing this by a decrease in fuel use, which leads to the conclusion that, for commercial aviation, lightweighting can compensate for increased impacts in other lifecycle phases within the first weeks of operations [31, 34]. When performing contribution analysis, emissions associated with mass-induced energy use typically make up more than 99% of impacts [46]. Because of this feature of commercial aviation, Keiser et al. [30] recommend to always represent the use phase in LCA studies. However, the reasoning behind this is not straightforward. By including lightweighting in the comparison, as will be done with the components described in Section 1.2, the assumption is made that the components are each interchangeable with each other. In reality, the design of an aircraft must carefully balance the mass of the wing with the lift it can generate and the forces of the engines it must carry. The challenge of representing this within an LCA has previously been addressed through numerous methods.

The methods with which lightweighting has been presented are compared numerically in Section B.6.3. To give a brief overview, previous studies have quantified lightweighting effects based on existing models (e.g., Scelsi et al. [31] and Vidal et al. [34]), regression analysis of historic aircraft (e.g., Cox, Jemiolo, and Mutel [15] and Calado, Leite, and Silva [47]), or directly based on aircraft dynamics (e.g., Stefanidi [1], Schäfer et al. [48], and Gnadt et al. [49]). There are also studies which cite estimates based on airline data and internal models (e.g., Huang et al. [13] and van Grootel et al. [33]). These studies also illustrate that there is no single lightweighting curve, and that the effects of lightweighting will depend on the type of aircraft and how it is used.

When quantifying how lightweighting affects fuel use, a natural step is to evaluate how fuel use affects emissions. The above studies all evaluate fossil kerosene. However, as was introduced in Section 1.1, there are ongoing efforts to shift the commercial aviation sector to renewable energy sources. Although there are many studies evaluating alternative energy carriers (see, e.g., Barke et al. [11], Li et al. [50], and Bicer and Dincer [51]), there are only a few which include (elements of) the aircraft product in this assessment (see, e.g., Scholz, Trifonov, and Hornung [10], Markatos and Pantelakis [16], and Sacchi et al. [52]). Markatos and Pantelakis [16] appear to be the only authors who explicitly discuss lightweighting and its influence on lifecycle impacts, while considering alternative energy carriers. They assess climate change through a simplified LCA and define a circularity metric, concluding that, depending on the priorities set, primary and recycled CFRP could have a comparable evaluation in a hydrogen-powered scenario. To the best of the author's knowledge, this type of question has not been answered using a detailed LCA method.

Furthermore, there are characteristics of flight emissions which distinguish their impacts from those of other activities. As is reviewed in Section 2.2, the understanding of these differences is improving, but this is a relatively novel development, which has not seen widespread application in LCA. Cox, Jemiolo, and Mutel [15] appear to be the first to adapt their method based on this emerging knowledge, deviating from typical impact assessment methods for climate change and air quality-related impacts. Since Cox, Jemiolo, and Mutel, several more studies have used similar techniques for climate change, such as Kossarev, Scholz, and Hornung [9], Ballal et al. [12], and Sacchi et al. [52].

2.2. Other literature

As discussed above, the past decades have seen significant developments in the understanding of environmental impacts of aviation, with limited integration in the LCA community so far. Rupcic et al. [23] point out the disconnect in impacts such as climate change, noise, and ecotoxicity.

Climate change is caused by shifting the energy balance of the Earth system. The atmosphere plays a key role here, as it reflects incoming and outgoing radiation, tied to cooling and warming, respectively. A short-lived particle such as NO_x causes warming and cooling effects through several mechanisms. These effects are more potent when the particles are high up. This is also true of CO_2, but because this is a long-lived particle that mixes throughout the atmosphere over the course of many years, where it is emitted does not change its warming effect. For short-lived species, not only is altitude an important factor to its net climate forcing, but so are time and place (relating to, e.g., whether it receives radiation from the sun and what atmospheric chemical reactions will occur). Advancing across several decades (see, e.g., Stevenson and Derwent [53], Fuglestvedt et al. [54], and Brasseur et al. [55]), the recent work of Lee et al. [8] compiles an overview of best-estimates for the climate forcing of aviation emissions, creating averages across the effects of time-and-place-dependent emissions, based on actual air traffic for 2018. Aerosol effects and cloud albedo are important factors here as well; aviation-induced cloudiness (i.e., contrails and resulting cirrus clouding) has a large net-warming effect.

Concerning air quality, aviation emissions high up are further away from the organisms impacted. Because of this, Cox, Jemiolo, and Mutel [15] choose to neglect certain damages to ecosystems and human health from emissions above 915 m. Grobler et al. [56] show that, although cruise emissions are less damaging to human health than the same quantity of emissions closer to the surface, the large volume of cruise emissions makes their total damage higher than that of low-altitude aviation emissions. For such studies (see also, e.g., Quadros, Snellen, and Dedoussi [57] and Barrett et al. [58]), it is important that emissions are spatially and temporally explicit, as was the case for short-lived climate forcers discussed above.

The above studies are just a few examples of why aviation emissions require special treatment in impact assessment. This is a major knowledge gap in the field of aviation LCA, as recent reviews point out [30, 59].

2.3. Reflection on energy analyses and available data

Having summarised the literature review, but before moving on to identifying the knowledge gaps, this section reflects on a subset of quantitative environmental assessments. Many studies which evaluate the sustainability of aviation products – particularly, their cradle-to-gate phase – do so from an energy analysis perspective. Studies such as those of Suzuki and Takahashi [60] and Song, Youn, and Gutowski [61] and reports by the Office of Energy Efficiency & Renewable Energy [62] primarily describe sustainability as a function of energy embodied in a product. Cumulative energy demand (CED) is one such metric. Over the past years, this has been used to compare various materials and manufacturing processes across studies (see, e.g., Lunetto et al. [28], Tapper et al. [40], and Bachmann, Hidalgo, and Bricout [41]). Subsequent studies use such figures to conduct impact assessment directly, skipping the creation of inventories typical to LCA. The following paragraphs explore this practise further.

In their review, Tapper et al. [40] point out the large discrepancy found in literature, rationalising that this is caused by the variation in primary energy sources from case to case. This is reasonable, as the conversion efficiency from primary energy to useful energy is much more efficient for renewables than for fossil fuels. However, Tapper et al. also state that "process CED is equivalent to onsite energy" [40, p. 4] – this indicates either a misunderstanding of CED, or an unusual use of "equivalent": any energy consumed on-site, either from electricity or fuel, is delivered through some series of inefficiencies, a priori requiring CED to be higher than the on-site energy demand. This same criticism can be levied at Stefanidi [1], where the energy demand values of ANSYS, Inc. [63] are considered to hold the same meaning as measurements for on-site electricity consumption.

Evaluating the use phase from an embodied energy perspective can also cause misalignment with the desired lifecycle perspective: of the studies reviewed by Keiser et al. [30], they report that 40% only considered the fuel burn itself in their representation of the use phase, neglecting the production of the fuel. Referring to the "embodied energy" in 1 kg kerosene, one might refer to the "primary energy" required *to obtain it*, while the "primary energy" *contained in* this kerosene is an entirely different figure. By only considering the second, the evaluation is incomplete.

The above are just a few examples of embodied energy being applied incorrectly. However, more broadly, the tendency to discuss processes and materials in terms of embodied energy decreases transparency. In their literature review, Lunetto et al. [28] point out that inconsistent reporting of these values reduces comparability between studies, as the physical meaning behind the values is muddied.

However, leaning on embodied energy values in assessments can be seen as a symptom, rather than the core issue. In the recent reviews of Rupcic et al. [23] and Keiser et al. [30], attention is drawn to the lack of transparency, quality, and comparability of inventory data of aviation LCA studies. The authors of these reviews recommend formalising both the creation of inventories and how to report these. To address these issues, this thesis clearly reports each unit process in Appendix C, with extensive supplementary information on how these processes were created in Appendix B.

2.4. Knowledge gaps

In the literature review report, several knowledge gaps are identified [29]. Some of these also become clear from the overviews provided above. However, not all of these knowledge gaps can be addressed within the scope of this thesis. The following sections describe the two main knowledge gaps which this thesis aims to contribute to.

2.4.1. Aviation energy transition

Lightweighting is a central theme for aerostructures, but is not straightforward to quantify in an environmental assessment. Particularly, there does not appear to be any research which investigates lightweighting in the context of the energy transition, e.g., alternative energy carriers for aviation. In this thesis, this knowledge gap will be addressed by considering various energy carrier scenarios. Both the ongoing energy transition is accounted for (increasing the share of clean electricity in energy systems), as well as the climate effects of high-altitude aviation emissions.

2.4.2. Waste generation and treatment

The generation and treatment of waste tied to manufacturing and end-of-life stages can be highly influential in understanding the environmental impacts of these lifecycle stages. The generation of manufacturing waste is often overlooked, and there is no universal way with which to evaluate waste treatment activities. This thesis addresses this by quantifying the main waste streams – making use of primary data – and by conducting in-depth analysis on how the accounting of waste treatment affects LCA results. The case study component of this thesis does not make use of recycled composite material, so this analysis will give no quantitative answer to potential trade-offs between lightweighting and using recycled material. However, the analysis will allow for a reflection on the application of recycled composite material and trade-offs regarding lightweighting more generally.

3

Research questions

Following from the problem statement provided in Chapter 1 and the literature study performed in Chapter 2, the research question is phrased as:

Considering the case study of a CF/PEKK wing rib, how can CFRTP improve the environmental performance of commercial aircraft?

Here, environmental performance is considered based on the environmental impacts associated with aerostructures, although it must be noted that this is not the only way of evaluating sustainability. The function of an aircraft is to transport payload. For aerostructures, this is simplified to providing structural support to an aircraft across its lifetime, rather than across specific operations. To answer the research question, several key sub research questions (SRQs) emerge. These are listed in Table 3.1. SRQ1 and SRQ5 are baseline questions of the LCA, while SRQ2, SQR3, and SRQ4 are phrased based on the problem statement of Section 1.1 and knowledge gaps of Section 2.4. Thereby, answering the sub-questions contributes to bridging these knowledge gaps and allows the main research question to be answered. Figure 3.1 illustrates the five aspects considered in the sub-questions and shows which factors contributing to these aspects are considered in this thesis.

Table 3.1: Sub research questions of the thesis and their identifiers.

Considering the environmental impacts of CFRTP aircraft components …	
SRQ1	…how do these compare to those of competing materials?
SRQ2	…how are these affected by recyclability?
SRQ3	…how are these affected by aircraft use?
SRQ4	…how are these affected by the energy transition?
SRQ5	…how can these be reduced?

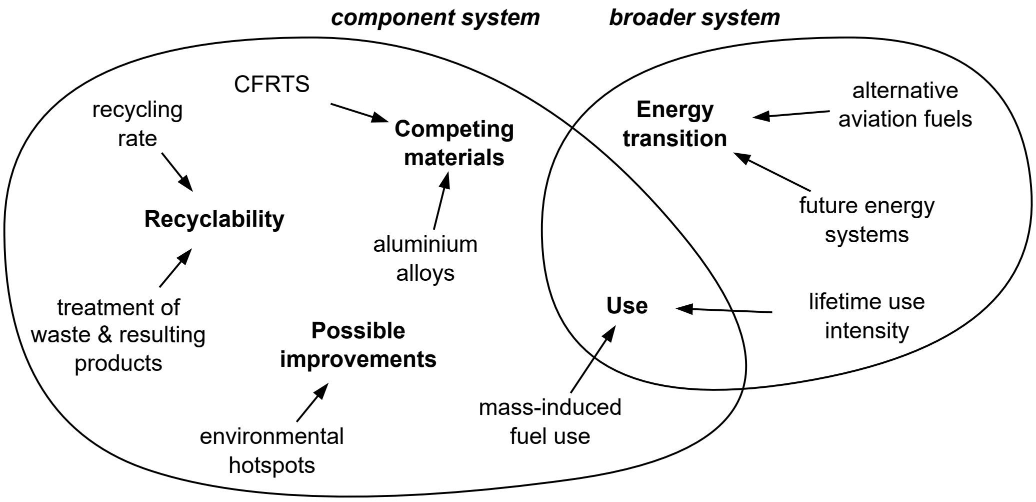

Figure 3.1: Schematic representation of the five aspects represented in the sub research questions of Table 3.1. For each aspect, contributing factors which are addressed in this research are shown. Aspects and factors can be grouped into the component system, which specifically considers the wing ribs themselves, and the broader system. The factors which fall outside of the component system do affect the environmental performance of the components, but are considered to not directly affect their design, manufacturing, or disposal.

4 Research approach

The research questions put forward in Chapter 3 are approached using the lifecycle assessment framework. This framework has already been discussed so far, but its formal structure is introduced in Section 4.1. LCA lends itself well to the questions at hand in several ways. For example, the maturity of the framework has resulted in robust databases and models to support assessments. Combined with the computational structure of LCA, this allows for a cradle-to-grave perspective, the assessment of a broad range of impact categories, and the identification of hotspots in the product system. Additionally, this research takes a prospective approach, looking forward in time. This comes with its own considerations, introduced in Section 4.2. Finally, these two aspects of the approach are framed according to their relationship to the five sub research questions of this thesis.

4.1. Lifecycle assessment framework

The principles, framework, and requirements of LCA have been defined by the International Organization for Standardization (ISO) since 1997 [64], with the most recent standards being laid out in ISO 14040:2006 [65] and ISO 14044:2006 [66]. An LCA study consists of four interconnected, iterative phases [66]:

1. goal and scope definition;
2. lifecycle inventory analysis (LCI);
3. lifecycle impact assessment (LCIA);
4. and interpretation.

An overview of the connections between these phases is illustrated in Figure 4.1. Each phase of the LCA conducted in this thesis is reported in Part II. In addition to this chapter, the goal and scope definition of Chapter 5 is of particular interest to understanding the research approach. Note that the LCA phases are iterative, with interpretation activities leading to iterations on the previous phases. For the purpose of clear communication, only the final version of the goal and scope definition, LCI phase, and LCIA phase are reported in their respective chapters. However Section 8.6 briefly discusses some of these iterations as part of the reporting on the interpretation phase.

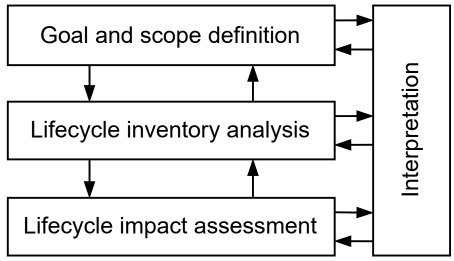

Figure 4.1: The LCA framework, consisting of four phases. Based on ISO 14040 [65].

4.2. Prospective lifecycle assessment and scenario analysis

Over the years, much work has been done to expand the capabilities of the LCA framework described in Section 4.1, resulting in a variety of approaches using different tools and theories [67]. A subset of these approaches takes a forward-looking lifecycle perspective [68]. In prospective LCA, the LCA evaluation includes some element of forecasting the system(s) at hand. An innovation in this field is to transform the background database (e.g., ecoinvent) based on a pathway described by an integrated assessment model (IAM). IAMs are economic models which integrate environmental effects in their feedback, and which can be used to reflect on possible socio-technical developments. Here, one of the concepts IAMs make use of are Shared Socio-economic Pathways (SSPs) [69]. These narratives were developed to explore possible futures, particularly in relation to climate change mitigation and adaptation. Mendoza Beltran et al. [70] are an early example of such an assessment, but the use of background scenarios has recently become available to LCA practitioners thanks to the development of *premise* (PRospective EnvironMental Impact AsSEssment) by Sacchi et al. [24]. In this thesis, *premise* (v1.4.2) is used to create future background systems following the “middle of the road” narrative (SSP2), based on the nationally determined contributions (NDCs) pathway of the IAM developed by Luderer et al. [71], REMIND (REgional Model of Investment and Development). Section A.1 elaborates on how the background scenarios of this thesis are defined.

The development of future background databases contributes to understanding impacts occurring in the future, but Van der Giesen et al. [68] also point out the importance of considering uncertainty in the foreground, meaning, the unit processes created within the LCA study. This is done here by developing and investigating a range of scenarios, each of which focuses on a particular aspect of the research questions at hand. The structure and terminology of the SIMPL approach (Scenario-based Inventory Modelling for Prospective LCA), developed by Langkau et al. [72], can serve as inspiration here. Langkau et al. distinguish between “key factors”, “main inventory parameters”, and “subordinate inventory parameters”. Across scenarios, certain key factors vary, which describe a change that affects the product system. Main inventory parameters identify how the inventory changes based on these changes, which is realised through subordinate inventory parameters. This thesis lacks the political, economic, legal, etc. analysis which key factors derive from, so the main distinction made is between main parameters and subordinate parameters. To apply changing inventory parameters, the superstructure approach of Steubing and de Koning [73] is used. This allows the LCA practitioner to create several alternative inventories from a single scenario difference file (SDF).

Although there are authors in the LCA community who recommend creating holistic scenarios which consider the full lifecycle in its societal context (e.g., Van der Giesen et al. [68], Langkau et al. [72], and Delpierre et al. [74]), this will not be done here. Instead, Section 4.3 describes a number of discrete scenarios, each of which considers different parameters. The reason for this approach is that the causal dependency between factors is generally limited, e.g., how much manufacturing scrap is recycled is considered to be independent from how intensively the components are used, although both factors are relevant.

4.3. Approach to each sub research question

Each of the five sub questions introduced in Chapter 3 will be answered through (prospective) lifecycle assessment, with some relying on a particular set of scenarios.

SRQ1: Competing materials

SRQ1 will be answered by comparing the impacts of the CF/PEKK wing rib to a rib machined from aluminium 7075, a CF/epoxy rib made from prepreg cured in an autoclave, and a CF/epoxy rib made through RTM. These alternatives were introduced in Section 1.2.

Since the results of an LCA are the product of a series of assumptions and choices, the LCA framework lends itself well to comparative assessments, where the consistency of the evaluation of each alternative can be taken into account. Here, this is expressed by how the alternatives are considered during the LCI phase and is reflected on further during the completeness and consistency checks. This way, a clear picture is created of what conclusions can (or cannot) be drawn about the relative environmental performance of the alternatives.

SRQ2: Recyclability

The possibility to (mechanically) recycle CFRTP into a composite material was discussed in Chapter 1 as a compelling property of the material. To explore how this feature affects the overall performance of CFRTP compared to the chosen alternatives, two aspects are investigated, as illustrated in Figure 3.1: (1) what the treatment options are for created waste, and what products are obtained from waste treatment; and (2) at what rate the different waste treatment options are utilised. Each of these can be translated into concrete inventory parameters. How this is operationalised will be described in depth as part of the LCI phase, in Section 6.4.1.

Another factor not to be looked over here is the quantity of waste created. The buy-to-fly ratio of the components can be highly influential to their cradle-to-gate impacts, but this is not considered here as directly tied to one of the SRQs. Instead, it is explored as sensitivity analysis (see Chapter 9).

SRQ3: Aircraft use

It becomes clear from Section 2.1 how important lightweighting is to the environmental performance of an aircraft. Others have asked where the break-even point is during the use phase, in which a lighter component with higher cradle-to-gate emissions outperforms a heavier component after a certain number of flights or days in service (e.g., Scelsi et al. [31] and Vidal et al. [34]). Such an analysis is not possible without knowing the component masses, and, as discussed in Section 1.2, only the design of the CFRTP rib is known. Therefore, another approach is taken here, where the break-even point is not determined by progressively increasing use, but by progressively decreasing/increasing the component mass relative to the CFRTP rib.

At the same time, how the components are used is, of course, still an important factor. While aircraft components are designed and certified for extensive use, often up to 30 years, it is increasingly common to decommission aircraft prematurely as newer, more efficient models enter the market and no buyer is found for the older model [17]. Because of this, the duration of the component lifetime will be considered as a parameter for scenario analysis. In the approach used here, this is comparable to varying the use intensity of the aircraft over a fixed period of time – i.e., 15 years of use would be equivalent to 30 years of use at half the conventional capacity (see Section 6.3.5).

The scenarios resulting from these two parameters will be described in depth as part of the LCI phase, in Section 6.4.2. Another factor, which would highly influence the emissions associated with the use phase of the components, is the use of alternative aviation fuels. This is also considered in the analysis, but as part of the scenarios associated with SRQ 4.

SRQ4: Energy transition

As discussed in Section 1.1, alternative aviation fuels are slowly joining the fossil kerosene used today. Here, three scenarios will be considered: (1) an aircraft continuously powered by fossil kerosene; (2) an aircraft continuously powered by a liquid hydrogen fuel cell; (3) an aircraft powered by a mix of fossil and alternative drop-in fuels, following a scenario based on the volume shares reported in the provisional agreement on the ReFuelEU Aviation proposal between the European Parliament and the Council [75]. For fuels of which the impact is heavily influenced by the electricity source used, *premise* is used to model the fuel production in the appropriate year.

As with the other scenarios, this approach will be described in further detail during the LCI phase, in Section 6.4.3. Modelling the future in this way also means that the end-of-life phase is positioned in a considerably different background system than the manufacturing phase is.

SRQ5: Reducing impacts

The contribution analysis is a standard part of the LCA framework. It is often found in the interpretation phase [76], but will be presented here as part of the impact assessment (see Chapter 7). Contribution analysis allows for environmental hotspots in the lifecycle to be identified – activities which form a large contribution to the lifecycle impacts. This on its own can be a valuable tool in identifying opportunities to reduce environmental impacts. Here, this approach is strengthened by the scenarios analysed for SRQs 2 through 4, which each provide further insight into how environmental impacts change under a variety of conditions.

II

Lifecycle assessment

5

Goal and scope definition

In the goal and scope definition phase, the aim of the study is formulated, which informs the breadth and depth with which the study will be performed, i.e., the scope. The scope of an LCA study can be expressed along several aspects [76]. Certain aspects of the scope, which are discussed in general terms here, are reported in more detail in Appendix A.

5.1. Goal

The aim of this study is to produce the insight necessary to answering the research questions laid out in Chapter 3. These questions take the perspective of actors in the commercial aviation sector who aim to reduce the environmental impacts associated with aerostructures, such as through decisions made in their design, manufacturing, and decommissioning.

Furthermore, this study is conducted as part of a thesis project for the degree of Aerospace Engineering at TU Delft. This study has no commissioner and is conducted for academic reasons. However, subject matter experts were involved, such as those at GKN Aerospace, who were consulted in the making of several assumptions and who provided qualitative and quantitative data. The thesis supervisors, Dr.ir. Irene Fernandez Villegas and Dr. Bernhard Steubing, also contributed throughout this study.

As will become clear in the following sections and chapters, much of the product system models are based on data not directly tied to the components in question. The contents and results of this study can provide academic insight into these product systems, but it would be inappropriate to make environmental claims based on this work. Due to this context and the aim of the study, it cannot constitute a public comparative assertion.

5.2. Scope

The analysis is cradle-to-grave, covering all lifecycle phases of the aircraft components. Note that this excludes activities such as airport construction and maintenance, which are considered as separate from the structural characteristics of aircraft. Furthermore, certain processes are cut off from the analysis due to a lack of data. This includes several notable processes (see Section 6.1.3), but is generally expected to have a minor influence on the results (see Chapter 8).

Further aspects of the scope to consider include the technologies, times, and places covered. However, these are not a single set, but depend on the scenario considered. Section 4.3 gave an introduction to these scenarios, which is elaborated on in Section 6.4. Further details on scope aspects and LCI aspects of these scenarios are reported in Appendix A and Appendix D, respectively. In short, manufacturing in Europe in 2020 is considered, with most input materials being produced in this region, but supply chains also bringing in materials from other regions. The use phase, which in reality would take the components in question across the world, is also modelled based on data for Europe, as is the end-of-life phase. Furthermore, end-of-life is placed 30 years after manufacturing, to reflect the long lifespan of the components.

Based on the definitions of Guinée et al. [76], this study is a detailed LCA. The product systems and their constituent flows are explored, analysed, and reported in depth. However, the primary data available to this study is limited, and extensive use was made of data from literature – such as the studies discussed in Section 2.1 – and the ecoinvent database [21]. Version 3.8 of the ecoinvent database serves as the background system, using the "allocation, cut-off by classification" system model. Depending on the temporal scope, this background system was transformed using the *premise* library (v.1.4.2) [24]. There are various philosophies to the mode of analysis of an LCA, with a major distinction being whether the analysis is attributional (ALCA) or consequential (CLCA) [67]. One area where these modes differ is their approach to multifunctionality. The approach taken here is discussed in Section 6.1.2, and has some alignment with CLCA, due to the use of substitution flows. However, the consideration of effects on secondary product systems is limited. Other aspects of the study, such as the use of the cut-off system model, align with ALCA. Within the goal and scope of this study, this combined approach has its advantages, but it is a source of inconsistency. This is discussed in Chapter 8.

The environmental impact categories covered are those of the Environmental Footprint family of midpoint characterisation models (EF v3.0), as recommended by the European Commission [20]. However, two exceptions are made. The "water use" impact category is excluded, as it is not considered to provide added value to this study. Secondly, the EF v3.0 characterisation model for climate change is not used, but another model is created for this. These choices are discussed further in Section 7.1.

5.3. Reference flows

The alternatives described in Section 1.2 all fulfil the same function: providing structural support to a single-aisle passenger aircraft. In order to compare the environmental performance of the alternatives, this function is parameterised to obtain a functional unit: providing structural support to a single-aisle passenger aircraft over 30 years. The flow of each product system which fulfils this functional unit, is known as the reference flow. The LCI and LCIA phases are defined in relation to these reference flows.

As discussed in Section 2.1, the lifecycle impacts of aerostructures are dominated by the use phase. By only considering reference flows which connect to the full lifecycle, other lifecycle phases would largely disappear in the assessment. To be able to also evaluate the cradle-to-gate and end-of-life phases, this study therefore frequently refers to the lifecycle excluding use. This can be thought of as an additional functional unit – the manufacturing of one wing rib – with corresponding reference flows which connect to the cradle-to-gate and end-of-life phases, but not the use phase.

The reference flows discussed here can be identified in the product system flowcharts of Section A.3. The function of the use phase which leaves the system boundary represents the full lifecycle and quantifies the functional unit. To quantify the lifecycle excluding use, the function of the production process which connects to the use process is used as reference flow. Note that, to enable this approach, the end-of-life ribs were connected to the production process, rather than the use process.

6

Inventory analysis

In the inventory analysis, the product systems are defined. This is done through qualitative and quantitative steps. Product systems and system boundaries are defined, which are also visualised in flowcharts. The unit processes of these product systems are then quantified. Having done so, inventory tables can be created for each reference flow, by following connected incoming goods and outgoing wastes to the system boundary. These inventory tables can then serve as input to the LCIA of Chapter 7.

6.1. System boundaries

In any LCA study, there are three system boundaries to be aware of [76]. One boundary separates the product systems – and economic activities more generally – from the natural environment these are embedded in. Flows passing through this boundary are known as environmental flows, elementary flows, or extensions. This system boundary is discussed in Section 6.1.1.

Another system boundary separates the product systems being studied from the wider economy. This system boundary is illustrated in the flowcharts of Section A.3 and is furthermore the subject of multifunctionality, which is discussed in Section 6.1.2.

The system boundaries shown in Section A.3 also represent the third boundary discussed here, which separates the flows quantified during the LCI phase from those not quantified. This is conceptually distinct from the boundary with other product systems, as it determines whether flows within the product system at hand are included in its representation or not. The flows which are not quantified are known as cut-offs and discussed in Section 6.1.3.

6.1.1. Economy-environment system boundary

The product system is constructed by following the reference flow to all economic activities enabling it. This economic system is embedded in an environmental system: every economic material or energy flow at some point came from the environment, and each flow at some point will return to the environment. This reality is a given, but where to draw the line between economy and environment, is not. There has been academic discussion on ambiguous cases, which can be found in mining, forestry, agriculture, and landfilling, to name a few examples [76]. In the product systems examined here, the ecoinvent conventions are followed for this system boundary [77]. The environmental flows encountered in foreground activities are typically direct emissions to air, with no noteworthy cases. However, there are a few cases where environmental flows are cut off from the analysis. This is discussed in Section 6.1.3.

6.1.2. Multifunctionality

As introduced in Section 6.1, evaluating the product systems at hand involves isolating them from the wider economy. This is done here following the steps of Guinée et al. [76].

Goods and wastes

First, a distinction is made between goods and wastes. A general definition is that goods have a positive (> 0) economic value, while wastes have a negative (≤ 0) economic value [76]. However, there are generally exceptions to this definition. Metal scrap, particularly when easily separated, can be remelted into a new product at a fraction of the costs to produce primary material [78]. It is therefore bought and sold as a good, rather than a waste. However, in LCA terms, it is generally considered as a waste. For example, in the lifecycle costing of Mami et al. [32], scrap leaves the system boundary when it is sold to a remelter. However, for the environmental impacts, remelting is included in the system boundary [32]. Similarly, Stefanidi [1] treats CFRTP scrap as waste, while also stating that this scrap can have a comparable economic value to primary CFRTP material. How goods and wastes are defined is intimately tied to the overall approach to multifunctionality, so should be considered together. Here, scrap is considered as a waste, even if it might have a positive economic value. The flowcharts of Section A.3 illustrate this distinction between goods and wastes. This is also indicated per unit process, in Appendix C.

Functional flows and multifunctional processes

Having defined whether each economic flow is a good or waste, the functional flows of each unit process become clear. There are two types of functions: production and waste treatment, respectively identified by the outflow of a good and the inflow of a waste. Reviewing each of the unit processes visualised in Section A.3 and reported in Appendix C, several have multiple functional flows, making these processes multifunctional. Table 6.1 provides an overview of these processes and how their multifunctionality is resolved.

Resolving multifunctionality

Resolving multifunctionality is not only important in defining system boundaries, but also for the computational soundness of LCA: the matrix structure requires each functional flow to align with precisely one unit process. When a unit process has any functional flow which does not contribute to the product system, some decision must be made on how to account for this difference. Two predominant methods are allocation, through which the unit process is virtually split into parts, and substitution, where unit processes from elsewhere in the economy are brought in to balance out flows not contributing to the reference flow. A third approach is system expansion, in which the functions being compared are expanded to include the co-functions.

Guinée et al. [76] recommend economic allocation, where the unit process is partitioned according to the economic value of functions provided. However, for recycling processes, this requires a strict application of the definition for goods and wastes given above, which breaks from the typical consideration of metal scrap, as reviewed in Section B.2.5. Additionally, limited information could be gathered on the economic value of the components and their materials. Therefore, the approach used to resolve recycling processes is based on the European Commission [20] Product Environmental Footprint (PEF) method, which introduces the Circular Footprint Formula (CFF). This formula has three components: material, energy, and disposal. The “disposal” component has no relation to multifunctionality. The “energy” component is effectively substitution of recovered heat and electricity, fully allocating this substitution to the primary system. The “material” component is more complicated. Here, the footprint (i.e., environmental impacts) of the primary system is determined through a modified substitution approach, meaning that substitution flows are scaled by some combination of factors. Equation 6.1 replicates the material component of the CFF.

$$E_{\text{material}} = (1-R_1)\cdot E_p + R_1 \cdot \left(A \cdot E_{\text{recycling}} + (1-A)\cdot E_p \cdot \frac{Q_{s_{\text{in}}}}{Q_p} \right) + (1-A)\cdot R_2 \cdot \left(E^*_{\text{recycling}} - E^*_p \cdot \frac{Q_{s_{\text{out}}}}{Q^*_p} \right) \tag{6.1}$$

In Equation 6.1, E is the inventory associated with the subscript, where “p” refers to the primary material and “recycling” refers to the impacts of the recycling process itself. Without asterisk, these refer to the materials entering the product system, while the asterisk denotes that the materials leave the product system (i.e., recyclates from end-of-life material). These inventories are scaled and attributed in a variety of ways. Of course, there are the recycling fractions R_1 (the share of secondary material in the input) and R_2 (the share of end-of-life material that is recycled). Seeing Equation 6.1 as the addition of three addends, where the second is a function of R_1 and the third is a function of R_2, it can be observed that these two addends complement each other. This can be illustrated by considering a quantity of recyclable material going from one system to another. When this material is recycled, the recycling inventory is allocated to the system of origin by a share of $1 - A$, while a share of A is allocated to the destination system, thereby together adding up to the full original inventory. Similarly, the system of origin receives a substitution flow of $(1 - A) \cdot E^*_p$, which is precisely balanced by the destination system receiving a debit of $(1 - A) \cdot E_p$ (in this illustration, $E^*_p = E_p$, as a single recycling process is considered). This A factor has a value of 0.5 by default, meaning that credits and burdens would be shared equally across the systems of origin and destination. However, when there is a high demand for recyclable material (as is the case for many metals and alloys), it is 0.2, while for cases where there is a strong surplus of recyclable materials (as is the case for certain textiles and organic materials), it is 0.8. Substitution flows are furthermore scaled by a corrective quality (Q) fraction. These fractions relate the quality ratio between the recycled material and the primary material it would substitute. Quality can be determined based on economic or physical aspects [20].

Table 6.1 provides an overview of all multifunctional processes in the studied product systems. The A factors used align with those recommended [20], while quality ratios, when applicable, are based on literature [79, 80]. Note that the PEF method additionally allows for closed-loop recycling [20]. This means that recyclates coming from the manufacturing process, which are suitable to reenter this process, are kept in a closed loop, without allocating any flows to a secondary system. Here, this is treated as substitution. Something not covered by the CFF is co-production, instead referring to the ISO guidelines [20]. In this study, most co-products are dealt with through substitution, which is thought to be logically consistent with the substitution-based approach of the CFF. These decisions are evaluated in the sensitivity analyses of Chapter 9.

Lastly, note that much of the multifunctionality discussed here is covered within the ecoinvent system model used – in this case, “allocation, cut-off by classification”. This system model is not consistent with the CFF. For example, it provides certain manufacturing scrap free of burden and does not allocate recovered energy to waste. This is discussed as part of the consistency check (see Chapter 8).

Table 6.1: Overview of multifunctional processes, their functional flows, and how multifunctionality is resolved. Functional flows are inputs of waste (W) and outputs of goods (G). These flows are numbered to facilitate their identification in the "multifunctionality approach" column. The A factor and quality ratios are characteristics of the "material" aspect of the CFF approach to multifunctionality. Note that the quality ratio is relative to the substitution flow, not the original manufacturing material.

Process identifier	Functional flows	Multifunctionality approach	A factor; quality ratio
C.8	*(1)* [W] aluminium 7075 manufacturing scrap *(2)* [G] aluminium, cast alloy	CFF: material	0.2; 1
C.9	*(1)* [W] aluminium 7075 manufacturing scrap *(2)* [G] aluminium alloy, 7075	substitution of *(2)* (i.e., closed loop)	-
C.11	*(1)* [W] aluminium 7075 end-of-life scrap *(2)* [G] aluminium, cast alloy	CFF: material	0.2; 1
C.12	*(1)* [W] aluminium 7075 end-of-life scrap *(2)* [G] aluminium alloy, 7075, future	CFF: material	0.2; 1
C.14	*(1)* [G] utilities estimate, chemical production *(2)* [G] heat, from steam, in chemical industry	substitution of *(2)*	-
C.15	*(1)* [W] hazardous waste, organic chemistry *(2)* [G] electricity, medium voltage *(3)* [G] heat, district or industrial, natural gas	CFF: energy	-
C.16	*(1)* [G] hexachloroxylene *(2)* [G] hydrochloric acid	substitution of *(2)*	-
C.17	*(1)* [G] iso- and terephthaloyl chloride *(2)* [G] hydrochloric acid	substitution of *(2)*	-
C.18	*(1)* [G] diphenyl ether *(2)* [G] phenol *(3)* [G] hydrochloric acid	mass allocation of *(2)*, followed by substitution of *(3)*	-
C.19	*(1)* [G] polyetherketoneketone *(2)* [G] hydrochloric acid	substitution of *(2)*	-
C.30	*(1)* [W] waste carbon fibre/PEKK *(2)* [G] carbon fibre/PEKK prepreg	CFF: material	0.5; 0.25
C.31	*(1)* [W] waste, composite manufacturing *(2)* [G] electricity, medium voltage *(3)* [G] heat, district or industrial, natural gas	CFF: energy	-
C.33	*(1)* [W] waste carbon fibre/PEKK, end-of-life *(2)* [G] carbon fibre/PEKK prepreg, future	CFF: material	0.5; 0.25
C.34	*(1)* [W] waste, composite end-of-life *(2)* [G] electricity, medium voltage *(3)* [G] heat, district or industrial, natural gas	CFF: energy	-
C.59	*(1)* [W] waste carbon fibre/epoxy *(2)* [G] carbon fibre	CFF: material	0.5; 0.25
C.61	*(1)* [W] waste carbon fibre/epoxy, future *(2)* [G] carbon fibre, future	CFF: material	0.5; 0.25
C.69	*(1)* [W] waste carbon fibre *(2)* [G] carbon fibre	CFF: material	0.5; 0.25

6.1.3. Cut-offs

Cut-offs are flows belonging to the real-life product system which are not represented in the LCI. There is an uncountable number of such flows: from the exhausts of the cars bringing workers to the manufacturing site, to the electricity used to run the computers with which the ribs were designed. These examples are intuitively inconsequential to the outcome of the study, but other flows cut off warrant some further discussion. In the following paragraphs, several such flows are listed, with the motivation behind cutting them off. The effect of these cut-offs on the analysis is considered in the completeness and consistency checks of Chapter 8.

Industrial facilities

With the exception of activities which are adapted from ecoinvent or certain processes for which default values for infrastructure are available, industrial facilities are not included in inventories. This includes products such as buildings, machinery, and moulds. Although these could form notable contributions to the cradle-to-gate phase for certain impact categories (see, e.g., Forcellese et al. [37] and Rupcic et al. [59]), they are excluded here due to a lack of data.

Transport

Since the location of the manufacturing site is generalised (see Section 5.2), transport to this site and subsequently to assembly sites is challenging to represent. However, it is known that transport forms a minor contribution, as demonstrated by, e.g., Priarone et al. [81]. Estimates are made for the transport of primary materials, but transport for assembly and end-of-life treatment are cut off. This way, transport can show up in the contribution analysis, indicating when further transport activities should be investigated.

On-site cooled storage

The uncured epoxies used in aviation require cooled storage to prevent curing reactions from taking place before the material is formed. Stefanidi [1] reports that this is $-18\,°C$. This is reflected in the LCI through the transportation processes (see Section 6.3.4), but due to a lack of data, no unit process for on-site storage was created. Suzuki and Takahashi [60] make the consideration that, for industrial production, storage would form a minor contribution, as material would only be stored for a short period.

Forming of composite parts

To create a CFRP product, its material must at some point be formed into the desired shape. When dealing with continuous fibres, this is done layer by layer and is known as lay-up. Lay-up is often done manually, particularly for complex parts such as the rib in question. However, the CFRP ribs are also relatively thick, making manual lay-up highly time-intensive. The lay-up technique would therefore likely involve automated tape laying (ATL) or automated fibre placement (AFP) [T. de Bruijn, personal communication, May 11, 2023]. Although there are examples of manual lay-up in literature (see, e.g., van Grootel et al. [33], Forcellese et al. [37], Witik et al. [38], Vita et al. [82], and Calado, Leite, and Silva [83]), only two example of automated lay-up were identified: Timmis et al. [14], where the process is called ATL, but, considering the geometry of the part, is likely a process such as filament winding; and Hohmann et al. [39], where electricity consumption measurements are made for dry fibre placement, but no inventory data is shared. Although the inventory of Hohmann et al. [39] could not be retrieved, they indicate that the preforming step would typically only form a small contribution (roughly 5%) to their cradle-to-gate analysis. Another factor, which does not appear to be considered by any of the studies mentioned here, is that CF/epoxy lay-up requires clean-room-like conditions to prevent contamination from outside particles. This could form a considerable contribution to the on-site energy demand [T. de Bruijn, personal communication, May 11, 2023] and has been reported as an advantage of CFRTP over CFRTS [7]. However relevant these processes might be, they are cut off here due to a lack of data.

Surface treatment and testing
Although Stefanidi [1] represented various stages of testing and coating the ribs, these are largely cut off here due to a lack of reliable data. The only two activities which were modelled are the degreasing and anodising of the aluminium part.

Assembly, disassembly, and component servicing
There is very little inventory data available on these activities, as was discussed in Section 2.1.1. These activities therefore had to be cut off, due to lack of data. Vidal et al. [34] estimate that this is only relevant to the extent that material is replaced during maintenance. However, experts do consider the ease of assembly and reduced servicing requirements of CFRTP as a major advantage, which would translate into some environmental gains (see, e.g., Mason [26]).

Gas formation from polymers
As epoxy is cured at elevated temperatures, the material emits volatile organic compounds (VOCs) [84]. Due to a lack of data, these emissions are cut off. However, the gasses released during the production of carbon fibres are included, as these are reported in the work of, e.g., Pillain et al. [42].

Aviation induced cloudiness
Although this study makes an effort to adapt the evaluation to the high-altitude emissions of aviation, aircraft contrails and subsequent impacts on cloudiness are not included. This phenomenon, known as aviation-induced cloudiness (AIC), is a prominent contributor to aviation's warming effect [8]. Like NO_x emissions, the formation and effects of AIC is highly dependent on local conditions [8, 54]. However, for AIC, this means that the distance flown becomes a primary variable, and not necessarily fuel use [8, 85]. A decrease in emissions does impact contrail formation and lifetime, but this is not a linear relationship. For example, Bock and Burkhardt [85] find that a decrease in soot emissions of 50% would decrease AIC radiative forcing by 14% [85]. Because AIC is only driven by fuel use to a limited extent, and because the connection between mass-induced emissions and radiative forcing of AIC could not be quantified within the scope of this work, AIC is not taken into account.

6.2. Flowcharts

To illustrate how the product systems of each alternative are modelled, intricate flowcharts are created which represent system boundaries, unit processes, and economic flows. These flowcharts, provided in Section A.3, provide an (almost) complete overview of the product systems, but interpreting them might be unintuitive. To provide more accessible insight into the product systems, Figures 6.1, 6.2, 6.3 and 6.4 illustrate the flows of the component material for each alternative under the baseline scenario (see Section 6.4). How these values are obtained is explained in Section 6.3. Note that the processes which dictate how certain scrap is divided over processes (C.7 C.10, C.29, etc.), are hidden here, as these are purely virtual. The choice to illustrate the alternatives in this way is made because – apart from the large contribution of the use phase – a majority of environmental impacts are attributed to these materials (see Section 7.4.2).

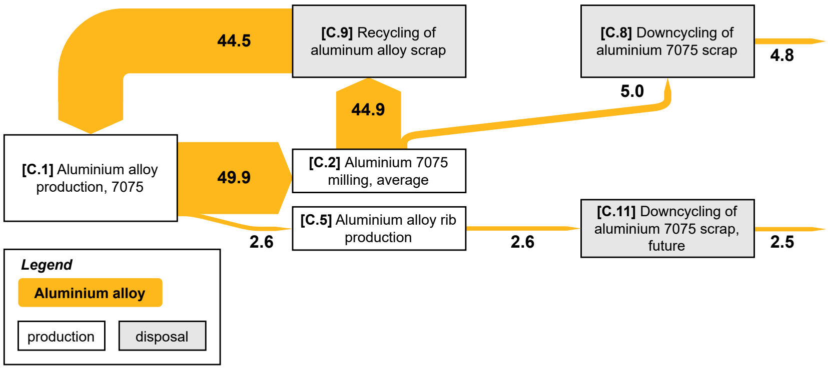

Figure 6.1: Flowchart illustrating the mass flows of aluminium alloy (aluminium 7075, aluminium alloy scrap, and downcycled aluminium alloy). All flows are scaled to the reference flow of one aluminium alloy rib, using kilogram as unit of mass. C.5 provides the rib used on the aircraft. Note the portion of aluminium alloy recycled in a closed loop through C.9. **??** depicts the full product system.

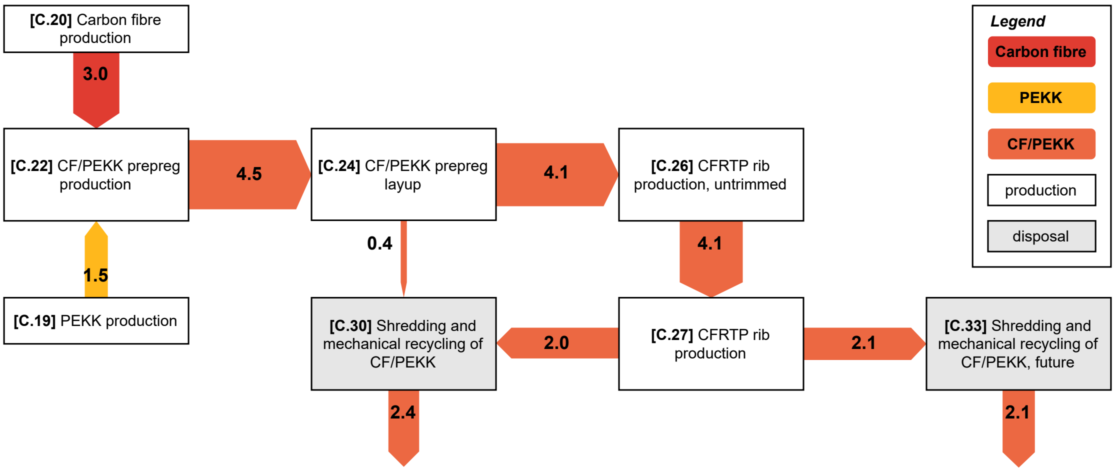

Figure 6.2: Flowchart illustrating the mass flows of carbon fibre, PEKK, and CF/PEKK composite (including CF/PEKK evaluated as waste). All flows are scaled to the reference flow of one CFRTP rib, using kilogram as unit of mass. C.27 provides the rib used on the aircraft. Note that C.30 and C.33 are illustrated without transformation by the CFF. When the CFF is applied, these values change, as explained in Section 6.1.2. Figure A.2 depicts the full product system.

Not all of the processes shown here appear to have a functional mass balance. This has two reasons. Firstly, only flows considered as belonging to the listed materials are depicted. Taking Figure 6.1 as example, this means that the ingredients required for the production of aluminium 7075 are not illustrated for C.1, nor is the slag created from aluminium alloy scrap illustrated in C.8 or C.11. Secondly, flows are illustrated with one decimal place, meaning that rounding occasionally gives the impression that the depicted flows are not balanced, when in the unit processes themselves, they are. C.64 in Figure 6.4 is an example of this.

6.3. Data collected and unit processes

This section provides brief descriptions of how each of the alternatives' product systems was constructed. The unit processes, corresponding to the flowcharts presented in Section A.3, are reported in Appendix C. To find supporting information on a particular activity, it is recommended to go to the corresponding unit process table in Appendix C, where the table caption will redirect to a section of Appendix B. Appendix B provides detailed descriptions, whereas this section only provides a basic overview.

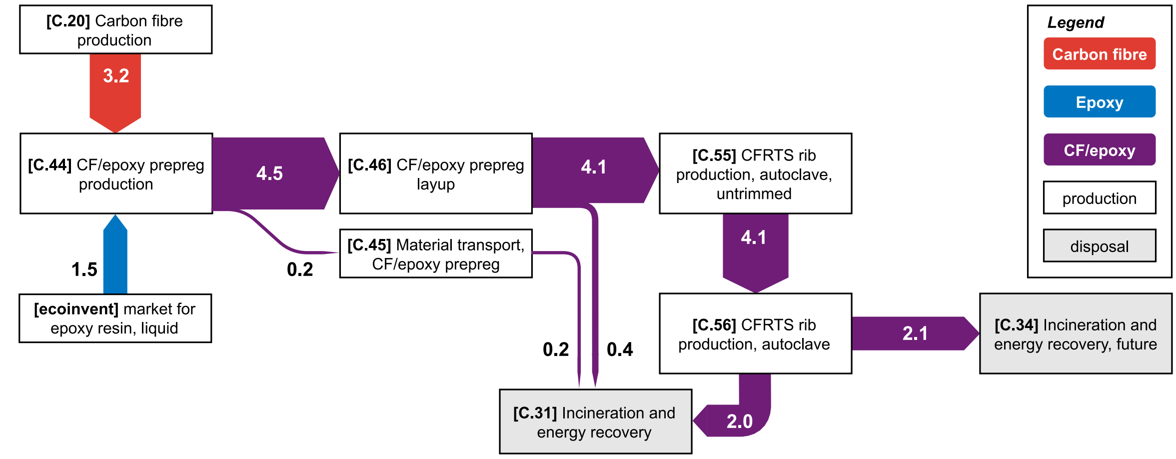

Figure 6.3: Flowchart illustrating the mass flows of carbon fibre, epoxy, and CF/epoxy composite (including CF/epoxy considered as waste). All flows are scaled to the reference flow of one CFRTS autoclave rib, using kilogram as unit of mass. C.56 provides the rib used on the aircraft. Figure A.3 depicts the full product system.

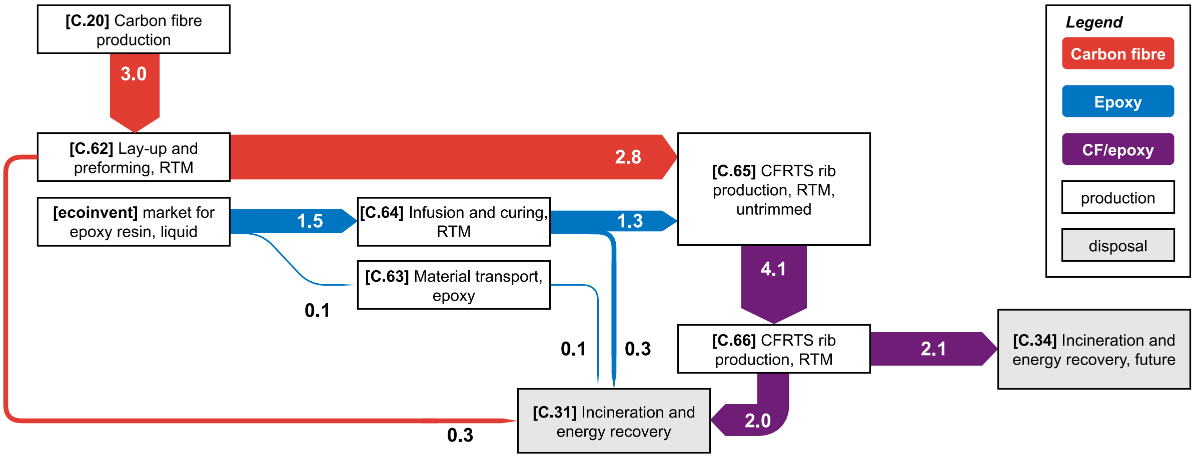

Figure 6.4: Flowchart illustrating the mass flows of carbon fibre, epoxy, and CF/epoxy composite (including carbon fibre, epoxy, and CF/epoxy considered as waste). All flows are scaled to the reference flow of one CFRTS RTM rib, using kilogram as unit of mass. C.66 provides the rib used on the aircraft. Figure A.4 depicts the full product system.

As described in Section 5.2, prospective background data is generated to represent future scenarios. This is indicated in Appendix C. It is not discussed further in this section, but rather in Section 6.4.

6.3.1. Aluminium alloy alternative

For the aluminium alloy alternative, the data gathered by Stefanidi [1] was mostly sufficient to fully construct the LCI based on ecoinvent data [86–91]. However, data on highly specialised alloys is limited, affecting the data quality for production and manufacturing activities [13, 92]. The LCI was complemented by material data [93] and a few literature-based assumptions on the component and its material flows. Specifically, the CFRTS component was assumed to be 20% lighter than an aluminium alloy design [14, 31, 40, 94], and the buy-to-fly ratio was assumed to be 20:1 [1, 13, 14]. Additionally, all scrap generated is assumed to enter recycling [1, 14, 31, 32]. A distinction is made between closed-loop recycling and open-loop “downcycling”, where a loss of quality is modelled. 90% of manufacturing scrap is modelled using this closed-loop, with the remaining 10%, as well as all end-of-life scrap, being modelled as downcycling. The term “downcycling” is used to distinguish the open-loop recycling of aluminium from closed-loop recycling. Note that, when composite recycling is discussed, this is implicitly open-loop, accompanied by a decrease in quality. Section 6.1.2 explains how the multifunctionality of scrap treatment is addressed. As was introduced in Section 2.1.1, how waste is modelled is one of the most influential factors for the excluding-use lifecycle of materials with a high buy-to-fly ratio. Therefore, this is extensively addressed through scenarios (Section 6.4.1) and sensitivity analyses (Chapter 9).

6.3.2. CFRTP alternative

Although Stefanidi [1] provides several key data for the manufacturing-to-gate phase of the CFRTP alternative, little data is available on the production of the required CF/PEKK prepreg. Here, the production of carbon fibre was based on literature [36, 42], while the PEKK inventory was created from stoichiometry-based estimation following established methods [95–97], using industrial chemistry literature [98–102]. The prepregging process was adapted from Suzuki and Takahashi [60]. Most mass flows, from lay-up to consolidation and trimming – as illustrated in Section 6.2 – were taken directly from Stefanidi [1], as well as the energy input for consolidation. As the recyclability of CFRTP is part of what makes the material attractive, it is assumed that all scrap is mechanically recycled. Here, the shredding of the fibres is assumed to result in a quality decrease of 75% [79, 80]. This waste treatment also returns in Section 6.4.1.

6.3.3. CFRTS alternatives

Both CFRTS alternatives are hypothetical components, with no primary data for this case study. However, the autoclave and RTM technologies are known and documented more broadly. The reporting of Witik et al. [38] was used to model the consumables required for autoclave processing, while the work of Ogugua et al. [103] was chosen to model autoclave energy demand. For RTM, the ecoinvent "injection moulding" process was used [36, 104], supplemented by the estimation from Stefanidi [1] that a 20% surplus of resin is used during infusion. Although in the realm of composite structures, there are important interactions between the material, manufacturing technology, and structural design, it is unclear how this would reflect on CFRTS alternatives [T. de Bruijn, personal communication, February 13, 2023]. As a result, the choice was made to model each composite wing rib as having the same mass. Furthermore, the primary data on manufacturing off-cuts – during lay-up and, later, trimming – was extended to the CFRTS alternatives, as illustrated in Section 6.2. It is generally unattractive to find a second life for CFRTS waste, so this is incinerated by default. Through scenarios (see Section 6.4.1), alternative waste treatments are considered, namely pyrolysis [42] and the recycling of dry fibres. Pyrolysis refers to a category of thermal recycling methods: under controlled atmosphere and temperature, the composite decomposes so that fibres are the only solids remaining, with the matrix breaking down into gaseous and liquid co-products which can be combusted for energy recovery [42]. It is a relatively mature process for CFRTS recycling [105, 106].

6.3.4. Transport

For each alternative, some transport activities are included, although – as discussed in Section 6.1.3 – there is generally a lack of data on these. Broadly, a single distance is assumed for each material which must make its way to the manufacturing site. Aluminium alloy, epoxy, and composite prepregs all use the same estimate of 1400 km by road, following an estimate by Stefanidi [1]. Autoclave consumables are assumed to travel 500 km by road, following an estimate by Witik et al. [38]. Furthermore, an important feature of transporting CF/epoxy prepreg is that it must be kept at freezing temperature. Occasionally, this results in shipments being discarded as a result of some malfunction in the cooling or temperature measuring equipment [T. de Bruijn, personal communication, February 13, 2023]. This is estimated as a 5% loss of material. Finally, there is the case of carbon fibre, which is predominantly produced outside of Europe [107]. Its transport is modelled as 15 000 km by freight ship.

6.3.5. Use processes

As discussed in Section 2.1, the use phase of aircraft products has been modelled in a variety of ways. These are compared in Section B.6.3, exploring the energy required to transport 1 kg of additional structural mass for 1 year, resulting in the unit GJ/kg-year. Note that this refers to the energy content of the fuel, based on the lower heating value (LHV) – e.g., 43 MJ/kg for fossil kerosene [33]. The comparison of Section B.6.3 reveals that, although there is a noticeable spread in values, almost all approaches considered fall within a limited range: 3.33 GJ/kg-year to 10 GJ/kg-year. This range will be used during sensitivity analysis (see Chapter 9). In the meantime, 4.47 GJ/kg-year will be used for convenience, based on Huang et al. [13].

To fulfil this energy demand, a range of scenarios is considered (see Section 6.4.3). Fossil kerosene is based on the ecoinvent database [108], while production of drop-in alternative fuels, as well as hydrogen, is taken from *premise* (v1.4.2) [109]. The drop-in fuels considered have a LHV of 45 MJ/kg and are synthesised using the Fischer-Tropsch process, with inputs from either wood gasification or power-to-liquid (hydrogen from water electrolysis with carbon dioxide from direct air capture), using energy allocation. Emissions for fossil kerosene are similarly based on ecoinvent [110] – with adjusted emissions of water vapour [8], which is further adjusted to represent the drop-in fuels. Specifically, emissions of sulphur oxides, particulate matter, and (heavy) metals which appear in the combustion of fossil kerosene are removed, based on expert judgement and literature [12, 111, 112]. When hydrogen is considered (LHV of 120 MJ/kg), the assumptions are made that mass-induced energy demand does not change in terms of energy content [113] and that the hydrogen flow from *premise* is directly applied by the aircraft. Notably, this includes hydrogen transport, but neglects liquefaction in case of the use of liquid hydrogen. Although direct combustion is likely to be a more technologically feasible solution, fuel cell propulsion is considered here, as this is environmentally favoured, resulting only in water emissions [114]. Note that this is a highly simplified assessment of hydrogen propulsion, but that further analysis falls outside of the scope of this thesis.

6.4. Scenario descriptions

To address the research questions, scenarios are developed, as explained in Chapter 4. In the following section, the scenarios described in Section 4.3 are quantified according to the involved changes to inventory parameters. How these inventory parameters express themselves in unit processes is reported in Appendix D. This effectively gives an understanding of what the scenario difference files used look like.

As all scenarios affect the product system inventories, there is a need to define what inventories to use when a particular scenario is not under investigation. This is called the “baseline” or “default” scenario. It is constructed from specific values for the main inventory parameters (and connected subordinate parameters) discussed in the following sections.

Beyond the scenarios discussed here, there are also the sensitivity analyses of Chapter 9. These also alter certain inventory parameters, but are considered separately. The reasoning is that the scenarios are directly connected to the sub research questions of this thesis, while the sensitivity analyses serve the more general purpose of gaining insight into the influence of the modelling choices made.

Table 6.2: Values of inventory parameters in disposal scenarios. Three scenarios are considered: linear, baseline, and circular. The baseline scenario is similar to the linear scenario, with the exception of 90% of aluminium alloy manufacturing scrap and all CFRTP scrap being recycled.

Flow	Disposal parameters	Unit	Linear	Baseline	Circular
aluminium alloy manufacturing waste	recycling / downcycling	%	0 / 100	90 / 10	100 / 0
aluminium alloy end-of-life waste	recycling / downcycling	%	0 / 100	0 / 100	100 / 0
CFRTP manufacturing waste	mechanical recycling / incineration	%	0 / 100	100 / 0	100 / 0
CFRTP end-of-life waste	mechanical recycling / incineration	%	0 / 100	100 / 0	100 / 0
carbon fibre manufacturing waste	mechanical recycling / incineration	%	0 / 100	0 / 100	100 / 0
CFRTS manufacturing waste	pyrolysis / incineration	%	0 / 100	0 / 100	100 / 0
CFRTS end-of-life waste	pyrolysis / incineration	%	0 / 100	0 / 100	100 / 0

6.4.1. Waste disposal and treatment

Connecting alternative waste treatment options and to what degree each option is used are considered together in a single array of scenarios, shown in Table 6.2. For pragmatic reasons, the number of scenarios is limited to three: the baseline, one where the (relatively) linear treatment methods are used, and one where the (relatively) circular treatment methods are used.

Section 6.3.1 already discussed the recycling and downcycling of aluminium alloy. For the purpose of the waste treatment scenarios, the possibility of same-quality end-of-life recycling is considered. However, while a closed-loop approach was considered appropriate for manufacturing waste, the same cannot be said of end-of-life waste, so this is modelled as an open loop.

Incineration and landfilling of composite waste are the most typical disposal options [115, 116]. For CFRTP, mechanical recycling is considered as baseline, with incineration as less a circular alternative. For the CFRTS alternatives, pyrolysis is introduced as recycling option, as described in Section 6.3.3, as well as the collection of dry fibres for application in new fabric [106].

6.4.2. Component mass and use intensity

The baseline use phase for all alternatives is 30 years, which is evaluated as described in Section 6.3.5. To consider scenarios in which the components are used less intensively, two alternatives are considered: 20 years and 10 years, as shown in Table 6.3. 10 years is chosen as this is the lowest estimate found in literature (see the comparison of Section B.6.3). Furthermore, it is not much lower than the reported average time after which airlines seek to replace single-aisle passenger aircraft, which Kito [17] reports as 13.42 years, based on Japanese airlines. However, this of course highly depends on the financial position of the airline.

The component masses in the baseline scenario are discussed in Section 6.3 and illustrated in Section 6.2. As discussed in Section 4.3, the exploration of component mass is done through break-even points. This means keeping the mass of the CFRTP rib at 2.1 kg and exploring how much lighter/heavier the alternative ribs could be while still performing worse/better than the CFRTP component. This is done in small steps, although it should be noted that manufacturing margins are around 4%, which leads to variations orders of magnitudes larger than the step used here [T. de Bruijn, personal communication, June 8, 2023]. As opposed to other inventory parameters discussed so far, which are implemented by changing no more than one unit processes per alternative, there are several unit processes for each alternative which depend on the component mass. These are individually reported in Section D.2.

Table 6.3: Values of inventory parameters in use intensity scenarios. Three scenarios are considered: baseline, shorter, and much shorter. No scenario with longer/more intensive use of the component is considered, as current pressures are already driving operators to maximise utility from aircraft.

Use parameter	Unit	Baseline	Shorter	Much shorter
transport of structural mass	year	30	20	10

Table 6.4: Volume shares from Annex I of the ReFuelEU Aviation agreement [75]. There is some nuance lost in this reproduction and subsequent translation to the SAF scenario, which is discussed in Section D.3. Note that the minimum share of e-fuel is relative to the volume of SAF, not the volume of total aviation fuel.

Start year	Unit	Minimum share of SAF in total fuel	Minimum share of e-fuel in SAF
2025	%	2	0
2030	%	6	1.2
2032	%	6	2.0
2035	%	20	5
2040	%	34	10
2045	%	42	15
2050	%	70	35

6.4.3. Alternative energy carriers

Two alternatives to fossil kerosene are considered. In one, drop-in alternative fuels are gradually introduced, following the volume shares agreed on in the ReFuelEU initiative – from 2% in 2025 to 70% in 2050, with the additional demand for increasing shares of e-fuels [75]. These volume shares are reproduced in Table 6.4. This is named the SAF scenario. Another alternative scenario, named the hydrogen scenario, considers an aircraft fully powered by a hydrogen fuel cell. The inventories related to these energy carriers are described in Section 6.3.5. There is limited (or negative) environmental benefit from hydrogen from electrolysis and drop-in e-fuel produced from a fossil-powered energy system [11, 12]. All alternative fuels are analysed using prospective background databases created using the *premise* library, as detailed in Section A.1.

6.5. Results of inventory analysis

To perform the calculations that quantify the reference flows, this study makes use of the Activity Browser (v2.8.0) [22]. Using this software, the unit processes as reported in Appendix C are connected to the background data and the reference flows are evaluated. This is done for each scenario using scenario difference files [73], which are, in part, generated using *premise* (v1.4.2) [24]. The resulting inventory tables are reported in spreadsheets (see Appendix H). These inventory tables serve as input for the LCIA, as described in Chapter 7.

7

Impact assessment results and contribution analyses

Chapter 6 established the inventories for each alternative, in a range of scenarios. In this chapter, these inventories serve as input to determine environmental impacts. Characterisation models classify the flows into a range of impact categories, where these flows are then characterised with respect to the category's indicator. To complement the impact assessment phase, this chapter also includes contribution analyses. These are traditionally a part of the interpretation phase, but make sense to consider alongside the characterisation results.

7.1. Selected impact categories and characterisation models

As was discussed in Section 2.1, the impact of aviation on climate change is increasingly well understood, but deviates from typical characterisation models. Furthermore, the authors of *premise*, introduced in Section 4.2, note that emissions of H_2 and the absorption/capture of CO_2 from the atmosphere could respectively result in considerable warming and cooling effects in the future [109]. They provide an adjusted characterisation model which accounts for this. In this study, the characterisation method is adapted further to reflect aircraft emissions, based on the work of Lee et al. [8]. These adjustments and their rationale is further detailed in Section B.7.

For other environmental impacts, this study uses the EF family of midpoint characterisation models (v3.0), as recommended by the European Commission [20]. This family considers a robust collection of environmental impacts, and the goal of the EF method to harmonise the LCA framework is considered particularly appropriate in the European context of this study. It must be noted again that certain impacts of aviation, such as those related to air quality and noise, receive no special consideration in these assessment models. Furthermore, the EF "water use" impact category is excluded from the analysis, as this impact category focuses on water emitted to the air. In this study, water is generally not emitted to the air as a (direct) result of water being used, but because of the combustion of hydrocarbons. This impact category therefore adds no new information not already reflected in other impacts.

7.2. Environmental flows lacking characterisation

The knowledge of environmental impacts is perfectly translated (or translatable) to the LCA methods, as brought up again in Section 7.1. This also means that some environmental flows are not classified into any impact category, thereby being omitted from the characterisation results [76]. An overview of such flows is included in Appendix H. Notable is that discrepancies can appear between the LCI method and LCIA method. For example, the ecoinvent database occasionally uses metrics such as chemical oxygen demand (COD) and dissolved organic carbon (DOC) to define environmental flows, but these flows are not classified in EF v3.0.

7.3. Economic flows not followed to system boundary

From the reference flows evaluated in Section 6.5, inputs of goods and outputs of wastes are followed until they reach the economy-environment system boundary. Before delving into the characterisation of the inventory results, it is worth emphasising that certain flows are excluded from the product systems. This was discussed in Section 6.1.3, where a selection of such exclusions was presented. It should be kept in mind that the environmental impacts presented in Section 7.4 and beyond are truncated compared to the actual product systems.

7.4. Baseline scenario

In this section, the characterisation results and contribution analysis of the baseline scenario are presented. These results form a sound foundation from which to evaluate the results of the various scenarios, which are presented in Sections 7.5, 7.6, and 7.7.

The lifecycle impacts are presented side by side with impacts for the lifecycle excluding use. As with the full inventory results, the unaltered LCIA results are included in Appendix H.

7.4.1. Characterisation results

The characterisation results for the baseline scenario are listed in Table 7.1 and visualised in Figure 7.1. As can be observed, when the use phase is included, the performance of the CFRP alternatives is virtually identical across impact categories. This is because these ribs are each assumed to have equal mass in this scenario. Because the composite ribs are assumed to be 20% lighter than the aluminium alloy rib, this heavier rib has considerably higher impacts. However, when considering the lifecycles excluding use, the relative performance of the alternatives is much more dynamic, with the CFRTP rib, aluminium alloy rib, and CFRTS rib, RTM each being the top performer in several impact categories. For each impact category, either the aluminium alloy rib or the CFRTS autoclave rib has the highest impact.

7.4.2. Contribution analysis

To understand the characterisation results shown in Section 7.4.1, contribution analysis is performed, connecting environmental impacts to the foreground processes these are connected to. This type of contribution analysis reveals which phases of the lifecycle are responsible for certain impacts. To quantify these contributions, the Sankey diagram feature of the Activity Browser is used [22], with some calculation of individual economic flows as verification. This allows the contributions to be identified in a way which does not double count environmental credits or burdens, while giving (some) indication of how impacts tie into the product system. Contributions are presented in Figure 7.2 and Figure 7.3.

Table 7.1: Characterisation results for the baseline scenario, using the EF v3.0 impact categories and the climate change method described in Section 7.1. The including use results represent the full lifecycle, while the excluding use results exclude mass-induced energy demand and connected fuel production.

including use:

Impact category	Unit	CFRTP rib	Aluminium alloy rib	CFRTS rib, autoclave	CFRTS rib, RTM
climate change	kg CO_2-eq	3.38×10^4	4.22×10^4	3.38×10^4	3.38×10^4
acidification	mol H+-eq	1.24×10^2	1.55×10^2	1.24×10^2	1.24×10^2
ecotoxicity: freshwater	CTUe	1.81×10^5	2.30×10^5	1.81×10^5	1.80×10^5
eutrophication: freshwater	P	3.66×10^{-1}	4.62×10^{-1}	3.74×10^{-1}	3.57×10^{-1}
eutrophication: marine	kg N-eq	4.53×10^1	5.66×10^1	4.53×10^1	4.53×10^1
eutrophication: terrestrial	mol N-eq	4.95×10^2	6.18×10^2	4.95×10^2	4.95×10^2
human toxicity: carcinogenic	CTUh	2.22×10^{-6}	3.04×10^{-6}	2.18×10^{-6}	2.17×10^{-6}
human toxicity: non-carcinogenic	CTUh	2.90×10^{-4}	3.69×10^{-4}	2.90×10^{-4}	2.90×10^{-4}
ionising radiation: human health	kBq U_{235}-eq	1.54×10^3	1.91×10^3	1.54×10^3	1.53×10^3
photochemical ozone formation: human health	kg NMVOC-eq	1.28×10^2	1.60×10^2	1.28×10^2	1.28×10^2
ozone depletion	kg CFC-11-eq	5.42×10^{-3}	6.77×10^{-3}	5.46×10^{-3}	5.42×10^{-3}
particulate matter formation	disease incidence	2.37×10^{-4}	3.01×10^{-4}	2.39×10^{-4}	2.38×10^{-4}
energy resources: non-renewable	MJ, net calorific value	3.25×10^5	4.04×10^5	3.25×10^5	3.25×10^5
material resources: metals/minerals	kg Sb-eq	4.90×10^{-3}	1.71×10^{-2}	5.01×10^{-3}	4.92×10^{-3}
land use	-	4.09×10^4	5.25×10^4	4.1×10^4	4.09×10^4

excluding use:

Impact category	Unit	CFRTP rib	Aluminium alloy rib	CFRTS rib, autoclave	CFRTS rib, RTM
climate change	kg CO_2-eq	1.82×10^2	1.57×10^2	2.25×10^2	1.97×10^2
acidification	mol H+-eq	8.43×10^{-1}	1.18	9.83×10^{-1}	8.59×10^{-1}
ecotoxicity: freshwater	CTUe	3.77×10^3	9.40×10^3	3.93×10^3	3.56×10^3
eutrophication: freshwater	P	7.17×10^{-2}	9.45×10^{-2}	7.99×10^{-2}	6.32×10^{-2}
eutrophication: marine	kg N-eq	2.05×10^{-1}	2.33×10^{-1}	2.44×10^{-1}	2.14×10^{-1}
eutrophication: terrestrial	mol N-eq	1.76	1.85	2.09	1.83
human toxicity: carcinogenic	CTUh	1.05×10^{-7}	3.95×10^{-7}	6.58×10^{-8}	5.59×10^{-8}
human toxicity: non-carcinogenic	CTUh	1.40×10^{-6}	8.26×10^{-6}	1.82×10^{-6}	1.54×10^{-6}
ionising radiation: human health	kBq U_{235}-eq	3.02×10^1	2.53×10^1	3.38×10^1	2.28×10^1
photochemical ozone formation: human health	kg NMVOC-eq	4.70×10^{-1}	5.11×10^{-1}	5.46×10^{-1}	4.76×10^{-1}
ozone depletion	kg CFC-11-eq	1.90×10^{-5}	1.32×10^{-5}	5.66×10^{-5}	1.21×10^{-5}
particulate matter formation	disease incidence	6.63×10^{-6}	1.30×10^{-5}	8.18×10^{-6}	7.28×10^{-6}
energy resources: non-renewable	MJ, net calorific value	2.77×10^3	1.68×10^3	3.20×10^3	2.71×10^3
material resources: metals/minerals	kg Sb-eq	4.39×10^{-4}	1.15×10^{-2}	5.50×10^{-4}	4.64×10^{-4}
land use	-	2.55×10^2	1.71×10^3	3.22×10^2	2.66×10^2

The values for the graphs can be found in Appendix H. To facilitate the discussion of how activities and environmental flows contribute to impacts, additional data is included in Section E.1.

Figure 7.2 demonstrates the impact of the fuel production (the well-to-tank phase) and fuel use (the tank-to-wake phase). Which activities contribute more varies a lot per impact category, but the lifecycle excluding use contributes $<$ 1% to more than half of the categories for each alternative, with only a few seeing a share of $>$ 5%. One observation to draw is that only including emissions from fuel use, but

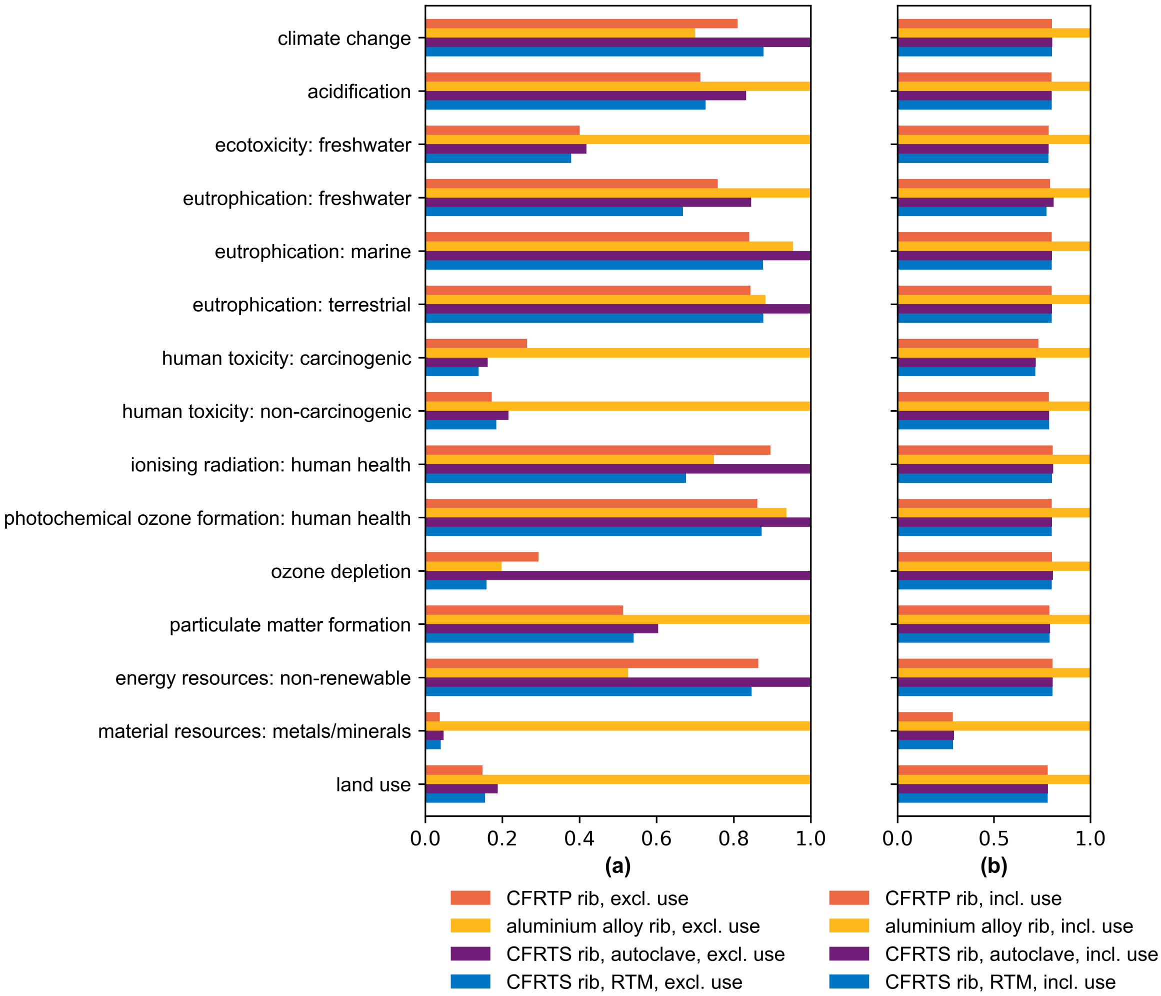

Figure 7.1: Characterisation results for the baseline scenario, using the EF v3.0 impact categories and the climate change method described in Section 7.1, presented comparatively for **(a)** the lifecycle excluding use of the alternatives and **(b)** the lifecycle including use (i.e., the full lifecycle) of the alternatives.

not from fuel production, vastly underestimates impacts, as pointed out by Keiser et al. [30]. It should be kept in mind that impacts such as ozone depletion, particulate matter formation, and ecotoxicity: freshwater primarily occur along the kerosene supply chain, rather than at the site of aviation activities. However, excluding the fuel well-to-tank would appear to have a limited impact for climate change – although the characterisation method for climate change used here also contributes to increasing the share of the tank-to-wake phase (see Section 7.1). The lifecycle excluding use has a relatively prominent role in impacts on eutrophication: freshwater, human toxicity: carcinogenic, and material resources: metals/minerals.

Figure 7.3 particularly illustrates the impact of carbon fibre production and aluminium alloy production. The diagrams of Section 6.2 are important to remember here: the composite components require much more carbon fibre than the amount contained in the ribs, with a buy-to-fly ratio around 2.1:1 – for the aluminium alloy rib, this number is much higher, at 20:1. This particularly works against the CFRTS autoclave alternative, which includes the disposal of expired prepreg. End-of-life disposal processes generally provide a minor environmental benefit, due to the prospective modelling of substitution flows (discussed further in Section 9.1.1). Recycling of manufacturing waste provides a notable benefit to

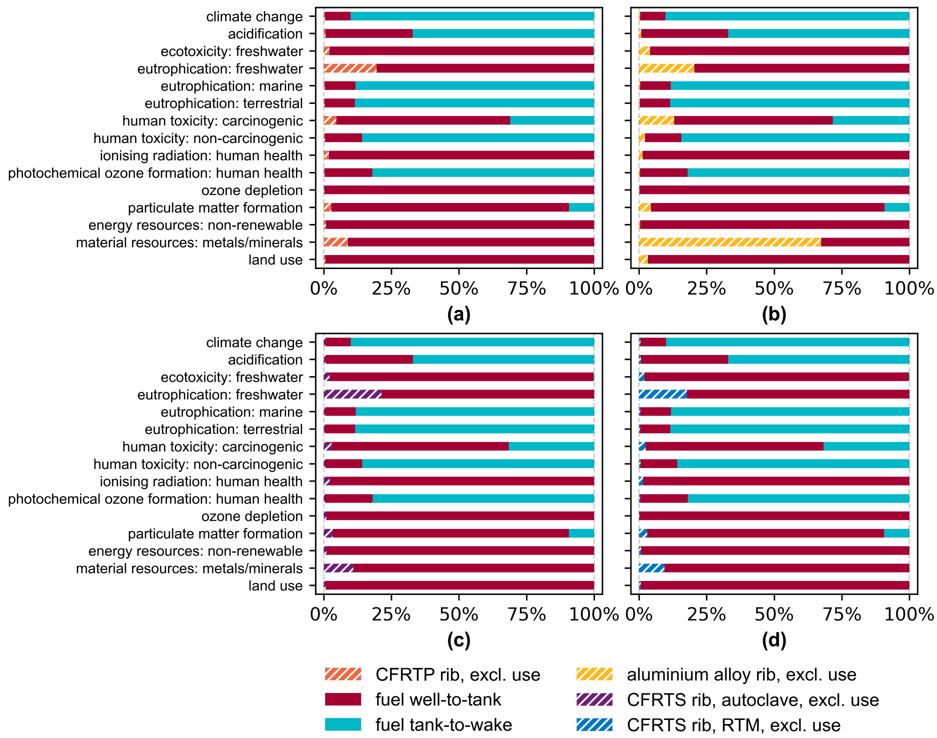

Figure 7.2: Contribution analysis of the baseline scenario **lifecycle including use** of **(a)** the CFRTS rib, **(b)** the aluminium alloy rib, **(c)** the CFRTS rib, autoclave, and **(d)** the CFRTS rib, RTM. Contributions are allocated to foreground processes according to the Sankey tool of the Activity Browser and add up to 100% for each impact category. Dashed lines indicate 0% and 100%.

the CFRTP rib. To the aluminium alloy rib, it provides a large environmental benefit, due to the high buy-to-fly ratio of this rib. Notable is that the aluminium alloy alternative receives comparatively little environmental credits from recycling in the material resources category; this is because much of the impacts here can be traced back to the copper used in energy systems, rather than the material content of the aluminium alloy. Several other impact categories stand out: the CFRTP and CFRTS autoclave alternatives have a relatively high contribution to ozone depletion, respectively because of the production of PEKK (particularly: bromomethane emissions in the production of terephthalic acid) and the production of release film, one of the autoclave consumables (particularly: emissions of chlorofluorocarbons (CFCs) and hydrochlorofluorocarbons (HCFCs) in the production chain of chlorodifluoromethane). The impact of PEKK production on human toxicity: carcinogenic also stands out, which is caused by benzene-related emissions. Sankey diagrams illustrating these high-impact processes are included in Appendix H. Surprisingly, the high impact of the aluminium alloy alternative on land use is driven by the metal factory used in the milling process. This means that it cannot directly be compared to the composite alternatives, where the manufacturing facility is cut off, potentially obscuring an impact of a similar magnitude. This is an indication of the alternatives not being compared on equal footing, which is discussed in Section 8.2.

7.5. Waste treatment

If there was any doubt about the significance of the use phase after reading Section 2.1.2, Section 7.4 makes its magnitude with respect to the other lifecycle phases clear. Because of this, the waste treatment scenarios described in Section 6.4.1 are only presented for the lifecycles excluding use in Fig-

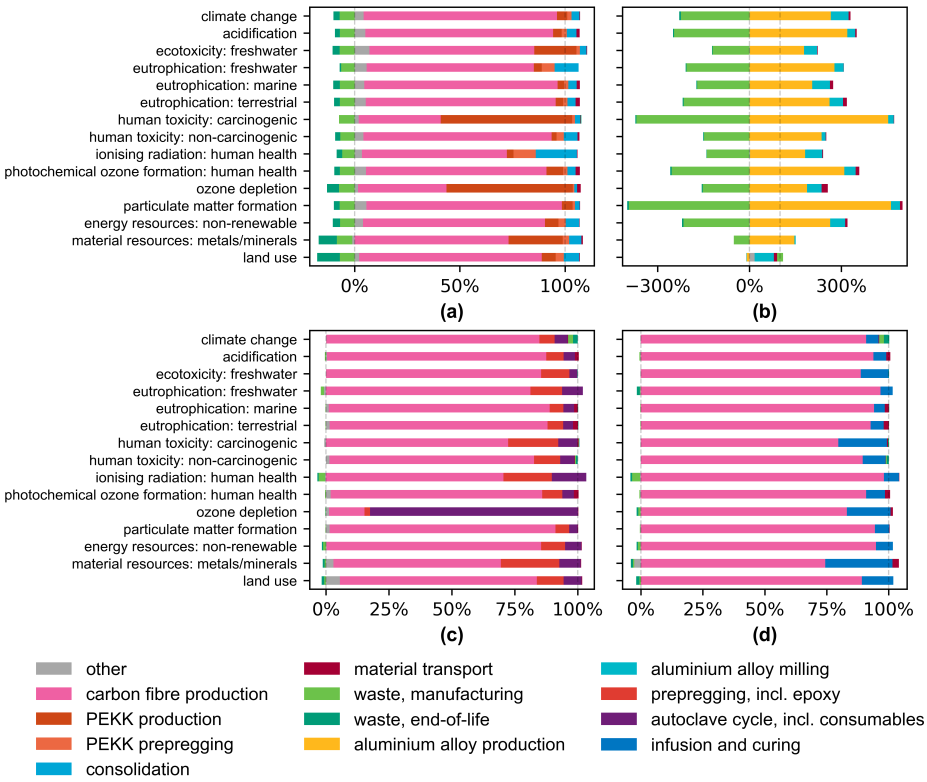

Figure 7.3: Contribution analysis of the baseline scenario **lifecycle excluding use** of **(a)** the CFRTS rib, **(b)** the aluminium alloy rib, **(c)** the CFRTS rib, autoclave, and **(d)** the CFRTS rib, RTM. Contributions are allocated to foreground processes according to the Sankey tool of the Activity Browser and add up to 100% for each impact category. Dashed lines indicate 0% and 100%.

ure 7.4. Full characterisation results can be found in Appendix H, with additional graphs of the individual scenarios in Figure 7.4.

Figure 7.4 shows both linear and circular scenarios, along with an indication of the highest impact in the baseline scenario (i.e., the position of the 1 value in Figure 7.1). Comparing each subfigure to the baseline scenario, it is clear that the linear scenario has much higher maximum impacts. This is due to the more linear treatment option for aluminium alloy resulting in higher impacts for categories such as acidification, eutrophication: freshwater, human toxicity impacts, and material resources. However, it also has a relatively lower land use impact, becoming closer to the composite alternatives. These shifts are reversed in the circular scenario, were particularly the impacts of the aluminium alloy alternative on human toxicity: carcinogenic and particulate matter formation are much lower.

The impacts of the composite alternatives do not change much across scenarios, in part due to the way in which waste treatment credits and burdens were allocated. Figure 7.4 shows that, although the CFRTP rib was favoured in several impact categories in the baseline scenario, it is overtaken by the CFRTS RTM rib in almost all impact categories in both linear and circular scenarios. Meaning that, if both ribs were to be incinerated or both ribs were to be recycled (with the respective processes selected), the RTM rib would generally be preferred. However, the fact remains that CFRTS is generally less attractive to recycle than CFRTP. For example, pyrolysis is costly [105] and turning short-length carbon fibre back into a usable product requires additional process steps, complicating its application [T. de Bruijn, personal communication, May 11, 2023].

In lieu of further contribution analyses as presented in Section 7.4.2 and Section E.1, the aspects of

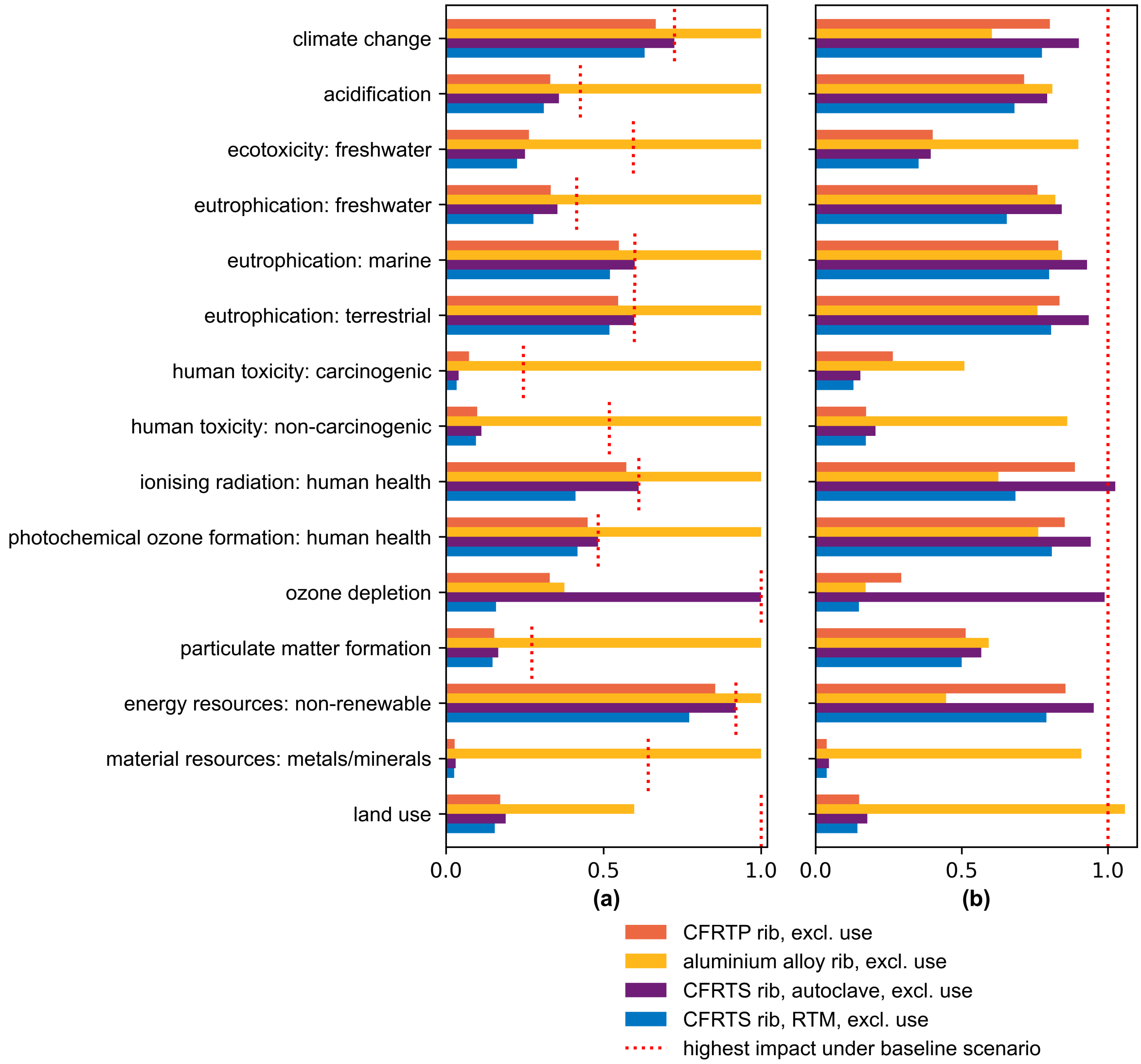

Figure 7.4: Characterisation results for **(a)** the linear waste treatment scenario and **(b)** the circular waste treatment scenario. Results for the lifecycle excluding use are presented comparatively with respect to the highest impacts within the respective scenario and the baseline scenario.

multifunctionality and prospective end-of-life waste treatment are explored. This is considered as part of the sensitivity analysis (see Section 9.1.1).

7.6. Component mass and use intensity

The results of the break-even approach to component mass described in Section 6.4.2 are listed in Table E.1 and visualised in Figure 7.5 for the baseline use intensity scenario. This approach considers the effect of component mass on all stages of the lifecycle. The impact categories where break-even occurs close to the mass of the CFRTP rib – 2.1 kg – are generally more impacted by the use phase (see Section 7.4.2). Changing the use intensity does not shift the break-even values for these impact categories much, but has a more pronounced effect on other impact categories. This is presented in Section E.2, alongside additional characterisation results to frame the creation of break-even plots. Alternative energy carriers are also analysed in this way (see Section 7.7.3).

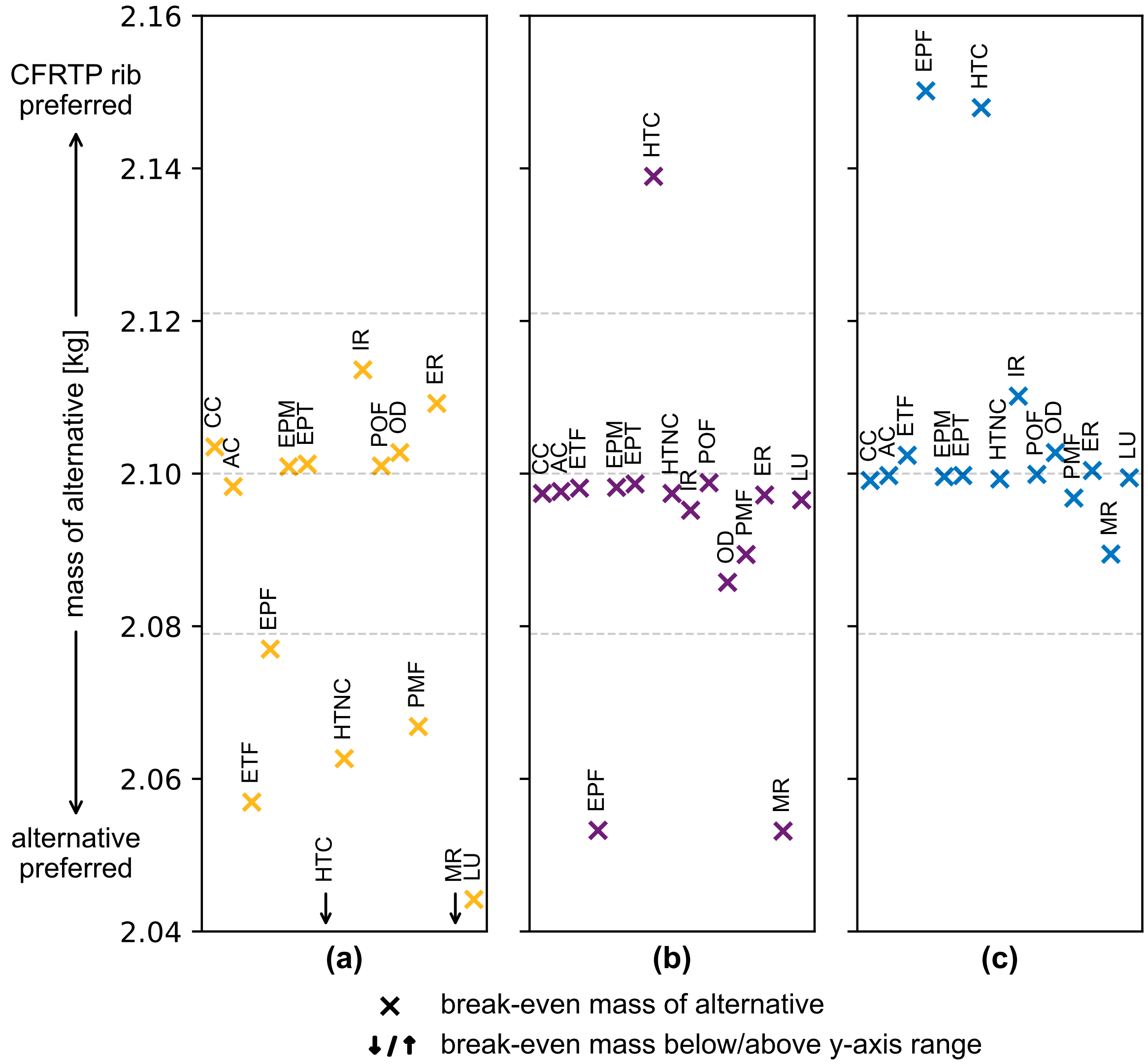

Figure 7.5: Visualisation of the masses at which **(a)** the aluminium alloy rib, **(b)** the CFRTS autoclave rib, and **(c)** the CFRTS RTM rib have an equal impact to the CFRTP rib (with a mass of 2.1 kg) in the baseline scenario. Above these masses, the CFRTP rib is preferred in this scenario; below, the respective alternative is preferred. Dashed lines indicate a mass difference of +1%, 0%, and −1%, respectively, from top to bottom. All values, including those which fall outside of the y-axis range, can be found in Table E.1. CC = climate change; AC = acidification; ETF = ecotoxicity: freshwater; EPF = eutrophication: freshwater; EPM = eutrophication: marine; EPT = eutrophication: terrestrial; HTC = human toxicity: carcinogenic; HTNC = human toxicity: non-carcinogenic; IR = ionising radiation: human health; POF = photochemical ozone formation: human health; OD = ozone depletion; PMF = particulate matter formation; ER = energy resources: non-renewable; MR = material resources: metals/minerals; LU = land use.

7.7. Alternative energy carriers

The energy scenarios described in Section 6.4.3 introduced two alternatives to baseline scenario powered by fossil kerosene. In the following sections, the LCIA results, including contribution and break-even analyses, are presented and briefly discussed.

7.7.1. Characterisation results

How the characterisation results of the baseline scenario are changed in the scenario which introduces SAF and the scenario fully powered by hydrogen are illustrated in Figure 7.6. As can be observed, in the

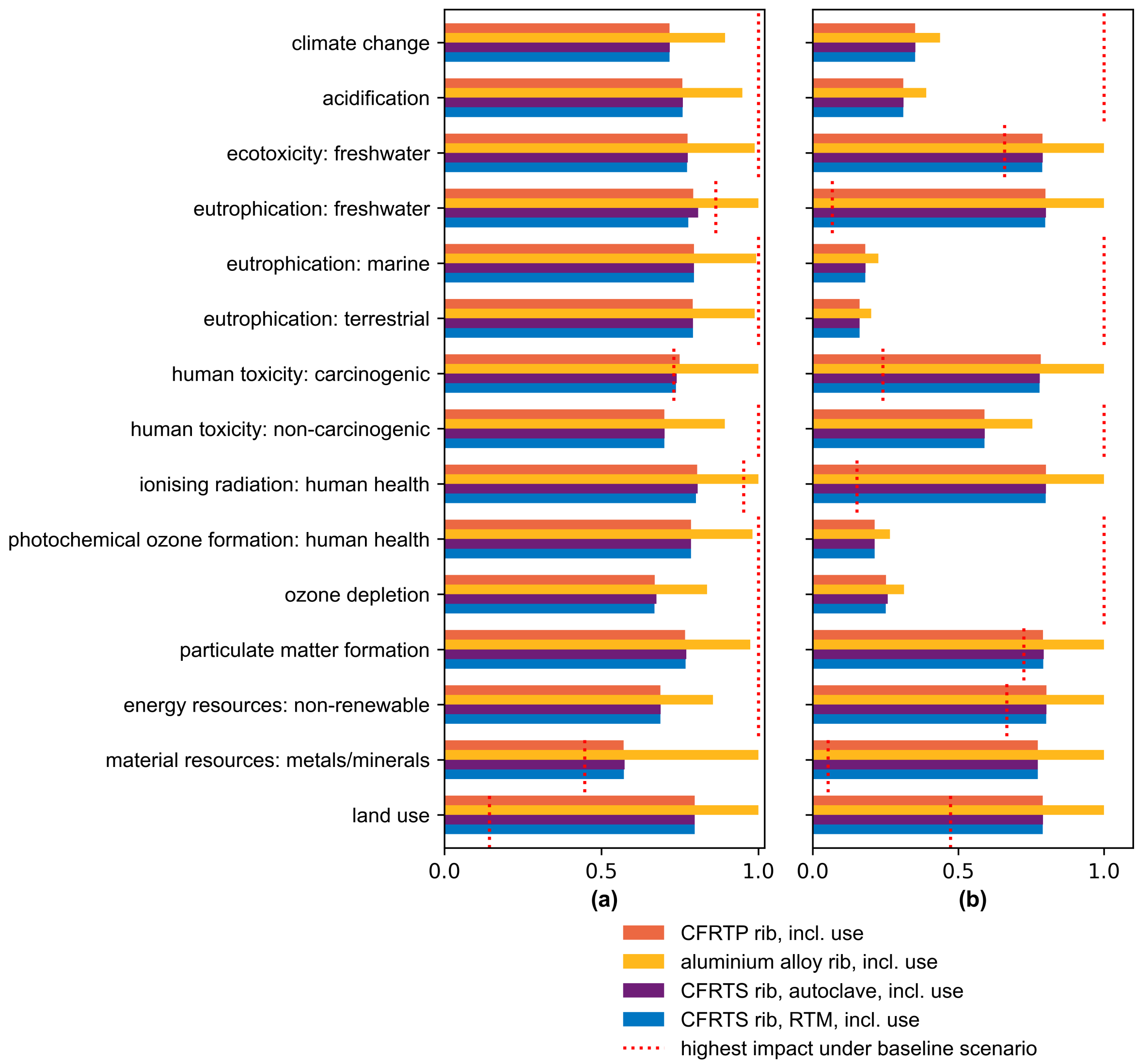

Figure 7.6: Characterisation results for **(a)** the SAF energy scenario **(b)** the hydrogen energy scenario. Results for the lifecycle including use are presented comparatively with respect to the highest impacts within the respective scenario and the baseline (i.e., fossil kerosene) scenario.

cases where the SAF scenario realises a reduction compared to the baseline, this reduction is limited. This is unsurprising, given the high share fossil kerosene has in this scenario (see Table 6.4). Furthermore, there are several impact categories where the SAF scenario causes an increase in impacts. This can be understood as being primarily driven by the energy required to produce SAF (see Section 7.7.2). The hydrogen scenario shows an even sharper increase in these impact categories compared to the baseline. However, several of the remaining impact categories – such as climate change, acidification, and photochemical ozone formation – show a decrease in impacts of $>$ 50%. Being highly influenced by the surrounding energy system, evaluating these energy carriers across a different timeline or using different prospective pathways can bring new insight. This is done in Section 9.1.3.

7.7.2. Contribution analysis

Contribution analyses of the energy scenarios, such as done for the baseline scenario in Figure 7.2, are presented in Section E.1. To illustrate the meaning of the energy carrier scenarios, this section provides

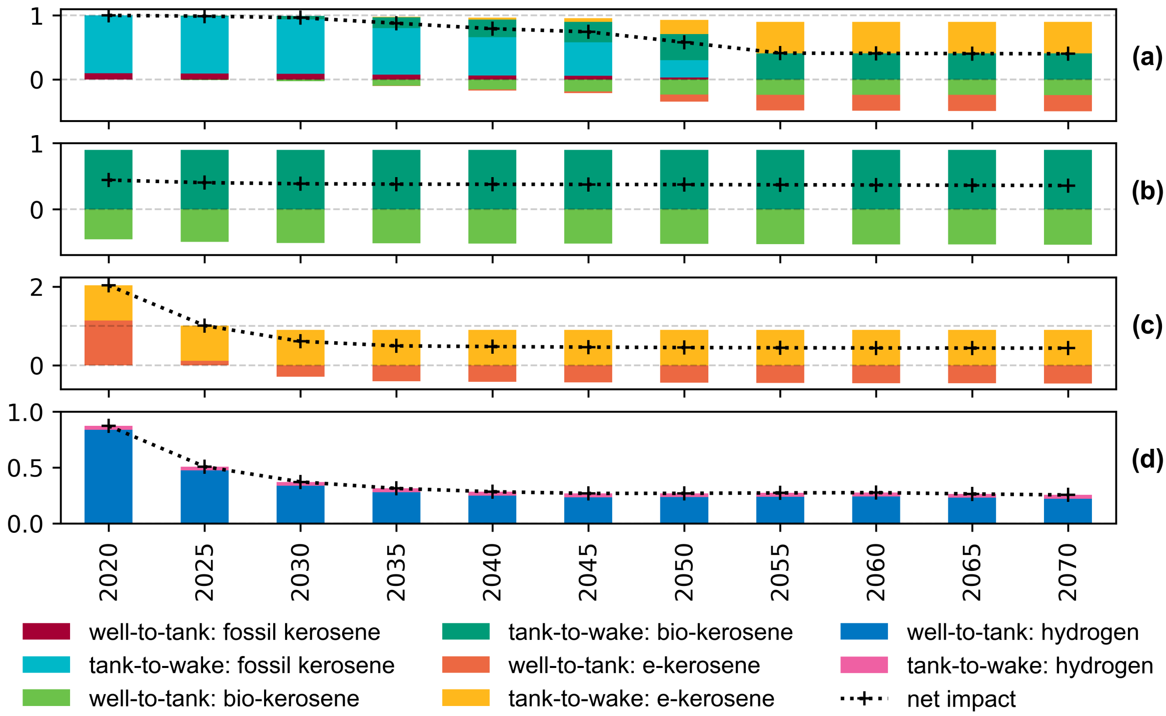

Figure 7.7: Climate change impact per time step of five years for **(a)** the SAF scenario, **(b)** bio-kerosene, **(c)** e-kerosene, and **(d)** the hydrogen scenario. Impacts are shown relative to the impacts of a quantity of fossil kerosene of equal energy content.

impacts and contributions in the form of a timeline. The changing background scenarios were evaluated with time steps of five years, as is detailed in Section A.1 and Section D.3. As a reminder, this approach uses *premise*, by Sacchi et al. [24], to transform and expand the background database based on the SSP2-NDC pathway of REMIND, by Luderer et al. [71]. Figures 7.7, 7.8, and 7.9 illustrate how, for each timestep the impacts of alternative energy carriers change on climate change, particulate matter formation, and material resources, respectively. These impact categories were chosen because climate change is a much-discussed impact, which should benefit greatly from alternative energy carriers. The other two are examples of impact categories which see a shift in impacts to various degrees. To extend the SAF scenario to 2070, the 2050 volume share of bio-SAF is assumed to remain constant, while the e-SAF share grows to displace all remaining fossil kerosene in 2055. This is not necessarily a realistic scenario, but will be used in Section 9.1.3 to illustrate the potential future decarbonisation efforts could have.

The figures provide a few points of insight. Firstly, SAF and hydrogen can contribute significantly to climate change mitigation (see Figure 7.7), with each alternative energy carrier resulting in a reduction $>$ 50% compared to fossil kerosene from around 2035 onward. However, such a decrease accomplishes little when fossil kerosene remains the main energy source. Additionally, these alternative fuels can cause impacts to increase elsewhere. Although the decreased particulate matter formation from in-flight emissions is seen as a benefit of hydrogen and SAF propulsion (see, e.g., Gangoli Rao, Yin, and Werij [117] and Tran, Brown, and Olfert [118]), this does not necessarily lead to a net benefit (see Figure 7.8). Even after 2050, when the REMIND pathway has decarbonised much of the energy system, e-kerosene would lead to a net increase in particulate matter formation of over 50%. Extractive impacts should also be kept in mind: as can be seen in Figure 7.9, alternative fuels bring about an increased impact on material resources: metals/minerals, which remains high over time.

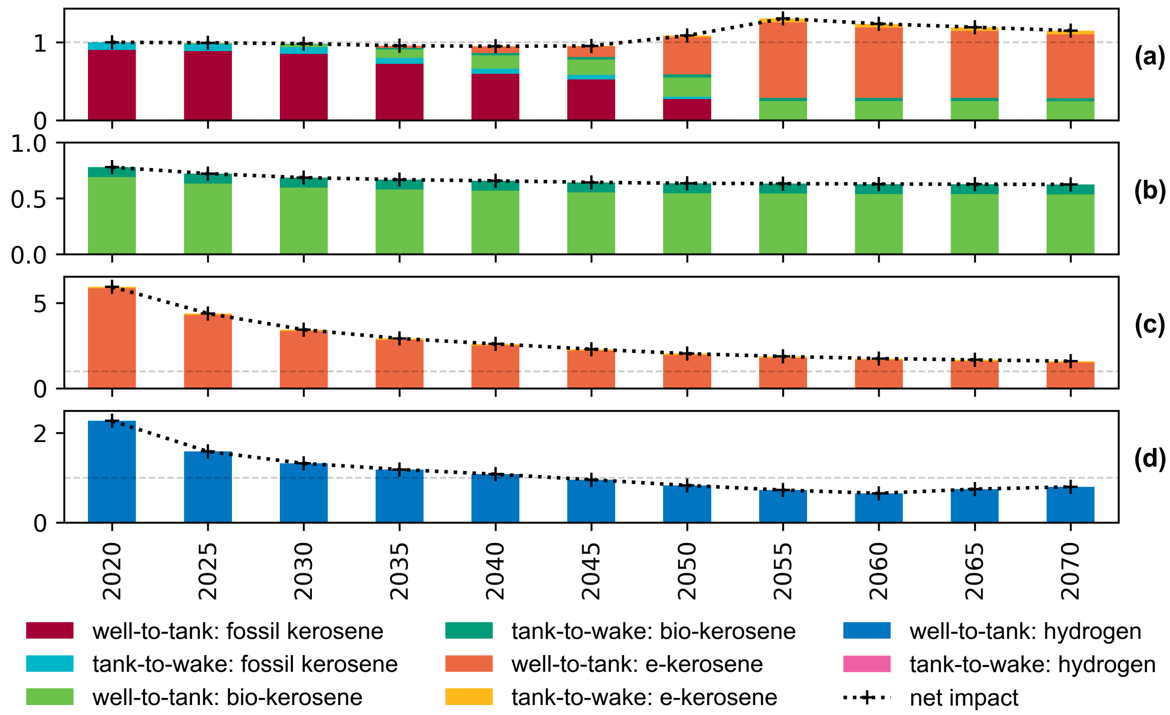

Figure 7.8: Particulate matter formation: human health impact per time step of five years for **(a)** the SAF scenario, **(b)** bio-kerosene, **(c)** e-kerosene, and **(d)** the hydrogen scenario. Impacts are shown relative to the impacts of a quantity of fossil kerosene of equal energy content.

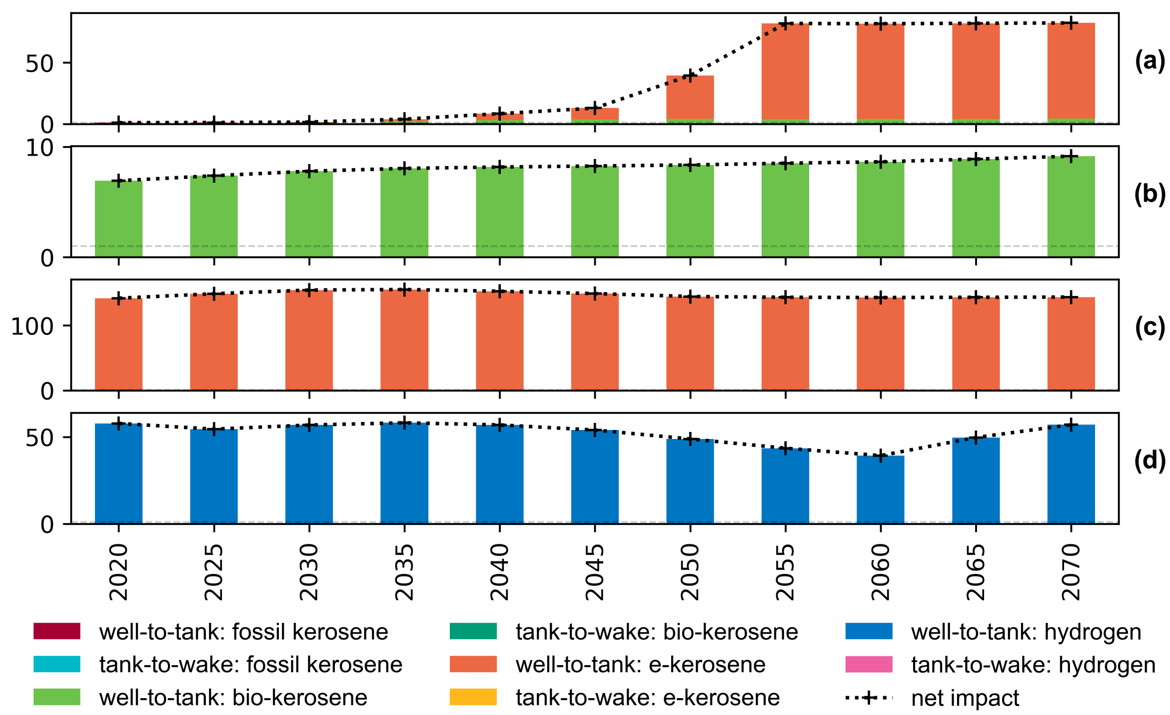

Figure 7.9: Material resources: metals/minerals impact per time step of five years for **(a)** the SAF scenario, **(b)** bio-kerosene, **(c)** e-kerosene, and **(d)** the hydrogen scenario. Impacts are shown relative to the impacts of a quantity of fossil kerosene of equal energy content.

7.7.3. Break-even analysis

As can be gathered from the above sections, the SAF scenario does not bring substantial improvement to component lifecycle impacts, in part due to the prominent use of fossil kerosene. The hydrogen scenario is generally more favourable. To illustrate the relevance of this reduction to component mass and use, Figure 7.10 presents the break-even masses for the hydrogen scenario assuming use intensity equivalent to 10 years. Break-even masses for the remaining scenarios are included in Section E.2. For this, it can be observed that the break-even mass for most impact categories remains close to the initial rib mass (within 30 g; which is around 1.4% of the initial mass). However, several impact categories result in a more pronounced difference, such as the impacts on human toxicity and material resources for the aluminium alloy rib. In these impact categories, the lifecycle excluding use of an alternative is outperformed by CFRTP by a large margin (see Figure 7.3). This indicates that, while mass-induced energy demand remains to be a dominant factor in this scenario, the available bandwidth for mass differences increases slightly. This also means that the potential need to prioritise one impact over another becomes more apparent: in this scenario, an aluminium alloy component might outperform CFRTP in climate change and ozone depletion, but not in any other impact category. The question then becomes how to value these impacts against each other – a topic beyond the scope of this thesis.

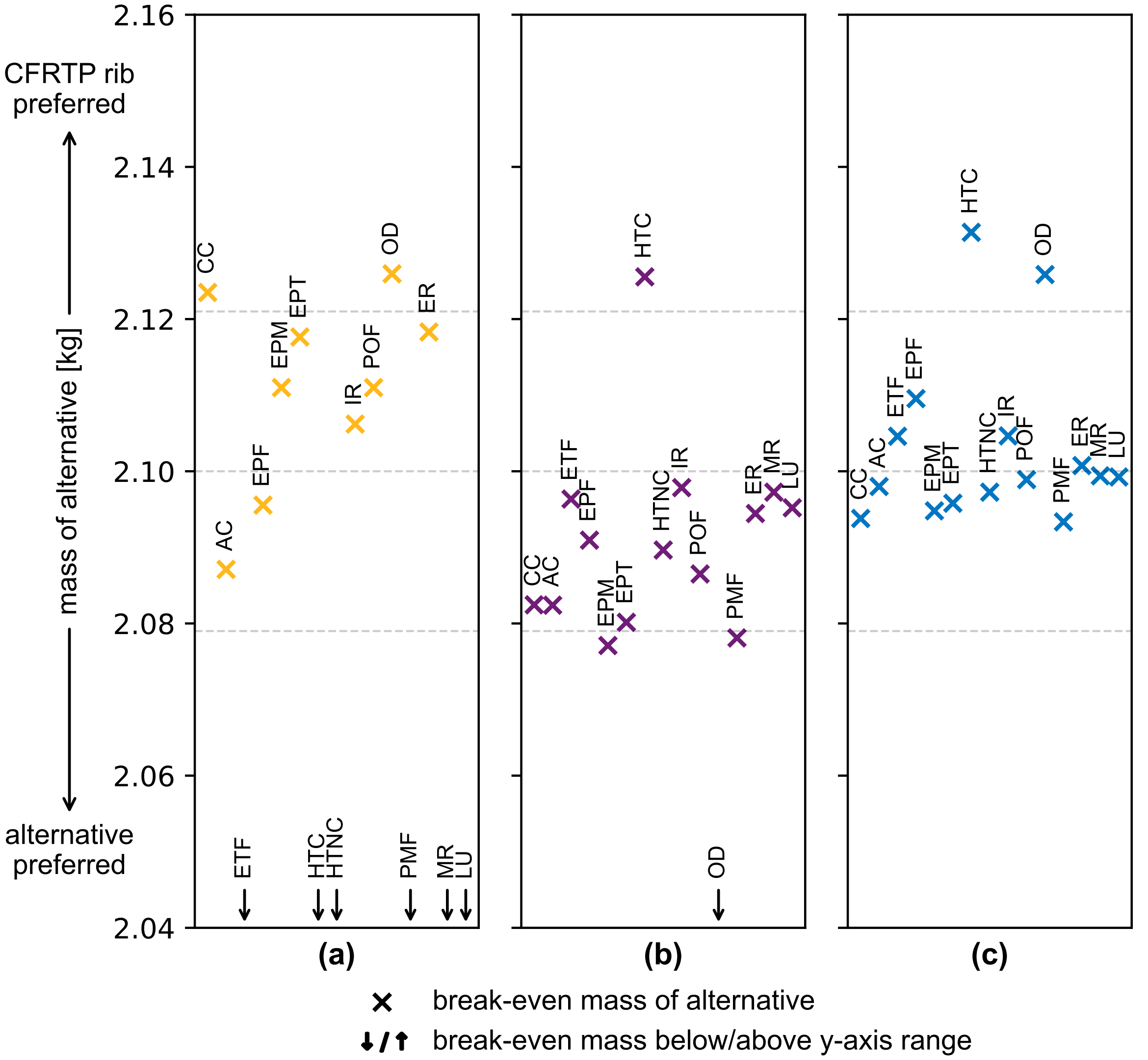

Figure 7.10: Visualisation of the masses at which **(a)** the aluminium alloy rib, **(b)** the CFRTS autoclave rib, and **(c)** the CFRTS RTM rib have an equal impact to the CFRTP rib (with a mass of 2.1 kg) in the **hydrogen energy scenario assuming use intensity equivalent to 10 years**. Above these masses, the CFRTP rib is preferred in this scenario; below, the respective alternative is preferred. Dashed lines indicate a mass difference of $+1\%$, 0%, and -1%, respectively, from top to bottom. All values, including those which fall outside of the y-axis range, can be found in Table E.3. CC = climate change; AC = acidification; ETF = ecotoxicity: freshwater; EPF = eutrophication: freshwater; EPM = eutrophication: marine; EPT = eutrophication: terrestrial; HTC = human toxicity: carcinogenic; HTNC = human toxicity: non-carcinogenic; IR = ionising radiation: human health; POF = photochemical ozone formation: human health; OD = ozone depletion; PMF = particulate matter formation; ER = energy resources: non-renewable; MR = material resources: metals/minerals; LU = land use.

8 Consistency and completeness checks

The lifecycle impact assessment phase has been conducted in Chapter 7 and the first interpretation activities have taken place through means of contribution analyses, break-even analyses, and the general exploration of environmental impacts. In this chapter, the interpretation phase continues through qualitative and quantitative reflection on the consistency and completeness of the LCA study. Consistency primarily reflects back on whether the study adhered to the scope set out in Chapter 5 across its analysis. Completeness normally involves expert review. This study did involve personal communication with subject-matter experts, but no detailed review took place. Instead, completeness is evaluated based on a comparison to LCA literature.

8.1. Consistency of mode of analysis

As already identified in the scope definition (see Section 5.2), the mode of analysis of this thesis is not fully aligned with ALCA nor CLCA. As discussed in Section 6.1.2, this results in an inconsistent treatment of multifunctionality. This inconsistency can be traced back to the goal of the study, which includes addressing commercial aviation actors involved with aerostructures. The case study is therefore approached in an attributional way, to determine how to isolate the impact of aerostructures from the global economic system. However, this case study finds itself in a context of transitions that go beyond the wing ribs in question, as discussed in Chapter 1. The research question – which asks how environmental impacts can be reduced – is a question of consequences.

Although the ISO standards for LCA [65, 66] are not explicitly against combining aspects of ALCA and CLCA, authors such as Brander and Wylie [45] are highly critical of introducing substitution into studies which are otherwise attributional, stating: “the results are neither a true inventory of actual emissions, nor do they show the full consequences associated with the product” [p. 164]. They recommend that guidelines which ought to be attributional – such as the PEF method, for products – are amended to exclude the use of substitution. Although the inclusion of substitution flows was considered appropriate for this study, it is important to be clear about the implications of this choice. To reflect on this further, a few alternative modes of analysis are included in the sensitivity analyses (see Chapter 9).

8.2. Consistency between alternatives

Many of the assumptions made to set up the CFRTS alternatives were based directly on the CFRTP alternative. This means that, although little knowledge is available on these alternatives in the specific setting of this case study, the comparison between composite alternatives becomes more straightforward. The main inconsistencies relate to matrix material production and the inputs for production processes. The PEKK inventory was constructed through several chemical production activities, while the epoxy inventory was readily obtained from ecoinvent. The hot press consolidation process has limited inputs, and the main input – electricity – was previously obtained through on-site measurements. On the other hand, the inputs for CFRTS manufacturing are more varied, with no primary measurements for this case study. This is investigated further in Appendix F, leading to sensitivity analysis (see Section 9.1.2).

For the aluminium alloy alternative, the degreasing and anodising steps, which are part of the post-processing, are modelled. However, this is not the case for the composite alternatives, due to a lack of reliable data. This inconsistency means the relative impacts of the aluminium alloy alternative are overestimated. However, due to the minuscule contribution which post-processing has (see Section 7.4.2), this inconsistency is considered inconsequential.

The inconsistency in the mode of analysis discussed in Section 8.1 has a particular effect on the aluminium alloy alternative, as it makes use of closed-loop recycling in the treatment of manufacturing scrap, which is not implemented for other waste material. The aluminium alloy alternative is harder to compare in several ways, as its inventories are also based on much more robust data collection in comparison to those of composite materials. The metallurgical processes in the creation and remelting of aluminium alloy were found to comprise the vast majority of impacts when excluding use (see Section 7.4.2), but the corresponding composite processes – notably, the production of carbon fibre – are not modelled using the same level of detail. This could result in impacts for the composite alternatives being underestimated. However, this should still be seen in light of the full lifecycle. The results of Section 7.7.3 suggest that the lightweighting use phase benefits of shifting from metal alloys to composites of around 20% would completely overshadow any difference in cradle-to-gate or end-of-life impacts.

There are also a few limitations of this study which are detrimental to comparability across all alternatives. Values representing recycling rate, quality of recycling, and the allocation of recycling credits had to be assumed for all manufacturing and end-of-life waste streams in the foreground system. As discussed in Section 8.1, this caused some inconsistency. In sensitivity analysis, the influence of these recycling rates and qualities should also be considered. In addition to the ways in which data for some alternatives is more complete and robust than for others discussed in the above paragraphs, there are some activities which were cut off for all alternatives, e.g., assembly, disassembly, and component servicing. That these were cut off for all alternatives is a detriment to comparability when it is expected that impacts of these activities differ between alternatives. For example, CFRP can require less frequent and less invasive inspection than metal alloys [26], which could translate into reduced impacts. Secondly, composite forming processes were only represented by how much material is lost during forming, but a particular disadvantage in the layup of CF/epoxy prepreg is the positive pressure and intensive ventilation required, which are thought to be significant contributors to on-site energy demand [T. de Bruijn, personal communication, May 11, 2023]. As these processes were cut off due to lack of data, it is also not possible to implement them through a quantitative sensitivity analysis. Instead, it is important to consider these factors in the conclusions of the study.

8.3. Consistency of additional scope aspects

The scope defined in Section 5.2 and detailed further in Appendix A was guiding throughout the study. However, issues regarding data quality, such as those discussed in Section 8.2, affect how representative the assessment is of the defined scope. Particularly the spatial and technological coverage is limited due to the available data often not being specific or recent enough to ensure that the scope is met. The temporal scope sees the cradle-to-gate phase in a present setting, while use and end-of-life involve placing the product in a future time. This was applied consistently. In doing so, several assumptions had to be made which might be in conflict with the real-life product systems, for which manufacturing also occurs in the future and for which future economies do not fully align with those modelled here. This can be explored through sensitivity analysis (see Section 9.1.3).

The LCIA method applied is also part of the scope. The use of the EF method was justified in Section 7.1 and applied consistently. Additionally, climate change was assessed by adjusting the *premise* model – which considers H_2 and additional CO_2 flows [109] – by adjusting the characterisation of high-altitude emissions [8]. Although it is consistent with the scope described initially, it is clear that this method has its limitations. To explore the effect which the choice of climate change characterisation method had, other methods are applied as sensitivity analysis (see Section 9.2). Furthermore, the approach is compared to approaches found in literature in Section 8.4.

8.4. Completeness comparison to literature

Overall, the assumptions made in this study which lead to cut-offs can also be found in literature. For example, Forcellese et al. [37] also assume that no waste is created during the prepregging process. Excluding many capital goods, as was done here, is also a common assumption. However, a few examples can be found where the authors did include tools and machinery based on discussions with industry experts (e.g., Forcellese et al. [37] and Stelzer et al. [44]). Forcellese et al. illustrate that tools which require frequent replacement can have a sizeable impact when considering the on-site manufacturing steps. It was shown in the present study that the component materials generally had the largest impact in the lifecycle excluding use, meaning that the impacts isolated by Forcellese et al. as a whole are relatively small, but drawing this conclusion here is, of course, influenced by the cut-offs made.

Treating waste in a consistent way from a lifecycle perspective can be complicated. Several studies neglect the buy-to-fly ratio (e.g., Cox, Jemiolo, and Mutel [15] and Duflou et al. [36]), thereby eliminating the impacts of both manufacturing waste and those linked to the production of the material that is wasted. Other studies ignore waste as a whole (e.g., Van Grootel et al. [33]). A point of interest in the present study is considering how substitution flows for end-of-life recycling activities, as can be found in literature (e.g., Mami et al. [32], Duflou et al. [36], and Witik et al. [43]) would differ when placing the activities substituted in a future background system, to align with the temporal scope of the study. This effect is considered through sensitivity analysis (see Section 9.1.1).

Finally, the LCIA method was adapted to high-altitude emissions, following only a handful of previous LCA studies (see Section 2.1.2). In contrast to these studies, the climate forcing effect of aviation induced cloudiness was neglected here, as the mechanisms through which this effect is affected by lightweighting were too complex to include. Furthermore, only the climate change LCIA method was adapted in the present study, as the adjustments to air quality suggested by Cox, Jemiolo, and Mutel [15] are considered inappropriate in light of more recent studies. As with other aspects discussed here, the completeness of this thesis is relatively on par with the state of the art. However, it is clear that

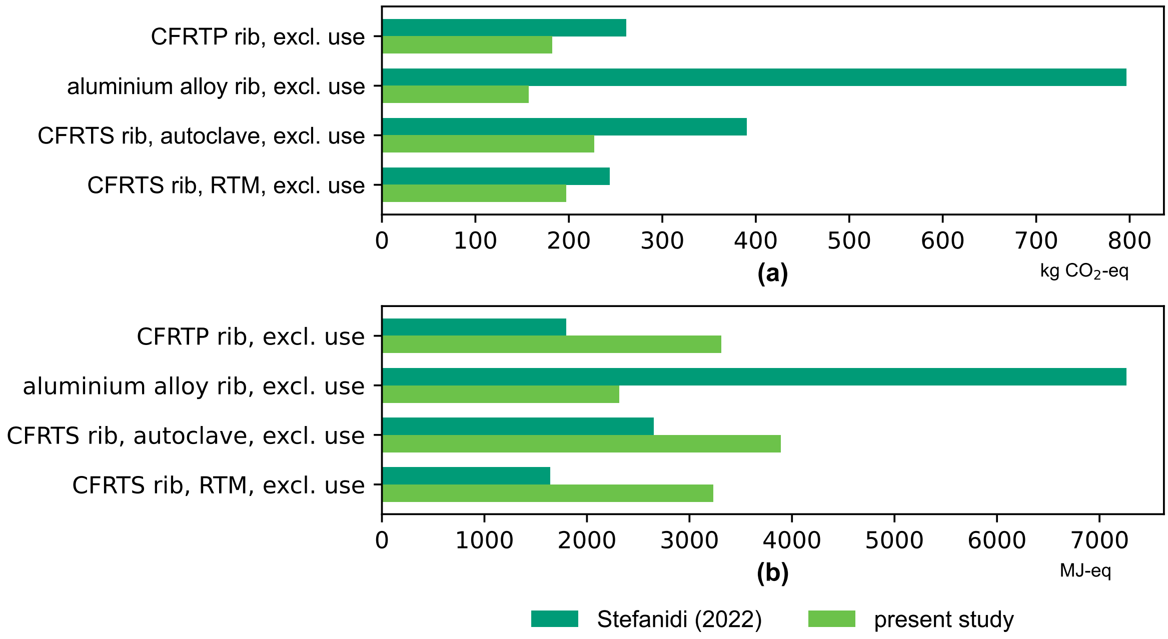

Figure 8.1: Characterisation results for the lifecycle excluding use obtained in the present study and in the previous work on this case study, by Stefanidi [1], comparing results for **(a)** climate change and **(b)** cumulative energy demand.

more work is needed to represent the environmental impacts of lightweighting through LCA.

8.5. Quantitative comparison to literature

Ideally, the results of an LCA study are also compared quantitatively to those of similar studies [76]. For this study, the only direct analogue is Stefanidi [1]. The results of these studies are compared, which requires evaluating the inventory results of this study using cumulative energy demand. This is done for the lifecycle excluding use phase. The comparison is visualised in Figure 8.1. The results are as expected. As was discussed in Section 2.3, Stefanidi treated on-site energy demand as equivalent to embodied energy, which leads to a systematic underestimation of cumulative energy demand and, by then treating all embodied energy as electricity, an overestimation of climate change impacts. Furthermore, since Stefanidi included all burdens from waste treatment, but none of the credits, the evaluation of the aluminium alloy rib is comparatively much less favourable.

There are no directly equivalent studies with which to compare this one, as the functional unit used here is fundamentally tied to the component analysed. Keiser et al. [30] identify this as a hurdle in the comparison of aviation LCA studies. Instead, some general aspects of the results can be discussed, as well as comparing individual activities and flows to those found in literature. This second approach is explored in Appendix F, which essentially is a stepping stone to some of the sensitivity analyses of Chapter 9. For the first approach, several studies introduced in Section 2.1 are revisited in the following paragraph.

The results of this study indicate that emissions connected to use-phase mass-induced energy demand far outweigh other lifecycle phases. This is universally true across similar studies comparing aluminium alloy to composites, including Timmis et al. [14] and Scelsi et al. [31], as well as studies comparing either only metal alloys or only composites, such as Huang et al. [13], Mami et al. [32], and Vidal et al. [34]. The comparison between autoclaved CFRTS and hot-pressed CFRTP of Ogugua, Sinke, and Dransfeld [4] shows similar results to those of this study: the thermoplastic matrix has a higher impact than epoxy for some categories, but the efficiency of the out-of-autoclave process counteracts this to varying degrees. Interesting to observe is that the relative performance of CFRTP seems stronger in this study, likely due to including the recycling of CFRTP manufacturing waste, as opposed to incineration. A result of the present study is that, even when excluding use, the aluminium alloy rib is the optimal choice in only a few impact categories. This is contrary to the studies of Timmis et al. [14] and Scelsi et al. [31], who report composite manufacturing as having an overall much larger impact. Two aspects should be pointed out here: (1) these studies only report LCIA results using a single-score metric, making a direct comparison difficult and (2) these studies assumed a lower buy-to-fly than was assumed here, 8:1 versus 20:1. A comparison can also be made to the work of Markatos and Pantelakis [16], who consider lightweighting and recyclability in light of future energy carriers. Their results suggest that, depending on the priorities set, a heavier, recycled material is preferred over a lighter, linear material. The results of the present study deviate from theirs in a few ways. Firstly, Markatos and Pantelakis assume hydrogen propulsion reduces climate change impacts by 90%. The present study estimates that this would be closer to 60% (although, of course, still very dependent on the temporal scope). Furthermore, Markatos and Pantelakis do not consider the effects of the energy transition on future cradle-to-gate and end-of-life phases, unlike the present study. To explore these differences, sensitivity analysis is performed on the prospective aspects of this study (see Section 9.1.3).

8.6. Additional verification

The interpretation phase contributes to the verification and validation of the study. In this case, validation only encompasses a limited expert review and a comparison to literature. On the other hand, a variety of verification steps were conducted throughout the study. This includes reflections on the contribution analyses, consistency checks, sensitivity analyses, which can reveal ways in which the created LCA models deviate from their intended functioning. These steps themselves, and what these contribute to the understanding of the final model, are reported elsewhere in this thesis. This section takes a moment to discuss what these and other steps – which are not explicitly reported elsewhere – have contributed to verification.

The contribution analyses presented in Chapter 7 include some unexpected results. At this stage, these results can each be explained. During earlier iterations, trying to explain such unexpected results also revealed errors. For example, when autoclave consumables were first shown to have a large contribution to certain impact categories, investigating this revealed that an incorrect conversion was used in constructing one of the unit processes. Fixing this drastically decreased the contribution of autoclave consumables. What remains of this large contribution can be explained.

As mentioned by Guinée et al. [76], reporting steps can have a secondary benefit of contributing to verification. Guinée et al. [76] mention this with regards to flowcharts of product systems and their corresponding inventory models. As the inventory models evolve throughout the study, cross referencing economic exchanges with the flow charts reveals inconsistencies which can be resolved. Another activity is the reporting within this thesis (e.g., Appendix B and Appendix C): as this documentation involves going over each unit process, the reasoning followed during data collection activities is reflected on again. This way, errors were identified in copying calculated inventory values to the Activity Browser inventories, which could then be rectified.

Steubing and de Koning [73], in the discussion of their superstructure approach to scenario modelling, point out that repeatedly changing inventory values is error prone. Indeed, using SDFs makes these tasks more dependable, while not fully error proof. Because of the approach described in Section 4.2, most key factors affected several corresponding inventory parameters. As part of ensuring all inventory parameters were accounted for, the flowcharts could be used here too as a visual reference.

Verification also took place in the application of SDFs, by comparing the scenario outcomes to the expected outcomes. This was necessary to ensure the SDFs worked as intended, but, when unexpected results could not be explained through the SDFs themselves, it revealed an error in a unit process that had slipped through previous verification steps. Having already performed the scenario analyses, it is perhaps not surprising that the later sensitivity analyses did not result in changes to the model. The sensitivity analyses reported in Chapter 9 reveal that the results are somewhat sensitive to certain modelling choices. However, the extensive discussion and verification of these modelling choices through other mechanisms precludes further adjustments.

9

Sensitivity analyses

Data gaps and subjective modelling choices are inevitable in any LCA study. While these choices may be made unconsciously or left unexpressed, they are inherently tied to the study's outcome. The previous chapters identified several data gaps and modelling choices which warrant quantitative analysis. In sensitivity analysis, factors which were uncertain during the LCI phase or which appear particularly critical during later phases are changed, to reflect on how sensitive the LCIA results are to the uncertainty range of this factor. In Appendix F and Appendix G, factors of interest for sensitivity identified so far are collected, and alternative values/approaches/choices/etc. are determined. This chapter presents a brief overview of this process, its results, and what insight this brings to the study. Sensitivity analysis is broadly divided into two parts here, concerning either the LCI phase or the LCIA phase.

9.1. Sensitivity analyses of LCI choices

The following sections discuss sensitivity analyses of the LCI choices made in Chapter 6. This includes how waste is processed, the consideration of multifunctionality, the consideration of process inputs based on literature, and characteristics of the prospective background data used. Several of these factors are then combined in a generalised break-even analysis.

9.1.1. Waste and multifunctionality

This research aims to understand the potential benefits of recycling aerostructures. As such, the consideration of multifunctionality plays a big role. As discussed previously, such as in Section 8.1, the approach used here has conceptual downsides. To understand the relevance of these downsides, alternative approach to multifunctionality are explored. In Figure 9.1, the effect of the CFF and the prospective approach to end-of-life are illustrated for the recycling of composite waste. The CFRTP rib can benefit more from substitution than the CFRTS RTM rib can, but this is also somewhat tempered by considering end-of-life waste in a prospective background system. Without this prospective background system, the CFRTP rib could be framed as having an impact close to zero, due to the ease with which CFRTP scrap can be recovered as a good. However, as the production of primary CFRTP becomes less environmentally intensive in future decades, creating CFRTP today to use 30 years later is less beneficial than one might initially expect. This is illustrated and discussed with additional results

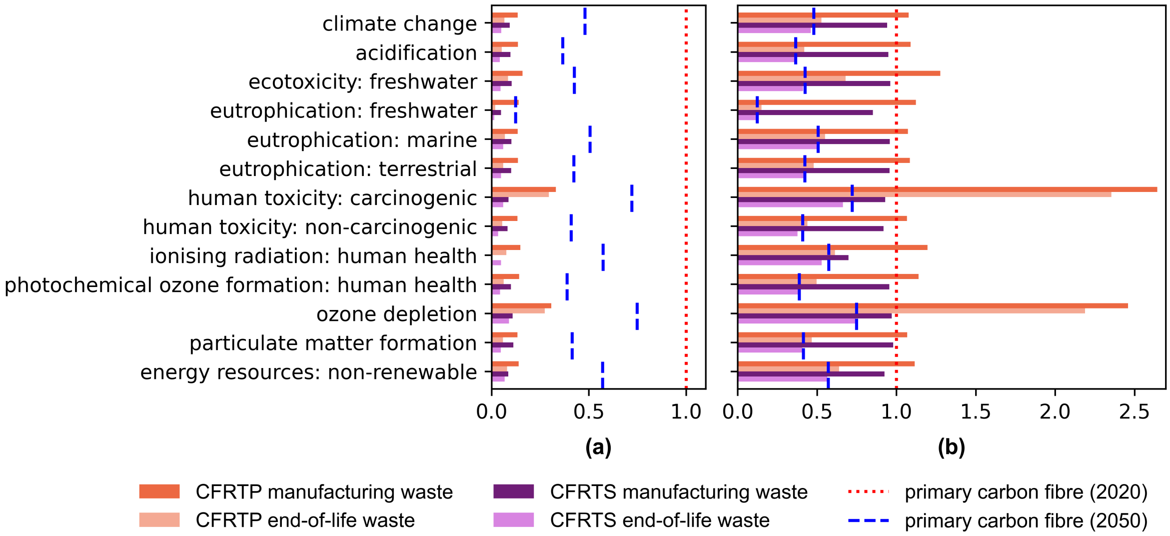

Figure 9.1: Magnitude of net environmental credits from waste treatment in the circular scenario with respect to the impacts of primary carbon fibre, allocating credits using **(a)** the CFF as applied here and **(b)** the full substitution of the recyclate, assuming no quality loss. Note that the credits for CFRTP waste reflect CF/PEKK and not just carbon fibre. Because of the energy transition, impacts in material resources: metals/minerals and land use increase in 2050. To improve the readability of the graph, these impact categories are not shown, but can be found in Appendix H.

in Section G.1. As could already be deduced from the scenarios (see Section 7.5), the aluminium alloy is not only sensitive to what waste treatment is considered, but also how it is accounted.

9.1.2. Processes and inputs

The construction of lifecycle inventories involved many assumptions and several cut-offs. From discussions in, for example, Section 6.3.5 and Section 8.2, it becomes clear that there are several notable sources of uncertainty in the product systems, typically driven by a lack of relevant data. Appendix F explores a number of aspects of this. For example, Section F.1 compares the material production processes used here to those from literature. This reveals that there are some notable differences – the impacts of aluminium alloy could be lower, PEKK could have considerably higher or lower impacts, as is the case for carbon fibre – but overall, the available data is too limited to enable a sensitivity analysis centred around material production. The manufacturing processes, on the other hand, do have some relevant data available, for which values are collected in Table G.1. Figure 9.2 illustrates the effect of changing manufacturing values in three set-ups: (1) choosing the lowest option for each value; (2) choosing the values used in Chapter 6 and Chapter 7; and (3) choosing the highest option for each value.

Another factor of interest is the buy-to-fly ratio. The creation of waste – and resulting mass-balancing of on-site material requirements – was largely based on the reports of Stefanidi [1]. First of all, it can be said that these values result in higher buy-to-fly ratios than the averages reported elsewhere in literature. Bachmann, Hidalgo, and Bricout [41] report average values for composites around 1.5:1; see Section B.2.1 for reports on aluminium alloy, which has averages around 8:1 [14]. The effect of changing the buy-to-fly ratio is illustrated in Figure G.2. The lifecycle impacts excluding use for all alternatives would benefit substantially from a reduction in waste, through a combined demand for both primary material production and waste treatment services. These benefits only have a slight impact on lifecycle impacts including use, with eutrophication: freshwater seeing slight improvements across

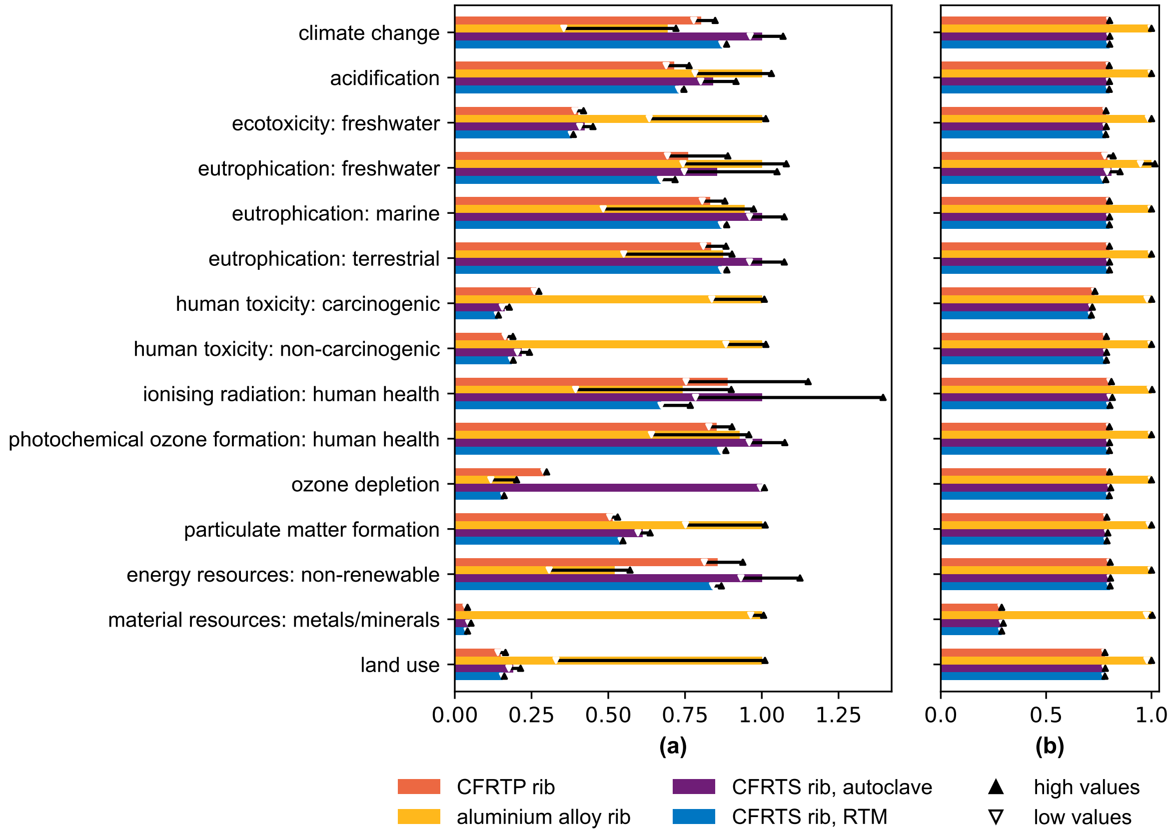

Figure 9.2: Comparison of characterisation results of three cases, based on the values presented in Table G.1, for each alternative using the highest values, lowest values, and values the values used in Chapter 7. Results are shown for **(a)** the lifecycles excluding use and **(b)** the lifecycles including use.

alternatives and the substantial reduction in impacts of the aluminium alloy rib on material resources: metals/minerals extending to the lifecycle including use.

Thirdly, there is the value used to quantify mass-induced energy demand, 4.47 GJ/kg-year, determined in Section B.6.3. Van Grootel et al. [33] reports the range of possible values as 3.33 GJ/kg-year to 10 GJ/kg-year. The effect which this range of values might have on the comparison of alternatives is not particularly interesting when assuming all composite components have an equal mass. It is therefore considered as part of the sensitivity break-even analysis (see Section 9.1.4).

9.1.3. Timeline and pathway of prospective assessment

As sensitivity, two dimensions of the prospective assessment are altered. On one hand, shifting the manufacturing to end-of-life timeline from 2020-2050 to 2040-2070. This is a realistic time frame for the component at hand to be in series production [T. de Bruijn, personal communication, May 11, 2023] and it is only from 2035 onward that hydrogen could be getting a foothold as aviation energy carrier (see, e.g., Airbus [119]). Secondly, the pathway used here, SSP2-NDC, is changed to two alternative ones, SSP2-PkBudg500 and SSP2-NPi, again based on scenarios of REMIND (see Sacchi [109]). The former pathway is highly ambitious, with global emissions in line with the 1.5 °C target of the Paris Agreement. The latter pathway is less ambitious than the NDC scenario and is based on current national policies. These changes are implemented in a similar way to the original method described in Section A.1, using *premise* (v1.4.2).

The results of this sensitivity analysis are shown in Figure 9.3 for the 2020-2050 temporal scope and in Figure 9.4 for the 2040-2070 temporal scope. The full characterisation results can be found in Appendix H. As can be seen, up to 2050, which pathway is chosen has a limited effect on the lifecycle excluding use. It was shown in Section 9.1.1 that placing end-of-life in the future does have a noticeable effect, but it turns out that, in this case, the difference between futures considered matters little. However, there are some notable changes to the use phase, particularly reflected in climate change. It makes sense that climate change is most affected, as this is the impact category which REMIND – and IAMs more generally – focus their environmental integration on. However, this does have consequences for the analysis (see Section 11.1.1). There are more notable changes when shifting the timeline forward. Already in the lifecycle excluding use, the difference in outcomes is noticeable. However, this difference affects each alternative similarly. Of course, the same can be said for the lifecycle including use. What is notable here is that the impacts for the SAF scenario are quite similar across pathways. This is because the main impacts of SAF production come from the fuel supply chain (particularly, the collection and management of biomass), rather than electricity generation, as is the case for hydrogen. Also notice that the PkBudg500 pathway results in net negative emissions for the hydrogen scenario here. This does not mean that flying becomes burden free – as is evident from the other impact categories. It should also be taken into account that these figures imply a particular supply and demand of energy carriers, with the PkBudg500 scenario describing a drastic reduction in fuel production for the European region [109]. To summarise, changing the temporal scope creates clear differences. However, differences between pathways for a particular scope are limited to a few impact categories, of which climate change is a primary example, due to the approach of the prospective database.

9.1.4. Generalised sensitivity of break-even masses

To compare the 2.1 kg CFRTP rib to the ribs for which component mass was estimated, Section 7.7.3 determined for which mass an alternative has the same impact as the CFRTP rib in a given impact category. This results in the break-even masses for each of the three energy scenarios considered there. In the previous sections, several additional factors of interest were identified which change the outlook of this approach. To analyse how sensitive the break-even analyses are to LCI choices, break-even analyses are performed for generalised alternatives under a range of scenarios, as elaborated in Section G.4. Note that these are no longer the wing ribs, but generalised components made from CF/PEKK, CF/epoxy, and aluminium 7075. The results of this analysis are illustrated in Figure 9.5 and Figure G.4 with a focus on small mass differences; larger mass differences are visualised in Figure G.3 and Figure G.5. Which scenario the extreme cases depict is listed in Table G.2 and Table G.3.

9.2. Sensitivity analyses to LCIA choices

The sensitivity to the LCIA methods used is evaluated in two ways. Firstly, by considering alternative climate change methods, which do not make the adaptations based on Sacchi et al. [24] and Lee et al. [8] used here (see Section B.7). A comparison of climate change methods is provided in Figure 9.6. This overview includes the method proposed by the authors of *premise*, as well as the IPCC 2013, EF, and ReCiPe methods. Comparing the lifecycles excluding use in Figure 9.6(a), the most notable difference is found for the aluminium alloy rib. This is because, for this product system, a relatively large share of greenhouse gas emissions is non-fossil methane, from activities such as municipal waste incineration, connected in the background system. Each of the methods has slightly different ways of accounting for

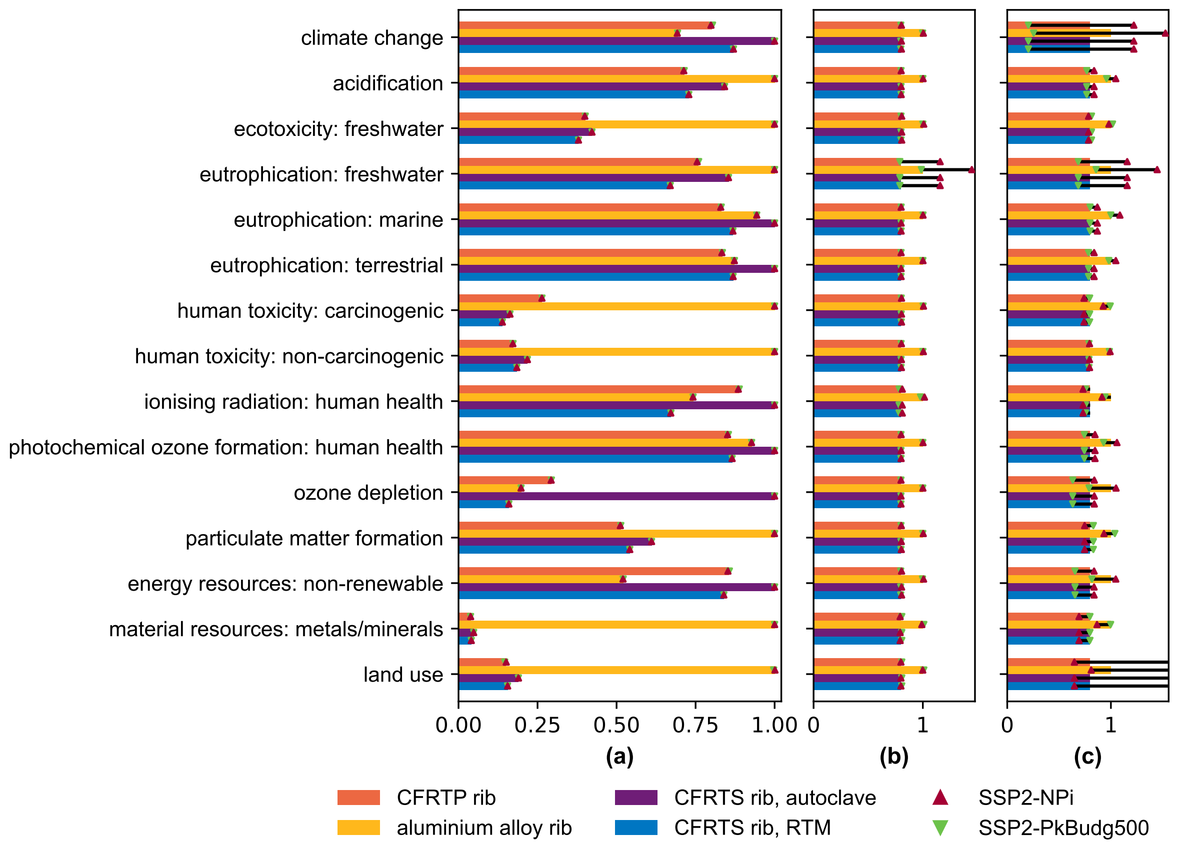

Figure 9.3: Comparison of characterisation results of the SSP2-NPi and SSP2-PkBudg500 pathways compared to the original SSP2-NDC pathway, all for a temporal scope of 2020-2050. Results are shown for **(a)** the lifecycles excluding use, **(b)** the lifecycles including use in the SAF scenario, and **(c)** the lifecycles including use in the hydrogen scenario, each scaled to the highest impacts using SSP2-NDC and the respective energy carrier, resulting in some impacts not being fully visible. Full results can be found in Appendix H.

non-fossil methane, which is one of the factors explaining this difference. When comparing the energy scenarios in Figure 9.6(b), the classification of hydrogen and water can be seen to have a noticeable, but relatively minor effect on the hydrogen energy scenario. However, the additional classifications of high-up emissions such as NO_x can be seen to have a clear effect. On this note it is good to recall that (1) climate forcing from aviation-induced cloudiness were excluded in this assessment and that (2) the characterisation of NO_x is relatively uncertain, due to the localised nature of short-lived climate forcers.

As another sensitivity analysis, the LCIA family of characterisation models chosen here, from the Environmental Footprint method, is compared to another family, ReCiPe, in Section G.5. This comparison reveals differences in several impact categories, with the most prominent examples being found in freshwater ecotoxicity, marine eutrophication, and particulate matter formation. Differences in classification and characterisation methods lead to changes in relative performance, affecting both the analysis for lifecycles excluding use, as well as the comparison between energy scenarios. This highlights the uncertain and incomplete representation of environmental impacts in quantitative assessments. It would be imprudent to discard these impact categories because of the differences identified. However, these differences are reflected in the discussion.

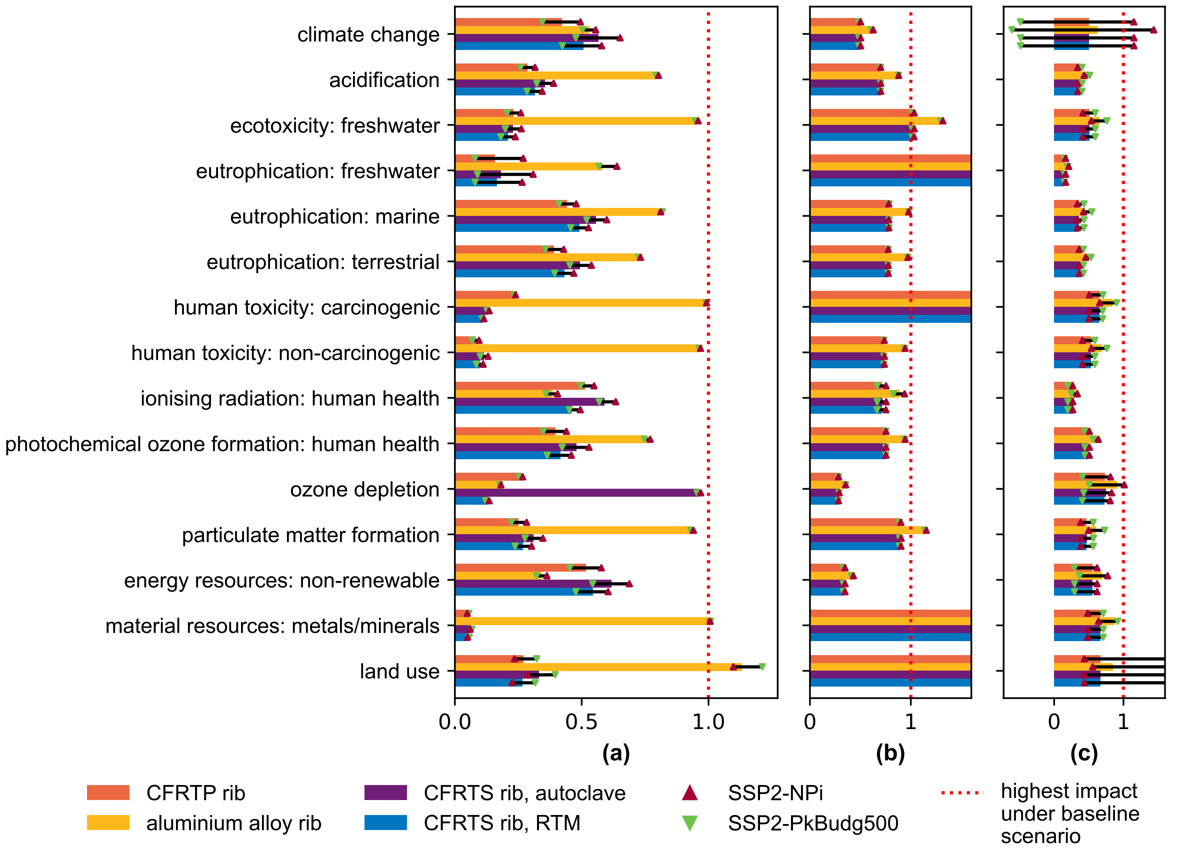

Figure 9.4: Comparison of characterisation results of the SSP2-NPi and SSP2-PkBudg500 pathways compared to the original SSP2-NDC pathway, all for a temporal scope of 2040-2070. Results are shown for **(a)** the lifecycles excluding use, **(b)** the lifecycles including use in the SAF scenario, and **(c)** the lifecycles including use in the hydrogen scenario, each scaled to the highest impacts using SSP2-NDC (2020-2050) and the respective energy carrier, resulting in some impacts not being fully visible. Full results can be found in Appendix H.

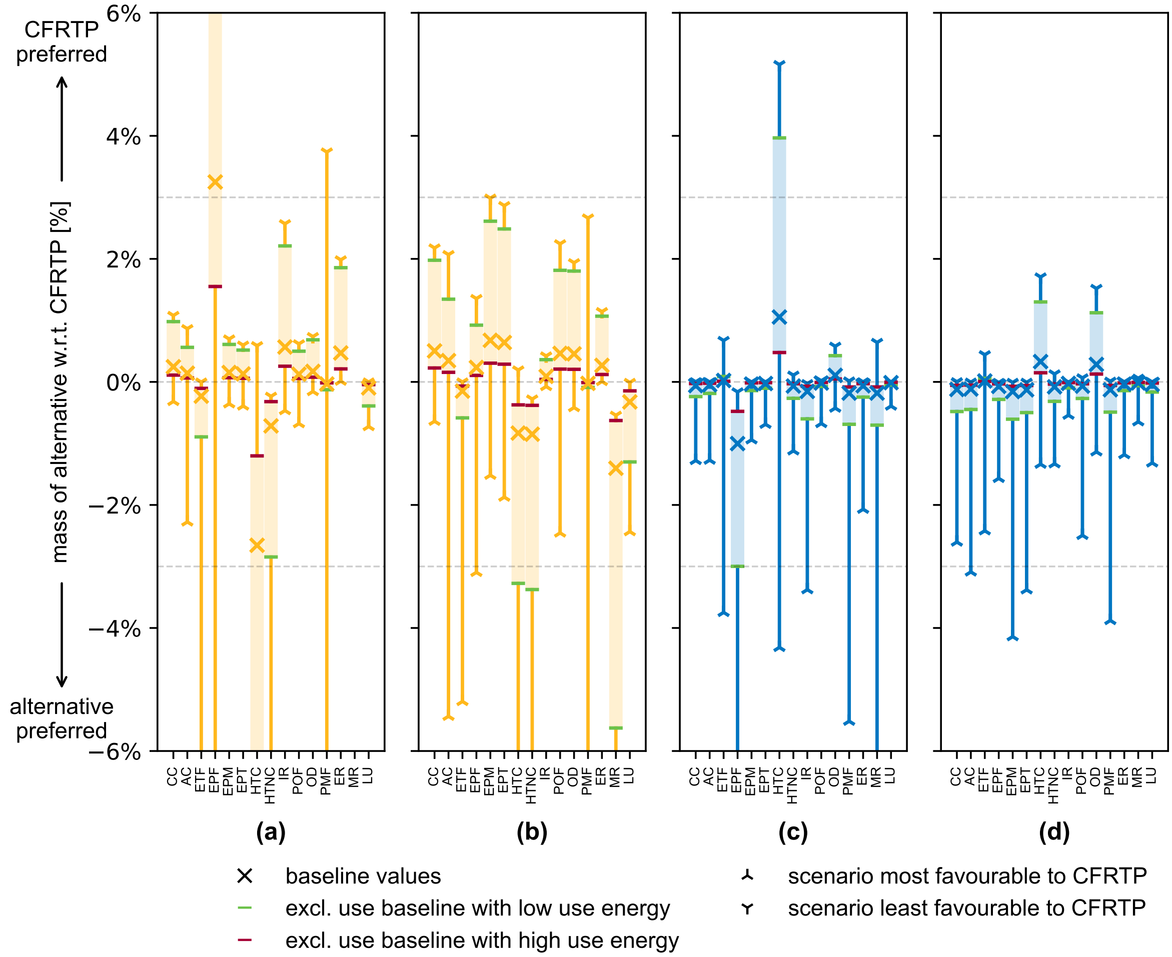

Figure 9.5: Generalised break-even masses using the 2020-2050 temporal scope and NDC pathway for **(a)** aluminium alloy using the SAF scenario; **(b)** aluminium alloy using the hydrogen scenario; **(c)** CFRTS using the SAF scenario; and **(d)** CFRTS using the hydrogen scenario, as elaborated in Section G.4. Dashed lines indicate a mass difference of $+3\%$, 0%, and -3%, respectively, from top to bottom. The y-axis is limited to improve readability, but an alternative visualisation is presented in Figure G.3.

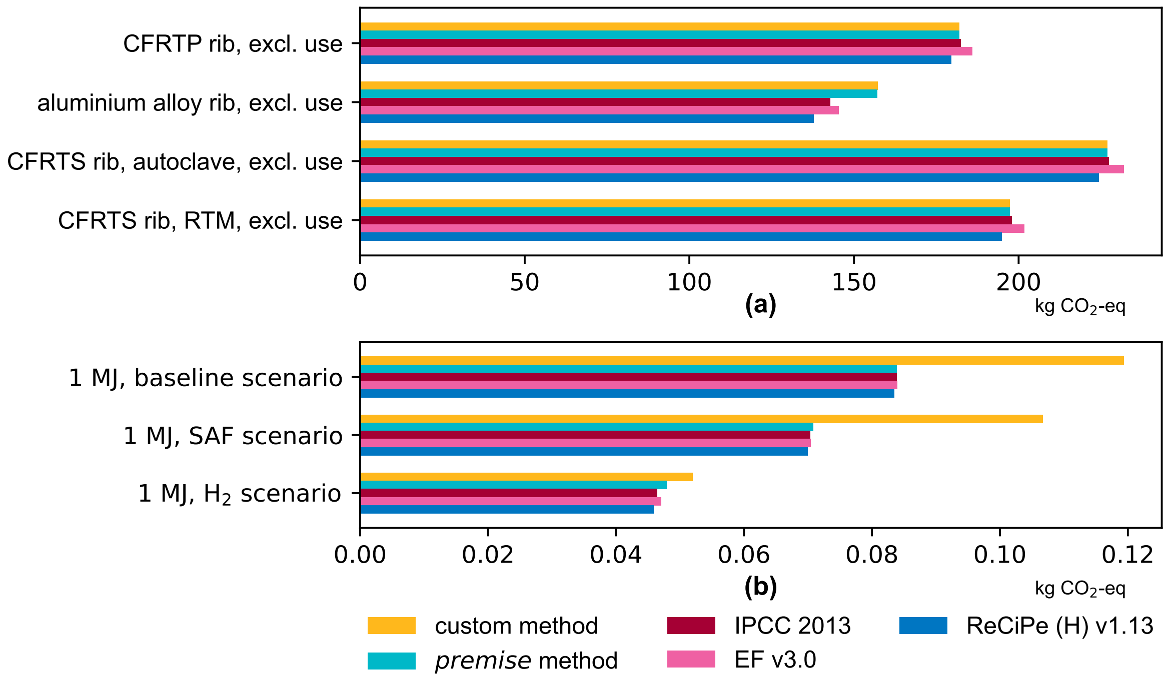

Figure 9.6: Comparison of climate change characterisation results for **(a)** the lifecycle excluding use of the alternatives, scaled to 1 wing rib; and **(b)** 1 MJ of mass-induced energy in the three energy scenarios, covering well-to-wake.

III

Discussion and conclusion

10
Discussion of results

After constructing cradle-to-grave lifecycle inventories in Chapter 6, the environmental impacts of each alternative were assessed in Chapter 7. Through a range of interpretation steps, in Chapter 8 and Chapter 9, the implications of these impacts were explored further. This completes the analysis required to answer the research questions introduced in Chapter 3. In this chapter, each sub research question is answered, followed by the main research question. For the sake of convenience, these questions are restated when they are treated.

10.1. SRQ1: Comparing competing materials

Considering the environmental impacts of CFRTP aircraft components, how do these compare to those of competing materials?

Comparing the alternatives on their lifecycle excluding use, there are impact categories which clearly favour the aluminium alloy rib and there are those which favour the composite ribs (see Figure 7.1). Aluminium alloy appears to primarily have advantages regarding climate change and energy resource consumption. In several of the impact categories where the composites are favoured, the impacts of the aluminium alloy rib are multiple times higher – such as in human toxicity and freshwater toxicity impact categories. This effect is even larger when using the ReCiPe family instead of the EF family (see Section G.5). However, it should be kept in mind that the quality of reporting for metallurgical processes is much higher than that of the production processes for composite materials, particularly carbon fibre. Because of this, impacts relating to the composite ribs could be greatly underestimated. This is discussed further in Section 11.1.1. Comparing the CFRTP rib to the CFRTS alternatives, three main observations are that:

1. autoclave consumables have a sizeable impact, the lack of which is a primary advantage of out-of-autoclave processes (see Section 7.4);
2. on-site energy consumption and buy-to-fly ratios play a large role in determining cradle-to-gate impacts (see Figure 9.2 and Figure G.2, respectively);
3. the environmental impacts of PEKK and epoxy differ to varying degrees, which is particularly noticeable for the impact categories human toxicity: carcinogenic and ozone depletion, where PEKK has a higher impact (see Figure 7.3).

Particularly the sizeable stream of manufacturing waste is noticeable. Because of these streams, what waste treatment strategy is assumed – and how it is accounted for – is highly influential to which alternative is preferred when excluding use (see Section G.1). This is discussed further in relation to SRQ2. When use is included, the component mass becomes the dominant factor, with even small changes in mass being sufficient for any one alternative to be favoured over another in the majority of impact categories (see Section 7.6 and Section 9.1.4). This is discussed further in relation to SRQ3.

In short, how CFRTP aircraft components compare to competing materials can only be judged when the situation in which they are compared is clear. When masses can be assumed to be near-identical, understanding the generation and treatment of waste becomes important. Furthermore, there is a select number of impact categories which shows large differences between materials. This should not be neglected.

10.2. SRQ2: Recyclability

Considering the environmental impacts of CFRTP aircraft components, how are these affected by recyclability?

It is clear from the analysis of scenarios, contributions, and break-even masses of Chapter 7 that the environmental benefits that can be gained from recycling are much smaller than the environmental benefits which could be gained from minimal lightweighting, with a mass difference of 1-2% being enough to make any one alternative preferable over another. Assessing break-even masses more broadly, there are cases where a 2% difference would be insufficient to determine a clear preference, bringing this value to around 3% for a 2020-2050 temporal scope, or around 5% for a 2040-2070 temporal scope (see **??**). This is discussed further in relation to SRQ3.

From the lifecycle perspective of this study, there appears to be little incentive to avoid primary carbon fibre, if this would lead to any noticeable increase in mass. However, as introduced in Section 1.2, CFRTP scrap could be used as cost-effective lightweighting material. I.e., there is no displacement of primary CFRTP, but of another material, typically a metal alloy. From the results of this study, such potential applications become a clear priority for further research. Currently, it is still uncertain how much potential there is for such lightweighting, as this varies from component to component [T. de Bruijn, personal communication, July 27, 2023]. Furthermore, understanding this effect would require a more consequential study than the one performed here. This is discussed in Section 11.1.5.

There are also studies which neglect the use phase. This thesis clearly shows that this practise severely limits the perception of environmental impacts. There are cases in which the use phase is less relevant – e.g., when components are expected to have identical masses and/or when dealing with an application less fuel-intensive than aviation. For example, Stelzer et al. [44] examine the use of secondary carbon fibre to replace primary carbon fibre in an automotive component. This results in a mass increase of around 1%, while still decreasing impacts across the lifecycle. This thesis can also provide insight to such applications. First of all, it was observed in the lifecycle excluding use of alternatives that waste indeed plays an important role. This is particularly the case for manufacturing waste, which has at times been neglected in previous studies (see Section 2.1.1). Secondly, because the creation and disposal of waste is so important from this perspective, it is also important to reflect on how this waste is accounted. As demonstrated in Section 9.1.1, scenarios which are ostensibly quite similar can end up with results differing by several factors, simply because of how multifunctionality is resolved. This is not unexpected. However, of the articles analysed by Keiser et al., a small minority report their system model (13%) or allocation method (24%) [30, p. 12]. Based on the present study, when it is relevant to the goal of the study to evaluate the manufacturing and disposal of components, it is implicitly relevant to consider waste. Although composite recycling is a hot topic, discussion of its accounting and position regarding environmental impacts more broadly has been limited thus far.

What also stands out is that, for the alternatives compared here, manufacturing waste is much more impactful than end-of-life waste. To illustrate the influence of the buy-to-fly ratio, compare Figure G.2 and Figure 9.2: reducing manufacturing waste can influence impacts to a larger degree than the uncertainty in manufacturing on-site energy demand does. It therefore makes sense to place a larger focus on the reduction of waste, rather than its treatment. For composites this is true because of the quality loss associated with even state-of-the-art waste treatment, while for the aluminium alternative this is true because of the very high buy-to-fly ratio. The stream of end-of-life waste is not only relatively small, but it also has a lower potential benefit than present-day waste does. This is because material created today generally has higher environmental burdens than the primary material it might replace in the future (see Figure 9.1). This observation was also made by Šimaitis, Allen, and Vagg [120] on the topic of end-of-life batteries.

To summarise, the recyclability of CFRTP had limited quantitative impact on the results of this thesis. This is primarily because of the dominating influence of mass-induced energy demand on the lifecycle. To a lesser extent, the relevance of recyclability is further decreased due to the quality loss of mechanical recycling and the decreased benefits of end-of-life recycling when comparing present-day and future material production. At the same time, these results do not indicate that composite recycling is irrelevant. First of all, there is ample opportunity to explore how CFRTP scrap – a relatively low-cost composite material – could enable further lightweighting. Secondly, in other applications, such as in the automotive sector, the use phase is less intensive. This provides more space for possible trade-offs surrounding circularity, which can make use of the approach used here.

10.3. SRQ3: Aircraft use

Considering the environmental impacts of CFRTP aircraft components, how are these affected by aircraft use?

It is clear that mass-induced energy demand and resulting emissions play a large role. The break-even analysis of Chapter 7 shows that two alternatives cannot have a mass difference of larger than around 2% to be at all competitive in a comparative analysis, even in a hydrogen-powered scenario. Looking at break-even masses more broadly, as was done in Section 9.1.4, this range remains fairly constant, even when shifting the whole lifetime ahead to a more decarbonised energy system. However, Section 9.1.4 also shows that which alternative is preferred can change depending on the use intensity, waste disposal, and mode of analysis. This leads to particularly large ranges for the break-even mass when comparing CFRTP and aluminium alloy, exceeding -5% to $+5\%$, and several reaching lower than -20% (meaning that an aluminium alloy part could be 20% lighter than a CFRTP part and still perform worse in these impact categories). When comparing CFRTP and CFRTS, these ranges are smaller, with a minority exceeding -2% to $+2\%$. What can be noticed here is that, under the circumstances which are the most favourable to CFRTS, the break-even mass difference with CFRTP is around 0%. On the other hand, under the circumstances which are the most favourable to CFRTP, the break-even mass difference to CFRTS is $> 1\%$ in many cases. This indicates a budget in which a heavier recyclable component is preferred over a lighter component that is incinerated, particularly if the heavier component was already made from recycled material itself. As was discussed in relation to SRQ2, this budget is extremely small for aviation, but can be expected to be larger for other sectors, such as automotive.

10.4. SRQ4: Energy transition

Considering the environmental impacts of CFRTP aircraft components, how are these affected by the energy transition?

Within the energy transition, a pathway can be forged to low-impact aviation fuels. This study showed that the current development of drop-in fuels means that fossil kerosene will still dominate the lifecycle of components entering operation today (at least, for most impact categories). When considering hydrogen propulsion or when looking even further into the future, the climate change impacts of the use phase drop considerably. However, even with a sharp decrease, these impacts are still much larger than those of the lifecycle excluding use (see, e.g., Figure 9.4 and Figure E.2). As discussed in relation to SRQ3, prospective analysis of aviation fuels is relevant to lightweighting. Furthermore, new trade-offs emerge, as these alternative energy carriers can have higher impacts on human health (ionising radiation and particulate matter formation), material resources: metals/minerals, and land use. However, beyond stating that these impacts are likely to emerge, little can be concluded about their prominence or severity. Particularly the hydrogen-powered scenario is heavily simplified, yielding results which cannot be fully understood within the scope of this thesis. Still, the orders of magnitude involved are clear. Even when assuming aircraft use intensity far below the lifetime limits, the role of lightweighting in the use-phase outweighs any potential increase or decrease of impacts elsewhere in the lifecycle (see Figure 7.10). One exception was identified using the PkBudg500 pathway, in which hydrogen use has a net-cooling effect on climate change, due to carbon capture in the energy system (see Figure 9.3). This is notable, but should be considered in a context of energy availability, which is part of the discussion of Section 11.1.5.

Another product of the prospective assessment is placing end-of-life in the future. This was discussed in the context of SRQ2. In short, future recycling has its benefits, but these are limited. This is, on one hand, because the stream of end-of-life waste is smaller than other mass flows in the product systems. Secondly, future production of primary materials is cleaner than current production. Because of these two factors, the potential impacts that can be mitigated through end-of-life recycling are small when compared to other possible improvements, such as reducing manufacturing waste.

10.5. SRQ5: Impact reduction

Considering the environmental impacts of CFRTP aircraft components, how can these be reduced?

As was already discussed with respect to SRQ3, perhaps the largest strength of CFRTP lies in its potential for lightweighting. Even in scenarios where environmental impacts of aviation have drastically been reduced, it appears that not much lightweighting would be necessary for CFRTP to become the preferred material. This creates synergy with the discussion of SRQ2, which noted that the recyclability of CFRTP brings limited benefits on its own, but that overall benefits can be influential when new opportunities for lightweighting can be capitalised on. From another perspective, evaluations such as shown in Figure 9.1 and Figure G.2 illustrate that, rather than recycling waste, it is considerably better not to produce waste at all. At the moment, the buy-to-fly ratio of the CFRTP rib is relatively high, which the cut-outs in the rib geometry contribute to. Strategies to reduce off-cuts could reduce environmental impacts. For example, by keeping the cut-outs in mind when forming the component, to reduce material use. Finally, there are several environmental impact categories in which the CF/PEKK material performed relatively poorly: ozone depletion and human toxicity: carcinogenic, due to the PEKK production chain. These impacts make sense, given the chemical makeup of PEKK, and can be expected to appear for other polymers containing phenylene rings. These impacts warrant further investigation to evaluate what environmental risks can be mitigated. This is discussed as part of Section 11.1.1 and Section 11.2.

10.6. Main research question

Considering the case study of a CF/PEKK wing rib, how can CFRTP improve the environmental performance of commercial aircraft?

Each sub-question provides its own perspective in answering the main research question. Across these perspectives, there are many unique observations, but also a few common themes. When considering the ribs by themselves, lightweighting is the most important factor. Although factors relating to manufacturing waste can be influential when considering the cradle-to-gate, a small mass difference is enough to change the use phase in such a way that other lifecycle phases become irrelevant. How large a mass difference should be for this to be the case was found to be around 1.5% across scenarios. It is larger when accounting for possible differences during the sensitivity analysis, increasing it to around 3% for a 2020-2050 temporal scope, and even more (around 5-10%) with a 2040-2070 temporal scope. Within these boundaries, it appears that there could be cases in which the environmentally preferable course would be to suffer a very small increase in component mass to reduce impacts in other lifecycle stags. That being said, the main strength of CFRTP over CFRTS could lie in its manufacturing waste, should it be used to enable new avenues for lightweighting. This was not something directly evaluated in this thesis, but this would be a highly valuable topic for future research. These conclusions are summarised as a decision tree in Figure 10.1.

Before this thesis can reach its conclusion, Chapter 11 reflects on the main limitations of this work. Next, recommendations are given to researchers (see Section 11.2) and to industry stakeholders (see Section 11.3).

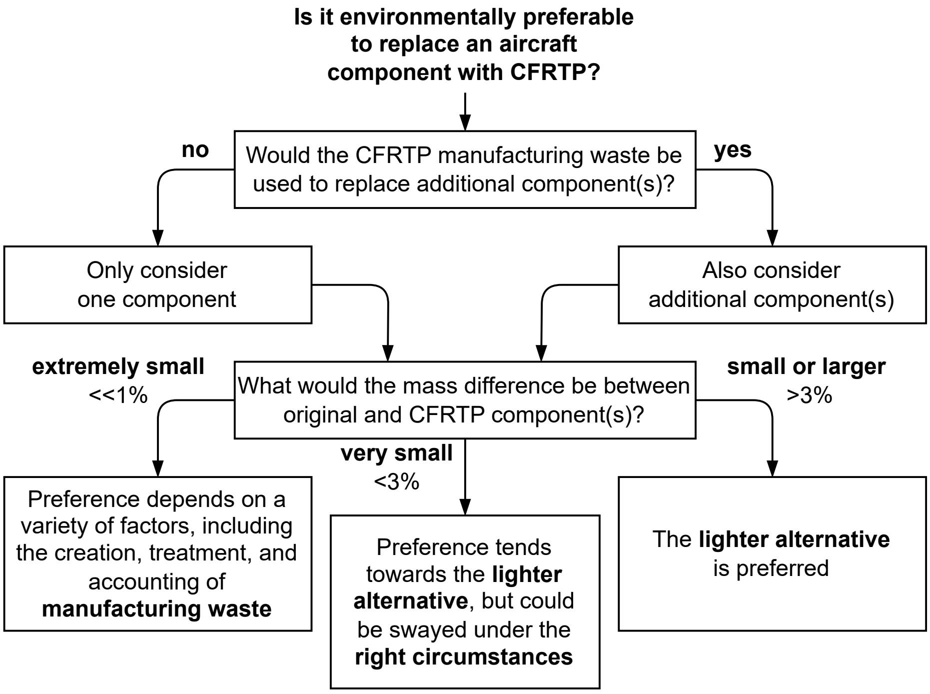

Figure 10.1: Decision tree summarising when CFRTP would offer environmental benefits, based on the insights obtained in this thesis. For a mass difference between alternatives to be very small, it must be no more than roughly 3% under the 2020-2050 temporal scope. This value does not hold for a 2040-2070 temporal scope. These mass differences go both ways, whether the original component(s) are lighter or heavier. Note that the analyses of this thesis did not include system expansion to additional components and that observations on this topic are inferred.

11

Limitations and recommendations

Chapter 10 synthesised how the results obtained in this thesis can be used to answer the research questions laid out in Chapter 3. However, before this thesis can be concluded, the limitations of the research are compiled and discussed. After this addition, recommendations are formulated.

11.1. Limitations

Based on the previous chapters, many limitations were identified. These are discussed in the following sections based on a few overarching themes.

11.1.1. There is little primary data and much uncertainty

Across Chapters 8, 9, and 10 and Appendices B, F, and G, limitations regarding data availability and quality were identified. This section summarises this first for the cradle-to-gate lifecycle and in the paragraph after for the prospective lifecycle phases, with a focus on use-phase fuel production.

Data quality is sub-optimal for activities such as carbon fibre production and PEKK production. The manufacturing processes in particular required several cut-offs to be made. Although some data was available to inform the manufacturing processes, this differed per alternative and included limited data on energy consumption. These processes also change over time, so reporting from previous decades – or even today – might not hold up in the coming years. These factors were explored in the previous chapters. Being aware of them, their relevance to this research can be accounted for when drawing conclusions. However, for future research, where it might be important to obtain a higher resolution, such data would need to be improved.

The inventories of alternative energy carriers must be approached with caution for a variety of reasons. Elements such as the use of purpose-grown biomass, the introduction of carbon capture, utilisation, and storage technologies, and the accelerating use of renewables such as wind and solar are each nuanced subjects. This nuance was beyond the scope of this thesis, but is still relevant. Furthermore, considering that these are emerging technologies, their performance is expected to improve in the coming decades – but the degree to which this happens is unknown. Basic fuel production processes were used here, but plant designs such as the one analysed by Habermeyer et al. [121] combine several feedstocks to improve energy and material efficiency. Socio-technological changes in the background system are centred around climate change, as this is the main environmental focus of REMIND – and IAMs more generally. Other impact categories follow the course set in terms of climate change. This resulted in large increases to extractive impacts in particular. Steubing, Mendoza Beltran, and Sacchi [122] describe how, as circularity increases, these impacts could be lower than forecast here. They go on to recommend that improving the environmental scope of prospective databases should be a top priority.

11.1.2. Impact assessment of aviation emissions is underdeveloped

As discussed in Section 2.2, although understanding of the impacts of aviation is growing, LCA practitioners do not yet have the tools to adopt this knowledge. In this thesis, an attempt was made to bridge this gap for climate change impacts: factors calculated by Lee et al. [8] were applied, in a similar way in which Cox, Jemiolo, and Mutel [15] implemented the factors of Fuglestvedt et al. [54] (see Section B.7). However, this means that, while Lee et al. and Fuglestvedt et al. provide factors which cover all aviation emissions, the implementation into LCIA only considered emissions above a certain altitude. Another example within climate change is contrail formation, which was considered less relevant to this study and was excluded, but is important to aviation more generally.

Although this thesis consulted several state-of-the-art environmental impact studies, the LCIA method was only adapted for climate change, and even then to a degree which does not fully cover the scope of present scientific knowledge. This illustrates the relevance of the recommendations to LCIA method developers made by Rupcic et al. [23].

11.1.3. The number and scope of alternatives was limited

In this research, a CFRTP component was compared to several reasonable alternatives: one using the material of the component being replaced, aluminium alloy, and two using a competing composite material, CFRTS. These alternatives were selected in conversation with experts, providing a relatively comprehensive scope of contemporary materials which might be used for load-bearing structures such as the wing rib in question. However, there are also other materials and manufacturing prospects on the horizon, including additive manufacturing, bio-based composites, and composites which include recycled carbon fibre. These innovations will not be applied in high-performance materials such as a wing rib – at least for the time being. One might therefore conclude that their exclusion from this research is justified. However, an observation made in Chapter 10 is that the destination of CFRTP manufacturing waste could be very important to the potential environmental benefits of this material. This can be addressed through system expansion to include the additional components manufactured. However, in such an analysis, other innovative alternatives would also need to be included in order to perform a complete analysis. This means that the conclusions drawn in the present study are a reflection on the relative differences between the materials analysed within its scope. It is true that components made from CFRTP scrap could bring benefits without parallels in the other product systems examined, but this does not preclude other (thermoplastic or otherwise) lightweight materials from being better alternatives to components made from CFRTP scrap.

Furthermore, limitations of the scope are reflected in the geographic coverage. The use phase was modelled as only taking place in Europe, while certain stakeholders might find it more relevant to reflect the production of energy carriers on a global scale in this phase. The same can be said of other lifecycle phases. These were primarily modelled using averages for the European region, but even within this region, impacts vary from country to country.

11.1.4. This assessment is not strictly attributional

As discussed in Section 8.1, the approach this study took to multifunctionality means it cannot be described as an attributional assessment. The inventories created here do not truly reflect the attribution of global environmental burdens to the alternatives in question. However, combined with sensitivity analyses, this mode of analysis is not thought to restrict the discussion of Chapter 10. Meaning, it does not limit the ability to answer the research questions of this study. What is limited, is the ability to extrapolate the findings of this study to other studies. As discussed in Section 2.3, LCA results become unreliable when extracting LCIA results from literature, and the sensitivity analyses of this study (e.g., Section 9.1.1) again illustrate how dependent LCIA results are on the assumptions of the study in question. The results of this study cannot be used to make quantitative attributional claims about the wing ribs. Furthermore, the impact assessment values obtained in this study should not be used to characterise product systems in other studies. However, the types of comparison (quantitative and qualitative) conducted in Chapter 8 can be extended to additional studies.

11.1.5. This assessment is not consequential

In addition to the limitation described in Section 11.1.4, this analysis does not encompass the full scope of consequences which the alternatives might bring to environmental impacts. There are several levels on which a consequential approach could have been implemented, but was not. This includes using the consequential ecoinvent system model; estimating the total numbers of components introduced into the sector over time, rather than a single component (see, e.g., Huang et al. [13]); but also having a concrete destination for recycled materials. This last point in particular can be highly influential for CFRTP if its manufacturing or end-of-life scrap could result in further lightweighting benefits. As was discussed in Chapter 10, particularly in relation to SRQ2, the scope of such benefits cannot yet be characterised, which directly impacts the completeness with which the research question can be answered. However, this thesis does identify that this should be a topic of further research (see Section 11.2).

Furthermore, a consequential approach might consider economic markets. Prior to the COVID-19 pandemic, the emissions of the aviation sector exponentially increased over time, while fuel efficiency has steadily improved as well. Some have argued that this is an example of the rebound effect or the Jevons paradox (see, e.g., Evans and Schäfer [123] and Devezas [124]). In short, improving fuel efficiency makes flight more economically attractive, growing the aviation sector and its emissions. Based on such observations, it is clear that improving the environmental performance of an aircraft cannot be directly translated to decreasing emissions across the aviation sector, but might even cause an increase. An analysis committed to consequences must grapple with these phenomena, which are outside the scope of this thesis.

Besides the direct implications regarding environmental impacts, energy and material availability are also relevant to a sector-level perspective. The prospective assessments performed here implicitly carry certain models for the future, which include future activities of the commercial aviation sector. These models must therefore be imagined exclusively with this context in mind. This is particularly relevant for the net-cooling that was observed for hydrogen under the PkBudg500 pathway (see Section 9.1.3). A future which fully dedicates itself to climate change mitigation does not have the bandwidth to drastically increase the energy it spends on flight. These topics are only briefly touched on here, but they are critical to a holistic understanding of the commercial aviation sector.

11.2. Recommendations to researchers

As is typical for LCA studies, data gaps had to be dealt with, which can be explored in future research. These were discussed in Section 11.1.1. Representing the environmental impacts of aviation in LCA also requires more work, as discussed in Section 11.1.2. These should be priorities to researchers who aim to characterise the environmental impacts of particular aerostructures.

For researchers who aim to explore possible pathways for improved environmental performance, several recommendations can be formulated. Firstly, there are several upcoming materials and manufacturing techniques. The position of CFRTP in this emerging landscape is not clear from this thesis alone. Furthermore, this research would have benefited from knowing how CFRTP scrap would be used, so that system expansion could be performed to include subsequent lightweighting effects. To make a quantitative statement about the full benefits of lightweighting, more knowledge is required on such components. These two points – considering a wider variety of alternatives and considering applications of (composite) secondary material – come together to achieve a comprehensive image of circularity prospects. CFRTP scrap is imagined here as a good option for new lightweighting, but bio-composites and additive manufacturing have also been proposed for this same application. Making such a comparison in the future would be useful. Another aspect of circularity, which is currently still lacking from studies such as this one, is that full circularity would require no input of primary materials for load-bearing components such as the ribs examined here. To inform an environmental assessment of how this circularity gap might be closed, additional technological development (manufacturing, recycling, testing, etc.) is required.

Note that the above recommendations are not limited to the study of aviation. Trade-offs between the use-phase and other lifecycle phases can emerge anywhere where lightweighting is relevant. This includes other transportation sectors, such as automotive or shipping, but also technologies which rely on lightweight structures for their performance, such as wind energy. The small mass budget identified here can be expected to be larger for these other applications, providing more stimuli to adopt and improve the approach of this research.

Finally, this thesis briefly touched on research which aims to define pathways for the environmental impacts on a societal or sectoral level. Section 11.1.5 discussed how the environmental performance of a particular component, even when assessed from a holistic lifecycle approach, cannot necessarily be translated to environmental performance on a societal level if the assessment method was not constructed with this goal in mind. Although this is not a novel concept in itself, it does not appear to be represented in LCA literature thus far.

11.3. Recommendations to aircraft manufacturers

It is common knowledge that lightweighting is a key objective in the design and manufacturing of aerostructures. The results of this research suggests that this will continue to be the case, as long as at least a small decrease in mass (around 3%) can be achieved. Based on this observation, the aim of aircraft manufacturers should be to continue the current trend, in which they go to extreme lengths to minimise structural mass.

However, this thesis grappled with many data gaps and analysed just a few alternatives, among other limitations. As discussed previously in this chapter, this means that this research should not be used as basis for a full commitment to CFRTP. A priority for aircraft manufacturers should be to align with researchers (see Section 11.2), to bring the environmental impacts of their supply chains into focus and to determine where environmental gains can be realised.

12 Conclusion

There are several concurrent technological trends in aviation, each of which carry claims of environmental benefit. Against this dynamic background, it is challenging to assess the environmental potential of any one individual development. For aerostructures, the environmental performance of manufacturing and end-of-life are of growing concern, while, at the same time, lightweighting is of the highest priority. The central focus of this research was to tackle these challenges by adopting a novel approach that considers the lifecycle phases of aerostructures against the backdrop of the energy transition.

The review of existing literature on aviation LCA, presented in Chapter 2, identified notable knowledge gaps that hinder a comprehensive and robust analysis. This thesis addresses several of these gaps through detailed collection and reporting of data, innovative scenario modelling, a prospective analysis, and in-depth interpretation. The topic of investigation centred around the case study of a CF/PEKK wing rib. By way of this case study, insight is gained into how the environmental performance of novel CFRTP aerostructures compares to more conventional aluminium alloy or CFRTS structures. This amounts to a comprehensive study, encompassing analyses of waste treatment, mass-induced energy demand, and alternative energy carriers.

The rigorous method employed is a distinctive feature of this research. Accuracy and depth were obtained through an unprecedented combination of primary manufacturing data, novel lifecycle inventories based on industrial chemistry, the use of *premise* to achieve a forward-looking perspective, and an array of specialised characterisation models. The interpretation phase fortified the study, including sensitivity analyses and a pioneering break-even analysis.

From the results, it is evident that lightweighting remains pivotal in shaping the environmental footprint of aircraft products. This observation holds across diverse environmental impact categories, even in scenarios where aviation energy carriers are rapidly decarbonised. CFRTP can make a contribution to lightweighting, both in the form of primary continuous-fibre components, as well as by using CFRTP manufacturing waste to lightweight less critical components. However, if replacing one primary material for another no longer brings substantial mass reductions, this research suggests that there is a very small mass budget to implement low-impact materials. This is summarised in Figure 10.1. Interestingly, the temporal scope and energy carrier considered were observed to have a large influence on the total impacts, but their influence on the mass budget is moderate. This can be attributed to a number of factors. For one, alternative energy carriers do see a large decrease in some impact categories, but this change is not large enough to bridge the orders of magnitude separating the comparatively small impacts of other lifecycle phases. Secondly, alternative energy carriers also bring increased impacts to some impact categories, shifting which break-even points provide upper and lower bounds to the budget. Thirdly, shifting the whole lifecycle into the future does not only benefit the use phase, but also the manufacturing phase, again limiting how much this budget can shift. Particularly the creation, treatment, and accounting of manufacturing waste were identified as influential topics. Comparing materials across impact categories also reveals several hotspots, such as the impact on ozone depletion of autoclave consumables and PEKK, as well as the impact on human toxicity: carcinogenic of aluminium alloy and PEKK.

The identification of a mass range which acts as both a minimum from the perspective of lightweighting and a maximum from the perspective of introducing low-impact materials is a novel achievement. Its relevance is broader than the realm of aerostructures. As discussed in Section 11.2, potential applications extend to any sector for which lightweighting is relevant, spanning across and beyond transportation.

However, it is prudent to acknowledge the existing limitations. Notably, there is a need for further data refinement and broader industry engagement. With further research, the small, murky window created in this work can become bigger and clearer. Furthermore, it is worth reflecting on the meaning of environmental performance more broadly. While this research highlighted how trade-offs between impact categories can occur, this can only be addressed on a societal level when considering what environmental budgets aviation should be allowed. Balancing the interests of diverse stakeholders necessitates interdisciplinary collaboration.

In summary, this thesis advances our understanding of the complex interplay between material choices, socio-technological trends, and environmental impacts in aviation. The emphasis on lightweighting as a primary driver of environmental performance underscores the pivotal role of this research, particularly in the context of emerging materials like CFRTP. The developed method has potential to guide sustainable decision-making across various materials, applications, and sectors. As aviation and other industries navigate the intricacies of environmental responsibility, this thesis offers a valuable compass for informed choices and a solid foundation for future exploration.

IV

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A

Extended scope definition and product system flowcharts

The scope of the LCA study was provided in Section 5.2. This chapter provides a more complete review of certain aspects of this scope. Additionally, Section A.3 presents product system flowcharts which illustrate the system boundaries and model structure for the reference flow of each alternative.

A.1. Prospective background databases

Using *premise*, the ecoinvent 3.8 cut-off system model is transformed into equivalent databases set in future scenarios. As introduced in Section 4.2, this is done here based on the SSP2-NDC pathway of REMIND. SSP2-NDC is chosen here because SSP2 (“middle of the road”) and NDC (naturally determined contributions – a term relating to the Paris Agreement) are considered as a reasonable baseline for future climate action.

Based on this pathway, *premise* can apply several transformations. Here, the “electricity” and “fuel” transformations were applied. This means that electricity and fuel systems are updated, while other systems, such as production of steel and cement, are not. Furthermore, *premise* adds several inventories relevant to this thesis. This includes hydrogen from water electrolysis and several drop-in alternative aviation fuels [109]. Notably, direct air capture (DAC) and carbon capture, utilisation, and storage (CCUS) processes are also introduced, as these often play some role in the pathways described by IAMs. Considering the long use phase, multiple prospective background databases are created to cover its duration. Since it is computationally intensive to create inventories for a given pathway and year, time steps of five years are used (2020, 2025, 2030, etc.). This is discussed further in Section D.3, but is considered to provide a sufficient resolution for further analysis.

Exchanges labelled [premise] in Appendix C connect to one of these prospective background databases. When this is because the process in question relates to component end-of-life, this is a database for 2050. When this is because the process relates to the use phase, this is resolved differently, as explained in Section D.3.

A.2. Coverage in time, geography, and technology

These sections expand on some of the coverage discussed in Section 5.2. Certain aspects are maintained across alternatives and scenarios, while others vary depending on the scenario in question.

A.2.1. Independent of scenario

As the setting up of new production lines is considered, processes are intended to reflect the best available technologies. However, because of the available data, this is often reduced to a technological average. The wing rib is developed in a joined development between GKN Aerospace facilities in the Netherlands and the United Kingdom. The manufacturing site for series production is currently unknown [T. de Bruijn, personal communication, February 13, 2023]. Because of this, the geographical scope is defined as Europe. This typically means using the ecoinvent Europe (RER) region, but sometimes results in the most applicable process being described as Europe without Switzerland, rest of world (RoW), or global (GLO). Europe is also selected as geographic scope for the use and end-of-life phases for each scenario.

Across scenarios, the end-of-life phase takes place 30 years after the manufacturing phase, reflecting the long component lifetime. There are scenarios in which the effect of a shorter or less intensive use phase is explored, but the computational structure of these scenarios does not lend itself well to varying the year in which end-of-life takes place. However, this is investigated as a sensitivity analysis. Additionally, the use of the NDC pathway to construct future background systems, as explained in Section A.1, is also constant across scenarios.

A.2.2. Depending on scenario

The temporal scope and future pathway of the background system remain consistent across scenarios, but the way in which these background systems are connected to the foreground changes. This is done by identifying specific factors, which are translated into inventory parameters. These factors often reflect a particular change in technology – e.g., the adoption of a novel recycling technology, the production of alternative aviation fuel, or an improvement to the design or manufacturing of the alternatives. The *premise* library considers technological improvements (e.g., through learning curves) through set parameters [109]. The way foreground scenarios are structured here does not use learning curves or similar techniques, but represents generic changes to the technologies in question.

The implementation of scenarios is conducted during the LCI phase. It is discussed in Section 6.4, with detailed reporting in Appendix D.

A.3. Product system flowcharts

Figures A.1, A.2, A.3, and A.4 represent the product systems of the four alternatives. To facilitate readability, the majority of the use phase processes are not repeated in these flowcharts, but are instead shown in Figure A.5. Furthermore, the flowcharts illustrate how the alternatives are evaluated when the use phase is excluded: the reference flow then becomes the flow crossing the “excluding use” system boundary into the general system boundary.

The flowcharts are presented following the recommendations of Guinée et al. [76]. Unit processes are represented by boxes and economic flows by arrows. Economic flows which connect to the background system are indicated as orange arrows which stay within the system boundary. For practical reasons, such flows are at times indicated as a bullet list of flows with a single orange arrow. Note that environmental flows are not visualised in these diagrams.

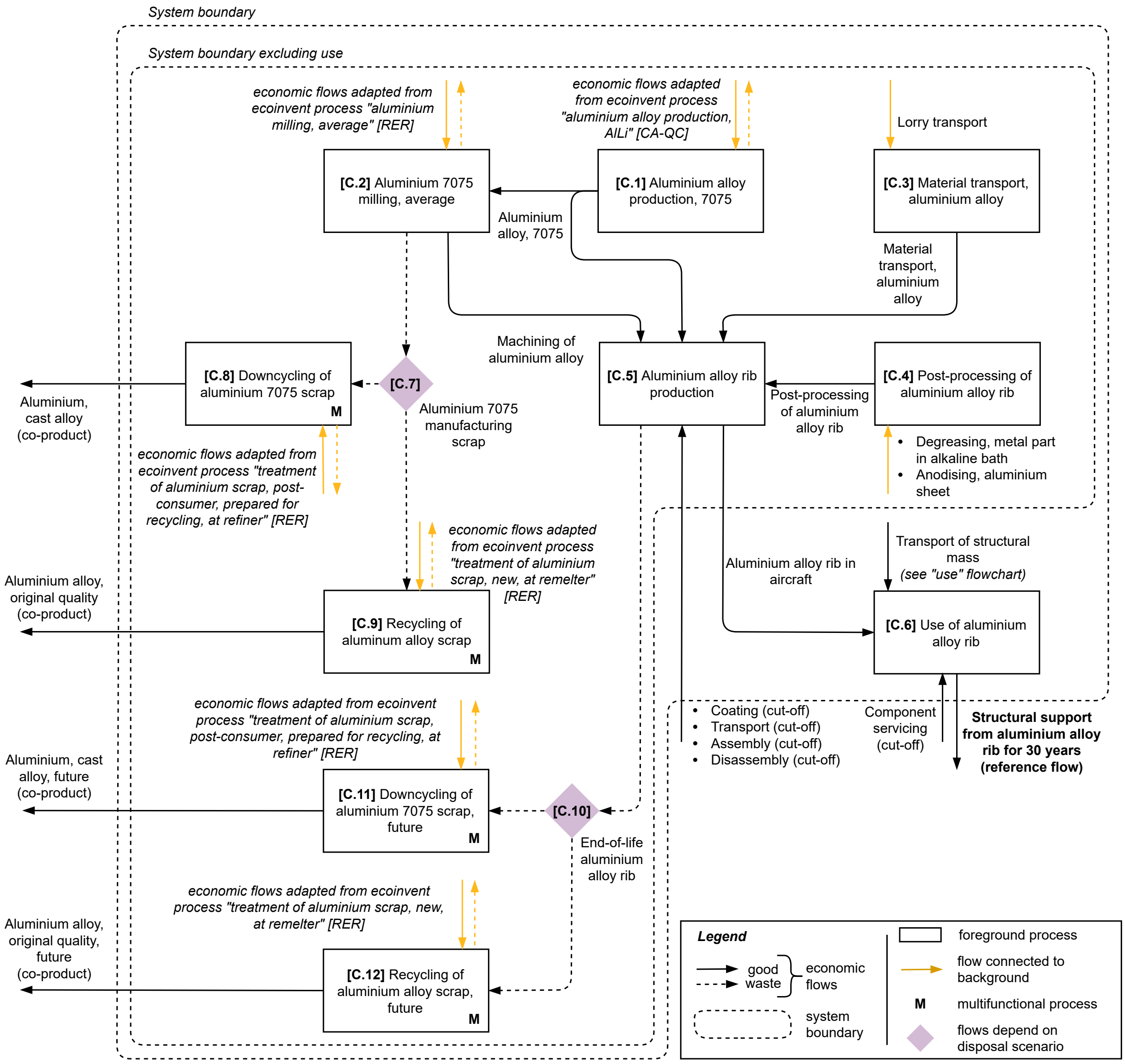


Figure A.1: Flowchart representation of the product system for the aluminium alloy alternative.

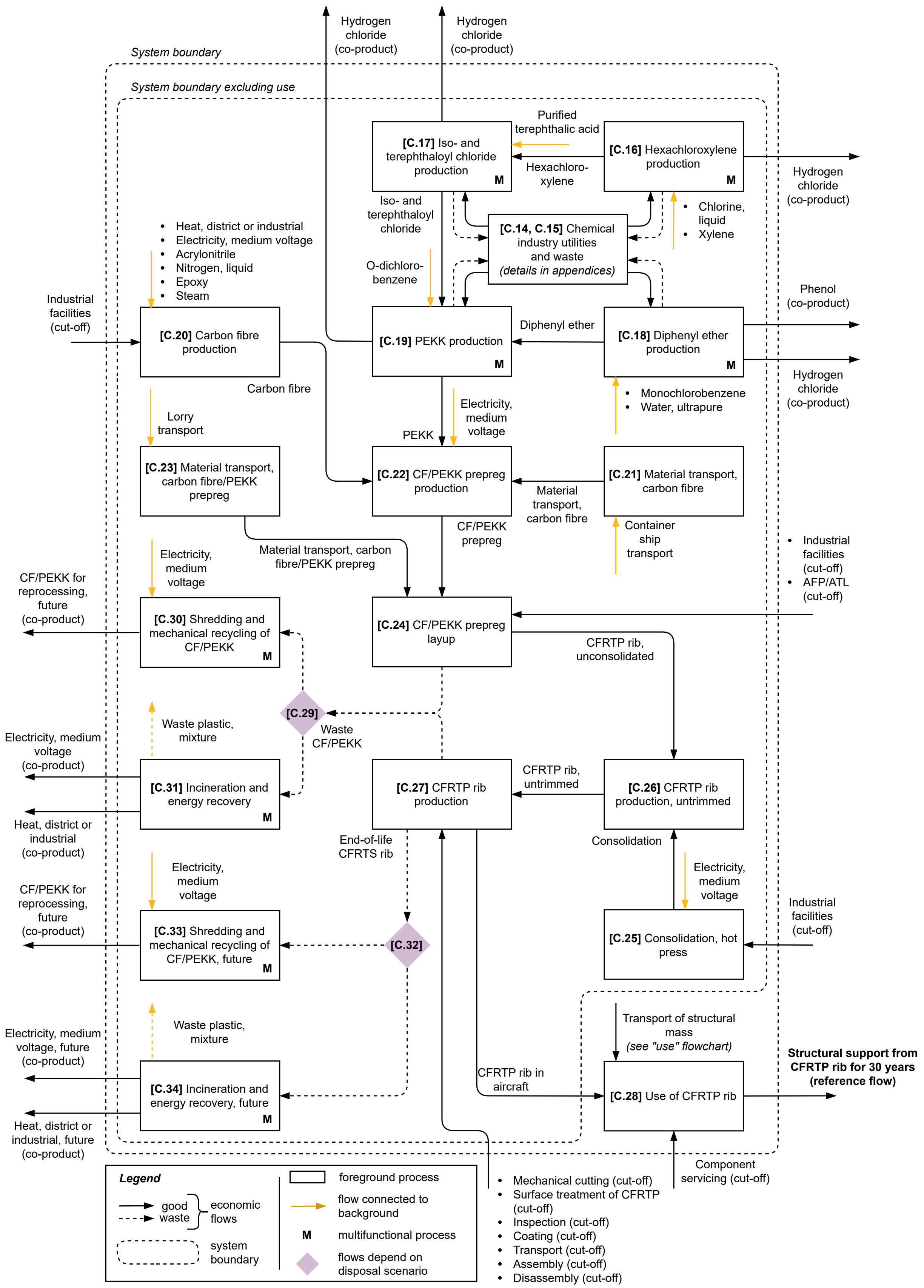


Figure A.2: Flowchart representation of the product system for the CFRTP alternative. The unit processes C.14 and C.15 are not included for pragmatic reasons, but can be found in Appendix C.

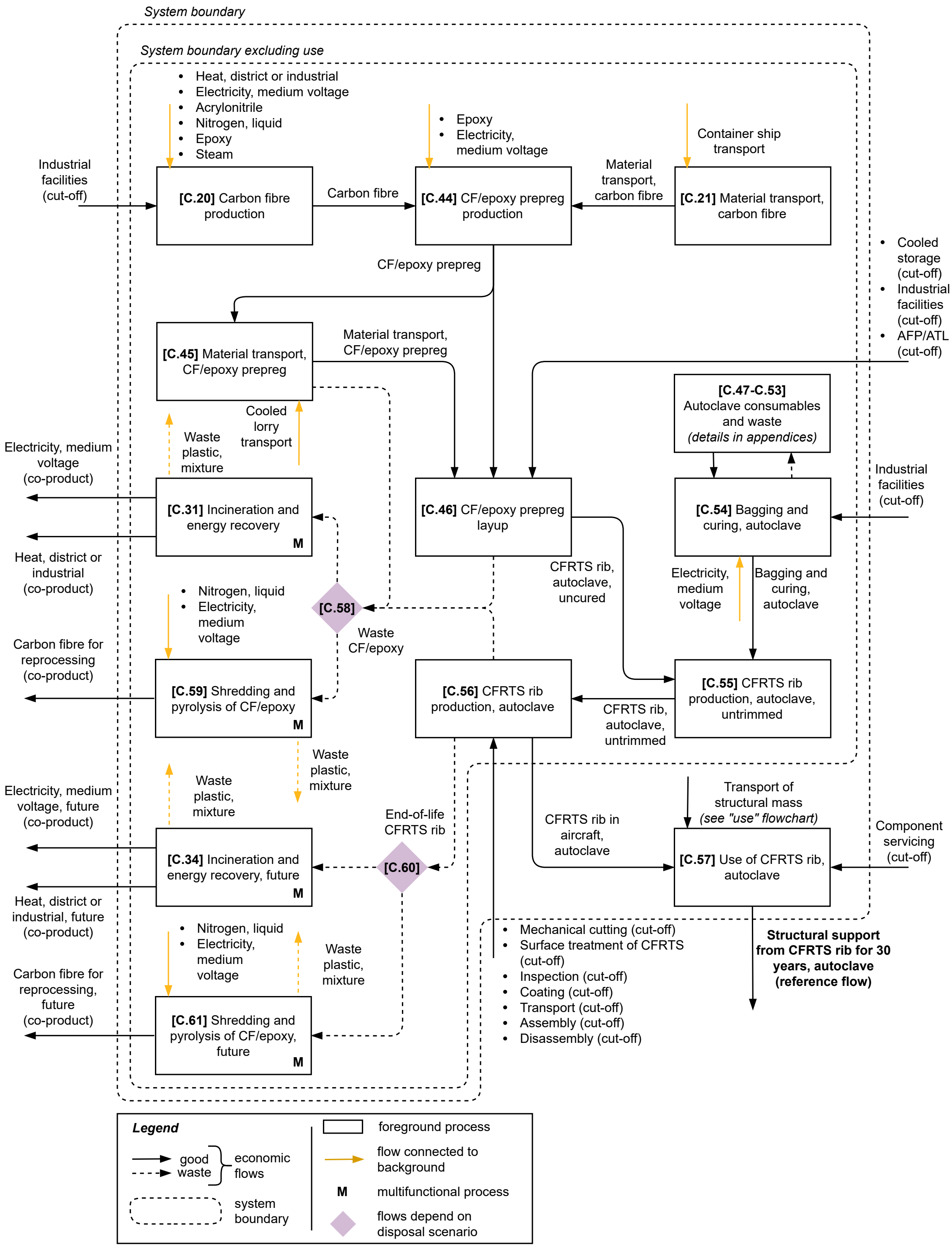


Figure A.3: Flowchart representation of the product system for the CFRTS, autoclave alternative. The unit processes C.47 through C.53 are not included for pragmatic reasons, but can be found in Appendix C.

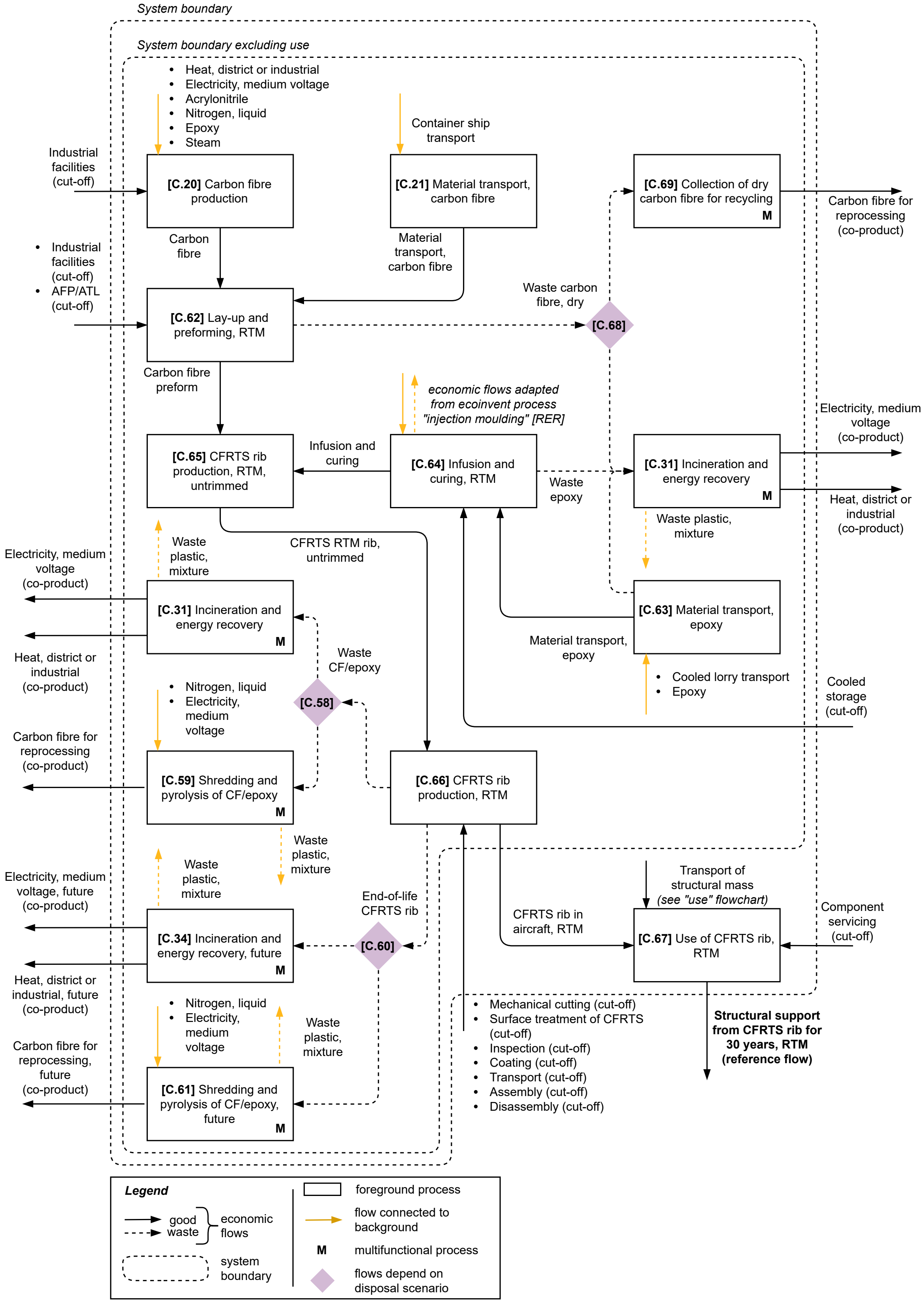


Figure A.4: Flowchart representation of the product system for the CFRTS, RTM alternative.

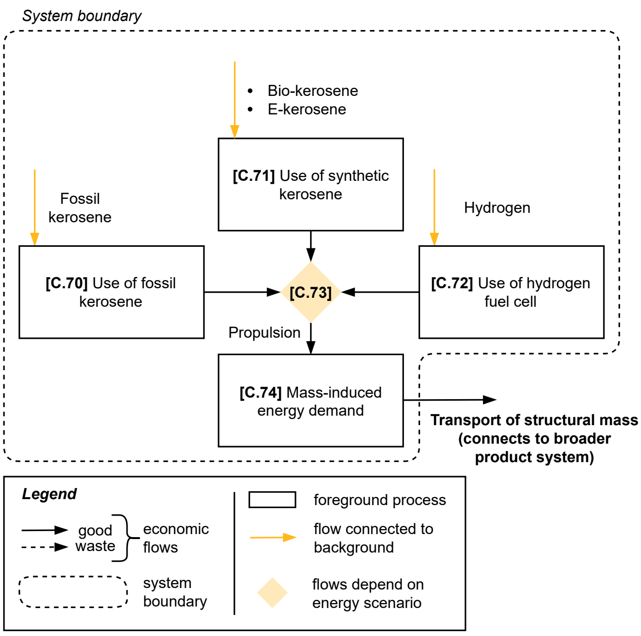


Figure A.5: Flowchart representation of the transportation of structural mass, which is a flow connecting to the use process of each alternative.

B

Data and calculations

This appendix further details the calculations and data collection which supported the LCA. With the exception of Section B.7, which is about LCIA, the data in this appendix are in service of the LCI. These sections therefore reference the foreground unit processes, which are reported in Appendix C.

B.1. Data previously collected through GKN Aerospace

Several relevant data were collected by Stefanidi [1]. Table B.1 provides an overview of these. Some of these values were taken over directly, while others were changed or discarded, as discussed in the following sections.

B.2. Aluminium alloy alternative

The following sections elaborate on the construction of the unit processes for the aluminium alloy alternative: C.1 through C.13 – with the exception of C.3, which is a transport activity (see Section B.5).

B.2.1. General characteristics of the aluminium alloy rib

As described in Section 1.2, the CF/PEKK rib is the only one with concrete design and manufacturing parameters. It is claimed that this rib, weighing 2.1 kg, would replace the mass of 3.66 kg of aluminium ribs [1]. However, this value is not the mass of a single rib, but includes a redesign of the whole wing [T. de Bruijn, personal communication, March 1, 2023]. This value is therefore considered inappropriate for the comparison at hand. Instead, an estimation is made that a CFRP rib is 20% lighter than an aluminium alloy rib. This estimation is commonly found in literature (e.g., Timmis et al. [14], Scelsi et al. [31], Tapper et al. [40], and Marino and Sabatini [94]) and generally aligns with expert estimates [T. de Bruijn, personal communication, May 11, 2023]. Other studies have performed estimates based on case-dependent structural performance to compare metal alloys to composites (e.g., Markatos and Pantelakis [16]), but the design criteria and limitations of this rib are unavailable, making such an estimate beyond the scope of this study. Using this estimate of 20%, the mass of the aluminium alloy rib is 2.625 kg.

Table B.1: Overview of relevant data gathered by Stefanidi [1]. For each variable, the overview includes the page number on which the provided value can be found, as well as whether this value is used in the LCA study of this report, and, if applicable, where in this appendix this variable is discussed.

Variable	Value	Unit	Page	Value used?	Discussion
Service life of rib	30	years	46	yes	Section B.6
Mass of aluminium alloy rib	3.66	kilogram	43	no	Section B.2.1
Mass of composite ribs	2.1	kilogram	57	yes	Section B.3.1 Section B.4.1
Buy-to-fly ratio of aluminium alloy rib	20:1	-	43	yes	Section B.2.1
Fibre volume fraction of composite ribs	60	%	64	yes	Section B.3.4 Section B.4.2 Section B.4.5
RTM excess resin	20	%	64	yes	Section B.4.5
Prepreg required for lay-up of CFRTP rib	4.5	kilogram	64	yes	Section B.3.1
Pre-trimming mass of CFRTP rib	4.1	kilogram	64	yes	Section B.3.1
Prepreg required for lay-up of CFRTS rib	3.5	kilogram	64	no	Section B.4.1
Pre-trimming mass of CFRTS rib	3.5	kilogram	64	no	Section B.4.1
Recycling rate aluminium alloy	100	%	44	yes	Section B.2.5
Recycling rate PEKK	0.1	%	71	no	Section B.3.7
Aluminium alloy, transportation distance, land	1.40×10^{3}	kilometer	43	yes	Section B.5
Aluminium alloy, transportation distance, air	5.26×10^{3}	kilometer	43	no	Section B.5
CF/epoxy prepreg, transportation distance, air	8.07×10^{3}	kilometer	57	no	Section B.5
CF/PEKK prepreg, transportation distance, air	5.70×10^{3}	kilometer	57	no	Section B.5
Surface area of the full rib	3.60×10^{-1}	square meter	44	yes	Section B.2.4
Electricity input for hot press consolidation of CFRTP rib	8.2×10^{1}	megajoule	38	yes	Section B.3.6
Heat to cure the coating of the rib	1.17	megajoule	23	no	Section B.2.4

Another important characteristic of an aluminium alloy rib's production is the buy-to-fly ratio. Averages here range around 8:1 [14] and 10:1 [41], but since the rib is milled from a solid block, it is estimated here as 20:1, following Stefanidi [1]. Such a high buy-to-fly ratio is not unheard of. High-end estimates reach 25:1 [14] or 30:1 [13]. 20:1 was confirmed to be a reasonable estimate [T. de Bruijn, personal communication, May 11, 2023].

The unit process bringing the production of the aluminium alloy rib together (C.5) represents these variables. With the buy-to-fly of 20:1, 49.9 kg of material is milled away. Since the milling process is itself mass balanced, the aluminium alloy coming in and scrap going out of C.5 represent the mass of the rib alone. However, the transport of the milled mass does need to be accounted for: 52.5 kg aluminium alloy is transported to the manufacturing facility.

B.2.2. Aluminium alloy production

An ecoinvent process is modified to represent the production of aluminium 7075 (C.1). The ecoinvent database represents several aluminium alloys. Two main products are "aluminium, cast alloy" and "aluminium, wrought alloy" [86]. Previously, Zhao et al. [92] used the ecoinvent activity for "aluminium alloy, AlMg3" to represent aluminium 7075. This is likely due to the magnesium content of aluminium 7075. However, this alloy is based on cast alloy aluminium, which is generally of a lower quality [86]. Because of this, the activity "aluminium alloy production, AlLi" [87] was chosen instead. This process represents an aluminium-lithium alloy which is primarily used for aviation. The production plant is in Quebec. It is known that part of the aluminium alloy used at GKN Aerospace is sourced from Canada, with the remainder coming from France [1]. The assumptions are made that (1) the Canadian and French plants operate using similar technology and (2) the technology for the AlLi alloy is similar to aluminium 7075.

Goods and wastes are largely copied directly from the ecoinvent activity. Changes are made based on the composition of aluminium 7075. This composition is based on the data of ASM Aerospace Specification Metals, Inc. [93]. The mean value between minimum and maximum quantities of alloying elements are used. The difference to the AlLi alloy is presented in Table B.2. As shown, the flows of silver and titanium were removed, while flows of zinc, magnesium, and chromium were added. To maintain the mass balance with the overall increase in additives, the aluminium inputs are reduced, spreading the reduction such that the relative shares of primary ingot and scrap are maintained.

Besides the additives shown in Table B.2, the economic flows of the process are unchanged. The environmental flow of water to air is also maintained from the original process.

As a substitution flow of aluminium 7075 is required for C.12 (see Section B.2.5), the production process is copied and relinked to background data base for end-of-life processes, creating C.13.

B.2.3. Aluminium alloy milling

The milling of aluminium 7075 (C.2) is modelled using the ecoinvent process for aluminium milling (average) [89]. This activity supplies a service of removing 1 kg of material through milling. The flows are adjusted such that this activity includes both the inflow of the material that is removed and the outflow of this material as scrap, both of which are part of the foreground system. Besides these material flows, all other flows are unchanged.

The "average" qualifier refers to the shares of rough and fine milling done, where ecoinvent divides this into "large parts" (90%), "small parts" (9%) and "dressing" (1%) [88, p. 37]. The input of energy and consumables between these types of milling vary considerably. Using the distinction between "coarse" and "fine" machining of ANSYS, Inc. [63], Stefanidi [1, p. 45] estimated a respective split of

Table B.2: Comparison of the inputs of the original ecoinvent activity for the production of 1 kg AlLi and the changes made to represent aluminium 7075 in unit process C.1.

Alloying additive	**Input for AlLi [**g/kg**]**[87]	**Input for aluminium 7075 [**g/kg**]**[93]
Zinc	0	56
Magnesium	0	25
Copper	33	16
Chromium	0	2.3
Silver	3	0
Titanium	3	0
Aluminium scrap, new	396	373
Aluminium ingot, primary	583	548

70% and 30%. Assuming "coarse" relates only to large parts, the average value could be a considerable underestimation.

Furthermore, aluminium 7075 is more resistant to milling than unalloyed aluminium, which likely results in an underestimation of the energy input. This is discussed further in Section F.2.3.

B.2.4. Post-processing of aluminium alloy

The post-processing of the aluminium rib (C.4) is modelled based on two steps: degreasing and anodising, both taken from ecoinvent. Both of these scale based on the area of the rib, which was reported in Table B.1. The coating of the rib is cut off, as discussed in Section 6.1.3.

B.2.5. Treatment of aluminium alloy scrap

Which and how aluminium alloy scrap is recycled is highly influential and should be approached with nuance. The following sections dissect this topic.

Recycling rate

Stefanidi [1] considers that all aluminium scrap, from both manufacturing and end-of-life phases, is recycled without loss of quality. This assumption is not uncommon (see, e.g., Timmis et al. [14], Scelsi et al. [31], and Mami et al. [32]). However, Mami et al. [32] assume only 90% of the material entering recycling is recovered. Here, it is again assumed that all scrap enters recycling, with recovery rates taken from the cited ecoinvent processes.

Recycling quality

According to Timmis et al. [14], recycled aluminium are not used in aviation – although more recently, Zhao, Guo, and Xue [125] have stated that recycled aluminium alloys are used in non-critical components. Furthermore, ecoinvent documentation points out that manufacturing scrap "can be remelted with little preparation" when the quality and alloy of the material are known and it is uncoated [86, p. 52]. Compare this to end-of-life scrap, which is coated and could be of unknown quality and alloy. Here, it is assumed that 90% of manufacturing scrap can be remelted to such a standard as to effectively maintain its quality, creating a closed loop. The remaining 10%, as well as all end-of-life scrap, is instead downcycled as a lower-quality cast alloy. The value of 10% is an estimate, included to temper the effectiveness of closed-loop recycling.

Recycling multifunctionality

The recycling of aluminium alloy scrap is very valuable, but thereby also requires that multifunctionality is resolved, as explained in Section 6.1.2. Although not all authors state how multifunctionality is resolved, Timmis et al. [14], Scelsi et al. [31], Mami et al. [32], and Priarone et al. [81] are examples of substitution, while Huang et al. [13] and Paris et al. [35] appear to apply allocation. This choice can become particularly relevant when comparing various metal alloy alternatives – compare, for example, Priarone et al. [81] to Huang et al. [13] for the case of additive manufacturing. Consequently, the CFF used here should also be reflected on critically. The distinction made between the quality of recycled products also comes into play here, being reflected in the substitution flow (see C.8 and C.11).

Recycling unit processes

The share of scrap – from manufacturing (C.8) or end-of-life (C.11) – which is downcycled goes to a process based on the ecoinvent activity 'treatment of aluminium scrap, post-consumer, prepared for recycling, at refiner [RER]" [90]. This is a typical process for the remelting of post-consumer scrap [86]. In the system model used, this is a pure production process, as the aluminium scrap was cut off at allocation. To convert it to a recycling process (combined production and waste treatment), the outflow of recycled product becomes a substitution flow and the inflow of scrap is connected to C.7 instead. Because of the CFF – explained in Section 6.1.2 – the scrap inflow is modified by the inverse of 0.8, changing from 1.03 kg to 1.29 kg. This means that, for a given amount of scrap going to this process, only 80% of this activity is allocated. Note that the quantities in C.8 and C.11 are identical, but that C.8 connects to the background system for the manufacturing phase and C.11 to that of the end-of-life phase.

The recycling processes – for manufacturing scrap (C.9) and end-of-life scrap (C.12) – are organised similarly to those for downcycling, with a few exceptions. Firstly, these processes are based on the activity "treatment of aluminium scrap, new, at remelter [RER]" [91]. This process is meant to represent remelting without loss of quality [86]. Secondly, where the downcycling processes applied a factor of 0.8 to allocate only a part of the activity to the product system, this is only done here for the recycling of end-of-life scrap. Recycling of manufacturing scrap, as discussed in Section 6.1.2, is treated as a closed loop, so no factor is applied.

That the recycling processes make use of a substitution flow also means that a version of the aluminium 7075 production process is required which connects to the end-of-life background system, rather than the manufacturing one. This is C.13. Besides connecting to a different background system, C.13 is identical to C.1.

B.3. CFRTP alternative

The inventory CFRTP is constructed in the following sections. This pertains to C.14 through C.43, with the exception of C.21, C.23, and C.42 as these are transport activities (see Section B.5). Note that some of the activities described here are also used in the product systems for the CFRTS alternatives, such as the production of carbon fibre (C.20).

B.3.1. General characteristics of the CFRTP rib

Stefanidi [1] describes several characteristics of the CFRTP rib, as presented in Table B.1. Primary data on the CFRTP rib manufactured by GKN Aerospace is taken over directly. This includes the flow of material illustrated in Section 6.2, with 4.5 kg CF/PEKK prepreg entering lay-up to create a 4.1 kg part prior to trimming, where it becomes a 2.1 kg rib.

B.3.2. Production of PEKK

From the literature analysed, the closest approximation to inventory data of PEKK is the values for climate change and primary energy demand of ANSYS, Inc. [63] (see Appendix F). ANSYS, Inc. [63] states that these are estimates, but provides no method for how the values are obtained. Looking into PEEK – a more common material in the same family as PEKK – some provide a primary energy demand value around 80 MJ/kg [5, 126], but this too is hard to substantiate.

Approach, utilities, and yield

Lacking inventory data, process chains are estimated based on stoichiometry and literature. As missing LCI data of chemicals is a common obstacle to LCA studies, several estimation methods have emerged over the years. Langhorst et al. [95] compare several such methods and evaluate which are the most reliable for the impact category climate change. They recommend to assume the synthesis yield of 87% (in the case that solvents are unknown) or 97% (in the case that solvents are known), as put forward by Geisler, Hofstetter, and Hungerbühler [96]. Concerning utilities, Langhorst et al. [95] recommend the assumptions of Kim and Overcash [97], being, per 1 kg of product: 0.6 MJ electricity, 7.7 MJ steam, and 0.15 MJ heating fuel, with recovery of 1.6 MJ steam, which is credited via substitution [95]. In this case, heat from natural gas is taken as heating fuel. To apply this method, the utilities are collected in C.14 and the incineration of surplus reactants (hazardous waste) is represented in C.15, including energy recovery based on the ecoinvent activity for “treatment of hazardous waste, hazardous waste incineration, with energy recovery” [127].

Having C.14 and C.15, any reaction can be modelled based on its reactants – and, optionally, its solvent(s). However, the reactants of PEKK are not present in ecoinvent either. Therefore, the inventories of these reactants need to be estimated as well, and so too any reactants which the reactants require. Doing so, PEKK is obtained through four synthesis processes: the production of hexachloroxylene, iso- and terephthaloyl chloride, diphenyl ether, and finally PEKK itself. To build a logical narrative, the following paragraphs move backwards, from PEKK to these other substances.

The production steps modelled here make prominent use of chlorides to promote the desired synthesis routes, creating hydrogen chloride (HCl) co-products along the way. In light of the approximation method of Langhorst et al. [95], these are not considered as major co-products. The creation of HCl uses the same yield as the main product, but it is not included in balancing the processes to 1 kg of product for the purpose of utilities. Created HCl is allocated by substitution (see Section 6.1.2).

Furthermore, note that each of the unit processes described in this section also have a version which is linked to the end-of-life background database (C.35 through C.40) to enable substitution flows for end-of-life recycling.

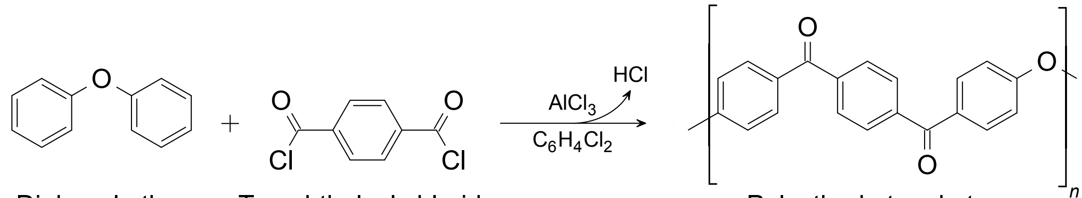
PEKK

The production of PEKK (C.19) is based on diphenyl ether, terephthalyol chloride, and isophthaloyl chloride. There are alternative routes, but this one is preferred according to Parker et al. [98]. A patent for copolyetherketones [99] describes the reactions shown in Scheme 1 and Scheme 2. The chain structure of PEKK depends on the mixture of iso- and terephthaloyl chloride, which affects the physical properties of the material (see, e.g., Zhang et al. [128]). The patent mentions the catalyst aluminum chloride ($AlCl_3$), but since LCI literature is hesitant to include catalysts in estimations (e.g., Langhorst et al. [95], Geisler, Hofstetter, and Hungerbühler [96], and Huber et al. [129]), this is cut off. The solvent orthodichlorobenzene ($C_6H_4Cl_2$), however, is included, assuming 0.2 kg per 1 kg PEKK, based again on the estimates of Geisler, Hofstetter, and Hungerbühler [96]. Because of this addition, a yield of

Table B.3: Overview of molar masses used in stoichiometric approximations. Here, acid chloride refers to iso- and terephthaloyl acid.

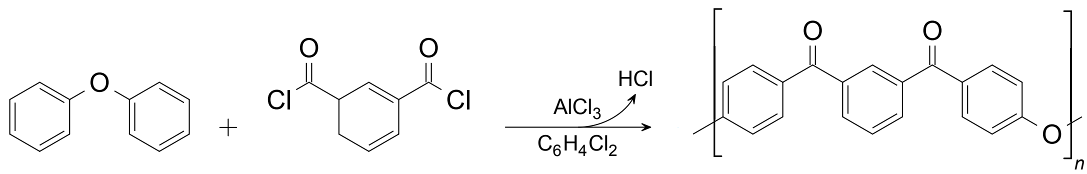
Name	**Chemical formula**	**Molar mass [g/mol]**
Acid chloride	$C_6H_4(COCl)_2$	2.03×10^2
Chlorine	Cl_2	7.09×10^1
Chlorobenzene	C_6H_5Cl	1.13×10^2
o-Dichlorobenzene	$C_6H_4Cl_2$	1.47×10^2
Diphenyl ether	$(C_6H_5)_2O$	1.70×10^2
Hexachloroxylene	$C_6H_4(CCl_3)_2$	3.13×10^2
Hydrogen chloride	HCl	3.65×10^1
Polyetherketoneketone *(per repeating unit)*	$[(C_6H_4)_3(CO)_2O]_n$	3.00×10^2
Terephthalic acid	$C_6H_4(CO_2H)_2$	1.66×10^2
Water	H_2O	1.80×10^1
Xylene	$C_6H_4(CH_3)_2$	1.06×10^2

97% is used, rather than 87%. To apply this yield to the stoichiometric values, the molar masses are calculated based on atomic mass [130]. These are compiled in Table B.3.



Diphenyl ether Terephthaloyl chloride Polyetherketoneketone

Scheme 1: Polymerisation of diphenyl ether with terephthaloyl chloride to obtain polyetherketoneketone.

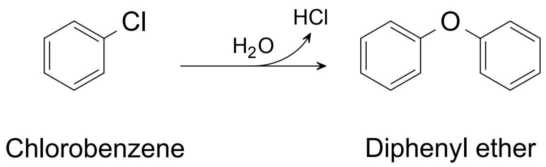


Diphenyl ether Isophthaloyl chloride Polyetherketoneketone

Scheme 2: Polymerisation of diphenyl ether with isophthaloyl chloride to obtain polyetherketoneketone.

Diphenyl ether

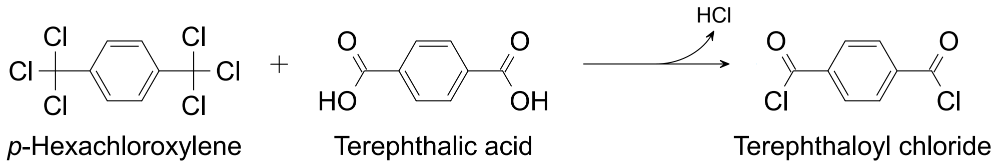
Diphenyl ether (C.18) is, according to Panten and Surburg [100], typically obtained from high-pressure hydrolysis of chlorobenzene (see Scheme 3), where it is a by-product of phenol production. It being the product of a multifunctional process could be resolved by looking into, for example, economic allocation – diphenyl ether has a low price [100]. However, this is instead resolved here by only looking at the inputs that would turn into diphenyl ether, in the same way as other chemicals modelled here are treated. This is effectively physical allocation by mass.



Scheme 3: Hydrolysis of chlorobenzene, obtaining diphenyl ether.

Iso- and terephthaloyl chloride

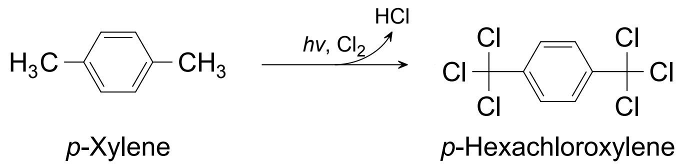
Iso- and terephthalyl chloride (C.17) are isomers. Their preparations are slightly different, as the difference in position of their functional groups can be followed up the process chain. For the sake of simplicity, terephthalyl chloride will be focused on here and in the following sections, but it will be assumed that this can be generalised to isophthalyl chloride. For example, by referring to hexachloroxylene rather than *p*-hexachloroxylene and *m*-hexachloroxylene. Lipper, Löser, and Brücher [101] briefly discuss the synthesis of terephthaloyl chloride from *p*-hexachloroxylene and terephthalic acid, as depicted in Scheme 4. Pfoertner and Oppenländer [102] describe a similar preparation for isophthalyl chloride.



Scheme 4: Reaction of *p*-hexachloroxylene with terephthalic acid to terephthaloyl chloride.

Hexachloroxylene

Hexachloroxylene (C.16) – as depicted in Scheme 5, *p*-hexachloroxylene – is industrially produced from xylene through photochlorination [101]. Photochemistry involves the addition of light, indicated in Scheme 5 as *hv*. Note that this light is not included in C.16.



Scheme 5: Photochlorination of *p*-xylene, obtaining *p*-hexachloroxylene

B.3.3. Production of carbon fibre

The ecoinvent database represents CFRP with the activity “carbon fibre reinforced plastic, injection moulded” [131], based on Cox, Jemiolo, and Mutel [15]. However, Cox, Jemiolo, and Mutel [15] do not report how this process was created, making it guesswork to justify some of its peculiar features, such as the inclusion of waste asphalt and the exclusion of a matrix material. Furthermore, while Cox, Jemiolo, and Mutel [15] use polyacrylonitrile (PAN), which is a common precursor for carbon fibre, the ecoinvent activity instead uses acrylonitrile-butadiene-styrene copolymer – a notably different material. Because of this, other literature was used in the creation of the carbon fibre unit process (C.20).

In search of carbon fibre inventories, a few works stand out: Duflou et al. [36], Pillain et al. [42], and Das [132]. The inputs of these studies vary, particularly the distribution of energy inputs from electricity, steam, and fuel. However, the combined energy input is in the same order of magnitude across studies. The inputs of Duflou et al. [36] were chosen for the construction of C.20, as they were considered to be the most complete, both in the reporting and the processes covered. The extensions created during fibre production are the exception, as these are mentioned, but not quantified in the text. However, Pillain et al. [42] do report these. These two inventories are therefore combined. As with the production of PEKK (see Section B.3.2), the production infrastructure is included using a default value.

While Duflou et al. [36] uses bisphenol A diglycidyl ether as sizing, a generic epoxy resin is used in C.20. Sizing is typically an epoxy [T. de Bruijn, personal communication, May 11, 2023]. However, sizing is also selected to match to the prepreg material [I. Fernandez Villegas, personal communication, April 5, 2023]. This is not specifically accounted for here – both epoxy and PEKK prepregs are assumed to use the same sizing.

The carbon fibre used is likely to come from outside of Europe [T. de Bruijn, personal communication, February 13, 2023]. In 2016, the USA and Mexico made up 46.3% of global carbon fibre production, and Japan made up 25% [107]. C.20 is therefore modelled as a global process, in line with the scope of this study. When the ecoinvent database does not have a global market process for a certain flow, it is instead made up of the European (RER) and rest-of-world (RoW) market processes for this flow, following the distribution of CF production reported by Witten, Kraus, and Kühnel [107]: 16.2% in Europe and 83.8% outside of Europe.

Considering that carbon fibre forms a large contribution across impact categories (see Section 7.4.2), the effect of choosing these inventories over others is addressed in Section F.1.

B.3.4. Production of CF/PEKK prepreg

The process of creating prepreg material from fibres, sizing, and matrix material is rarely included in studies. Of the studies reviewed which do include it, this can almost invariably be traced back to the work of Suzuki and Takahashi [60], whose values are reproduced in Table B.4. As discussed in Section 2.3, such “embodied energy” data are hard to assess. In their paper, Suzuki and Takahashi [60] write about the energy intensity of materials and processes, but do not discuss how these values are obtained. As a result, some have interpreted their values for prepregging as representing primary energy (e.g., Lunetto et al. [28], Tapper et al. [40], Song, Youn, and Gutowski [61], and ANSYS, Inc. [63]), while others have assumed that these values represent electricity (e.g., Forcellese et al. [37] and Office of Energy Efficiency & Renewable Energy [62]). Here, it is assumed that these values represent primary energy. As such, it can be converted to values for electricity by assuming that most of this energy comes down to on-site electricity consumption, and relating this to the Japanese electricity grid. In 2005, 8.62 MJ−eq was required per 1 kWh of electricity produced [133] – mostly from nuclear energy, coal, and natural gas. This way, the 40 MJ/kg reported by Suzuki and Takahashi [60] would be understood as 4.64 kWh/kg electricity.

For the production of CF/PEKK prepreg, the consideration is made that storage of raw materials and the prepreg would be significantly reduced. As opposed to thermoset epoxies, thermoplastics require no cooled storage. Therefore, for C.22, the values for storage in Table B.4 are excluded, obtaining 25.1 MJ/kg (2.91 kWh/kg electricity). The further consideration could be made that the atmosphere control would also be different, as this too includes cooling for CF/epoxy. However, much of this energy consumption comes down to preventing dust from entering the facility and contaminating the material, which is also a requirement for CF/PEKK [T. de Bruijn, personal communication, May 11, 2023]. Therefore, this value is still included.

To determine the required input of PEKK and carbon fibre, the known fibre volume fraction of 60% is used alongside the density of the materials. ANSYS, Inc. [63] reports the density of carbon fibre to be 1800 kg/m^2-1840 kg/m^2 and that of PEKK to be 1300 kg/m^2-1320 kg/m^2. For each material, the median value is used to calculate the values of C.22. Lacking any data to the contrary, the assumption is made that no PEKK or carbon fibre is wasted in the prepregging process.

Table B.4: "Energy intensity of prepreg production" reproduced from Suzuki and Takahashi [60, p. 16].

Production process	**Energy intensity [**MJ/kg**]**
Resin blending	0.1
Resin coating	1.4
Resin impregnation	2.1
Prepreg winding	0.2
Atmosphere control	20.8
Raw material storage	11.5
Prepreg storage	3.4
Release coated paper production	0.5
Total	40.0

B.3.5. CF/PEKK lay-up

Stefanidi [1] reported that, to lay up 4.1 kg, 4.5 kg is required. Losses of around 5-10% are to be expected [T. de Bruijn, personal communication, May 11, 2023]. As discussed in Section 6.1.3, all other inputs to lay-up are cut off.

B.3.6. Hot press consolidation

As Stefanidi [1] reports primary data for the electricity consumption of hot press consolidation, this value is used here as well (C.25). It should be noted that this technique is still being developed. The energy demand is largely dictated by the mass of the mould in which the part is pressed, and will be reduced in the coming years [T. de Bruijn, personal communication, May 11, 2023]. Others have cited hot pressing to require 3.17 kWh/kg electricity [62]. This is explored in the sensitivity analysis of Chapter 9.

B.3.7. Treatment of CFRTP scrap

The mechanical recycling of CFRTP scrap is central to this thesis. This section describes how this is modelled following the multifunctionality approach laid out in Section 6.1.2.

Recycling rate

Of the PEKK on the market today, around 99.9% is primary material [63]. Stefanidi [1] assumed from this figure that 99.9% of PEKK would not be recycled after disposal, but this assumes that the demand for PEKK and the resulting amount of PEKK in the economy is unchanging. The PEKK input modelled here is also only primary material. However, when considering that the application of PEKK in aerostructures is an emerging technology and demand is increasing as a result, it makes sense that there is no market for end-of-life PEKK yet. Therefore, the 99.9% value should not reflect on the recycling rate of CFRTP discarded here. In fact, as with aluminium alloy (see Section B.2.5), it is common to assume a recycling rate of 100% (see, e.g., Katsiropoulos, Loukopoulos, and Pantelakis [5] and Pillain et al. [42]), although others model it as 0% (see, e.g., Ogugua, Sinke, and Dransfeld [4]). Here, the baseline scenario will assume a 100% recycling rate for both manufacturing and end-of-life scrap, but is explored through scenarios (see Section 6.4).

Recycling quality

When CFRTP waste is shredded, the fibres are reduced in length, reducing the mechanical properties which can be obtained from the material. This reduction in quality should somehow be reflected in the CFF. Markatos and Pantelakis [16] solve this using the ratio of specific stiffness (being, Young's modulus over density) between primary and recycled material. Pegoretti [80] collects several studies on the properties of mechanically recycled material, which generally demonstrate that their performance does not fall far behind primary material with short-length fibres. However, compared to continuous fibres – the material being compared in this case – there is a reduction in Young's modulus of $> 50\%$ [80]. Bensadoun et al. [79] specifically consider mechanical recycling for injection moulding, which is a technique considered for the CF/PEKK rib as well. They conclude a reduction in properties of around 75% [79].

There are also alternative possibilities which circumvent the need to use the quality factor in this way. Stelzer et al. [44] consider the application of CFRTP manufacturing waste, using what in the CFF is termed the A-factor, but including quality only through the amount of material needed to meet the desired performance. They account CFRTP end-of-life waste as burden free, in a similar approach to the ecoinvent cut-off system model. This approach to manufacturing waste makes sense, but cannot be applied without defining the second life of the material.

Stelzer et al. [44], Bensadoun et al. [79], and Pegoretti [80] each conclude that mechanically recycled thermoplastic composites have comparable performance to primary material with short-length fibres. Primary short-length CFRTP could therefore be used as a substitution flow. However, substitution should, by some standards, represent a flow being displaced elsewhere in the economy. This would not be the case here, as short-length fibre composites typically use cheaper fibres, such as glass fibre [42, 43]. Glass fibre would therefore need to be modelled as substitution flow. However, this too is undesirable. Substitution introduces negative emissions, so substituting material from a substantially different production processes could confuse what conclusions can be drawn from the LCIA.

The quality reduction will be considered through a quality factor of 75%. However, as discussed in this section, there are alternative ways of considering the recycled product. These considerations are explored in the sensitivity analysis of Chapter 9.

Recycling multifunctionality

The approach to multifunctionality described in Section 6.1.2, using the CFF, is applied. For recycling, the default A-factor of 0.5 is used, which is recommended for plastics [20]. In contrast to the aluminium alloy alternative, no closed-loop recycling is possible within this product system, nor is there an appropriate existing equivalent to the recycled product, which could be used as substitution flow. Instead, a quality reduction of 75% is included, as motivated above.

Recycling unit processes

Mechanical recycling is represented in C.30 and C.33. Grinding the waste to chips is modelled as an electricity flow, taken from Pillain et al. [42]. As with processes such as C.8, the A-factor is incorporated into the inflow of waste, turning the original 1 kg into 2 kg. The quality factor is incorporated into the outflow, turning the original 1 kg into 0.25 kg. Therefore, the overall substitution per 1 kg of CFRTP waste is set to 0.125 kg of primary CFRTP.

Incineration

The incineration processes for composite waste (C.31 and C.34) are also connected to the CFRTP alternative, but not used in the baseline scenario, in favour of recycling. As with the incineration of hazardous waste (see B.3.2), the process is represented by an ecoinvent process – in this case, "treatment of waste plastic, mixture, municipal incineration" [134]. The energy recovered is added again to align with the CFF, as this is cut off by default in the system model used. These values are much lower than the energy contents reported by some (see, e.g., Tapper et al. [40] and ANSYS, Inc. [63]). A possible explanation for this is that is not practically possible to recover the high energy content of CFRP through municipal incineration, as has been observed by Hedlund-Åström [135].

B.4. CFRTS alternatives

The unit processes unique to the CFRTS alternatives – the autoclaved rib and the RTM rib – are elaborated on in the following sections. Note that the product systems of these alternatives make use of several processes also present in the CFRTP alternative, which were discussed in Section B.3.

B.4.1. General characteristics of the CFRTS ribs

Stefanidi [1] assumes that the CFRTP and CFRTS ribs have the same mass. This assumption is made here as well for the baseline scenario. Additionally, the assumption is made that the manufacturing-to-gate material flows for the CFRTS ribs are comparable to those of the CFRTP rib. Stefanidi [1] assumed that the production of the CFRTS ribs would be more material efficient, using a standard buy-to-fly ratio of 1.4. However, lacking any motivation for why the lay-up and trimming of a rib from CF/epoxy prepreg would create less waste than the lay-up and trimming of a rib from CF/PEKK prepreg, this assumption is discarded. Instead, the material flows of the CF/epoxy prepreg rib are assumed to be equal to those of the CFRTP rib, and the creation of the preform for RTM is assumed to have the same off-cut rate of 10%, i.e., an input of 3.05 kg to create a 2.77 kg preform. This is discussed further in Section B.4.3.

B.4.2. Production of CF/epoxy prepreg

The CF/epoxy prepreg process (C.44) is produced in an analogous way to that for CF/PEKK (see Section B.3.4). However, the values for storage, which were excluded for CF/PEKK, are included for CF/epoxy.

Again, the material inputs are calculated based on the densities of the materials. Considering the variety of epoxies available, the densities have a range of 1110 kg/m^2-1400 kg/m^2 [63]. This range fully engulfs the density range for PEKK (see Section B.3.4), but its median value is slightly lower: 1255 kg/m^2 for epoxies compared to 1310 kg/m^2 for PEKK. To compare the two materials, the choice was made to maintain a constant mass across composite alternatives. The carbon fibres in any case provide the bulk of mechanical performance, and it is unclear what mass difference there would be between a CFRTS part designed for autoclave and a CFRTP part designed for hot press [T. de Bruijn, personal communication, February 13, 2023]. To maintain a consistent mass balance across alternatives, the choice was therefore made to assume that PEKK and epoxy have equal densities. This assumption is only relevant to the results in so far that it connects to component mass, and thus the mass-induced emissions, which are explored in the mass scenarios (see Section 6.4).

B.4.3. Lay-up of CF/epoxy and dry carbon fibre

The lay-up of CF/epoxy (C.46) is modelled as described in Section B.3.5, substitution CF/PEKK prepreg for CF/epoxy prepreg. However, a few adjustments must be made in order to model the preforming process for RTM (C.62), which is based on dry fibre placement. As introduced in Section B.4.1, the material efficiency of the forming process is assumed to be constant. Hohmann et al. [39], who involved an industry advisory board, state that a cut-off rate for dry fibre placement of 20% is reasonable, but could be as low as 5%. Maintaining the 10% off-cut rate observed for CF/PEKK is in line with these estimates.

To calculate what the preform mass should be, the fibre volume fraction of 60% is used. As discussed in Section B.4.2, the epoxy was assumed to have a density of 1310 kg/m^2. With a density for carbon fibre of 1820 kg/m^2, the preform of dry carbon fibre thus has a mass of 2.77 kg.

B.4.4. Autoclave processing

As introduced in Section 1.2.2, autoclave processing is a tried and true method to obtain high-quality composite parts, but it is also a highly intensive process which requires several consumables to operate. No quantitative data was collected on this from GKN Aerospace, but there are studies which report measurements of consumables used and energy consumed.

Autoclave consumables

Although autoclave consumables form an important requirement to the process, few studies provide explicit, quantified descriptions. Two exceptions are the studies of Forcellese et al. [37] and Witik et al. [38]. Both measure inputs for their respective case studies, which are then modelled through basic ecoinvent processes. Witik et al. [38] consider a 400 mm-by-400 mm square panel of 4 mm thickness, while Forcellese et al. [37] consider a 1.8 m^2 car hood, although they do not describe its dimensions further. Because the plate of Witik et al. [38] is considered to be a more straightforward reference case and because they include a few flows not mentioned by Forcellese et al. [37], the work of Witik et al. [38] was chosen as baseline.

Thus, the unit processes for the consumables themselves (C.48 through C.52) are based directly on Witik et al. [38], considering the dimensions of their panel and reported input of consumables. These are then scaled to the wing rib by assuming a required perimeter (in the case of bag tape) and covered area (in the case of breather fabric, peel ply, release film, and vacuum bagging). Additionally, the consideration is made that double the rib would require double the vacuum bagging as a plate of comparable area, due to the challenge of bagging a relatively complicated shape [I. Fernandez Villegas, personal communication, April 5, 2023; T. de Bruijn, personal communication, May 11, 2023]. Although the precise dimensions of the CFRTP rib could not be shared for this thesis, the web of the rib is around 0.90 m-by-0.24 m [26] and the figures of Stefanidi [1] indicate that the flanges at the base (see Figure 1.1) have a width of around 0.10 m. From this, and assuming that the rib is placed on its side, the perimeter is estimated as 2.28 m, the area to cover from below as 0.26 m^2, and the exposed area as 0.35 m^2 (see C.54).

For ease of use, the production process for each consumable also contains its transportation to the production site (C.47, see Section B.5) and its waste flow (C.53). Consumable waste is incinerated using the same process for other incineration of other composite manufacturing waste (C.31, see Section B.3.7).

Autoclave energy demand

Conventionally, autoclaves are considered as energy intensive and relatively inefficient compared to out-of-autoclave alternatives [4, 37]. Yet, very few measurements are reported in literature, with most studies instead referring to earlier values, which end up without transparent origin. This is discussed in Section F.2.4 and addressed in the sensitivity analyses of Chapter 9. Two data points which can clearly be traced to measurements are 38.7 kWh for a 0.4 kg-by-0.4 m panel [38] and 17.6 kWh for a 0.45 m-by-0.45 m panel [103]. A recent study by Ogugua et al. [103] found that the energy demand is, to a large extent, driven by heating up the autoclave itself, rather than the component being cured. The energy intensity of this process is thereby driven less by the rib itself, but by how many components can be cured simultaneously, relative to the size of the autoclave. Such data could not be obtained from GKN Aerospace, although it is known that attempts are made to cure multiple parts simultaneously [T. de Bruijn, May 11, 2023]. For this case, the value of 17.6 kWh from Ogugua et al. [103] is used, as this is a more recent measurement and, choosing the lower of the two recordings, the laboratory setting of these studies is considered, where in reality, it will typically not be a single part being cured at a time.

B.4.5. Resin transfer moulding

As with the energy consumption of autoclave cycles for composite curing (see Section B.4.4), there is a lack of reliable data on the energy consumption of RTM. As with the autoclave or hot press, the mass of the mould in which the preform is clamped plays a large role. Lacking process-specific data, authors such as Cox, Jemiolo, and Mutel [15] and Duflou et al. [36] consider the ecoinvent activity "injection moulding" [104] as proxy. Here, this same method applied by Duflou et al. [36] is used, where the injection of 1 kg plastic from the injection moulding process is considered to be equivalent to the infusion of 1 kg epoxy into the fibre preform.

As opposed to the prepregging processes (C.22 and C.44), where no waste is assumed due to a lack of data, it is well established that a surplus of matrix material is used in RTM to minimise the number of voids created during infusion. Stefanidi [1] reports the estimate of 20% surplus epoxy, which is taken over in C.64. Note that this is a relatively high estimate, with other experts placing the figure at a 10% surplus [T. de Bruijn, personal communication, July 25, 2023].

B.4.6. Treatment of CFRTS scrap

The incineration processes were explained in Section B.3.7. These are the processes used by default for the CFRTS alternatives, including for the end-of-life of autoclave consumables (C.53) and waste resin, such as from RTM (C.64). However, there are additional recycling processes connected, which are used in the scenarios (see Section 6.4). These processes represent pyrolysis (C.59 and C.61) and the recycling of dry carbon fibre (C.69).

Recovery of carbon fibre through pyrolysis

The pyrolysis process was introduced in Section 6.4.1. Pillain et al. [42] provide an inventory for pyrolysis which considers substitution of co-products: recovery from fibres, as well as electricity and heat recovered from the resulting gasses and liquids. This carbon fibre is, again, modelled using the features of the CFF, with an A factor of 0.5 and quality decrease of 75%. Pillain et al. [42] model the environmental flows from pyrolysis and subsequent energy recovery on the ecoinvent activity for plastic incineration. With the same reasoning, "treatment of waste plastic, mixture, municipal incineration" [134] is used here to represent the removed matrix material.

Recycling of dry carbon fibre

Although not currently practised, dry carbon fibre waste can be recycled into high-strength fabric [106]. This is represented in C.69 in a way similar to the recycling of other fibrous waste: with an A factor of 0.5 and a quality decrease of 75%, driven by the decrease in fibre length.

B.5. Transport activities

As introduced in Section 6.1.3, only a limited number of transportation movements are considered, due to a lack of data and the estimation that transport forms a minor contribution to environmental impacts, as shown by, e.g., Priarone et al. [81]. Furthermore, the transportation data of Stefanidi [1], listed in Section B.1, are not fully taken over here.

For the transport of aluminium alloy (C.3), Stefanidi [1] reports that a portion is transported by air from Canada to satisfy last-minute R&D needs. This is thought to be unrepresentative of large-scale production [T. de Bruijn, personal communication, January 9, 2023]. Therefore, only the distance by road, which is meant to represent aluminium alloy sourced from France, is included.

For the transport of CF/PEKK prepreg (C.23), CF/epoxy prepreg (C.45), and epoxy to the manufacturing site (C.63), the same distance by road is used as for aluminium. However, globally, most carbon fibre is produced outside of Europe, a large sharing coming from Japan, the USA, and Mexico [36, 107, 132]. In this case, the supplier might be based in the USA [T. de Bruijn, personal communication, February 13, 2023]. Because of these reasons, the transport of carbon fibre (C.21) is modelled by freight ship, over a distance representative of Europe to the USA or Japan: 15 000 km.

Furthermore, to ensure quality, aerospace materials which require cooling are monitored during transport. When the correct temperature is not maintained, or if the recording equipment malfunctions, the material is discarded. The share of material discarded in this way is estimated to be between 1% and 5% [T. de Bruijn, personal communication, February 13, 2023]. Stefanidi [1] describes on-site storage as another source of waste. To account for both waste sources, a 5% loss of material during cooled transport is assumed.

The transportation of autoclave consumables is also modelled (C.47). The study on which these consumables are based (see Section B.4.4), Witik et al. [38], estimates that, for composite production in Western Europe, a distance by road of 500 km is to be expected for autoclave consumables. This value is used here too.

B.6. Mass-induced energy demand and resulting emissions

To evaluate the use phase of the components, an amount of aviation fuel production and consumption is allocated to reflect mass-induced emissions. As introduced in Section 2.1.2, this is in any case valuable context to the lifecycle and can provide very different results to assessments which neglect either fuel production or the use phase entirely.

B.6.1. Production of energy carriers

The ecoinvent database has kerosene production processes for several locations, as well as a market process for the European economic region [108]. This process will be used to represent kerosene production across the lifespan of the component.

The production of alternative energy carriers is also based on background processes. However, these are not included in the ecoinvent database, but rather imported from the *premise* library. Based on state-of-the-art scientific literature, *premise* imports several processes representing emerging technologies that contribute to the societal pathways described in IAM scenarios. This includes several drop-in alternative aviation fuels, as well as a (liquified) hydrogen market. For the drop-in fuels, several aspects are considered:

- whether the Fischer-Tropsch process (FT) or alcohol-to-jet (AtJ) production pathway is used;
- sourcing the CO_2 used in the synthesis from biomass gasification (modelled as wood), coal gasification, direct air capture (DAC), or point-source carbon capture and utilisation (CCU, modelled at a cement plant) – hydrogen is sourced from the same process which created the CO_2, except in the cases of DAC and CCU, where hydrogen from water electrolysis is added;
- whether processes which create a surplus of CO_2 (gasification of wood or coal) use carbon capture and storage (CCS);
- whether co-products from the synthesis (e.g., other hydrocarbons, such as diesel, but also surplus electricity and heat generated) are allocated based on energy content or economic value.

Not all CO_2 sources are considered for both production pathways: biomass only for FT and CCU only for AtJ. Considering all combinations including and excluding CCS and the two allocation methods, a total of eighteen possible products are obtained for the European region (RER) alone. Here, energy allocation will be used. Ballal et al. [12] discuss that economic allocation is unpredictable for these technologies, as markets for synthetic hydrocarbons are still emerging and could behave unexpectedly. To meet the ReFuelEU targets (elaborated on in Section D.3), biomass will be the largest contributor. However, the relatively mature bio-based processes, such as the hydroprocessed esters and fatty acids (HEFA) and synthetic iso-paraffinic (SIP) pathways [136] are not included in this inventory. This requires substituting these for another process in short-term modelling, but overall has little impact, as HEFA requires (waste) oils and fats as feedstock, which are highly limited in supply, and the sugars required for SIP would fall under energy crops, which are explicitly not supported under ReFuelEU Aviation [75]. To simplify the analysis, only Fischer Tropsch processes will be considered, with the bio-based volume share being met with wood gasificiation and the synthetic volume share being met with DAC and electrolysis. Because of the way biogenic CO_2 will be accounted for, modelling wood gasification with CCS would attribute a slight cooling effect to the fuel, as CO_2 is captured and stored. As the current outlook is that there will be a lack of CO_2 to utilise, it is unlikely that there will be much left to store, and that this is instead directly recycled in a subsequent process (e.g., Habermeyer et al. [121]). Therefore, no CCS will be assumed, with the caveat that this assessment makes use of a rudimentary biomass supply chain. Thus, two drop-in alternatives are connected to the assessment, from the *premise* processes “kerosene production, synthetic, from Fischer Tropsch process, hydrogen from wood gasification, energy allocation, at fuelling station” and “kerosene production, synthetic, from Fischer Tropsch process, hydrogen from electrolysis, energy allocation, at fuelling station”.

For hydrogen, the hydrogen economy represented in *premise* is used, with the market process “market for hydrogen, gaseous” for the European Union (EUR) combining several production methods and supply chains. Note that the EUR region as defined in REMIND refers to the European Union, while the ecoinvent RER region also encompasses areas outside of the European Union. Within the context of this study, EUR is considered an appropriate proxy to treat as RER.

B.6.2. Use emissions of energy carriers

The emissions from kerosene combustion (C.70) are based on the ecoinvent process “transport, freight, aircraft, dedicated freight, medium haul” [110], which is one of the activities clearly reporting the combustion of a quantity of kerosene. The environmental flows of this process were scaled up to align with a kerosene input of 1 kg (from the original 0.2329 kg). A notable feature of this process is that it includes the emission of several trace elements that show up in the petrochemical industry – such as lead, zinc, and mercury – which are often excluded from other inventories, as these do not contribute to climate change (e.g., Ballal et al. [12] and Cavalett and Cherubini [111]). However, in countries such as the Netherlands, aviation is a major contributor to lead emissions to air [137]. Furthermore, the water emissions in such ecoinvent processes are remarkably low: around 7.63×10^{-6} m^3 water per 1 kg kerosene. As kerosene is a hydrocarbon, its combustion with oxygen produces a lot of water. These values are increased in line with Lee et al. [8], who cite 1.23 kg water (1.23×10^{-3} m^3) per 1 kg kerosene.

For the combustion of synthetic kerosene (C.71), there is no consensus view on the degree to which the trace elements mentioned for fossil kerosene (notably, lead) would show up. However, expert judgement states that these quantities would in any case be greatly reduced [J.A. Posada Duque, personal communication, May 4, 2023]. The choice is made here to remove these trace elements entirely, in line with assumptions made for SO_x and particulate matter. All other emissions from the fossil kerosene process are maintained, but switched to non-fossil environmental flows where applicable. Furthermore, while fossil kerosene has an energy content of around 43 MJ/kg based on lower heating value (LHV), synthetic kerosene is typically more energy dense, due in part by its lack of impurities [12, 138], bringing it to 45 MJ/kg [109]. The same combustion inventories are maintained for both types of synthetic kerosene used.

For hydrogen fuel cell propulsion (C.73), the only emission is water [114]. The molecular masses of H_2, O_2, and H_2O are used [130] to calculate that 1 kg H_2 creates 8.94 kg H_2O. A LHV of 120 MJ/kg is considered [114].

B.6.3. Representing mass-induced energy demand

From the literature review conducted previously (see Arblaster [29]), several approaches appeared to quantifying mass-induced energy demand. Van Grootel et al. [33] report 10 TJ-30 TJ of fuel saved across a 30-year lifetime, per 100 kg mass reduction, based on airline estimates. Huang et al. [13] consult additional estimates, leading them to a more limited range of 13.4 TJ-20 TJ. Note that this is energy physically contained in the fuel. This does not mean that this amount of energy is converted into useful power for the aircraft (as there are inefficiencies) and it certainly does not relate to the energy accounting concepts of embodied energy which were discussed in Section 2.1.2.

Besides airline estimates, Section 2.1.2 introduced several alternative methods of estimating mass-induced energy demand and its effects. Table B.5 compares several of these methods, each adjusted to the fuel difference caused by 1 kg over the course of 1 year. When needed, methods are converted from kilogram to joule using the energy density 43 MJ/kg [33]. Furthermore, this occasionally required assuming a particular distance flown per year. In these cases, this was always assumed to be 2.0×10^6 km/year, in line with distances reported for the A320 by Markatos and Pantelakis [16] and Fabre et al. [18]. However, it should be noted that wide-body aircraft, such as the Boeing 787, are reported with yearly distances around twice as high (e.g., Timmis et al. [14], Scelsi et al. [31], and Vidal et al. [34]). Finally, converting the values of Cox, Jemiolo, and Mutel [15] also requires assuming flight distances. This will be done twice: once assuming the narrow-body aircraft is performing relatively short flights (500 km) and once assuming it is performing relatively long flights (4000 km).

From Table B.5, the only estimates which do not fall in the range of Van Grootel et al. [33] are that of Scelsi et al. [31] (which is much higher) and that of Vidal et al. [34] (which is slightly lower). This can be explained by the models these authors use. Scelsi et al. [31] use the ecoinvent model for air freight. The way emissions and fuel use are attributed to cargo is fundamentally distinct from

Table B.5: Overview of mass-induced energy demand per year per kilogram of mass obtained from literature. A combination of assumptions was used to convert all values to the same unit, which are described in the text.

Study	**Mass-induced energy demand [GJ/kg-year]**
Van Grootel et al. [33] (low end)	3.33
Van Grootel et al. [33] (high end)	1.00×10^1
Huang et al. [13] (low end)	4.47
Huang et al. [13] (high end)	6.66
Scelsi et al. [31]	1.88×10^1
Vidal et al. [34]	2.98
Cox, Jemiolo, and Mutel [15] (short flights)	6.39
Cox, Jemiolo, and Mutel [15] (long flights)	4.12
Calado, Leite, and Silva [47]	3.50
Stefanidi [1]	3.44

attributing fuel use to lightweighting. Vidal et al. [34] also used a fundamentally distinct approach, by using fuel flow models of a full aircraft, and then dividing the fuel used by the aircraft mass (including estimates for payload and fuel carried) to obtain a relationship between fuel use and in-flight mass. By not considering mass change as a marginal effect, it appears that Vidal et al. underestimate the effect of lightweighting. However, it does appear that both the ranges of Van Grootel et al. [33] and Huang et al. [13] appear to be relatively high compared to the other estimates. This is likely because the yearly flight distance assumed to compare these figures – 2.0×10^6 km/year, based on a narrow-body aircraft – is lower than the distance of other aircraft included in the airline estimates.

Moving forward, the low-end estimate of Huang et al. [13] is used (4.47 GJ/kg-year). This number is chosen because (1) it is originally reported relative to years of operation, rather than flight distance (which had to be assumed for other methods); (2) it falls within the range of Van Grootel et al. [33]; and (3) it falls within the range derived from the work of Cox, Jemiolo, and Mutel [15], which is considered to use a particularly transparent and robust approach.

B.6.4. Unit processes

For each case, the transformation from fuel into energy is conducted in the same process to which the emissions from the fuel use are connected. Note that, in contrast to other scenarios, C.71, C.72, and C.73 are not only dynamic in how they are connected to the reference flows, but also in how they are connected to the background, as this background system changes over time (see Section D.3). Then, this energy contributes to C.74, which dictates what the energy makeup of the use phase is.

The unit process for transport of structural mass thereby has the inputs required to transport 1 kg for 1 year. Therefore in the unit process for use of, e.g., aluminium alloy (C.6), the component mass of 2.625 kg is multiplied by 30 years to obtain 78.75 kg−year. Note, of course, that the lifetime use of 30 years shown in the unit processes is subject to change depending on the scenario, as described in Section 6.4.

Table B.6: Climate change characterisation factors (CFs) in terms of GWP 100a for the compartment "air - lower stratosphere + upper troposphere". Only values which are adjusted from the original characterisation method are included in this table.

Flow name	Unit	Adjusted CF [8]	Original CF [109]
nitrogen oxides	kg CO_2-eq/kg	1.14×10^2	0
particulates, < 2.5 um	kg CO_2-eq/kg	1.17×10^3	0
sulfur dioxide	kg CO_2-eq/kg	-2.26×10^2	0
water	kg CO_2-eq/m^3	6.00×10^1	0

B.7. LCIA method for climate change

As discussed in Section 2.2, the impact of aviation emissions depends, in part, on the altitude of the emissions, which is not accounted for in conventional LCIA models. Lee et al. [8] provide adjusted impact categories for a number of climate change impact categories. These are reproduced in Table B.6 in terms of GWP 100a.

Although the methods of Lee et al. [8] are spatially explicit, the characterisation factors reported are not. As can be seen in C.70, C.71, and C.72, aviation emissions to air are divided into the compartments "air - non-urban air or from high stacks" and "air - lower stratosphere + upper troposphere". Adjustments cannot be made by changing the characterisation factors for both models, since "air - non-urban air or from high stacks" is also used for many industrial emissions which do not occur at such high altitude as aviation emissions. Therefore, the characterisation factors of Table B.6 are implemented for the compartment "air - lower stratosphere + upper troposphere". The boundary between these two compartments is set at flight level 240 (this is 24 000 feet, or 7315 m) for aviation emissions [110]. Going by the CO_2 emissions in C.70, 91.1% of emissions take place above this altitude. This means that 8.9% of emissions do not use the characterisation factors of Lee et al. [8], but the generic ones. This is a similar solution to the one employed by Cox, Jemiolo, and Mutel [15]. However, Ballal et al. [12] present another approach, by changing all aviation emissions to be in a single compartment, so that these can be adjusted without affecting other emissions. This would be possible here too. However, it is still the case that emissions of long-haul flights are relatively higher in magnitude and average altitude per distance flown (see, e.g., Quadros, Snellen, and Dedoussi [57]). Such effects are implicitly included by Lee et al. [8], which means the impacts of shorter flights – such as those of single-aisle aircraft, as evaluated here – would be overestimated. The approach used by Cox, Jemiolo, and Mutel [15] is therefore considered appropriate to apply here.

Notable is that these adjustments still do not comprise the full picture. The short-term effects described are dependent on the time and place of emissions, for example affecting which chemical reactions occur [57]. The approach used here assumes that a linear change in these emissions also linearly changes the atmospheric reactions these emissions cause. Furthermore, aviation-induced cloudiness is not included, as justified in Section 6.1.3. Note that this means that the inventories and impacts of a component, as described in this study, cannot be generalised to the use phase of an entire aircraft.

C
Unit process data

This chapter reports each of the modelled unit processes. The values reported are for the baseline scenario. What flows are scenario dependent and how these change is explained in Appendix D. For readers using a digital version of this document, the activity codes (e.g., C.1) can be clicked to move to the unit process in question.

Note that when the ecoinvent database is referred to in the following pages, this is ecoinvent 3.8 with the “allocation, cut-off by classification” system model, as defined in Section 5.2. When premise is referred to, this is similarly a background database generated using *premise*, based on this same ecoinvent version and system model, as explained in Section A.1.

Table C.1: Unit process: aluminium alloy production, 7075. Additional documentation in Section B.2.2.

Economic flows, out:

Amount	*Unit*	*Product*	*Activity*	*Location*	*Data source*
1.00	kilogram	[G] aluminium alloy, 7075	[C.1] aluminium alloy production, 7075	[GLO]	[87]
		[W] several additional flows, copied from “aluminium alloy production, AlLi [CA-QC]”			[87]

Economic flows, in:

Amount	*Unit*	*Product*	*Activity*	*Location*	*Data source*
5.60×10^{-2}	kilogram	[G] zinc	[ecoinvent] market for zinc	[GLO]	[93]
2.50×10^{-2}	kilogram	[G] magnesium	[ecoinvent] market for magnesium	[GLO]	[93]
2.30×10^{-3}	kilogram	[G] chromium	[ecoinvent] market for chromium	[GLO]	[93]
1.60×10^{-2}	kilogram	[G] copper, cathode	[ecoinvent] market for copper, cathode	[GLO]	[93]
5.48×10^{-1}	kilogram	[G] aluminium, primary, ingot	[ecoinvent] market for aluminium, primary, ingot	[IAI Area, North America]	[93]
3.73×10^{-1}	kilogram	[W] aluminium scrap, new	[ecoinvent] market for aluminium scrap, new	[RoW]	[93]
		[G] several additional flows, copied from “aluminium alloy production, AlLi [CA-QC]”			[87]

Environmental flows, out:

Amount	*Unit*	*Flow name*	*Compartments*	*Data source*
7.35×10^{-5}	cubic meter	water	air - non-urban air or from high stacks	[87]

Environmental flows, in:

Amount	*Unit*	*Flow name*	*Compartments*	*Data source*

Table C.2: Unit process: aluminium 7075 milling, average. Additional documentation in Section B.2.3.

Economic flows, out:					
Amount	*Unit*	*Product*	*Activity*	*Location*	*Data source*
1.00	kilogram	[G] aluminium 7075 removed by milling, average	[C.2] aluminium 7075 milling, average	[RER]	[89]
1.00	kilogram	[W] aluminium 7075 manufacturing scrap	[C.7] treatment of aluminium alloy manufacturing scrap	[RER]	
3.73×10^{-3}	kilogram	[W] waste mineral oil	[ecoinvent] market for waste mineral oil	[Europe without Switzerland]	[89]
9.23×10^{-5}	kilogram	[W] waste mineral oil	[ecoinvent] market for waste mineral oil	[CH]	[89]

Economic flows, in:					
Amount	*Unit*	*Product*	*Activity*	*Location*	*Data source*
1.00	kilogram	[G] aluminium alloy, 7075	[C.1] aluminium alloy production, 7075	[GLO]	
3.56×10^{-1}	kilowatt hour	[G] electricity, low voltage	[ecoinvent] market group for electricity, low voltage	[RER]	[89]
		[G] several additional flows, copied from “aluminium milling, average [RER]”			[89]

Environmental flows, out:				
Amount	*Unit*	*Flow name*	*Compartments*	*Data source*
1.04×10^{-2}	cubic meter	water	water	[89]
6.30×10^{-3}	cubic meter	water	air	[89]

Environmental flows, in:				
Amount	*Unit*	*Flow name*	*Compartments*	*Data source*
1.48×10^{-2}	cubic meter	water, cooling, unspecified natural origin	natural resource - in water	[89]
1.91×10^{-3}	cubic meter	water, unspecified natural origin	natural resource - in water	[89]

Table C.3: Unit process: material transport, aluminium alloy. Additional documentation in Section B.5.

Economic flows, out:

Amount	*Unit*	*Product*	*Activity*	*Location*	*Data source*
1.00×10^3	kilogram	[G] material transport, aluminium alloy	[C.3] material transport, aluminium alloy	[GLO]	[1]

Economic flows, in:

Amount	*Unit*	*Product*	*Activity*	*Location*	*Data source*
1.40×10^3	ton kilometer	[G] transport, freight, lorry, unspecified	[ecoinvent] market for transport, freight, lorry, unspecified	[RER]	[1]

Environmental flows, out:

Amount	*Unit*	*Flow name*	*Compartments*	*Data source*

Environmental flows, in:

Amount	*Unit*	*Flow name*	*Compartments*	*Data source*

Table C.4: Unit process: post-processing of aluminium alloy rib. Additional documentation in Section B.2.4.

Economic flows, out:

Amount	*Unit*	*Product*	*Activity*	*Location*	*Data source*
1.00	unit	[G] post-processing of aluminium alloy rib	[C.4] post-processing of aluminium alloy rib	[RER]	[1]

Economic flows, in:

Amount	*Unit*	*Product*	*Activity*	*Location*	*Data source*
3.60×10^{-1}	square meter	[G] degreasing, metal part in alkaline bath	[ecoinvent] degreasing, metal part in alkaline bath	[RER]	[1]
3.60×10^{-1}	square meter	[G] anodising, aluminium sheet	[ecoinvent] anodising, aluminium sheet	[RER]	[1]

Environmental flows, out:

Amount	*Unit*	*Flow name*	*Compartments*	*Data source*

Environmental flows, in:

Amount	*Unit*	*Flow name*	*Compartments*	*Data source*

Table C.5: Unit process: aluminium alloy rib production. Additional documentation in Section B.2.1.

Economic flows, out:

Amount	*Unit*	*Product*	*Activity*	*Location*	*Data source*
1.00	unit	[G] aluminium alloy rib	[C.5]	[RER]	
2.63	kilogram	[W] aluminium 7075 end-of-life scrap	[C.10] treatment of aluminium alloy end-of-life scrap	[RER]	

Economic flows, in:

Amount	*Unit*	*Product*	*Activity*	*Location*	*Data source*
2.63	kilogram	[G] aluminium alloy, 7075	[C.1] aluminium alloy production, 7075	[GLO]	
4.99×10^1	kilogram	[G] aluminium 7075 removed by milling, average	[C.2] aluminium 7075 milling, average	[RER]	
5.25×10^1	kilogram	[G] material transport, aluminium alloy	[C.3] material transport, aluminium alloy	[GLO]	
1.00	unit	[G] post-processing of aluminium alloy rib	[C.4] post-processing of aluminium alloy rib	[RER]	

Environmental flows, out:

Amount	*Unit*	*Flow name*	*Compartments*	*Data source*

Environmental flows, in:

Amount	*Unit*	*Flow name*	*Compartments*	*Data source*

Table C.6: Unit process: use of aluminium alloy rib. Additional documentation in Section B.6.

Economic flows, out:					
Amount	*Unit*	*Product*	*Activity*	*Location*	*Data source*
3.00×10^1	year	[G] structural support from aluminium alloy rib	[C.6] use of aluminium alloy rib	[RER]	[1]

Economic flows, in:					
Amount	*Unit*	*Product*	*Activity*	*Location*	*Data source*
1.00	unit	[G] aluminium alloy rib	[C.5] aluminium alloy rib production	[RER]	[1]
7.88×10^1	kilogram year	[G] transport of structural mass	[C.75] mass-induced energy demand	[RER]	

Environmental flows, out:				
Amount	*Unit*	*Flow name*	*Compartments*	*Data source*

Environmental flows, in:				
Amount	*Unit*	*Flow name*	*Compartments*	*Data source*

Table C.7: Unit process: treatment of aluminium alloy manufacturing scrap. Additional documentation in Section B.2.5.

Economic flows, out:

Amount	*Unit*	*Product*	*Activity*	*Location*	*Data source*
9.00×10^{-1}	kilogram	[W] aluminium 7075 manufacturing scrap	[C.9] recycling of aluminium 7075 scrap	[RER]	
1.00×10^{-1}	kilogram	[W] aluminium 7075 manufacturing scrap	[C.8] downcycling of aluminium 7075 scrap	[RER]	

Economic flows, in:

Amount	*Unit*	*Product*	*Activity*	*Location*	*Data source*
1.00	kilogram	[W] aluminium 7075 manufacturing scrap	[C.7] treatment of aluminium alloy manufacturing scrap	[RER]	

Environmental flows, out:

Amount	*Unit*	*Flow name*	*Compartments*	*Data source*

Environmental flows, in:

Amount	*Unit*	*Flow name*	*Compartments*	*Data source*

Table C.8: Unit process: downcycling of aluminium 7075 scrap. Additional documentation in Section B.2.5.

Economic flows, out:					
Amount	*Unit*	*Product*	*Activity*	*Location*	*Data source*
1.00	kilogram	[G] aluminium, cast alloy	[ecoinvent] market for aluminium, cast alloy	[GLO]	[90]
		[W] several additional flows, copied from "treatment of aluminium scrap, post-consumer, prepared for recycling, at refiner [RER]"			[90]

Economic flows, in:					
Amount	*Unit*	*Product*	*Activity*	*Location*	*Data source*
1.29	kilogram	[W] aluminium 7075 manufacturing scrap	[C.8] downcycling of aluminium 7075 scrap	[RER]	[90]
3.57	megajoule	[G] heat, district or industrial, natural gas	[ecoinvent] market group for heat, district or industrial, natural gas	[RER]	[90]
5.94×10^{-2}	kilowatt hour	[G] electricity, medium voltage	[ecoinvent] market group for electricity, medium voltage	[RER]	[90]
		[G] several additional flows, copied from "treatment of aluminium scrap, post-consumer, prepared for recycling, at refiner [RER]"			[90]

Environmental flows, out:				
Amount	*Unit*	*Flow name*	*Compartments*	*Data source*
8.60×10^{-6}	cubic meter	water	water	[90]
1.96×10^{-5}	kilogram	ammonia	air	[90]
1.96×10^{-6}	kilogram	chlorine	air	[90]
4.89×10^{-5}	kilogram	hydrocarbons, chlorinated	air	[90]
		several additional flows, copied from "treatment of aluminium scrap, post-consumer, prepared for recycling, at refiner [RER]"		[90]

Environmental flows, in:				
Amount	*Unit*	*Flow name*	*Compartments*	*Data source*
1.74×10^{-2}	cubic meter	water, unspecified natural origin	natural resource - water	[90]

Table C.9: Unit process: recycling of aluminium 7075 scrap. Additional documentation in Section B.2.5.

Economic flows, out:					
Amount	*Unit*	*Product*	*Activity*	*Location*	*Data source*
1.00	kilogram	[G] aluminium alloy, 7075	[C.1] aluminium alloy production, 7075	[RER]	[91]
		[W] several additional flows, copied from “ treatment of aluminium scrap, new, at remelter [RER]”			[91]

Economic flows, in:					
Amount	*Unit*	*Product*	*Activity*	*Location*	*Data source*
1.01	kilogram	[G] aluminium 7075 manufacturing scrap	[C.9] recycling of aluminium 7075 scrap	[RER]	[91]
3.09	megajoule	[G] heat, district or industrial, natural gas	[ecoinvent] market group for heat, district or industrial, natural gas	[RER]	[91]
1.33×10^{-1}	kilowatt hour	[G] electricity, medium voltage	[ecoinvent] market group for electricity, medium voltage	[RER]	[91]
		[G] several additional flows, copied from “treatment of aluminium scrap, new, at remelter [RER]”			[91]

Environmental flows, out:				
Amount	*Unit*	*Flow name*	*Compartments*	*Data source*
9.17×10^{-6}	cubic meter	water	water	[91]
6.00×10^{-6}	kilogram	chlorine	air	[91]
3.90×10^{-6}	kilogram	hydrocarbons, chlorinated	air	[91]
		several additional flows, copied from “ treatment of aluminium scrap, new, at remelter [RER]”		[91]

Environmental flows, in:				
Amount	*Unit*	*Flow name*	*Compartments*	*Data source*
9.66×10^{-3}	cubic meter	water, unspecified natural origin	natural resource - water	[91]

Table C.10: Unit process: treatment of aluminium alloy end-of-life scrap. Additional documentation in Section B.2.5.

Economic flows, out:					
Amount	*Unit*	*Product*	*Activity*	*Location*	*Data source*
0	kilogram	[W] aluminium 7075 end-of-life scrap	[C.11] recycling of aluminium 7075 scrap, future	[RER]	
1.00	kilogram	[W] aluminium 7075 end-of-life scrap	[C.10] downcycling of aluminium 7075 scrap, future	[RER]	

Economic flows, in:					
Amount	*Unit*	*Product*	*Activity*	*Location*	*Data source*
1.00	kilogram	[W] aluminium 7075 end-of-life scrap	[C.10] treatment of end-of-life aluminium alloy scrap	[RER]	

Environmental flows, out:				
Amount	*Unit*	*Flow name*	*Compartments*	*Data source*

Environmental flows, in:				
Amount	*Unit*	*Flow name*	*Compartments*	*Data source*

Table C.11: Unit process: downcycling of aluminium 7075 scrap, future. Additional documentation in Section B.2.5.

Economic flows, out:

Amount	*Unit*	*Product*	*Activity*	*Location*	*Data source*
1.00	kilogram	[G] aluminium, cast alloy	[premise] market for aluminium, cast alloy	[GLO]	[90]
		[W] several additional flows, copied from "treatment of aluminium scrap, post-consumer, prepared for recycling, at refiner [RER]"			[90]

Economic flows, in:

Amount	*Unit*	*Product*	*Activity*	*Location*	*Data source*
1.29	kilogram	[W] aluminium 7075 end-of-life scrap	[C.11] downcycling of aluminium 7075 scrap, future	[RER]	[90]
3.57	megajoule	[G] heat, district or industrial, natural gas	[premise] market group for heat, district or industrial, natural gas	[RER]	[90]
5.94×10^{-2}	kilowatt hour	[G] electricity, medium voltage	[premise] market group for electricity, medium voltage	[RER]	[90]
		[G] several additional flows, copied from "treatment of aluminium scrap, post-consumer, prepared for recycling, at refiner [RER]"			[90]

Environmental flows, out:

Amount	*Unit*	*Flow name*	*Compartments*	*Data source*
8.60×10^{-6}	cubic meter	water	water	[90]
1.96×10^{-5}	kilogram	ammonia	air	[90]
1.96×10^{-6}	kilogram	chlorine	air	[90]
4.89×10^{-5}	kilogram	hydrocarbons, chlorinated	air	[90]
		several additional flows, copied from "treatment of aluminium scrap, post-consumer, prepared for recycling, at refiner [RER]"		[90]

Environmental flows, in:

Amount	*Unit*	*Flow name*	*Compartments*	*Data source*
1.74×10^{-2}	cubic meter	water, unspecified natural origin	natural resource - water	[90]

Table C.12: Unit process: recycling of aluminium 7075 scrap, future. Additional documentation in Section B.2.5.

Economic flows, out:

Amount	*Unit*	*Product*	*Activity*	*Location*	*Data source*
1.00	kilogram	[G] aluminium alloy, 7075, future	[C.13] aluminium alloy production, 7075, future	[RER]	[91]
		[W] several additional flows, copied from " treatment of aluminium scrap, new, at remelter [RER]"			[91]

Economic flows, in:

Amount	*Unit*	*Product*	*Activity*	*Location*	*Data source*
1.01	kilogram	[G] aluminium 7075 end-of-life scrap	[C.12] recycling of aluminium 7075 scrap, future	[RER]	[91]
3.09	megajoule	[G] heat, district or industrial, natural gas	[premise] market group for heat, district or industrial, natural gas	[RER]	[91]
1.33×10^{-1}	kilowatt hour	[G] electricity, medium voltage	[premise] market group for electricity, medium voltage	[RER]	[91]
		[G] several additional flows, copied from "treatment of aluminium scrap, new, at remelter [RER]"			[91]

Environmental flows, out:

Amount	*Unit*	*Flow name*	*Compartments*	*Data source*
9.17×10^{-6}	cubic meter	water	water	[91]
6.00×10^{-6}	kilogram	chlorine	air	[91]
3.90×10^{-6}	kilogram	hydrocarbons, chlorinated	air	[91]
		several additional flows, copied from " treatment of aluminium scrap, new, at remelter [RER]"		[91]

Environmental flows, in:

Amount	*Unit*	*Flow name*	*Compartments*	*Data source*
9.66×10^{-3}	cubic meter	water, unspecified natural origin	natural resource - water	[91]

Table C.13: Unit process: aluminium alloy production, 7075, future. Additional documentation in Section B.2.2.

Economic flows, out:

Amount	*Unit*	*Product*	*Activity*	*Location*	*Data source*
1.00	kilogram	[G] aluminium alloy, 7075, future	[C.13] aluminium alloy production, 7075, future	[GLO]	[87]
		[W] several additional flows, copied from "aluminium alloy production, AlLi [CA-QC]"			[87]

Economic flows, in:

Amount	*Unit*	*Product*	*Activity*	*Location*	*Data source*
5.60×10^{-2}	kilogram	[G] zinc	[premise] market for zinc	[GLO]	[93]
2.50×10^{-2}	kilogram	[G] magnesium	[premise] market for magnesium	[GLO]	[93]
2.30×10^{-3}	kilogram	[G] chromium	[premise] market for chromium	[GLO]	[93]
1.60×10^{-2}	kilogram	[G] copper, cathode	[premise] market for copper, cathode	[GLO]	[93]
5.48×10^{-1}	kilogram	[G] aluminium, primary, ingot	[premise] market for aluminium, primary, ingot	[IAI Area, North America]	[93]
3.73×10^{-1}	kilogram	[W] aluminium scrap, new	[premise] market for aluminium scrap, new	[RoW]	[93]
		[G] several additional flows, copied from "aluminium alloy production, AlLi [CA-QC]"			[87]

Environmental flows, out:

Amount	*Unit*	*Flow name*	*Compartments*	*Data source*
7.35×10^{-5}	cubic meter	water	air - non-urban air or from high stacks	[87]

Environmental flows, in:

Amount	*Unit*	*Flow name*	*Compartments*	*Data source*

Table C.14: Unit process: utilities estimate, chemical production. Additional documentation in Section B.3.2.

Economic flows, out:					
Amount	*Unit*	*Product*	*Activity*	*Location*	*Data source*
1.00	kilogram	[G] utilities estimate, chemical production	[C.14] utilities estimate, chemical production	[RER]	[97]
1.60	megajoule	[G] heat, from steam, in chemical industry	[ecoinvent] market for heat, from steam, in chemical industry	[RER]	[97]

Economic flows, in:					
Amount	*Unit*	*Product*	*Activity*	*Location*	*Data source*
1.67×10^{-1}	kilowatt hour	[G] electricity, medium voltage	[ecoinvent] market group for electricity, medium voltage	[RER]	[97]
7.70	megajoule	[G] heat, from steam, in chemical industry	[ecoinvent] market for heat, from steam, in chemical industry	[RER]	[97]
1.50×10^{-1}	megajoule	[G] heat, district or industrial, natural gas	[ecoinvent] market for heat, district or industrial, natural gas	[Europe without Switzerland]	[97]
4.00×10^{-10}	unit	[G] chemical factory, organics	[ecoinvent] chemical factory construction, organics	[RER]	[21]

Environmental flows, out:				
Amount	*Unit*	*Flow name*	*Compartments*	*Data source*

Environmental flows, in:				
Amount	*Unit*	*Flow name*	*Compartments*	*Data source*

Table C.15: Unit process: treatment of hazardous waste. Additional documentation in Section B.3.2.

Economic flows, out:

Amount	*Unit*	*Product*	*Activity*	*Location*	*Data source*
3.53×10^{-1}	kilowatt hour	[G] electricity, medium voltage	[ecoinvent] market group for electricity, medium voltage	[RER]	[127]
1.71×10^{1}	megajoule	[G] heat, district or industrial, natural gas	[ecoinvent] market group for heat, district or industrial, natural gas	[RER]	[127]
1.00	kilogram	[W] hazardous waste, for incineration	[ecoinvent] treatment of hazardous waste, hazardous waste incineration, with energy recovery	[Europe without Switzerland]	[127]

Economic flows, in:

Amount	*Unit*	*Product*	*Activity*	*Location*	*Data source*
1.00	kilogram	[W] hazardous waste, organic chemistry	[C.15] treatment of hazardous waste	[RER]	[127]

Environmental flows, out:

Amount	*Unit*	*Flow name*	*Compartments*	*Data source*

Environmental flows, in:

Amount	*Unit*	*Flow name*	*Compartments*	*Data source*

Table C.16: Unit process: hexachloroxylene production. Additional documentation in Section B.3.2.

Economic flows, out:

Amount	*Unit*	*Product*	*Activity*	*Location*	*Data source*
1.00	kilogram	[G] hexachloroxylene	[C.16] hexachloroxylene production	[RER]	[102]
6.99×10^{-1}	kilogram	[G] hydrochloric acid	[ecoinvent] market for hydrochloric acid, without water, in 30% solution state	[RER]	[102]
2.54×10^{-1}	kilogram	[W] hazardous waste, for incineration	[C.15] treatment of hazardous waste	[RER]	[95]

Economic flows, in:

Amount	*Unit*	*Product*	*Activity*	*Location*	*Data source*
1.56	kilogram	[G] chlorine, liquid	[ecoinvent] market for chlorine, liquid	[RER]	[102]
3.90×10^{-1}	kilogram	[G] xylene	[ecoinvent] market for xylene	[RER]	[102]
1.00	kilogram	[G] utilities estimate, chemical production	[C.14] utilities estimate, chemical production	[RER]	[95]

Environmental flows, out:

Amount	*Unit*	*Flow name*	*Compartments*	*Data source*

Environmental flows, in:

Amount	*Unit*	*Flow name*	*Compartments*	*Data source*

Table C.17: Unit process: iso- and terephthaloyl chloride production. Additional documentation in Section B.3.2.

Economic flows, out:

Amount	*Unit*	*Product*	*Activity*	*Location*	*Data source*
1.00	kilogram	[G] iso- and terephthaloyl chloride	[C.17] iso- and terephthaloyl chloride production	[RER]	[101]
1.80×10^{-1}	kilogram	[G] hydrochloric acid	[ecoinvent] market for hydrochloric acid, without water, in 30% solution state	[RER]	[101]
1.76×10^{-1}	kilogram	[W] hazardous waste, for incineration	[C.15] treatment of hazardous waste	[RER]	[95]

Economic flows, in:

Amount	*Unit*	*Product*	*Activity*	*Location*	*Data source*
8.86×10^{-1}	kilogram	[G] hexachloroxylene	[C.16] hexachloroxylene production	[RER]	[101]
4.70×10^{-1}	kilogram	[G] purified terephthalic acid	[ecoinvent] market for purified terephthalic acid	[GLO]	[101]
1.00	kilogram	[G] utilities estimate, chemical production	[C.14] utilities estimate, chemical production	[RER]	[95]

Environmental flows, out:

Amount	*Unit*	*Flow name*	*Compartments*	*Data source*

Environmental flows, in:

Amount	*Unit*	*Flow name*	*Compartments*	*Data source*

Table C.18: Unit process: diphenyl ether production. Additional documentation in Section B.3.2.

Economic flows, out:					
Amount	*Unit*	*Product*	*Activity*	*Location*	*Data source*
1.00	kilogram	[G] diphenyl ether	[C.18] diphenyl ether production	[RER]	[100]
4.28×10^{-1}	kilogram	[G] hydrochloric acid	[ecoinvent] market for hydrochloric acid, without water, in 30% solution state	[RER]	[100]
2.13×10^{-1}	kilogram	[W] hazardous waste, for incineration	[C.15] treatment of hazardous waste	[RER]	[95]

Economic flows, in:					
Amount	*Unit*	*Product*	*Activity*	*Location*	*Data source*
1.52	kilogram	[G] monochlorobenzene	[ecoinvent] market for monochlorobenzene	[RER]	[100]
1.22×10^{-1}	kilogram	[G] water, ultrapure	[ecoinvent] market for water, ultrapure	[RER]	[100]
1.00	kilogram	[G] utilities estimate, chemical production	[C.14] utilities estimate, chemical production	[RER]	[95]

Environmental flows, out:				
Amount	*Unit*	*Flow name*	*Compartments*	*Data source*

Environmental flows, in:				
Amount	*Unit*	*Flow name*	*Compartments*	*Data source*

Table C.19: Unit process: polyetherketoneketone production. Additional documentation in Section B.3.2.

Economic flows, out:

Amount	*Unit*	*Product*	*Activity*	*Location*	*Data source*
1.00	kilogram	[G] polyetherketoneketone	[C.19] polyetherketoneketone production	[RER]	
2.43×10^{-1}	kilogram	[G] hydrochloric acid	[ecoinvent] market for hydrochloric acid, without water, in 30% solution state	[RER]	
2.38×10^{-1}	kilogram	[W] hazardous waste, for incineration	[C.15] treatment of hazardous waste	[RER]	

Economic flows, in:

Amount	*Unit*	*Product*	*Activity*	*Location*	*Data source*
5.84×10^{-1}	kilogram	[G] diphenyl ether	[C.18] diphenyl ether production	[RER]	
6.97×10^{-1}	kilogram	[G] iso- and terephthaloyl chloride	[C.17] iso- and terephthaloyl chloride production	[RER]	
2.00×10^{-1}	kilogram	[G] o-dichlorobenzene	[ecoinvent] market for o-dichlorobenzene	[RER]	
1.00	kilogram	[G] utilities estimate, chemical production	[C.14] utilities estimate, chemical production	[RER]	

Environmental flows, out:

Amount	*Unit*	*Flow name*	*Compartments*	*Data source*

Environmental flows, in:

Amount	*Unit*	*Flow name*	*Compartments*	*Data source*

Table C.20: Unit process: carbon fibre production. Additional documentation in Section B.3.3.

Economic flows, out:

Amount	*Unit*	*Product*	*Activity*	*Location*	*Data source*
1.00	kilogram	[G] carbon fibre	[C.20] carbon fibre production	[GLO]	[36]

Economic flows, in:

Amount	*Unit*	*Product*	*Activity*	*Location*	*Data source*
1.88	kilogram	[G] acrylonitrile	[ecoinvent] market for acrylonitrile	[GLO]	[36]
1.94×10^{-3}	kilogram	[G] epoxy resin, liquid	[ecoinvent] market for epoxy resin, liquid	[RER]	[36]
1.01×10^{-2}	kilogram	[G] epoxy resin, liquid	[ecoinvent] market for epoxy resin, liquid	[RoW]	[36]
9.66	kilogram	[G] nitrogen, liquid	[ecoinvent] market for nitrogen, liquid	[RoW]	[36]
1.86	kilogram	[G] nitrogen, liquid	[ecoinvent] market for nitrogen, liquid	[RER]	[36]
2.84×10^{1}	kilogram	[G] steam, in chemical industry	[ecoinvent] market for steam, in chemical industry	[RoW]	[36]
5.48	kilogram	[G] steam, in chemical industry	[ecoinvent] market for steam, in chemical industry	[RER]	[36]
4.49×10^{1}	kilowatt hour	[G] electricity, medium voltage	[ecoinvent] market group for electricity, medium voltage	[GLO]	[36]
1.91×10^{2}	megajoule	[G] heat, district or industrial, natural gas	[ecoinvent] market group for heat, district or industrial, natural gas	[GLO]	[36]
4.00×10^{-10}	unit	[G] chemical factory, organics	[ecoinvent] market for chemical factory, organics	[GLO]	[21]

Environmental flows, out:

Amount	*Unit*	*Flow name*	*Compartments*	*Data source*
1.16×10^{-3}	kilogram	ammonia	air - non-urban air or from high stacks	[42]
1.01	kilogram	carbon dioxide, fossil	air - non-urban air or from high stacks	[42]
3.24×10^{-3}	kilogram	carbon monoxide, fossil	air - non-urban air or from high stacks	[42]
1.57×10^{-2}	kilogram	cyanide	air - non-urban air or from high stacks	[42]
1.01×10^{-4}	kilogram	ethane	air - non-urban air or from high stacks	[42]
6.74×10^{-4}	kilogram	nitrogen oxides	air - non-urban air or from high stacks	[42]

Environmental flows, in:

Amount	*Unit*	*Flow name*	*Compartments*	*Data source*

Table C.21: Unit process: material transport, carbon fibre. Additional documentation in Section B.5.

Economic flows, out:					
Amount	*Unit*	*Product*	*Activity*	*Location*	*Data source*
1.00×10^{3}	kilogram	[G] material transport, carbon fibre	[C.21] material transport, carbon fibre	[GLO]	

Economic flows, in:					
Amount	*Unit*	*Product*	*Activity*	*Location*	*Data source*
1.50×10^{4}	ton kilometer	[G] transport, freight, sea, container ship	[ecoinvent] market for transport, freight, sea, container ship	[GLO]	

Environmental flows, out:				
Amount	*Unit*	*Flow name*	*Compartments*	*Data source*

Environmental flows, in:				
Amount	*Unit*	*Flow name*	*Compartments*	*Data source*

Table C.22: Unit process: carbon fibre/PEKK prepreg production. Additional documentation in Section B.3.4.

Economic flows, out:

Amount	*Unit*	*Product*	*Activity*	*Location*	*Data source*
1.00	kilogram	[G] carbon fibre/PEKK prepreg	[C.22] carbon fibre/PEKK prepreg production	[RER]	

Economic flows, in:

Amount	*Unit*	*Product*	*Activity*	*Location*	*Data source*
6.76×10^{-1}	kilogram	[G] carbon fibre	[C.20] carbon fibre production	[GLO]	[1]
6.76×10^{-1}	kilogram	[G] material transport, carbon fibre	[C.21] material transport, carbon fibre	[GLO]	[1]
3.24×10^{-1}	kilogram	[G] polyetherketoneketone	[C.19] polyetherketoneketone production	[RER]	[1]
2.91	kilowatt hour	[G] electricity, medium voltage	[ecoinvent] market group for electricity, medium voltage	[RER]	[60]

Environmental flows, out:

Amount	*Unit*	*Flow name*	*Compartments*	*Data source*

Environmental flows, in:

Amount	*Unit*	*Flow name*	*Compartments*	*Data source*

Table C.23: Unit process: material transport, carbon fibre/PEKK prepreg. Additional documentation in Section B.5.

Economic flows, out:

Amount	*Unit*	*Product*	*Activity*	*Location*	*Data source*
1.00×10^3	kilogram	[G] material transport, carbon fibre/PEKK prepreg	[C.23] material transport, carbon fibre/PEKK prepreg	[RER]	

Economic flows, in:

Amount	*Unit*	*Product*	*Activity*	*Location*	*Data source*
1.40×10^3	ton kilometer	[G] transport, freight, lorry, unspecified	[ecoinvent] market for transport, freight, lorry, unspecified	[RER]	

Environmental flows, out:

Amount	*Unit*	*Flow name*	*Compartments*	*Data source*

Environmental flows, in:

Amount	*Unit*	*Flow name*	*Compartments*	*Data source*

Table C.24: Unit process: carbon fibre/PEKK prepreg layup. Additional documentation in Section B.3.5.

Economic flows, out:

Amount	*Unit*	*Product*	*Activity*	*Location*	*Data source*
1.00	unit	[G] CFRTP rib, unconsolidated	[C.24] carbon fibre/PEKK prepreg layup	[RER]	
4.00×10^{-1}	kilogram	[W] waste carbon fibre/PEKK	[C.29] treatment of waste carbon fibre/PEKK	[RER]	

Economic flows, in:

Amount	*Unit*	*Product*	*Activity*	*Location*	*Data source*
4.50	kilogram	[G] carbon fibre/PEKK prepreg	[C.22] carbon fibre/PEKK prepreg production	[RER]	[1]
4.50	kilogram	[G] material transport, carbon fibre/PEKK prepreg	[C.23] material transport, carbon fibre/PEKK prepreg	[RER]	[1]

Environmental flows, out:

Amount	*Unit*	*Flow name*	*Compartments*	*Data source*

Environmental flows, in:

Amount	*Unit*	*Flow name*	*Compartments*	*Data source*

Table C.25: Unit process: consolidation, hot press. Additional documentation in Section B.3.6.

Economic flows, out:

Amount	*Unit*	*Product*	*Activity*	*Location*	*Data source*
1.00	unit	[G] consolidation, hot press	[C.25] consolidation, hot press	[RER]	

Economic flows, in:

Amount	*Unit*	*Product*	*Activity*	*Location*	*Data source*
2.28×10^{1}	kilowatt hour	[G] electricity, medium voltage	[ecoinvent] market group for electricity, medium voltage	[RER]	

Environmental flows, out:

Amount	*Unit*	*Flow name*	*Compartments*	*Data source*

Environmental flows, in:

Amount	*Unit*	*Flow name*	*Compartments*	*Data source*

Table C.26: Unit process: CFRTP rib production, untrimmed. Additional documentation in Section B.3.6.

Economic flows, out:

Amount	*Unit*	*Product*	*Activity*	*Location*	*Data source*
1.00	unit	[G] CFRTP rib, untrimmed	[C.26] CFRTP rib production, untrimmed	[RER]	

Economic flows, in:

Amount	*Unit*	*Product*	*Activity*	*Location*	*Data source*
1.00	unit	[G] CFRTP rib, unconsolidated	[C.24] carbon fibre/PEKK prepreg layup	[RER]	
1.00	unit	[G] consolidation, hot press	[C.25] consolidation, hot press	[RER]	

Environmental flows, out:

Amount	*Unit*	*Flow name*	*Compartments*	*Data source*

Environmental flows, in:

Amount	*Unit*	*Flow name*	*Compartments*	*Data source*

Table C.27: Unit process: CFRTP rib production. Additional documentation in Section B.3.1.

Economic flows, out:

Amount	*Unit*	*Product*	*Activity*	*Location*	*Data source*
1.00	unit	[G] CFRTP rib	[C.27] CFRTP rib production	[RER]	
2.00	kilogram	[W] waste carbon fibre/PEKK	[C.29] treatment of waste carbon fibre/PEKK	[RER]	[1]
2.10	kilogram	[W] end-of-life CFRTP	[C.32] treatment of end-of-life CFRTP	[RER]	[1]

Economic flows, in:

Amount	*Unit*	*Product*	*Activity*	*Location*	*Data source*
1.00	unit	[G] CFRTP rib, untrimmed	[C.26] CFRTP rib production, untrimmed	[RER]	

Environmental flows, out:

Amount	*Unit*	*Flow name*	*Compartments*	*Data source*

Environmental flows, in:

Amount	*Unit*	*Flow name*	*Compartments*	*Data source*

Table C.28: Unit process: use of CFRTP rib. Additional documentation in Section B.6.

Economic flows, out:

Amount	*Unit*	*Product*	*Activity*	*Location*	*Data source*
3.00×10^{1}	year	[G] structural support from CFRTP rib	[C.28] use of CFRTP rib	[RER]	[1]

Economic flows, in:

Amount	*Unit*	*Product*	*Activity*	*Location*	*Data source*
1.00	unit	[G] CFRTP rib	[C.27] CFRTP rib production	[RER]	[1]
6.30×10^{1}	kilogram year	[G] transport of structural mass	[C.75] mass-induced energy demand	[RER]	[1]

Environmental flows, out:

Amount	*Unit*	*Flow name*	*Compartments*	*Data source*

Environmental flows, in:

Amount	*Unit*	*Flow name*	*Compartments*	*Data source*

Table C.29: Unit process: treatment of waste carbon fibre/PEKK. Additional documentation in Section B.3.7.

Economic flows, out:

Amount	*Unit*	*Product*	*Activity*	*Location*	*Data source*
1.00	kilogram	[W] waste carbon fibre/PEKK	[C.30] shredding and mechanical recycling, waste carbon fibre/PEKK	[RER]	
0	kilogram	[W] waste, composite manufacturing	[C.31] incineration and energy recovery	[RER]	

Economic flows, in:

Amount	*Unit*	*Product*	*Activity*	*Location*	*Data source*
1.00	kilogram	[W] waste carbon fibre/PEKK	[C.29] treatment of waste carbon fibre/PEKK	[RER]	

Environmental flows, out:

Amount	*Unit*	*Flow name*	*Compartments*	*Data source*

Environmental flows, in:

Amount	*Unit*	*Flow name*	*Compartments*	*Data source*

Table C.30: Unit process: shredding and mechanical recycling, waste carbon fibre/PEKK. Additional documentation in Section B.3.7.

Economic flows, out:

Amount	*Unit*	*Product*	*Activity*	*Location*	*Data source*
2.50×10^{-1}	kilogram	[G] carbon fibre/PEKK prepreg	[C.22] carbon fibre/PEKK prepreg production	[RER]	

Economic flows, in:

Amount	*Unit*	*Product*	*Activity*	*Location*	*Data source*
2.00	kilogram	[W] waste carbon fibre/PEKK	[C.30] shredding and mechanical recycling, waste carbon fibre/PEKK	[RER]	
7.50×10^{-2}	kilowatt hour	[G] electricity, medium voltage	[ecoinvent] market group for electricity, medium voltage	[RER]	[42]

Environmental flows, out:

Amount	*Unit*	*Flow name*	*Compartments*	*Data source*

Environmental flows, in:

Amount	*Unit*	*Flow name*	*Compartments*	*Data source*

Table C.31: Unit process: incineration and energy recovery. Additional documentation in Section B.3.7.

Economic flows, out:

Amount	*Unit*	*Product*	*Activity*	*Location*	*Data source*
1.09	kilowatt hour	[G] electricity, medium voltage	[ecoinvent] market group for electricity, medium voltage	[RER]	[134]
7.66	megajoule	[G] heat, district or industrial, natural gas	[ecoinvent] market group for heat, district or industrial, natural gas	[RER]	[134]
1.00	kilogram	[W] waste plastic, mixture	[ecoinvent] treatment of waste plastic, mixture, municipal incineration	[RoW]	

Economic flows, in:

Amount	*Unit*	*Product*	*Activity*	*Location*	*Data source*
1.00	kilogram	[W] waste, composite manufacturing	[C.31] incineration and energy recovery	[RER]	

Environmental flows, out:

Amount	*Unit*	*Flow name*	*Compartments*	*Data source*

Environmental flows, in:

Amount	*Unit*	*Flow name*	*Compartments*	*Data source*

Table C.32: Unit process: treatment of end-of-life CFRTP. Additional documentation in Section B.3.7.

Economic flows, out:

Amount	*Unit*	*Product*	*Activity*	*Location*	*Data source*
1.00	kilogram	[W] waste carbon fibre/PEKK, end-of-life	[C.33] shredding and mechanical recycling, waste carbon fibre/PEKK, future	[RER]	
0	kilogram	[W] waste, composite end-of-life	[C.34] incineration and energy recovery, future	[RER]	

Economic flows, in:

Amount	*Unit*	*Product*	*Activity*	*Location*	*Data source*
1.00	kilogram	[W] end-of-life CFRTP	[C.32] treatment of end-of-life CFRTP	[RER]	

Environmental flows, out:

Amount	*Unit*	*Flow name*	*Compartments*	*Data source*

Environmental flows, in:

Amount	*Unit*	*Flow name*	*Compartments*	*Data source*

Table C.33: Unit process: shredding and mechanical recycling, waste carbon fibre/PEKK, future. Additional documentation in Section B.3.7.

Economic flows, out:					
Amount	*Unit*	*Product*	*Activity*	*Location*	*Data source*
2.50×10^{-1}	kilogram	[G] carbon fibre/PEKK prepreg, future	[C.43] carbon fibre/PEKK prepreg production, future	[RER]	

Economic flows, in:					
Amount	*Unit*	*Product*	*Activity*	*Location*	*Data source*
2.00	kilogram	[W] waste carbon fibre/PEKK, end-of-life	[C.33] shredding and mechanical recycling, waste carbon fibre/PEKK, future	[RER]	
7.50×10^{-2}	kilowatt hour	[G] electricity, medium voltage	[premise] market group for electricity, medium voltage	[RER]	[42]

Environmental flows, out:				
Amount	*Unit*	*Flow name*	*Compartments*	*Data source*

Environmental flows, in:				
Amount	*Unit*	*Flow name*	*Compartments*	*Data source*

Table C.34: Unit process: incineration and energy recovery, future. Additional documentation in Section B.3.7.

Economic flows, out:

Amount	*Unit*	*Product*	*Activity*	*Location*	*Data source*
1.09	kilowatt hour	[G] electricity, medium voltage	[premise] market group for electricity, medium voltage	[RER]	[134]
7.66	megajoule	[G] heat, district or industrial, natural gas	[premise] market group for heat, district or industrial, natural gas	[RER]	[134]
1.00	kilogram	[W] waste plastic, mixture	[premise] treatment of waste plastic, mixture, municipal incineration	[RoW]	

Economic flows, in:

Amount	*Unit*	*Product*	*Activity*	*Location*	*Data source*
1.00	kilogram	[W] waste, composite end-of-life	[C.34] incineration and energy recovery, future	[RER]	

Environmental flows, out:

Amount	*Unit*	*Flow name*	*Compartments*	*Data source*

Environmental flows, in:

Amount	*Unit*	*Flow name*	*Compartments*	*Data source*

Table C.35: Unit process: utilities estimate, chemical production, future. Additional documentation in Section B.3.2.

Economic flows, out:

Amount	*Unit*	*Product*	*Activity*	*Location*	*Data source*
1.00	kilogram	[G] utilities estimate, chemical production, future	[C.35] utilities estimate, chemical production, future	[RER]	[97]
1.60	megajoule	[G] heat, from steam, in chemical industry	[premise] market for heat, from steam, in chemical industry	[RER]	[97]

Economic flows, in:

Amount	*Unit*	*Product*	*Activity*	*Location*	*Data source*
1.67×10^{-1}	kilowatt hour	[G] electricity, medium voltage	[premise] market group for electricity, medium voltage	[RER]	[97]
7.70	megajoule	[G] heat, from steam, in chemical industry	[premise] market for heat, from steam, in chemical industry	[RER]	[97]
1.50×10^{-1}	megajoule	[G] heat, district or industrial, natural gas	[premise] market for heat, district or industrial, natural gas	[Europe without Switzerland]	[97]
4.00×10^{-10}	unit	[G] chemical factory, organics	[premise] chemical factory construction, organics	[RER]	[21]

Environmental flows, out:

Amount	*Unit*	*Flow name*	*Compartments*	*Data source*

Environmental flows, in:

Amount	*Unit*	*Flow name*	*Compartments*	*Data source*

Table C.36: Unit process: treatment of hazardous waste, future. Additional documentation in Section B.3.2.

Economic flows, out:

Amount	*Unit*	*Product*	*Activity*	*Location*	*Data source*
3.53×10^{-1}	kilowatt hour	[G] electricity, medium voltage	[premise] market group for electricity, medium voltage	[RER]	[127]
1.71×10^{1}	megajoule	[G] heat, district or industrial, natural gas	[premise] market group for heat, district or industrial, natural gas	[RER]	[127]
1.00	kilogram	[W] hazardous waste, for incineration	[premise] treatment of hazardous waste, hazardous waste incineration, with energy recovery	[Europe without Switzerland]	[127]

Economic flows, in:

Amount	*Unit*	*Product*	*Activity*	*Location*	*Data source*
1.00	kilogram	[W] hazardous waste, organic chemistry, future	[C.36] treatment of hazardous waste, future	[RER]	[127]

Environmental flows, out:

Amount	*Unit*	*Flow name*	*Compartments*	*Data source*

Environmental flows, in:

Amount	*Unit*	*Flow name*	*Compartments*	*Data source*

Table C.37: Unit process: hexachloroxylene production, future. Additional documentation in Section B.3.2.

Economic flows, out:

Amount	*Unit*	*Product*	*Activity*	*Location*	*Data source*
1.00	kilogram	[G] hexachloroxylene, future	[C.37] hexachloroxylene production, future	[RER]	[102]
6.99×10^{-1}	kilogram	[G] hydrochloric acid	[premise] market for hydrochloric acid, without water, in 30% solution state	[RER]	[102]
2.54×10^{-1}	kilogram	[W] hazardous waste, for incineration, future	[C.36] treatment of hazardous waste, future	[RER]	[95]

Economic flows, in:

Amount	*Unit*	*Product*	*Activity*	*Location*	*Data source*
1.56	kilogram	[G] chlorine, liquid	[premise] market for chlorine, liquid	[RER]	[102]
3.90×10^{-1}	kilogram	[G] xylene	[premise] market for xylene	[RER]	[102]
1.00	kilogram	[G] utilities estimate, chemical production, future	[C.35] utilities estimate, chemical production, future	[RER]	[95]

Environmental flows, out:

Amount	*Unit*	*Flow name*	*Compartments*	*Data source*

Environmental flows, in:

Amount	*Unit*	*Flow name*	*Compartments*	*Data source*

Table C.38: Unit process: iso- and terephthaloyl chloride production, future. Additional documentation in Section B.3.2.

Economic flows, out:

Amount	*Unit*	*Product*	*Activity*	*Location*	*Data source*
1.00	kilogram	[G] iso- and terephthaloyl chloride, future	[C.38] iso- and terephthaloyl chloride production, future	[RER]	[101]
1.80×10^{-1}	kilogram	[G] hydrochloric acid	[premise] market for hydrochloric acid, without water, in 30% solution state	[RER]	[101]
1.76×10^{-1}	kilogram	[W] hazardous waste, for incineration, future	[C.36] treatment of hazardous waste, future	[RER]	[95]

Economic flows, in:

Amount	*Unit*	*Product*	*Activity*	*Location*	*Data source*
8.86×10^{-1}	kilogram	[G] hexachloroxylene, future	[C.37] hexachloroxylene production, future	[RER]	[101]
4.70×10^{-1}	kilogram	[G] purified terephthalic acid	[premise] market for purified terephthalic acid	[GLO]	[101]
1.00	kilogram	[G] utilities estimate, chemical production, future	[C.35] utilities estimate, chemical production, future	[RER]	[95]

Environmental flows, out:

Amount	*Unit*	*Flow name*	*Compartments*	*Data source*

Environmental flows, in:

Amount	*Unit*	*Flow name*	*Compartments*	*Data source*

Table C.39: Unit process: diphenyl ether production, future. Additional documentation in Section B.3.2.

Economic flows, out:

Amount	*Unit*	*Product*	*Activity*	*Location*	*Data source*
1.00	kilogram	[G] diphenyl ether, future	[C.39] diphenyl ether production, future	[RER]	[100]
4.28×10^{-1}	kilogram	[G] hydrochloric acid	[premise] market for hydrochloric acid, without water, in 30% solution state	[RER]	[100]
2.13×10^{-1}	kilogram	[W] hazardous waste, for incineration, future	[C.36] treatment of hazardous waste, future	[RER]	[95]

Economic flows, in:

Amount	*Unit*	*Product*	*Activity*	*Location*	*Data source*
1.52	kilogram	[G] monochlorobenzene	[premise] market for monochlorobenzene	[RER]	[100]
1.22×10^{-1}	kilogram	[G] water, ultrapure	[premise] market for water, ultrapure	[RER]	[100]
1.00	kilogram	[G] utilities estimate, chemical production, future	[C.35] utilities estimate, chemical production, future	[RER]	[95]

Environmental flows, out:

Amount	*Unit*	*Flow name*	*Compartments*	*Data source*

Environmental flows, in:

Amount	*Unit*	*Flow name*	*Compartments*	*Data source*

Table C.40: Unit process: polyetherketoneketone production. Additional documentation in Section B.3.2.

Economic flows, out:

Amount	Unit	Product	Activity	Location	Data source
1.00	kilogram	[G] polyetherketoneketone, future	[C.40] polyetherketoneketone production, future	[RER]	
2.43×10^{-1}	kilogram	[G] hydrochloric acid	[premise] market for hydrochloric acid, without water, in 30% solution state	[RER]	
2.38×10^{-1}	kilogram	[W] hazardous waste, for incineration, future	[C.15] treatment of hazardous waste, future	[RER]	

Economic flows, in:

Amount	Unit	Product	Activity	Location	Data source
5.84×10^{-1}	kilogram	[G] diphenyl ether, future	[C.39] diphenyl ether production, future	[RER]	
6.97×10^{-1}	kilogram	[G] iso- and terephthaloyl chloride, future	[C.38] iso- and terephthaloyl chloride production, future	[RER]	
2.00×10^{-1}	kilogram	[G] o-dichlorobenzene	[premise] market for o-dichlorobenzene	[RER]	
1.00	kilogram	[G] utilities estimate, chemical production, future	[C.35] utilities estimate, chemical production, future	[RER]	

Environmental flows, out:

Amount	Unit	Flow name	Compartments	Data source

Environmental flows, in:

Amount	Unit	Flow name	Compartments	Data source

Table C.41: Unit process: carbon fibre production, future. Additional documentation in Section B.3.3.

Economic flows, out:

Amount	*Unit*	*Product*	*Activity*	*Location*	*Data source*
1.00	kilogram	[G] carbon fibre, future	[C.41] carbon fibre production, future	[GLO]	[36]

Economic flows, in:

Amount	*Unit*	*Product*	*Activity*	*Location*	*Data source*
1.88	kilogram	[G] acrylonitrile	[premise] market for acrylonitrile	[GLO]	[36]
1.94×10^{-3}	kilogram	[G] epoxy resin, liquid	[premise] market for epoxy resin, liquid	[RER]	[36]
1.01×10^{-2}	kilogram	[G] epoxy resin, liquid	[premise] market for epoxy resin, liquid	[RoW]	[36]
9.66	kilogram	[G] nitrogen, liquid	[premise] market for nitrogen, liquid	[RoW]	[36]
1.86	kilogram	[G] nitrogen, liquid	[premise] market for nitrogen, liquid	[RER]	[36]
2.84×10^{1}	kilogram	[G] steam, in chemical industry	[premise] market for steam, in chemical industry	[RoW]	[36]
5.48	kilogram	[G] steam, in chemical industry	[premise] market for steam, in chemical industry	[RER]	[36]
4.49×10^{1}	kilowatt hour	[G] electricity, medium voltage	[premise] market group for electricity, medium voltage	[GLO]	[36]
1.91×10^{2}	megajoule	[G] heat, district or industrial, natural gas	[premise] market group for heat, district or industrial, natural gas	[GLO]	[36]
4.00×10^{-10}	unit	[G] chemical factory, organics	[premise] market for chemical factory, organics	[GLO]	[21]

Environmental flows, out:

Amount	*Unit*	*Flow name*	*Compartments*	*Data source*
1.16×10^{-3}	kilogram	ammonia	air - non-urban air or from high stacks	[42]
1.01	kilogram	carbon dioxide, fossil	air - non-urban air or from high stacks	[42]
3.24×10^{-3}	kilogram	carbon monoxide, fossil	air - non-urban air or from high stacks	[42]
1.57×10^{-2}	kilogram	cyanide	air - non-urban air or from high stacks	[42]
1.01×10^{-4}	kilogram	ethane	air - non-urban air or from high stacks	[42]
6.74×10^{-4}	kilogram	nitrogen oxides	air - non-urban air or from high stacks	[42]

Environmental flows, in:

Amount	*Unit*	*Flow name*	*Compartments*	*Data source*

Table C.42: Unit process: material transport, carbon fibre, future. Additional documentation in Section B.5.

Economic flows, out:					
Amount	*Unit*	*Product*	*Activity*	*Location*	*Data source*
1.00×10^3	kilogram	[G] material transport, carbon fibre, future	[C.42] material transport, carbon fibre, future	[GLO]	

Economic flows, in:					
Amount	*Unit*	*Product*	*Activity*	*Location*	*Data source*
1.50×10^4	ton kilometer	[G] transport, freight, sea, container ship	[premise] market for transport, freight, sea, container ship	[GLO]	

Environmental flows, out:				
Amount	*Unit*	*Flow name*	*Compartments*	*Data source*

Environmental flows, in:				
Amount	*Unit*	*Flow name*	*Compartments*	*Data source*

Table C.43: Unit process: carbon fibre/PEKK prepreg production, future. Additional documentation in Section B.3.4.

Economic flows, out:

Amount	*Unit*	*Product*	*Activity*	*Location*	*Data source*
1.00	kilogram	[G] carbon fibre/PEKK prepreg, future	[C.43] carbon fibre/PEKK prepreg production, future	[RER]	

Economic flows, in:

Amount	*Unit*	*Product*	*Activity*	*Location*	*Data source*
6.76×10^{-1}	kilogram	[G] carbon fibre, future	[C.41] carbon fibre production, future	[GLO]	[1]
6.76×10^{-1}	kilogram	[G] material transport, carbon fibre, future	[C.42] material transport, carbon fibre, future	[GLO]	[1]
3.24×10^{-1}	kilogram	[G] polyetherketoneketone, future	[C.40] polyetherketoneketone production, future	[RER]	[1]
2.91	kilowatt hour	[G] electricity, medium voltage	[premise] market group for electricity, medium voltage	[RER]	[60]

Environmental flows, out:

Amount	*Unit*	*Flow name*	*Compartments*	*Data source*

Environmental flows, in:

Amount	*Unit*	*Flow name*	*Compartments*	*Data source*

Table C.44: Unit process: carbon fibre/epoxy prepreg production. Additional documentation in Section B.4.2.

Economic flows, out:

Amount	*Unit*	*Product*	*Activity*	*Location*	*Data source*
1.00	kilogram	[G] carbon fibre/epoxy prepreg	[C.44] carbon fibre/epoxy prepreg production	[RER]	[60]

Economic flows, in:

Amount	*Unit*	*Product*	*Activity*	*Location*	*Data source*
6.85×10^{-1}	kilogram	[G] carbon fibre	[C.20] carbon fibre production	[GLO]	
3.15×10^{-1}	kilogram	[G] epoxy resin, liquid	[ecoinvent] market for epoxy resin, liquid	[RER]	
4.64	kilowatt hour	[G] electricity, medium voltage	[ecoinvent] market group for electricity, medium voltage	[RER]	[60]
6.85×10^{-1}	kilogram	[G] material transport, carbon fibre	[C.21] material transport, carbon fibre	[GLO]	

Environmental flows, out:

Amount	*Unit*	*Flow name*	*Compartments*	*Data source*

Environmental flows, in:

Amount	*Unit*	*Flow name*	*Compartments*	*Data source*

Table C.45: Unit process: material transport, carbon fibre/epoxy prepreg. Additional documentation in Section B.5.

Economic flows, out:

Amount	*Unit*	*Product*	*Activity*	*Location*	*Data source*
1.00	kilogram	[G] material transport, carbon fibre/epoxy prepreg	[C.45] material transport, carbon fibre/epoxy prepreg	[RER]	
5.00×10^{-2}	kilogram	[W] waste carbon fibre/epoxy	[C.58] treatment of waste carbon fibre/epoxy	[RER]	

Economic flows, in:

Amount	*Unit*	*Product*	*Activity*	*Location*	*Data source*
5.00×10^{-2}	kilogram	[G] carbon fibre/epoxy prepreg	[C.44] carbon fibre/epoxy prepreg production	[RER]	
1.47	ton kilometer	[G] transport, freight, lorry with refrigeration machine, freezing	[ecoinvent] market for transport, freight, lorry with refrigeration machine, freezing	[GLO]	

Environmental flows, out:

Amount	*Unit*	*Flow name*	*Compartments*	*Data source*

Environmental flows, in:

Amount	*Unit*	*Flow name*	*Compartments*	*Data source*

Table C.46: Unit process: carbon fibre/epoxy prepreg layup. Additional documentation in Section B.4.3.

Economic flows, out:

Amount	*Unit*	*Product*	*Activity*	*Location*	*Data source*
1.00	unit	[G] CFRTS rib, autoclave, uncured	[C.46] carbon fibre/epoxy prepreg layup	RER	
4.00×10^{-1}	kilogram	[W] waste carbon fibre/epoxy	[C.58] treatment of waste carbon fibre/epoxy	RER	

Economic flows, in:

Amount	*Unit*	*Product*	*Activity*	*Location*	*Data source*
4.50	kilogram	[G] carbon fibre/epoxy prepreg	[C.44] carbon fibre/epoxy prepreg production	RER	
4.50	kilogram	[G] material transport, carbon fibre/epoxy prepreg	[C.45] material transport, carbon fibre/epoxy prepreg	RER	

Environmental flows, out:

Amount	*Unit*	*Flow name*	*Compartments*	*Data source*

Environmental flows, in:

Amount	*Unit*	*Flow name*	*Compartments*	*Data source*

Table C.47: Unit process: material transport, consumables. Additional documentation in Section B.5.

Economic flows, out:					
Amount	*Unit*	*Product*	*Activity*	*Location*	*Data source*
1.00×10^{3}	kilogram	[G] material transport, consumables	[C.47] material transport, consumables	[RER]	[38]

Economic flows, in:					
Amount	*Unit*	*Product*	*Activity*	*Location*	*Data source*
5.00×10^{2}	ton kilometer	[G] transport, freight, lorry, unspecified	[ecoinvent] market for transport, freight, lorry, unspecified	[RER]	[38]

Environmental flows, out:				
Amount	*Unit*	*Flow name*	*Compartments*	*Data source*

Environmental flows, in:				
Amount	*Unit*	*Flow name*	*Compartments*	*Data source*

Table C.48: Unit process: bag tape production. Additional documentation in Section B.4.4.

Economic flows, out:

Amount	*Unit*	*Product*	*Activity*	*Location*	*Data source*
1.60	meter	[G] bag tape	[C.48] bag tape production	RER	[38]
1.50×10^{-1}	kilogram	[W] waste consumables	[C.53] treatment of waste consumables	RER	[38]

Economic flows, in:

Amount	*Unit*	*Product*	*Activity*	*Location*	*Data source*
1.50×10^{-1}	kilogram	[G] synthetic rubber	[ecoinvent] synthetic rubber production	RER	[38]
1.50×10^{-1}	kilogram	[G] extrusion, plastic film	[ecoinvent] extrusion, plastic film	RER	[38]
1.50×10^{-1}	kilogram	[G] material transport, consumables	[C.47] material transport, consumables	RER	[38]

Environmental flows, out:

Amount	*Unit*	*Flow name*	*Compartments*	*Data source*

Environmental flows, in:

Amount	*Unit*	*Flow name*	*Compartments*	*Data source*

Table C.49: Unit process: breather fabric production. Additional documentation in Section B.4.4.

Economic flows, out:					
Amount	*Unit*	*Product*	*Activity*	*Location*	*Data source*
1.60×10^{-1}	square meter	[G] breather fabric	[C.49] breather fabric production	RER	[38]
2.13×10^{-1}	kilogram	[W] waste consumables	[C.53] treatment of waste consumables	RER	[38]

Economic flows, in:					
Amount	*Unit*	*Product*	*Activity*	*Location*	*Data source*
2.13×10^{-1}	kilogram	[G] fleece, polyethylene	[ecoinvent] fleece production, polyethylene	RER	[38]
2.13×10^{-1}	kilogram	[G] material transport, consumables	[C.47] material transport, consumables	RER	[38]

Environmental flows, out:				
Amount	*Unit*	*Flow name*	*Compartments*	*Data source*

Environmental flows, in:				
Amount	*Unit*	*Flow name*	*Compartments*	*Data source*

Table C.50: Unit process: peel ply production. Additional documentation in Section B.4.4.

Economic flows, out:					
Amount	*Unit*	*Product*	*Activity*	*Location*	*Data source*
1.60×10^{-1}	square meter	[G] peel ply	[C.50] peel ply production	RER	[38]
2.90×10^{-2}	kilogram	[W] waste consumables	[C.53] treatment of waste consumables	RER	[38]

Economic flows, in:					
Amount	*Unit*	*Product*	*Activity*	*Location*	*Data source*
2.90×10^{-2}	kilogram	[G] nylon 6-6	[ecoinvent] market for nylon 6-6	RER	[38]
2.90×10^{-2}	kilogram	[G] weaving, synthetic fibre	[ecoinvent] weaving, synthetic fibre	RER	[38]
2.90×10^{-2}	kilogram	[G] material transport, consumables	[C.47] material transport, consumables	RER	[38]

Environmental flows, out:				
Amount	*Unit*	*Flow name*	*Compartments*	*Data source*

Environmental flows, in:				
Amount	*Unit*	*Flow name*	*Compartments*	*Data source*

Table C.51: Unit process: release film production. Additional documentation in Section B.4.4.

Economic flows, out:					
Amount	*Unit*	*Product*	*Activity*	*Location*	*Data source*
1.60×10^{-1}	square meter	[G] release film	[C.51] release film production	RER	[38]
7.50×10^{-3}	kilogram	[W] waste consumables	[C.53] treatment of waste consumables	RER	[38]

Economic flows, in:					
Amount	*Unit*	*Product*	*Activity*	*Location*	*Data source*
7.50×10^{-3}	kilogram	[G] tetrafluoroethylene	[ecoinvent] tetrafluoroethylene production	RER	[38]
7.50×10^{-3}	kilogram	[G] extrusion, plastic film	[ecoinvent] extrusion, plastic film	RER	[38]
7.50×10^{-3}	kilogram	[G] material transport, consumables	[C.47] material transport, consumables	RER	[38]

Environmental flows, out:				
Amount	*Unit*	*Flow name*	*Compartments*	*Data source*

Environmental flows, in:				
Amount	*Unit*	*Flow name*	*Compartments*	*Data source*

Table C.52: Unit process: vacuum bag production. Additional documentation in Section B.4.4.

Economic flows, out:

Amount	Unit	Product	Activity	Location	Data source
1.60×10^{-1}	square meter	[G] vacuum bag	[C.52] vacuum bag production	RER	[38]
2.30×10^{-2}	kilogram	[W] waste consumables	[C.53] treatment of waste consumables	RER	[38]

Economic flows, in:

Amount	Unit	Product	Activity	Location	Data source
2.30×10^{-2}	kilogram	[G] nylon 6-6	[ecoinvent] market for nylon 6-6	RER	[38]
2.30×10^{-2}	kilogram	[G] extrusion, plastic film	[ecoinvent] extrusion, plastic film	RER	[38]
2.30×10^{-2}	kilogram	[G] material transport, consumables	[C.47] material transport, consumables	RER	[38]

Environmental flows, out:

Amount	Unit	Flow name	Compartments	Data source

Environmental flows, in:

Amount	Unit	Flow name	Compartments	Data source

Table C.53: Unit process: treatment of waste consumables. Additional documentation in Section B.4.4.

Economic flows, out:

Amount	*Unit*	*Product*	*Activity*	*Location*	*Data source*
1.00	kilogram	[W] waste, composite manufacturing	[C.31] incineration and energy recovery	[RER]	

Economic flows, in:

Amount	*Unit*	*Product*	*Activity*	*Location*	*Data source*
1.00	kilogram	[W] waste consumables	[C.53] treatment of waste consumables	[RER]	

Environmental flows, out:

Amount	*Unit*	*Flow name*	*Compartments*	*Data source*

Environmental flows, in:

Amount	*Unit*	*Flow name*	*Compartments*	*Data source*

Table C.54: Unit process: bagging and curing, autoclave. Additional documentation in Section B.4.4.

Economic flows, out:					
Amount	*Unit*	*Product*	*Activity*	*Location*	*Data source*
1.00	unit	[G] bagging and curing, autoclave	[C.54] bagging and curing, autoclave	RER	

Economic flows, in:					
Amount	*Unit*	*Product*	*Activity*	*Location*	*Data source*
2.28	meter	[G] bag tape	[C.48] bag tape production	RER	
3.50×10^{-1}	square meter	[G] breather fabric	[C.49] breather fabric production	RER	
3.50×10^{-1}	square meter	[G] peel ply	[C.50] peel ply production	RER	
2.60×10^{-1}	square meter	[G] release film	[C.51] release film production	RER	
7.00×10^{-1}	square meter	[G] vacuum bag	[C.52] vacuum bag production	RER	
1.76×10^{1}	kilowatt hour	[G] electricity, medium voltage	[ecoinvent] market group for electricity, medium voltage	RER	[38]

Environmental flows, out:				
Amount	*Unit*	*Flow name*	*Compartments*	*Data source*

Environmental flows, in:				
Amount	*Unit*	*Flow name*	*Compartments*	*Data source*

Table C.55: Unit process: CFRTS rib production, autoclave, untrimmed. Additional documentation in Section B.4.4.

Economic flows, out:					
Amount	*Unit*	*Product*	*Activity*	*Location*	*Data source*
1.00	unit	[G] CFRTS rib, autoclave, untrimmed	[C.55] CFRTS rib production, autoclave, untrimmed	RER	

Economic flows, in:					
Amount	*Unit*	*Product*	*Activity*	*Location*	*Data source*
1.00	unit	[G] CFRTS rib, autoclave, uncured	[C.46] carbon fibre/epoxy prepreg layup	RER	
1.00	unit	[G] bagging and curing, autoclave	[C.54] bagging and curing, autoclave	RER	

Environmental flows, out:				
Amount	*Unit*	*Flow name*	*Compartments*	*Data source*

Environmental flows, in:				
Amount	*Unit*	*Flow name*	*Compartments*	*Data source*

Table C.56: Unit process: CFRTS rib production, autoclave. Additional documentation in Section B.4.1.

Economic flows, out:

Amount	*Unit*	*Product*	*Activity*	*Location*	*Data source*
1.00	unit	[G] CFRTS rib, autoclave	[C.56] CFRTS rib production, autoclave	RER	
2.00	kilogram	[W] waste carbon fibre/epoxy	[C.58] treatment of waste carbon fibre/epoxy	RER	
2.10	kilogram	[W] end-of-life CFRTS	[C.60] treatment of end-of-life CFRTS	RER	

Economic flows, in:

Amount	*Unit*	*Product*	*Activity*	*Location*	*Data source*
1.00	unit	[G] CFRTS rib, autoclave, untrimmed	[C.55] CFRTS rib production, autoclave, untrimmed	RER	

Environmental flows, out:

Amount	*Unit*	*Flow name*	*Compartments*	*Data source*

Environmental flows, in:

Amount	*Unit*	*Flow name*	*Compartments*	*Data source*

Table C.57: Unit process: use of CFRTS rib, autoclave. Additional documentation in Section B.6.

Economic flows, out:

Amount	*Unit*	*Product*	*Activity*	*Location*	*Data source*
3.00×10^{1}	year	[G] structural support from CFRTS rib, autoclave	[C.57] use of CFRTS rib, autoclave	[RER]	[1]

Economic flows, in:

Amount	*Unit*	*Product*	*Activity*	*Location*	*Data source*
1.00	unit	[G] CFRTS rib, autoclave	[C.56] CFRTS rib production, autoclave	[RER]	[1]
6.30×10^{1}	kilogram year	[G] transport of structural mass	[C.75] mass-induced energy demand	[RER]	[1]

Environmental flows, out:

Amount	*Unit*	*Flow name*	*Compartments*	*Data source*

Environmental flows, in:

Amount	*Unit*	*Flow name*	*Compartments*	*Data source*

Table C.58: Unit process: treatment of waste carbon fibre/epoxy. Additional documentation in Section B.4.6.

Economic flows, out:

Amount	*Unit*	*Product*	*Activity*	*Location*	*Data source*
1.00	kilogram	[W] waste, composite manufacturing	[C.31] incineration and energy recovery	[RER]	
0	kilogram	[W] waste carbon fibre/epoxy	[C.59] shredding and pyrolysis, waste carbon fibre/epoxy	[RER]	

Economic flows, in:

Amount	*Unit*	*Product*	*Activity*	*Location*	*Data source*
1.00	kilogram	[W] waste carbon fibre/epoxy	[C.58] treatment of waste carbon fibre/epoxy	[RER]	

Environmental flows, out:

Amount	*Unit*	*Flow name*	*Compartments*	*Data source*

Environmental flows, in:

Amount	*Unit*	*Flow name*	*Compartments*	*Data source*

Table C.59: Unit process: shredding and pyrolysis, waste carbon fibre/epoxy. Additional documentation in Section B.4.6.

Economic flows, out:

Amount	*Unit*	*Product*	*Activity*	*Location*	*Data source*
1.70×10^{-1}	kilogram	[G] carbon fibre	[C.20] carbon fibre production	[GLO]	[42]
3.20×10^{-1}	kilogram	[G] waste plastic, mixture	[ecoinvent] treatment of waste plastic, mixture, municipal incineration	[RoW]	[42]

Economic flows, in:

Amount	*Unit*	*Product*	*Activity*	*Location*	*Data source*
2.00	kilogram	[W] waste carbon fibre/epoxy	[C.59] shredding and pyrolysis, waste carbon fibre/epoxy	[RER]	[42]
6.46×10^{-1}	kilogram	[G] nitrogen, liquid	[ecoinvent] market for nitrogen, liquid	[RER]	[42]
5.49	kilowatt hour	[G] electricity, medium voltage	[ecoinvent] market group for electricity, medium voltage	[RER]	[42]

Environmental flows, out:

Amount	*Unit*	*Flow name*	*Compartments*	*Data source*

Environmental flows, in:

Amount	*Unit*	*Flow name*	*Compartments*	*Data source*

Table C.60: Unit process: treatment of end-of-life CFRTS. Additional documentation in Section B.4.6.

Economic flows, out:

Amount	*Unit*	*Product*	*Activity*	*Location*	*Data source*
1.00	kilogram	[W] waste, composite end-of-life	[C.34] incineration and energy recovery, future	[RER]	
0	kilogram	[W] waste carbon fibre/epoxy, future	[C.61] shredding and pyrolysis, waste carbon fibre/epoxy, future	[RER]	

Economic flows, in:

Amount	*Unit*	*Product*	*Activity*	*Location*	*Data source*
1.00	kilogram	[W] end-of-life CFRTS	[C.60] treatment of end-of-life CFRTS	[RER]	

Environmental flows, out:

Amount	*Unit*	*Flow name*	*Compartments*	*Data source*

Environmental flows, in:

Amount	*Unit*	*Flow name*	*Compartments*	*Data source*

Table C.61: Unit process: shredding and pyrolysis, waste carbon fibre/epoxy, future. Additional documentation in Section B.4.6.

Economic flows, out:					
Amount	*Unit*	*Product*	*Activity*	*Location*	*Data source*
1.70×10^{-1}	kilogram	[G] carbon fibre, future	[C.41] carbon fibre production, future	[GLO]	[42]
3.20×10^{-1}	kilogram	[G] waste plastic, mixture	[premise] treatment of waste plastic, mixture, municipal incineration	[RoW]	[42]

Economic flows, in:					
Amount	*Unit*	*Product*	*Activity*	*Location*	*Data source*
2.00	kilogram	[W] waste carbon fibre/epoxy, future	[C.61] shredding and pyrolysis, waste carbon fibre/epoxy, future	[RER]	[42]
6.46×10^{-1}	kilogram	[G] nitrogen, liquid	[premise] market for nitrogen, liquid	[RER]	[42]
5.49	kilowatt hour	[G] electricity, medium voltage	[premise] market group for electricity, medium voltage	[RER]	[42]

Environmental flows, out:				
Amount	*Unit*	*Flow name*	*Compartments*	*Data source*

Environmental flows, in:				
Amount	*Unit*	*Flow name*	*Compartments*	*Data source*

Table C.62: Unit process: layup and preforming, RTM. Additional documentation in Section B.4.3.

Economic flows, out:

Amount	*Unit*	*Product*	*Activity*	*Location*	*Data source*
1.00	kilogram	[G] carbon fibre preform	[C.62] layup and preforming, RTM	[RER]	
1.00×10^{-1}	kilogram	[W] waste carbon fibre	[C.68] treatment of waste carbon fibre	[RER]	

Economic flows, in:

Amount	*Unit*	*Product*	*Activity*	*Location*	*Data source*
1.10	kilogram	[G] carbon fibre	[C.20] carbon fibre production	[RER]	
1.10	kilogram	[G] material transport, carbon fibre	[C.21] material transport, carbon fibre	[RER]	

Environmental flows, out:

Amount	*Unit*	*Flow name*	*Compartments*	*Data source*

Environmental flows, in:

Amount	*Unit*	*Flow name*	*Compartments*	*Data source*

Table C.63: Unit process: material transport, epoxy. Additional documentation in Section B.5.

Economic flows, out:

Amount	*Unit*	*Product*	*Activity*	*Location*	*Data source*
1.00	kilogram	[G] material transport, epoxy	[C.63] material transport, epoxy	[RER]	
5.00×10^{-2}	kilogram	[W] waste, composite manufacturing	[C.31] incineration and energy recovery	[RER]	

Economic flows, in:

Amount	*Unit*	*Product*	*Activity*	*Location*	*Data source*
5.00×10^{-2}	kilogram	[G] epoxy resin, liquid	[ecoinvent] market for epoxy resin, liquid	[RER]	
1.47	ton kilometer	[G] transport, freight, lorry with refrigeration machine, freezing	[ecoinvent] market for transport, freight, lorry with refrigeration machine, freezing	[GLO]	

Environmental flows, out:

Amount	*Unit*	*Flow name*	*Compartments*	*Data source*

Environmental flows, in:

Amount	*Unit*	*Flow name*	*Compartments*	*Data source*

Table C.64: Unit process: infusion and curing, RTM. Additional documentation in Section B.4.5.

Economic flows, out:					
Amount	*Unit*	*Product*	*Activity*	*Location*	*Data source*
1.00	kilogram	[G] infusion and curing, RTM	[C.64] infusion and curing, RTM	[RER]	[104]
2.00×10^{-1}	kilogram	[W] waste, composite manufacturing	[C.31] incineration and energy recovery	[RER]	[1]
3.31×10^{-5}	kilogram	[W] hazardous waste, for underground deposit	[ecoinvent] market for hazardous waste, for underground deposit	[RER]	[104]
8.95×10^{-4}	kilogram	[W] municipal solid waste	[ecoinvent] market group for municipal solid waste	[RER]	[104]

Economic flows, in:					
Amount	*Unit*	*Product*	*Activity*	*Location*	*Data source*
1.20	kilogram	[G] material transport, epoxy	[C.63] material transport, epoxy	[RER]	[1]
1.20	kilogram	[G] epoxy resin, liquid	[ecoinvent] market for epoxy resin, liquid	[RER]	[1]
1.48	kilowatt hour	[G] electricity, medium voltage	[ecoinvent] market group for electricity, medium voltage	[RER]	[104]
4.21	megajoule	[G] heat, district or industrial, natural gas	[ecoinvent] market group for heat, district or industrial, natural gas	[RER]	[104]
2.29×10^{-1}	megajoule	[G] heat, district or industrial, other than natural gas	[ecoinvent] market group for heat, district or industrial, other than natural gas	[RER]	[104]
		[G] several additional flows, copied from “injection moulding [RER]”			[104]

Environmental flows, out:				
Amount	*Unit*	*Flow name*	*Compartments*	*Data source*
1.86×10^{-5}	kilogram	BOD5, Biological Oxygen Demand	water - surface	[104]
9.28×10^{-6}	kilogram	COD, Chemical Oxygen Demand	water - surface	[104]
3.44×10^{-6}	kilogram	DOC, Dissolved Organic Carbon	water - surface	[104]
		several additional flows, copied from “injection moulding [RER]”		[104]

Environmental flows, in:				
Amount	*Unit*	*Flow name*	*Compartments*	*Data source*
1.10×10^{-2}	cubic meter	water, cooling, unspecified natural origin	natural resource - water	[104]

Table C.65: Unit process: CFRTS rib production, RTM, untrimmed. Additional documentation in Section B.4.1, Section B.4.3, and Section B.4.5.

Economic flows, out:

Amount	*Unit*	*Product*	*Activity*	*Location*	*Data source*
1.00	unit	[G] CFRTS rib, RTM, untrimmed	[C.65] CFRTS rib production, RTM, untrimmed	[RER]	

Economic flows, in:

Amount	*Unit*	*Product*	*Activity*	*Location*	*Data source*
2.77	kilogram	[G] carbon fibre preform	[C.62] layup and preforming, RTM	[RER]	
1.33	kilogram	[G] infusion and curing, RTM	[C.64] infusion and curing, RTM	[RER]	

Environmental flows, out:

Amount	*Unit*	*Flow name*	*Compartments*	*Data source*

Environmental flows, in:

Amount	*Unit*	*Flow name*	*Compartments*	*Data source*

Table C.66: Unit process: CFRTS rib production, RTM. Additional documentation in Section B.4.1.

Economic flows, out:

Amount	*Unit*	*Product*	*Activity*	*Location*	*Data source*
1.00	unit	[G] CFRTS rib, RTM	[C.66] CFRTS rib production, RTM	[RER]	
2.00	kilogram	[W] waste carbon fibre/epoxy	[C.58] treatment of waste carbon fibre/epoxy	[RER]	
2.10	kilogram	[W] end-of-life CFRTS	[C.60] treatment of end-of-life CFRTS	[RER]	

Economic flows, in:

Amount	*Unit*	*Product*	*Activity*	*Location*	*Data source*
1.00	unit	[G] CFRTS rib, RTM, untrimmed	[C.65] CFRTS rib production, RTM, untrimmed	[RER]	

Environmental flows, out:

Amount	*Unit*	*Flow name*	*Compartments*	*Data source*

Environmental flows, in:

Amount	*Unit*	*Flow name*	*Compartments*	*Data source*

Table C.67: Unit process: use of CFRTS rib, RTM. Additional documentation in Section B.6.

Economic flows, out:

Amount	*Unit*	*Product*	*Activity*	*Location*	*Data source*
3.00×10^1	year	[G] structural support from CFRTS rib, RTM	[C.67] use of CFRTS rib, RTM	[RER]	[1]

Economic flows, in:

Amount	*Unit*	*Product*	*Activity*	*Location*	*Data source*
1.00	unit	[G] CFRTS rib, RTM	[C.66] CFRTS rib production, RTM	[RER]	[1]
6.30×10^1	kilogram year	[G] transport of structural mass	[C.75] mass-induced energy demand	[RER]	[1]

Environmental flows, out:

Amount	*Unit*	*Flow name*	*Compartments*	*Data source*

Environmental flows, in:

Amount	*Unit*	*Flow name*	*Compartments*	*Data source*

Table C.68: Unit process: treatment of waste carbon fibre. Additional documentation in Section B.4.6.

Economic flows, out:

Amount	*Unit*	*Product*	*Activity*	*Location*	*Data source*
1.00	kilogram	[W] waste, composite manufacturing	[C.31] incineration and energy recovery	[RER]	
0	kilogram	[W] waste carbon fibre	[C.69] collection for recycled fabric, waste carbon fibre	[RER]	

Economic flows, in:

Amount	*Unit*	*Product*	*Activity*	*Location*	*Data source*
1.00	kilogram	[W] waste carbon fibre	[C.68] treatment of waste carbon fibre	[RER]	

Environmental flows, out:

Amount	*Unit*	*Flow name*	*Compartments*	*Data source*

Environmental flows, in:

Amount	*Unit*	*Flow name*	*Compartments*	*Data source*

Table C.69: Unit process: collection for recycled fabric, waste carbon fibre. Additional documentation in Section B.4.6.

Economic flows, out:

Amount	*Unit*	*Product*	*Activity*	*Location*	*Data source*
2.50×10^{-1}	kilogram	[G] carbon fibre	[C.20] carbon fibre production	[GLO]	

Economic flows, in:

Amount	*Unit*	*Product*	*Activity*	*Location*	*Data source*
2.00	kilogram	[W] waste carbon fibre	[C.69] collection for recycled fabric, waste carbon fibre	[RER]	

Environmental flows, out:

Amount	*Unit*	*Flow name*	*Compartments*	*Data source*

Environmental flows, in:

Amount	*Unit*	*Flow name*	*Compartments*	*Data source*

Table C.70: Unit process: use of fossil kerosene. Additional documentation in Section B.6.

Economic flows, out:					
Amount	*Unit*	*Product*	*Activity*	*Location*	*Data source*
4.30×10^{1}	megajoule	[G] combustion energy, fossil kerosene	[C.70] use of fossil kerosene	[RER]	[33]

Economic flows, in:					
Amount	*Unit*	*Product*	*Activity*	*Location*	*Data source*
1.00	kilogram	[G] kerosene	[ecoinvent] market for kerosene	[Europe without Switzerland]	[33]

Environmental flows, out:				
Amount	*Unit*	*Flow name*	*Compartments*	*Data source*
8.84×10^{-10}	kilogram	cadmium	air - non-urban air or from high stacks	[110]
9.10×10^{-9}	kilogram	cadmium	air - lower stratosphere + upper troposphere	[110]
2.84	kilogram	carbon dioxide, fossil	air - lower stratosphere + upper troposphere	[110]
2.76×10^{-1}	kilogram	carbon dioxide, fossil	air - non-urban air or from high stacks	[110]
1.67×10^{-4}	kilogram	carbon monoxide, fossil	air - non-urban air or from high stacks	[110]
1.72×10^{-3}	kilogram	carbon monoxide, fossil	air - lower stratosphere + upper troposphere	[110]
4.55×10^{-8}	kilogram	chromium	air - lower stratosphere + upper troposphere	[110]
4.42×10^{-9}	kilogram	chromium	air - non-urban air or from high stacks	[110]
1.36×10^{-6}	kilogram	copper	air - lower stratosphere + upper troposphere	[110]
1.50×10^{-7}	kilogram	copper	air - non-urban air or from high stacks	[110]
1.82×10^{-5}	kilogram	lead	air - lower stratosphere + upper troposphere	[110]
1.77×10^{-6}	kilogram	lead	air - non-urban air or from high stacks	[110]
6.18×10^{-12}	kilogram	mercury	air - non-urban air or from high stacks	[110]
6.40×10^{-11}	kilogram	mercury	air - lower stratosphere + upper troposphere	[110]
6.18×10^{-9}	kilogram	nickel	air - non-urban air or from high stacks	[110]
6.40×10^{-8}	kilogram	nickel	air - lower stratosphere + upper troposphere	[110]
1.39×10^{-3}	kilogram	nitrogen oxides	air - non-urban air or from high stacks	[110]
1.43×10^{-2}	kilogram	nitrogen oxides	air - lower stratosphere + upper troposphere	[110]
2.03×10^{-4}	kilogram	NMVOC, non-methane volatile organic compounds, unspecified origin	air - lower stratosphere + upper troposphere	[110]
1.97×10^{-5}	kilogram	NMVOC, non-methane volatile organic compounds, unspecified origin	air - non-urban air or from high stacks	[110]

(*table continues*)

Table C.70: Unit process: use of fossil kerosene. Continued from the previous page.

Environmental flows, out:

Amount	*Unit*	*Flow name*	*Compartments*	*Data source*
1.26×10^{-4}	kilogram	particulates, < 2.5 um	air - lower stratosphere + upper troposphere	[110]
1.23×10^{-5}	kilogram	particulates, < 2.5 um	air - non-urban air or from high stacks	[110]
9.10×10^{-9}	kilogram	selenium	air - lower stratosphere + upper troposphere	[110]
8.84×10^{-10}	kilogram	selenium	air - non-urban air or from high stacks	[110]
7.66×10^{-4}	kilogram	sulfur dioxide	air - lower stratosphere + upper troposphere	[110]
7.43×10^{-5}	kilogram	sulfur dioxide	air - non-urban air or from high stacks	[110]
1.12×10^{-3}	cubic meter	water	air - lower stratosphere + upper troposphere	[8]
1.10×10^{-4}	cubic meter	water	air - non-urban air or from high stacks	[8]
9.10×10^{-6}	kilogram	zinc	air - lower stratosphere + upper troposphere	[110]
8.84×10^{-7}	kilogram	zinc	air - non-urban air or from high stacks	[110]

Environmental flows, in:

Amount	*Unit*	*Flow name*	*Compartments*	*Data source*

Table C.71: Unit process: use of bio-kerosene. Additional documentation in Section B.6.

Economic flows, out:					
Amount	*Unit*	*Product*	*Activity*	*Location*	*Data source*
4.50×10^{1}	megajoule	[G] combustion energy, bio- kerosene	[C.71] use of bio-kerosene	[RER]	[109]

Economic flows, in:					
Amount	*Unit*	*Product*	*Activity*	*Location*	*Data source*
1.00	kilogram	[G] kerosene, synthetic	[premise] kerosene production, synthetic, from Fischer Tropsch process, hydrogen from wood gasification, energy allocation, at fuelling station	[EUR]	[109]

Environmental flows, out:				
Amount	*Unit*	*Flow name*	*Compartments*	*Data source*
2.84	kilogram	carbon dioxide, non-fossil	air - lower stratosphere + upper troposphere	[110]
2.76×10^{-1}	kilogram	carbon dioxide, non-fossil	air - non-urban air or from high stacks	[110]
1.72×10^{-3}	kilogram	carbon monoxide, non-fossil	air - lower stratosphere + upper troposphere	[110]
1.67×10^{-4}	kilogram	carbon monoxide, non-fossil	air - non-urban air or from high stacks	[110]
1.39×10^{-3}	kilogram	nitrogen oxides	air - non-urban air or from high stacks	[110]
1.43×10^{-2}	kilogram	nitrogen oxides	air - lower stratosphere + upper troposphere	[110]
1.52×10^{-4}	kilogram	NMVOC, non-methane volatile organic compounds, unspecified origin	air - lower stratosphere + upper troposphere	[110]
1.47×10^{-5}	kilogram	NMVOC, non-methane volatile organic compounds, unspecified origin	air - non-urban air or from high stacks	[110]
1.12×10^{-3}	cubic meter	water	air - lower stratosphere + upper troposphere	[110]
1.10×10^{-4}	cubic meter	water	air - non-urban air or from high stacks	[110]

Environmental flows, in:				
Amount	*Unit*	*Flow name*	*Compartments*	*Data source*

Table C.72: Unit process: use of e-kerosene. Additional documentation in Section B.6.

Economic flows, out:

Amount	*Unit*	*Product*	*Activity*	*Location*	*Data source*
4.50×10^{1}	megajoule	[G] combustion energy, e-kerosene	[C.72] use of e-kerosene	[RER]	[109]

Economic flows, in:

Amount	*Unit*	*Product*	*Activity*	*Location*	*Data source*
1.00	kilogram	[G] kerosene, synthetic	[premise] kerosene production, synthetic, from Fischer Tropsch process, hydrogen from electrolysis, energy allocation, at fuelling station	[EUR]	[109]

Environmental flows, out:

Amount	*Unit*	*Flow name*	*Compartments*	*Data source*
2.84	kilogram	carbon dioxide, non-fossil	air - lower stratosphere + upper troposphere	[110]
2.76×10^{-1}	kilogram	carbon dioxide, non-fossil	air - non-urban air or from high stacks	[110]
1.72×10^{-3}	kilogram	carbon monoxide, non-fossil	air - lower stratosphere + upper troposphere	[110]
1.67×10^{-4}	kilogram	carbon monoxide, non-fossil	air - non-urban air or from high stacks	[110]
1.39×10^{-3}	kilogram	nitrogen oxides	air - non-urban air or from high stacks	[110]
1.43×10^{-2}	kilogram	nitrogen oxides	air - lower stratosphere + upper troposphere	[110]
1.52×10^{-4}	kilogram	NMVOC, non-methane volatile organic compounds, unspecified origin	air - lower stratosphere + upper troposphere	[110]
1.47×10^{-5}	kilogram	NMVOC, non-methane volatile organic compounds, unspecified origin	air - non-urban air or from high stacks	[110]
1.12×10^{-3}	cubic meter	water	air - lower stratosphere + upper troposphere	[110]
1.10×10^{-4}	cubic meter	water	air - non-urban air or from high stacks	[110]

Environmental flows, in:

Amount	*Unit*	*Flow name*	*Compartments*	*Data source*

Table C.73: Unit process: use of hydrogen fuel cell. Additional documentation in Section B.6.

Economic flows, out:

Amount	*Unit*	*Product*	*Activity*	*Location*	*Data source*
1.20×10^{2}	megajoule	[G] conversion energy, hydrogen fuel cell	[C.71] use of synthetic kerosene	[RER]	[109]

Economic flows, in:

Amount	*Unit*	*Product*	*Activity*	*Location*	*Data source*
1.00	kilogram	[G] hydrogen, gaseous	[premise] market for hydrogen, gaseous	[RER]	[109]

Environmental flows, out:

Amount	*Unit*	*Flow name*	*Compartments*	*Data source*
8.14×10^{-3}	cubic meter	water	air - lower stratosphere + upper troposphere	
7.99×10^{-4}	cubic meter	water	air - non-urban air or from high stacks	

Environmental flows, in:

Amount	*Unit*	*Flow name*	*Compartments*	*Data source*

Table C.74: Unit process: use of energy carrier. Additional documentation in Section B.6.

Economic flows, out:

Amount	*Unit*	*Product*	*Activity*	*Location*	*Data source*
1.00	megajoule	[G] energy, energy carrier	[C.74] use of energy carrier	[RER]	

Economic flows, in:

Amount	*Unit*	*Product*	*Activity*	*Location*	*Data source*
1.00	megajoule	[G] combustion energy, fossil kerosene	[C.70] use of fossil kerosene	[RER]	
0	megajoule	[G] combustion energy, bio-kerosene	[C.71] use of bio-kerosene	[RER]	
0	megajoule	[G] combustion energy, e-kerosene	[C.72] use of e-kerosene	[RER]	
0	megajoule	[G] conversion energy, hydrogen fuel cell	[C.73] use of synthetic kerosene	[RER]	

Environmental flows, out:

Amount	*Unit*	*Flow name*	*Compartments*	*Data source*

Environmental flows, in:

Amount	*Unit*	*Flow name*	*Compartments*	*Data source*

Table C.75: Unit process: mass-induced energy demand. Additional documentation in Section B.6.

Economic flows, out:

Amount	*Unit*	*Product*	*Activity*	*Location*	*Data source*
1.00	kilogram year	[G] transport of structural mass	[C.75] mass-induced energy demand	[RER]	[13]

Economic flows, in:

Amount	*Unit*	*Product*	*Activity*	*Location*	*Data source*
4.47×10^3	megajoule	[G] energy, energy carrier	[C.74] use of energy carrier	[RER]	[13]

Environmental flows, out:

Amount	*Unit*	*Flow name*	*Compartments*	*Data source*

Environmental flows, in:

Amount	*Unit*	*Flow name*	*Compartments*	*Data source*

D

Extended scenario descriptions

This chapter elaborates on how product system inventories are altered in the scenarios described in Section 6.4.

D.1. Waste treatment and use intensity scenarios

Due to how the product system models are structured, the scenarios described in Section 6.4.1 are easy to implement, as are the use intensity scenarios of Section 6.4.2. The factors reported in Table 6.2 each correspond to changing just one unit process. These are the unit processes illustrated as purple diamond shapes in the flowcharts of Section A.3. For the factors reported in Table 6.3, the unit processes adjusted are those which have transport of structural mass as input (C.6, C.28, C.57, and C.67). The calculations described in Section B.6.3 are adjusted to reflect the appropriate years of use.

D.2. Component mass scenarios

For the break-even analysis, all component masses are set to 2.1 kg and incrementally varied by 5×10^{-5} kg. This requires parameterising all unit processes which depend on the component mass. An overview of how this is implemented is presented in Table D.1. Note that, if the component mass is set to zero in the amounts listed in Table D.1, this does not necessarily mean that environmental impacts of the alternative become zero. This is because some processes are not parameterised based on the component mass, but based on another variable: C.4 and C.54 scale by area, and the energy demand for consolidation (C.25) and autoclave processing (C.54) is assumed to be driven by properties of the machinery, as discussed in Appendix B. This way, the CFRTS, RTM alternative is the only one for which emissions would be zero if component mass is set to zero in these product system models.

D.3. Alternative energy carriers scenarios

Prospective background databases are constructed using *premise*, where each future year is based on the NDC pathway of the REMIND IAM, as detailed in Section A.1. The time step of five years is implemented by using the background system (and in the case of drop-in fuels, the volume share) of the first year in the integral (2025-2029 uses the share and background system for 2025, 2030-2034 uses the share and background system for 2030, etc.). This means that the volume shares are effectively

Table D.1: Influence of inventory parameter component mass (m_{rib}) on flow values. The unit process column refers to the process in which the value of the flow is changed, not the process of which the flow in question is a functional flow. Several flows were initially defined in reference to the CFRTP rib mass ($m_{rib,0} = 2.1$ kg), a relationship which is maintained here.

Unit process	Flow	Amount equation [year]
C.5	aluminium 7075 end-of-life scrap	m_{rib}
C.5	aluminium alloy, 7075	m_{rib}
C.5	aluminium 7075 removed by milling, average	$19m_{rib}$
C.5	material transport, aluminium alloy	$20m_{rib}$
C.46	waste carbon fibre/epoxy	$0.4\frac{m_{rib}}{m_{rib,0}}$
C.46	carbon fibre/epoxy prepreg	$4.5\frac{m_{rib}}{m_{rib,0}}$
C.46	material transport, carbon fibre/epoxy prepreg	$4.5\frac{m_{rib}}{m_{rib,0}}$
C.56	waste carbon fibre/epoxy	$2\frac{m_{rib}}{m_{rib,\,0}}$
C.56	end-of-life CFRTS	m_{rib}
C.65	carbon fibre preform	$2.77\frac{m_{rib}}{m_{rib,0}}$
C.65	infusion and curing	$1.33\frac{m_{rib}}{m_{rib,0}}$
C.66	waste carbon fibre/epoxy	$2\frac{m_{rib}}{m_{rib,0}}$
C.66	end-of-life CFRTS	m_{rib}

operationalised with a left Riemann sum, but also that the background system is lagging behind the actual pathway described for four out of every five years. This way, environmental impacts can be expected to be overestimated in relation to the described pathway.

To implement the three scenarios of Section 6.4.3, C.74 is adjusted. In the SAF scenario, different energy sources are mixed, which involves a few further assumptions. The shares reproduced in Table 6.4 are in some cases a minimum *per year* and in other cases a minimum *across a longer period*. This distinction would be lost in any case due to the approximation method described in the previous paragraph. Furthermore, (liquid) hydrogen used as aviation energy carrier can also contribute to the ReFuelEU Aviation volume shares [75]. There could be a scenario in which the minimum shares are met to a large extent with hydrogen, and aircraft using drop-in fuels would see lower impact reductions than assumed here. Conversely, it is possible that the coming decades see a larger acceleration of SAF than dictated here. Both possibilities should be kept in mind.

E

Extended impact assessment results and contribution analyses

Note that unaltered characterisation results are also included in Appendix H.

E.1. Contribution analyses

Using the Sankey tool of the Activity Browser [22], a number of diagrams are created for inclusion in Appendix H. These show point sources for particular impact categories in the lifecycle excluding use.

Section 7.4.2 included the contributions of the lifecycle for the baseline scenario, fuelled by fossil kerosene. Figure E.1 and Figure E.2 illustrate contributions in the SAF and hydrogen energy scenarios, respectively. The values for these and other contribution analysis figures are included in Appendix H. Figure E.1 and Figure E.2 illustrate the contribution analysis for the lifecycle including use under the SAF scenario and hydrogen scenario, respectively. These again confirm what is discussed in Section 7.7.1: that the SAF scenario does not differ much from fossil kerosene and that the hydrogen scenario becomes (virtually) fully dependent on the broader energy system.

E.2. Break-even analyses approach and results

In the context of the break-even analyses discussed in Section 7.6 and Section 7.7.3, characterisation results for the lifecycle excluding use are illustrated in Figure E.3 for all components having the same mass of 2.1 kg and in Figure E.4 for all components having the same mass of 0 kg. These scenarios were instrumental in operationalising and verifying the break-even analyses. The aforementioned sections present and discuss several break-even results. In this section, each combination of use and energy scenarios is represented in one of the tables: Table E.1 for the baseline (fossil) scenario; Table E.2 for the SAF (mixed) scenario; and Table E.3 for the hydrogen scenario.

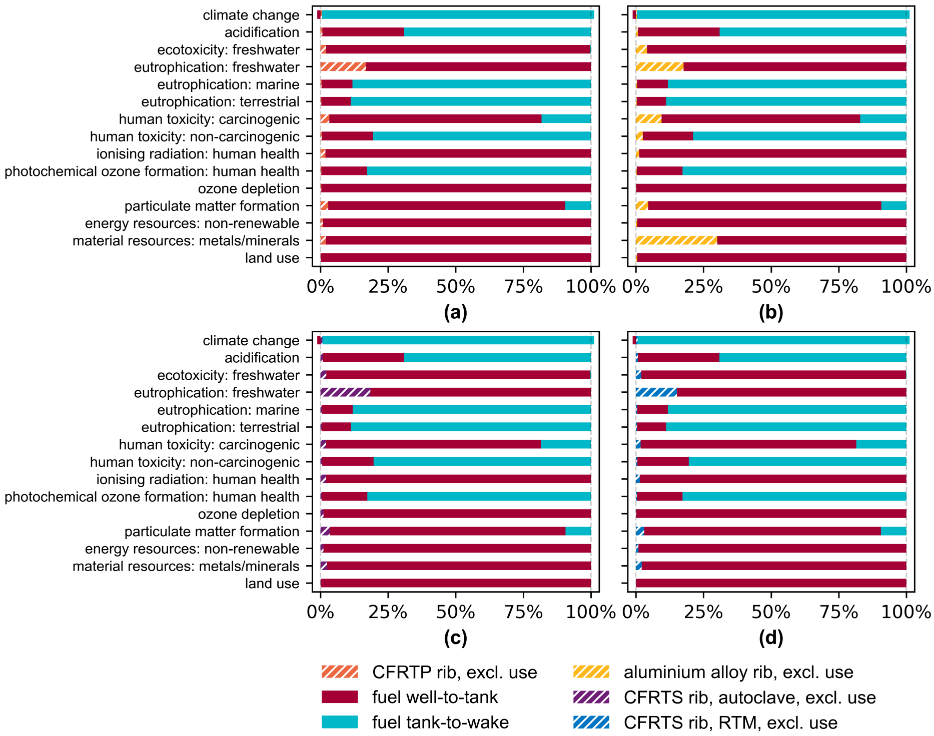


Figure E.1: Contribution analysis of the SAF scenario lifecycle including use of **(a)** the CFRTS rib, **(b)** the aluminium alloy rib, **(c)** the CFRTS rib, autoclave, and **(d)** the CFRTS rib, RTM. Contributions are allocated to foreground processes according to the Sankey tool of the Activity Browser and add up to 100% for each impact category. Dashed lines indicate 0% and 100%.

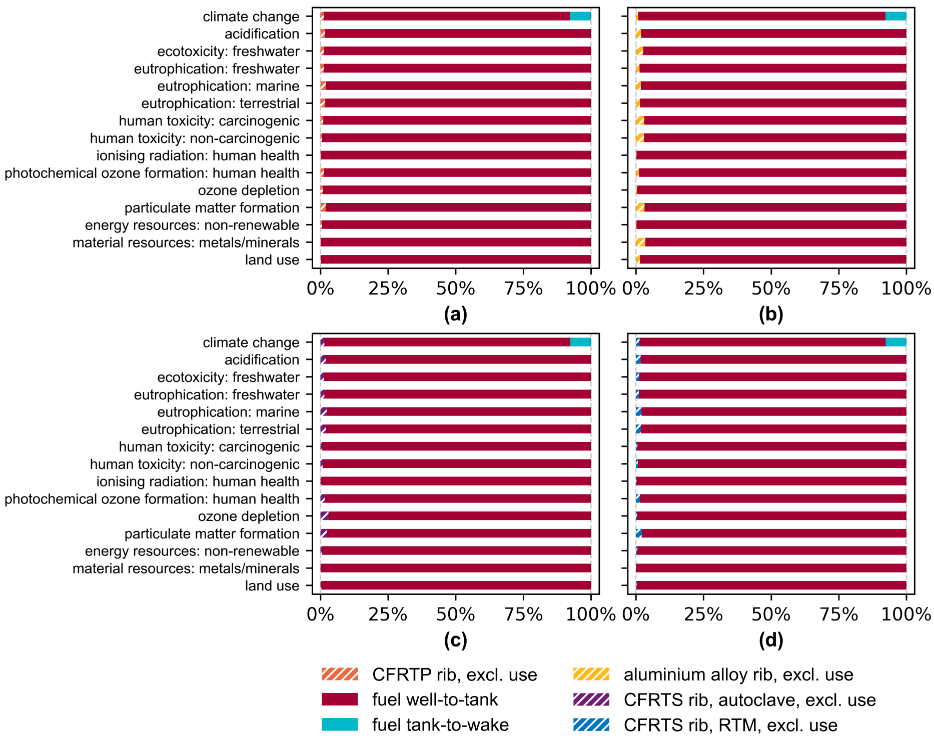


Figure E.2: Contribution analysis of the hydrogen scenario lifecycle including use of **(a)** the CFRTS rib, **(b)** the aluminium alloy rib, **(c)** the CFRTS rib, autoclave, and **(d)** the CFRTS rib, RTM. Contributions are allocated to foreground processes according to the Sankey tool of the Activity Browser and add up to 100% for each impact category. Dashed lines indicate 0% and 100%.

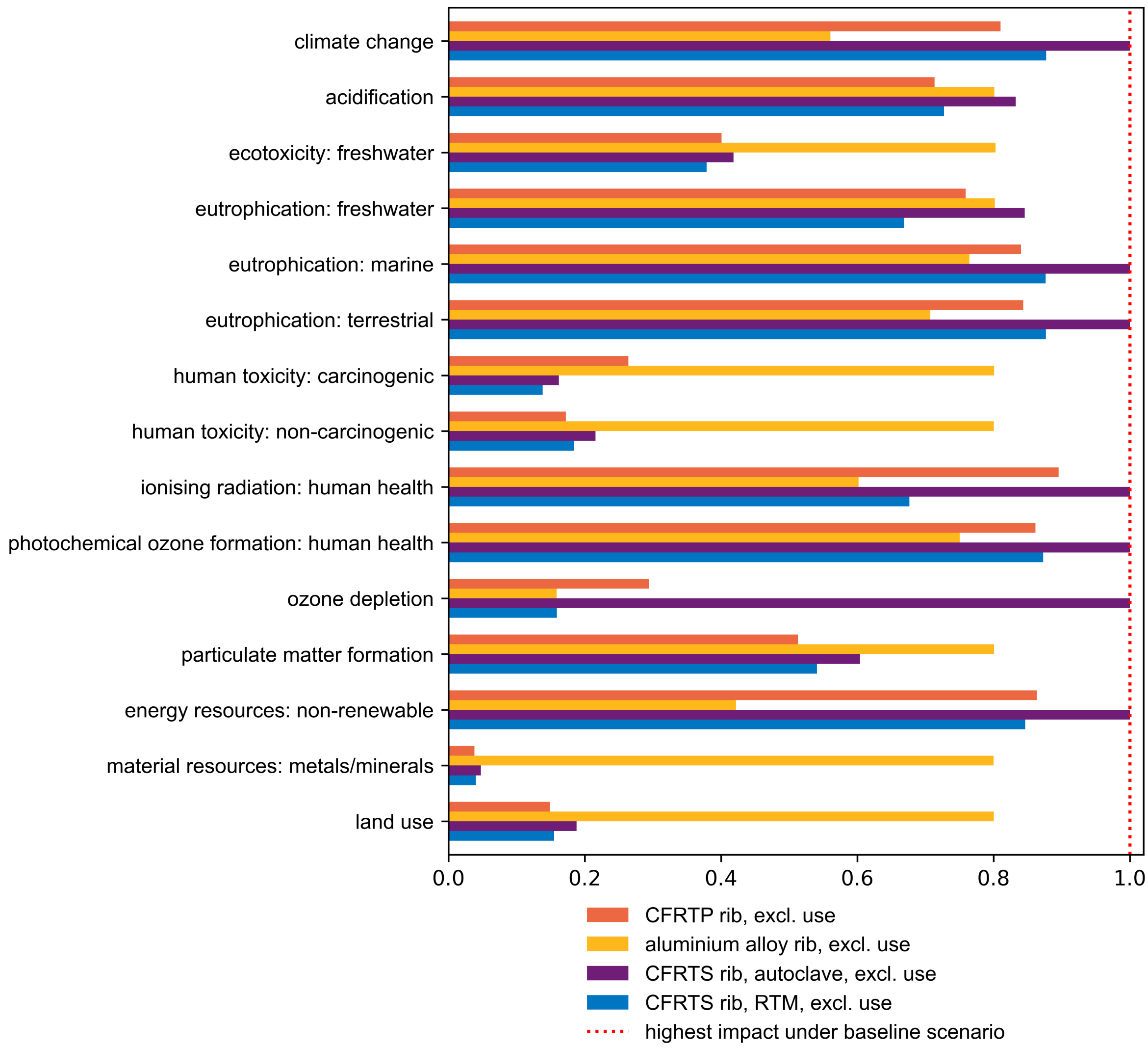


Figure E.3: Characterisation results for the lifecycle excluding use of the alternatives, if each alternative has a component mass of 2.1 kg. Results are presented comparatively with respect to the highest impact among these alternatives and the highest impact of the baseline mass scenario, in which the aluminium alloy rib is heavier than shown here.

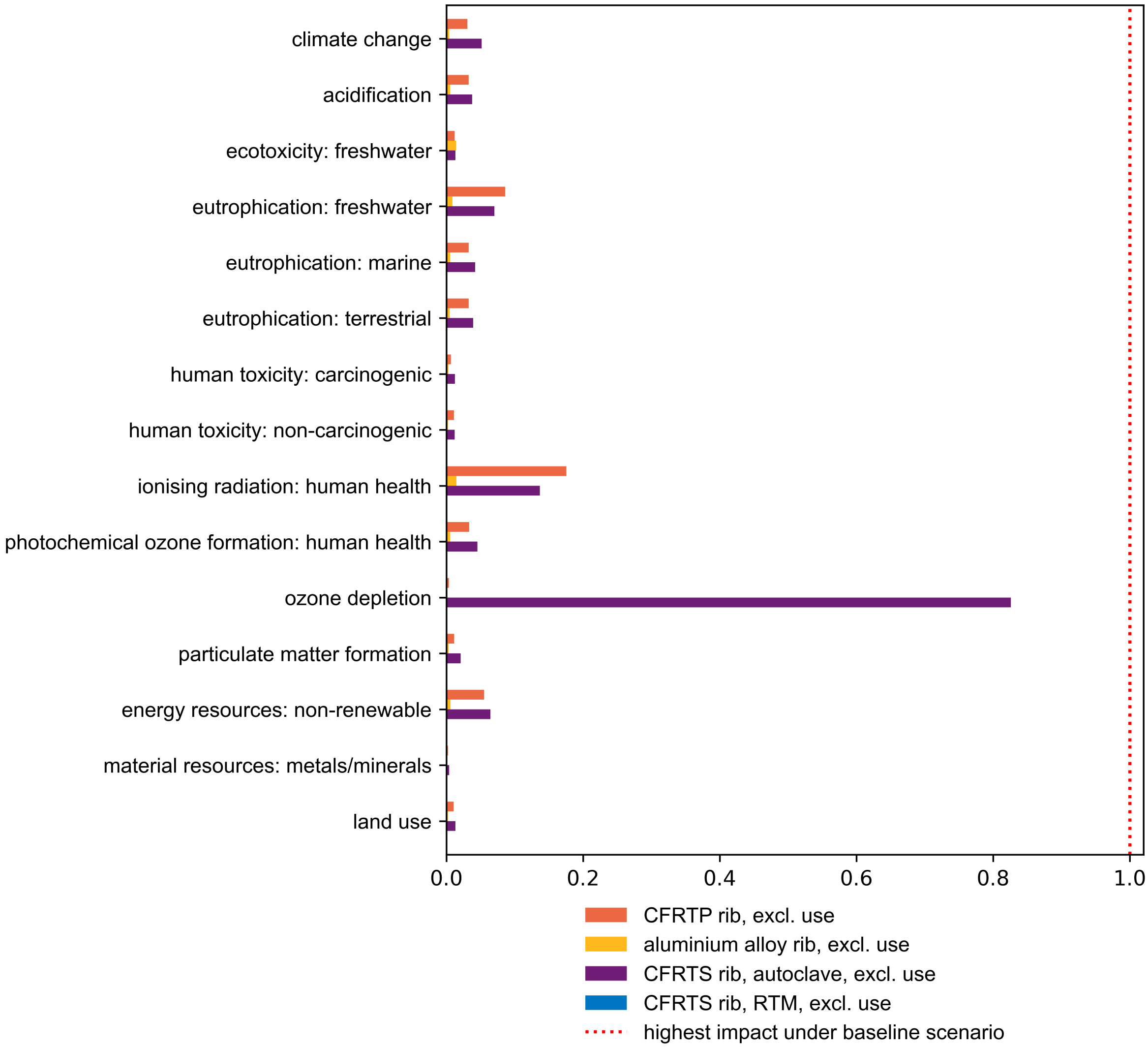


Figure E.4: Characterisation results for the lifecycle excluding use of the alternatives, if each alternative has a component mass of 0 kg. Results are presented comparatively with respect to the highest impact among these alternatives and the highest impact of the baseline mass scenario. Except for the CFRTS RTM rib, all alternatives still have some impact, due to not all processes scaling based on component mass, as laid out in Section D.2.

Table E.1: Overview of the masses at which each alternative has an equal lifecycle impact to the CFRTP rib (with a mass of 2.1 kg) in the **baseline energy scenario**, for each of the use intensity scenarios. Above these masses, the CFRTP rib is preferred in this scenario; below, the respective alternative is preferred. For each alternative, the highest and lowest values are bolded, signifying the range in which both the CFRTP rib and respective component could be environmentally competitive, depending on the priorities set.

Impact category	Aluminium alloy rib [kg]			CFRTS rib, autoclave [kg]			CFRTS rib, RTM [kg]		
	30-year use	20-year use	10-year use	30-year use	20-year use	10-year use	30-year use	20-year use	10-year use
climate change	2.104	2.105	2.110	2.097	2.096	2.092	2.099	2.099	2.097
acidification	2.098	2.097	2.095	2.098	2.096	2.093	2.100	2.100	2.099
ecotoxicity: freshwater	2.057	2.037	1.980	2.098	2.097	2.095	2.102	2.104	2.107
eutrophication: freshwater	2.077	2.069	2.051	2.053	2.036	2.000	**2.150**	2.169	2.211
eutrophication: marine	2.101	2.101	2.103	2.098	2.097	2.095	2.100	2.099	2.099
eutrophication: terrestrial	2.101	2.102	2.104	2.099	2.098	2.096	2.100	2.100	2.099
human toxicity: carcinogenic	1.917	1.843	1.665	**2.139**	**2.158**	**2.211**	2.148	**2.171**	**2.237**
human toxicity: non-carcinogenic	2.063	2.045	1.993	2.097	2.096	2.092	2.099	2.099	2.098
ionising radiation: human health	**2.114**	**2.120**	**2.140**	2.095	2.093	2.086	2.110	2.115	2.130
photochemical ozone formation: human health	2.101	2.102	2.103	2.099	2.098	2.096	2.100	2.100	2.100
ozone depletion	2.103	2.104	2.108	2.086	2.079	2.057	2.103	2.104	2.108
particulate matter formation	2.067	2.051	2.009	2.089	2.084	2.070	2.097	2.095	2.091
energy resources: non-renewable	2.109	2.114	2.127	2.097	2.096	2.092	2.100	2.101	2.101
material resources: metals/minerals	**0.752**	**0.587**	**0.377**	**2.053**	**2.033**	**1.983**	**2.089**	**2.085**	**2.073**
land use	2.044	2.018	1.943	2.097	2.095	2.090	2.099	2.099	2.098

Table E.2: Overview of the masses at which each alternative has an equal lifecycle impact to the CFRTP rib (with a mass of 2.1 kg) in the **SAF energy scenario**, for each of the use intensity scenarios. Above these masses, the CFRTP rib is preferred in this scenario; below, the respective alternative is preferred. For each alternative, the highest and lowest values are bolded, signifying the range in which both the CFRTP rib and respective component could be environmentally competitive, depending on the priorities set.

Impact category	Aluminium alloy rib [kg]			CFRTS rib, autoclave [kg]			CFRTS rib, RTM [kg]		
	30-year use	20-year use	10-year use	30-year use	20-year use	10-year use	30-year use	20-year use	10-year use
climate change	2.104	2.106	2.112	2.097	2.096	2.091	2.099	2.098	2.097
acidification	2.098	2.097	2.095	2.098	2.096	2.093	2.100	2.100	2.099
ecotoxicity: freshwater	2.056	2.036	1.979	2.098	2.097	2.094	2.102	2.104	2.107
eutrophication: freshwater	2.080	2.073	2.056	**2.060**	**2.044**	**2.010**	**2.143**	**2.160**	**2.199**
eutrophication: marine	2.101	2.101	2.103	2.098	2.097	2.095	2.100	2.099	2.099
eutrophication: terrestrial	2.101	2.102	2.104	2.099	2.098	2.096	2.100	2.100	2.099
human toxicity: carcinogenic	1.967	1.909	1.763	**2.128**	**2.141**	**2.180**	2.134	2.150	2.198
human toxicity: non-carcinogenic	2.058	2.038	1.981	2.097	2.096	2.091	2.099	2.099	2.098
ionising radiation: human health	**2.113**	**2.119**	**2.138**	2.095	2.093	2.087	2.110	2.114	2.128
photochemical ozone formation: human health	2.101	2.102	2.103	2.099	2.098	2.096	2.100	2.100	2.100
ozone depletion	2.103	2.105	2.110	2.083	2.074	2.049	2.103	2.105	2.110
particulate matter formation	2.066	2.050	2.006	2.089	2.084	2.069	**2.097**	**2.095**	**2.091**
energy resources: non-renewable	2.111	2.116	2.132	2.097	2.095	2.090	2.100	2.101	2.101
material resources: metals/minerals	**1.498**	**1.316**	**0.973**	2.089	2.084	2.070	2.098	2.097	2.093
land use	2.092	2.088	2.076	2.100	2.099	2.099	2.100	2.100	2.100

Table E.3: Overview of the masses at which each alternative has an equal lifecycle impact to the CFRTP rib (with a mass of 2.1 kg) in the **hydrogen energy scenario**, for each of the use intensity scenarios. Above these masses, the CFRTP rib is preferred in this scenario; below, the respective alternative is preferred. For each alternative, the highest and lowest values are bolded, signifying the range in which both the CFRTP rib and respective component could be environmentally competitive, depending on the priorities set.

Impact category	Aluminium alloy rib [kg]			CFRTS rib, autoclave [kg]			CFRTS rib, RTM [kg]		
	30-year use	20-year use	10-year use	30-year use	20-year use	10-year use	30-year use	20-year use	10-year use
climate change	2.108	2.112	2.124	2.094	2.091	2.082	2.098	2.097	2.094
acidification	2.096	2.093	2.087	2.094	2.091	2.082	2.099	2.099	2.098
ecotoxicity: freshwater	2.072	2.058	2.019	2.099	2.098	2.096	2.102	2.102	2.105
eutrophication: freshwater	2.099	2.098	2.096	2.097	2.095	2.091	2.103	2.105	2.110
eutrophication: marine	2.104	2.106	2.111	2.092	2.088	2.077	2.098	2.097	2.095
eutrophication: terrestrial	2.106	2.109	2.118	2.093	2.090	2.080	2.099	2.098	2.096
human toxicity: carcinogenic	2.056	2.035	1.976	**2.109**	**2.113**	**2.126**	**2.111**	**2.116**	**2.131**
human toxicity: non-carcinogenic	2.051	2.027	1.960	2.097	2.095	2.090	2.099	2.099	2.097
ionising radiation: human health	2.102	2.103	2.106	2.099	2.099	2.098	2.102	2.102	2.105
photochemical ozone formation: human health	2.104	2.106	2.111	2.095	2.093	2.087	2.100	2.099	2.099
ozone depletion	**2.109**	**2.113**	**2.126**	**2.055**	**2.032**	**1.965**	2.109	2.113	2.126
particulate matter formation	2.076	2.065	2.032	2.092	2.089	2.078	**2.098**	**2.097**	**2.093**
energy resources: non-renewable	2.106	2.109	2.118	2.098	2.097	2.094	2.100	2.100	2.101
material resources: metals/minerals	**2.029**	**1.996**	**1.902**	2.099	2.099	2.097	2.100	2.100	2.099
land use	2.074	2.061	2.023	2.098	2.098	2.095	2.100	2.100	2.099

F

Extended discussion of data quality and comparison to literature

Keiser et al. [30] remarked that data completeness and quality are particularly challenging to LCA in aviation, one of the reasons being that "specific manufacturing processes and materials are used" (p. 12). This observation is highly relevant to this study. To complement the discussion of Chapter 8 and to set-up the sensitivity analyses of Chapter 9, this chapter discusses the data quality of the LCA study and compares it to relevant data from literature.

F.1. Material production processes

The primary data gathered from GKN Aerospace, particularly by Stefanidi [1], gives a reasonable idea of what the on-site material flows look like during the manufacturing of the alternatives. However, there was no primary data on the production of the required materials – aluminium 7075, carbon fibre, and PEKK, in particular. To reflect on this, alternative inventories are explored and the values obtained here are compared to literature.

F.1.1. Alternative inventories

As the inventories were set up for the manufacturing materials, there were a few occasions where a choice was made to go one route over another. For example, aluminium 7075 was produced based on the ecoinvent process for AlLi (see Section B.2.2), while Zhao et al. [92] represented it as AlMg3. The choice was made to use the AlLi process because it uses wrought aluminium alloy, rather than cast alloy, which is of a lower quality [86]. The ecoinvent documentation describes AlLi as a typical aerospace alloy [87], but this does not necessarily mean that there are no significant deviations between its environmental impacts and those of aluminium 7075. There are already large differences between the impacts of the original AlLi and AlMg3 processes, for some impact categories exceeding a factor of two, so if such increases are seen again going from a fairly generic AlLi process to aluminium 7075, the assessment would look quite different.

Another important material is PEKK. As discussed in Section B.3.2, no inventories are available for this material, so it was constructed based on industrial chemistry literature and stoichiometry. Although no inventories are available, some claims regarding embodied energy were found, which are treated in Section F.1.2. Before doing so, it is worth pointing out a few concerns regarding data quality. First of all, the stoichiometry based method proposed by Langhorst et al. [95] was validated based on climate change impacts. The LCIA phase of this study found that climate change might not be PEKK's most relevant impact, which could instead be impacts such as ecotoxicity: freshwater, human toxicity: carcinogenic, and ozone depletion. The method used indicates that these impact categories would be good to investigate further, but this does not make it a solid foundation for a comparative assessment. Secondly, it should be kept in mind that this lack of knowledge also extends to the epoxy to some extent. There are ecoinvent processes for epoxy, but aerospace epoxies are specialised. There is a reason that GKN Aerospace is using PEKK, rather than a more conventional thermoplastic material. Using the same logic, the epoxy used might have a significantly higher impact than the generic product used here.

Furthermore, there is carbon fibre. Literature reports several primary energy values, dealt with in Section F.1.2. There were also several separate inventories reported in literature, discussed in Section B.3.3. The inventory used here was based primarily on Duflou et al. [36], rather than one of the other options. To interpret what the effect this had, the other inventories are recreated using ecoinvent and are compared in Figure F.1. Note that this required transferring the polyacrylonitrile inventory of Duflou et al. [36] to Pillain et al. [42] and not only changing the connected flows, but also adding flows of sulphuric acid, tap water, and an output of waste asphalt to accommodate the various process descriptions. Comparing the results, all characterisation results fall within a limit range, at most being 58% lower than the impacts of the baseline inventory. The inventory based on Pillain et al. [42] generally has the lowest impacts, as it also has the lowest inputs of both heat and electricity by quite a margin. The study this inventory is based on is the most recent of those included here. Possibly, this means that these lower impacts are more representative of the present state of global carbon fibre production. In light of this, two things to point out are that, firstly, if the impacts of carbon fibre were halved compared to the current analysis, carbon fibre production would still be the largest contributor to impact categories where its contribution is over 70%. This is generally the case for the composite alternatives (see Figure 7.3). Secondly, as the composite product systems were constructed around having a similar carbon fibre demand, this change is not expected to be influential to a comparative assessment. In addition to these observations, it is still the case that, of the inventories compared, none both transparently connect their data to a primary source and clearly report their figures. For these reasons, the consideration is made that a broader sensitivity analysis of the results using these alternative carbon fibre inventories is useful to this study.

F.1.2. Cumulative energy demand literature

Actual inventories for many aerospace materials are lacking, but for the most common materials, a value in terms of cumulative energy demand or embodied energy has been reported someplace. This practise has its faults, as discussed in Section 2.3, but lacking an alternative, it can provide some insight, however hazy this insight may be. To form such a comparison, the main materials used here are evaluated in the Activity Browser using the cumulative energy demand method and summing all results (for fossil, geothermal, solar, nuclear, etc.) per material. Note that this concerns cradle-to-gate, so excluding any foreground manufacturing waste. Waste generated in the background is still included. The results of this comparison are presented in Table F.1.

Broadly, the values based on the inventories of this study fall within the upper and lower estimates found in literature, generally leaning towards the higher side. Estimates for the impact on carbon fibre

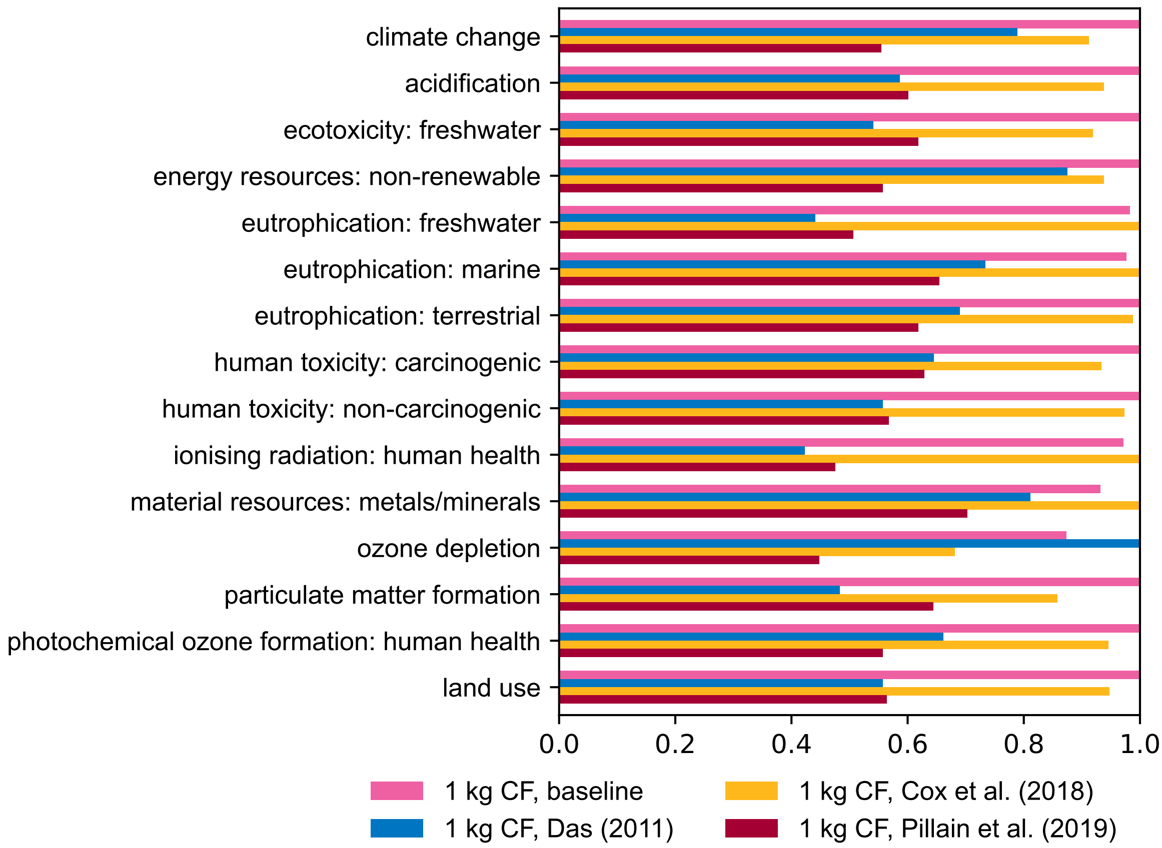


Figure F.1: Characterisation results for 1 kg carbon fibre (excluding end-of-life) according to the inventory compiled here, as well as adjusting this inventory according to three other studies.

differ substantially, as pointed out by Tapper et al. [40]. However, ANSYS, Inc. [63] report this as two ranges: 2.72×10^2 MJ/kg to 3×10^2 MJ/kg and 9.11×10^2 MJ/kg to 1.01×10^3 MJ/kg, for materials with "high" and "ultra high" mechanical properties, respectively. As ANSYS, Inc. does not explain how these ranges are obtained, this provides little concrete insight beyond the suggestion that carbon fibre products of different quality also differ in impact. As discussed in Section B.3.2, there are only a few values available for the family of materials PEKK finds itself in, and those few that are available differ wildly. The value obtained here for PEKK happens to find itself close to the mean value between the lower and upper values. These comparisons show that the values obtained here broadly fall in line with literature. However, due to a general lack of data and transparency – particularly for PEKK – it is not clear whether this also means that the models constructed here are indeed an accurate representation of the real world.

F.2. Manufacturing processes

Stefanidi [1] collected data on material flows and the energy demand of hot press consolidation. However, hot press consolidation for aviation is an emerging technology and for each of the other manufacturing methods considered, assumptions are made in estimating energy requirements.

Table F.1: Overview of cumulative energy demand or embodied energy values of materials modelled in this study and as obtained in literature. Values for PEEK and generic (aerospace) aluminium alloy are included to give a broader perspective on PEKK and aluminium 7075, respectively, as little data is available on these materials. When data is indicated with "(lit.)", this means that it is taken from a literature review. The citation is then not the original publication from which the value was obtained, but a literature review including this value in its overviews.

Material	Unit	This study	Literature, lower	Literature, upper	Literature data source
carbon fibre	MJ-eq/kg	1.02×10^3	2.72×10^2	1.010×10^3	ANSYS, Inc. [63]
			1.71×10^2	7.04×10^2	Tapper et al. [40] (lit.)
			1.90×10^2	1.563×10^3	Lunetto et al. [28] (lit.)
epoxy	MJ-eq/kg	1.05×10^2	1.15×10^2	1.27×10^2	ANSYS, Inc. [63]
			7.6×10^1	1.44×10^2	Tapper et al. [40] (lit.)
			4.7×10^1	1.39×10^2	Lunetto et al. [28] (lit.)
PEKK	MJ-eq/kg	1.49×10^2	3.02×10^2	3.33×10^2	ANSYS, Inc. [63]
PEEK	MJ-eq/kg		2.86×10^2	3.15×10^2	ANSYS, Inc. [63]
			8.0×10^1	8.0×10^1	Katsiropoulos, Loukopoulos, and Pantelakis [5]
aluminium 7075	MJ-eq/kg	1.16×10^2	1.10×10^2	1.28×10^2	ANSYS, Inc. [63]
generic (aerospace) aluminium alloy	MJ-eq/kg		1.97×10^2	2.98×10^2	Tapper et al. [40] (lit.)

F.2.1. Impregnation of carbon fibre

The prepregging processes for CF/epoxy and CF/PEKK constructed here were based on the values of Suzuki and Takahashi [60]. Their values, reproduced in Table B.4, were presented as "embodied energy" and were therefore converted based on the Japanese energy system of the time. However, some authors, such as Forcellese et al. [37] have interpreted their value to be an on-site electricity demand – 40 MJ being 11.1 kWh. Furthermore, Witik et al. [38] also cite Suzuki and Takahashi, but use a value of 1.05 kWh, evidently making some different conversion choice. This way, a considerable range is obtained. In the lifecycle excluding use, the contribution of prepregging is not negligible for several impact categories (see Figure 7.3). It is therefore worthwhile to evaluate how these values change the LCIA results.

F.2.2. Hot press consolidation

Stefanidi [1] reports electricity consumption of 82 MJ, i.e., 22.8 kWh, to consolidate the entire rib. This reflects an emerging technology, which is still being improved [T. de Bruijn, personal communication, May 11, 2023]. However, when compared to the Office of Energy Efficiency & Renewable Energy [62] report which cites a value of 4910 Btu/lb (around 3.17 kWh/kg) electricity for compression moulding, which would make 13.0 kWh based on the mass being consolidated, the value reported is not drastically higher. Still, this is one of the factors which can be considered as part of the sensitivity analysis (see Section G.2).

F.2.3. Milling of aluminium alloy

The milling of aluminium 7075 was based on an average process for aluminium milling (see Section B.2.3). This introduces two factors to consider: (1) that the share of dressing done is smaller or larger than represented in the average and (2) that the inputs required to remove 1 kg of aluminium 7075 are larger than for the reference aluminium. ANSYS, Inc. [63] reports that milling aluminium 7075 has an impact of 1.77 MJ−eq to 1.96 MJ−eq for coarse machining and 13.4 MJ−eq to 14.8 MJ−eq for fine machining. No sources are given for these values. Evaluating the full cumulative energy demand of C.2 and removing the aluminium 7075 input and output, 20.36 MJ−eq is obtained. This uses the ecoinvent distribution of 90% “large parts”, 9% “small parts”, and 1% “dressing”, although Stefanidi [1] reported 70% “coarse” and 30% “fine” (see Section B.2.3). Consider two scenarios: (1) the distribution of coarse and fine machining in ecoinvent is representative, but the CED presented by ANSYS, Inc. [63] is more accurate than the one obtained via ecoinvent; (2) the CED obtained via ecoinvent is representative of average milling of aluminium 7075, but in this case, the distribution between coarse and fine machining comes closer to the values reported by Stefanidi [1]. The combination of factors in case (1) hereby results in lower environmental impacts, while the combination of factors in case (2) results in a higher environmental impact.

The ecoinvent processes distinguish between milling processes based on the electricity input. To translate this to the above cases, “coarse” machining is considered equivalent to removing “large parts” and “fine” machining is considered to be a mix of removing “small parts” and “dressing” following the distribution of the average process: 9-to-1. This way, the 70-30 split becomes 70-27-3. Implementing this for the first case using the ecoinvent exchange values results in an electricity demand of 0.750 kWh/kg (compared to the original value of 0.356 kWh/kg). For the second case, ANSYS, Inc. [63] would suggest a CED of 2.93 MJ-eq/kg to 3.39 MJ-eq/kg. A CED this low cannot be achieved from the ecoinvent process by reducing the electricity input alone – other exchanges, such as the “energy and auxiliary inputs, metal working factory” and “metal working factory construction” would also need to be reduced. For simplicity, the mean value of 3.16 MJ-eq/kg can be achieved by reducing all inputs by 84.5%.

Interestingly, these cases show that the values of ANSYS, Inc. are much lower than those from ecoinvent. This is counter intuitive, as aluminium 7075 is relatively strong compared to conventional aluminium alloys, and would therefore require more energy input to machine. That the above comparison indicates the opposite, highlights the lack of reliable inventory data.

F.2.4. Autoclave processing

In Section B.4.4, several reports of autoclave measurements were compared. First of all are the consumables. The values used here are scaled from those reported by Witik et al. [38]. Forcellese et al. [37] also describe inventories for autoclave consumables, although this is in relation to a car hood of much larger dimensions. The two works are in agreement on the materials used and describe masses in the same order of magnitude, with Forcellese et al. using a relatively larger mass of vacuum bag and Witik et al. using a relative larger mass of breather. Section 7.4.2 found release film to have a particularly high contribution to ozone depletion. The masses reported in both studies are in agreement here too.

Another critical factor to autoclave processing is its on-site energy consumption. Section B.4.4 mentions the laboratory measurements of Witik et al. [38] and Ogugua et al. [103]. Where the value of Ogugua et al. was used in the LCI phase, the higher value of Witik et al. can be used as sensitivity analysis. The value reported by the Office of Energy Efficiency & Renewable Energy [62] – electricity consumption of 9570 Btu/lb (around 6.18 kWh/kg) – falls between these two previous values. Higher values can also be found in literature, such as Timmis et al. [14] reporting the maximum rating of an autoclave large enough to cure a fuselage section. However, in light of the research of Ogugua et al. [103], the maximum rating seems an inappropriate measure to use, even if the autoclave of Timmis et al. were to be scaled down. On the other side of the spectrum, there is often-cited literature which claims autoclave processing requires much lower energy inputs than those discussed so far. Forcellese et al. [37] perform a comparative assessment not dissimilar from this one, in which CFRTP components cured in an autoclave or through out-of-autoclave pressure bag moulding. They state [37, p. 3]: “[the out-of-autoclave] heating system is more efficient than the autoclave because the heating of laminate occurs by conduction from hot platens instead of convection taking place in autoclave curing. It allows to decrease the curing time of the resin and, thus, to increase productivity.” However, their measured energy consumption for pressure bag moulding is almost four times higher than the value based on literature for the autoclave cure cycle (17 kWh for their 11 kg composite car hood). This value is based on Song, Youn, and Gutowski [61], who report 21.9 MJ-eq/kg – a value picked by many studies, as reported in the literature reviews of Lunetto et al. [28] and Tapper et al. [40]. Series production of aviation components is different from a laboratory setting. Multiple parts are cured at a time, even if the autoclave is not always packed to its full capacity [T. de Bruijn, personal communication, May 11, 2023]. Converting this value to electricity in the same way Forcellese et al. did, this becomes 1.55 kWh/kg.

F.2.5. Resin transfer moulding

Except for epoxy, all inputs and outputs of RTM were modelled here based on the ecoinvent process for injection moulding [104], inspired by Duflou et al. [36]. The epoxy surplus of 20% used here could be an overestimation, although the production of epoxy itself is hardly noticeable in the contribution analysis. Similarly to hot press consolidation and autoclave processing, the energy consumption of RTM highly depends on the machinery being used. No literature which reports directly comparable measurements could be found. However, Suzuki and Takahashi [60] – in the same work used here to model prepregging – report an energy intensity of RTM of 12.8 MJ/kg. As was the case with prepregging, some interpret this as a primary energy metric (e.g., Lunetto et al. [28] and Tapper et al. [40]) while others interpret it as on-site energy demand (e.g., the Office of Energy Efficiency & Renewable Energy [62] assuming this is electricity). Using the method applied in Section B.3.4, 12.8 MJ-eq/kg is equivalent to 1.48 kWh/kg electricity – which (coincidentally, it seems) is also the electricity input for the ecoinvent process. Another question here is whether the values discussed are per kilogram infused epoxy or per kilogram created composite product. Assuming they are per kilogram composite product, none of these values are lower than the ecoinvent process, which, converted to CED per kilogram created product, has an impact of 11.7 MJ-eq/kg.

F.3. Mass-induced energy demand

Section B.6.3 discussed the ranges in which literature places mass-induced energy demand, gathering these in Table B.5. Although different authors are generally in agreement, the differences between the highest and lowest values reported is considerable. A representative range is the one presented by Van Grootel et al. [33]: 3.33 GJ/kg-year to 10 GJ/kg-year. Since mass-induced energy demand is highly influential to the analysis, this range of possible values should be evaluated in the sensitivity analysis. This is done in Section 9.1.2.

G
Extended sensitivity analyses

Chapter 9 discusses all the sensitivity analyses performed in this study. However, to facilitate the reader, not all values used and results obtained are included there. This chapter goes into depth on these. Numerical reporting on characterisation results in this context can be found in Appendix H.

G.1. Consideration of multifunctionality

As discussed at length in Section 6.1.2 and Section 8.1, multifunctionality is closely tied to the research question, but also a challenge to resolve in a consistent way. To explore how the choices made affect the outcome, the effect different approaches have on the lifecycle excluding use are illustrated in Figure G.1 for the linear and circular scenarios. For each scenario, four alternative approaches are chosen: one which aligns more with ALCA and does not use any substitution flows, but instead approaches waste in the way that the ecoinvent cut-off system model does (the primary system received no credits from waste, but does receive burdens in the case of incineration). The choice was also made to cut off the co-production of HCl in the production chain of PEKK. The reasoning is made that the small quantity of HCl created has a negligible value compared to the organic molecules created – at least for the purpose of this comparison. Another approach presented in Figure G.1 aligns more with a possible interpretation of CLCA, where the full substitution flow is allocated to the primary system, rather than dividing it across primary and secondary systems. For the purpose of this comparison, the quality ratio of the CFF is also changed to always be 1. Note that this is not necessarily the preferred method for a consequential analysis, which might use a different system model entirely and be more concerned with the supply and demand of recycling activities. It should be noted that these representations of ALCA and CLCA do not entail changes to the system the LCA model is representing, but only to how it is represented. The bottom half of Figure G.1 presents the CLCA and CFF approaches, but instead of placing the end-of-life phase (and its substitution flows) in 2050, it is placed in the “present” background system, 2020.

Comparing these figures, the impacts of the composite alternatives remain fairly similar across the linear scenario. This makes sense, as the only difference here is whether incineration energy recovery is substituted and whether end-of-life incineration is substituted in 2050 or 2020. For the aluminium alloy rib, the difference is larger, as it is highly influenced by substitution flows (see Figure 7.3). Figure 7.4 illustrated how just switching to a linear scenario results in very high increases for this alternative.

When even the downcycling processes do not receive any substitution, the net impact is even higher. Of course, using the ALCA approach outlined above results in the circular and linear scenarios having the same outcome for the aluminium alloy rib – neither receive any substitution.

Following the aluminium alloy rib, the CFRTP rib is the most affected by the change, for both linear and circular scenarios. When using the CFF, the gap is narrow between the CFRTP and CFRTS RTM ribs. At the same time, with the CLCA approach, impacts for the composite ribs (particularly, the CFRTP and CFRTS RTM ribs) are reduced, with the CFRTP becoming preferred across almost all impact categories. This makes sense: if without substitution, the CFRTS RTM rib is preferred, and a bit of substitution narrows this gap, it is unsurprising that full substitution is enough to bridge it entirely for most impact categories.

When comparing the bottom four subfigures – which consider the end-of-life phase in 2020, rather than 2050 – the difference using the CFF is minimal, as substitution flows played a small role in this analysis to begin with. However, comparing Figures G.1(d) and G.1(f), it is clear that there is a difference. By providing a full substitution flow to the CFRTP rib, its impact excluding use is reduced immensely. However, when considering that the end-of-life phase occurs in a less environmentally demanding system, this flow decreases too. Although this effect does not have a pronounced effect when using the CFF, its presence should be kept in mind when making claims about the benefits of end-of-life recycling in the coming decades.

G.2. Manufacturing energy inputs

Among the discussion of LCI values in Section F.2, the possible values of various energy demands stand out. For the milling of aluminium alloy, the impregnation of carbon fibre, the cure cycle of an autoclave, etc. there appears to be a broad range of possible values. The values reported in Section F.2 are collected in Table G.1. The effect on characterisation results is illustrated in Figure 9.2.

Table G.1: Overview of changes made to unit process exchanges based on reasonable alternatives identified in literature for the sensitivity analysis of manufacturing inputs.

Process	Flow	Unit	Low value	Baseline value	High value
[C.2] aluminium 7075 milling, average	electricity, low voltage	kWh	5.13×10^{-2}	3.56×10^{-1}	7.50×10^{-1}
[C.2] aluminium 7075 milling, average	*all other non-aluminium alloy inputs*	%	15.5	100	100
[C.22] carbon fibre/PEKK prepreg production	electricity, medium voltage	kWh	1.05	2.91	1.11×10^{1}
[C.25] consolidation, hot press	electricity, medium voltage	kWh	1.30×10^{1}	2.28×10^{1}	2.28×10^{1}
[C.44] carbon fibre/epoxy prepreg production	electricity, medium voltage	kWh	1.05	4.64	1.11×10^{1}
[C.54] bagging and curing, autoclave	electricity, medium voltage	kWh	6.33	1.76×10^{1}	3.87×10^{1}
[C.64] infusion and curing, RTM	electricity, medium voltage	kWh	1.48	1.48	1.1×10^{1}
[C.64] infusion and curing, RTM	heat, district or industrial, natural gas	kWh	4.21	4.21	0
[C.64] infusion and curing, RTM	heat, district or industrial, other than natural gas	kWh	2.29×10^{-1}	2.29×10^{-1}	0

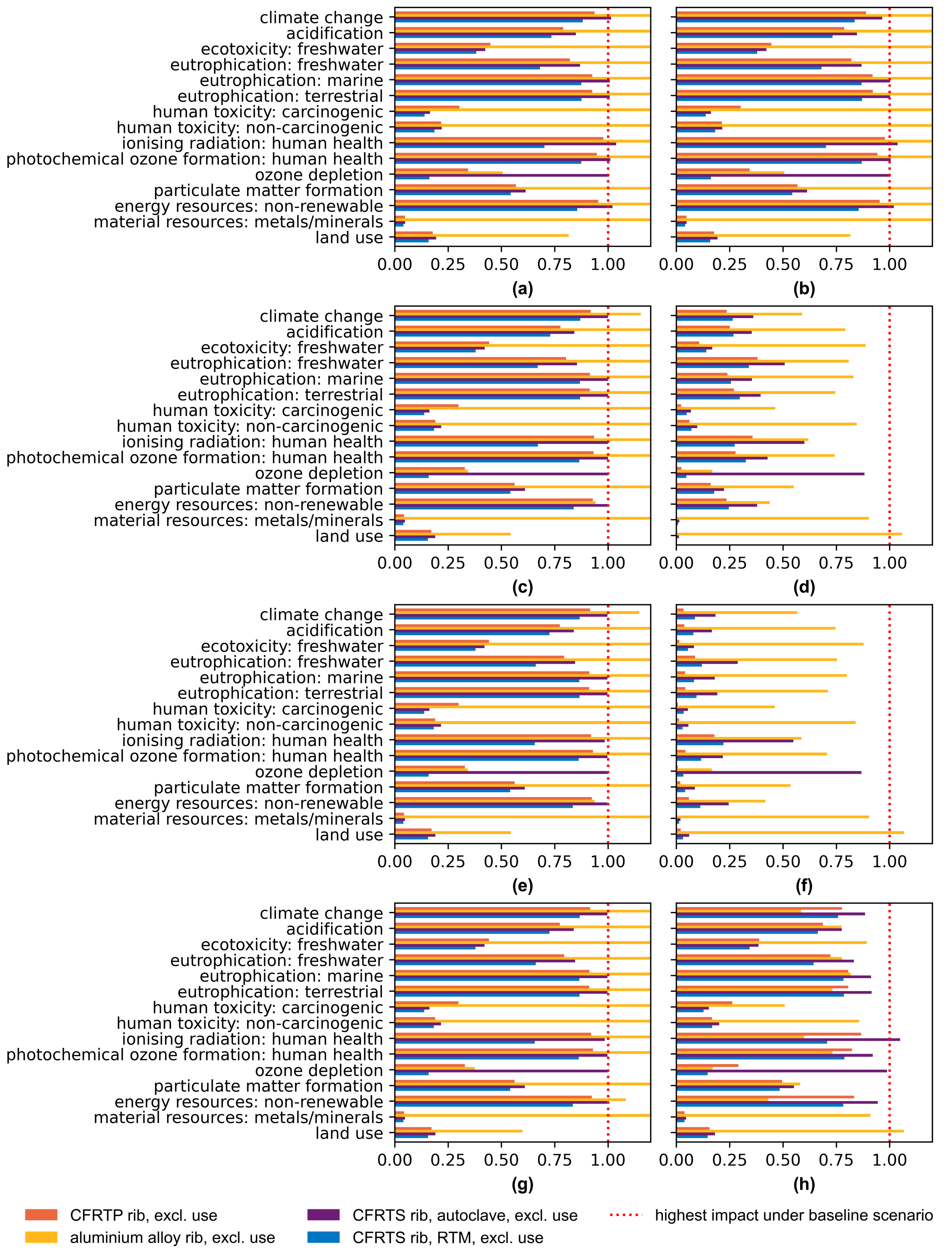


Figure G.1: Characterisation results for the lifecycle excluding use of the alternatives in the linear scenario (left subfigures) and circular scenario (right subfigures) with multifunctionality solved using **(a)** & **(b)**: a possible attributional approach; **(c)** & **(d)**: a possible consequential approach; **(e)** & **(f)**: a possible consequential approach, but without prospective end-of-life; and **(g)** & **(h)**: the CFF, but without prospective end-of-life. All results are presented comparatively with respect to the highest impacts of the baseline scenario (which uses the CFF with prospective end-of-life). Because of this, the full impacts of the aluminium alloy alternative are not shown in several subfigures. These impacts are similar in magnitude to those depicted in Figure 7.4.

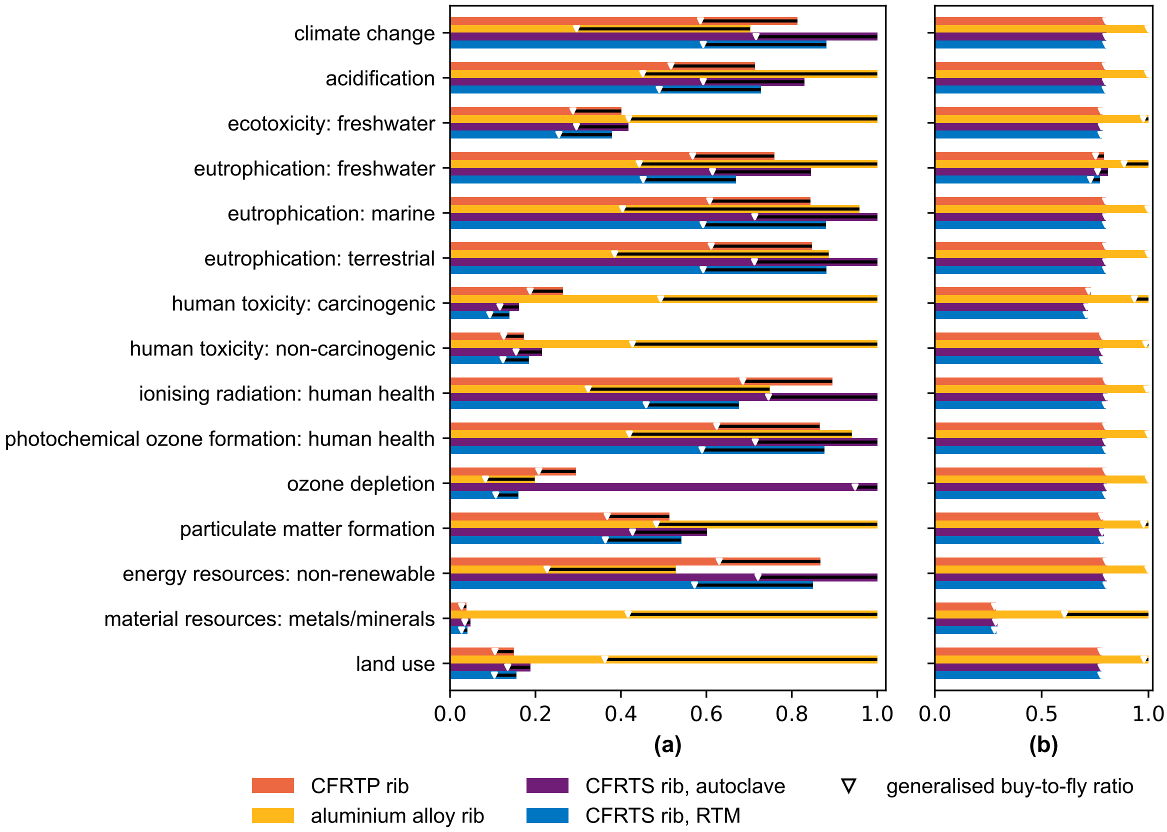


Figure G.2: Representation of the change in characterisation results when reducing the buy-to-fly ratio of alternatives to a literature-based average, as described in Section G.3. Results are shown for **(a)** the lifecycles excluding use and **(b)** the lifecycles including use.

G.3. Buy-to-fly ratio

Here, the buy-to-fly ratios used were relatively high. Figure G.2 demonstrates how impacts change when average values reported in literature are used: 1.5:1 for composites [41] and 8:1 for aluminium alloy [14]. This is implemented by reducing the mass cut off after cure/consolidation to 0.65 kg and adjusting connected flows accordingly. The buy-to-fly ratio of CFRTP is thereby exactly 1.5:1, while for CFRTS it is 1.58:1 (autoclave, due to the storage losses) or 1.51:1 (RTM, due to storage losses and injection of excess resin). In general, this seems to benefit the aluminium alloy rib in particular, and the CFRTP rib the least among the composites. This is to be expected, as a lower buy-to-fly ratio means less CFRTP is recycled, a benefit not transferred to the other composite alternatives. This illustrates something not considered in, for example, the break-even analyses, which is that a large enough difference in buy-to-fly ratios between composite alternatives (provided both have an equal component mass) could be enough to make one favourable across most impact categories. Put more generally, the environmental benefits that could be gained by decreasing the buy-to-fly ratio of the alternatives should not be overlooked.

G.4. Break-even analyses

To obtain a more general understanding of how sensitive the results are to the factors considered so far, a number of them are combined at once. To do so, three generic alternatives are created, considering only the manufacturing material. The generic CFRTP and CFRTS components have a buy-to-fly ratio of exactly 1.5:1 each. CFRTS is assumed to be prepreg, but no loss due to storage is considered. Energy demand for forming, curing, or consolidation is cut off. The generic aluminium alloy component has a buy-to-fly ratio of 8:1 and does include milling. This representation was chosen to eliminate the influences of some of the uncertain factors identified previously, such as the role of composite manufacturing energy demand and the potential decrease of the buy-to-fly ratio.

These three generic alternatives are considered under a variety of conditions. For each material, waste treatment and the consideration of multifunctionality is first evaluated in accordance with the baseline scenario for these materials (see Section 6.4.1). The alternative waste treatment and multifunctionality scenarios are also evaluated (see Section G.1) – covering linear, baseline, and circular treatment scenarios for three multifunctionality approaches, labelled in Section G.1 as CFF, CLCA, and ALCA. The energy demand for use is initially set at 4.47 GJ/kg-year and scaled from 3.33 GJ/kg-year to 10 GJ/kg-year. This energy is met using the SAF scenario or hydrogen scenario (see Section 6.4.3) from the REMIND SSP2-NDC pathway with a temporal scope of either 2020-2050 or 2040-2070 (see Section 9.1.3).

The break-even analysis varies – at times, drastically – when considering each of the above variations. The values considering the excluding use baseline (baseline disposal and CFF multifunctionality) are shown in Figures 9.5, G.3, G.4, and G.5, alongside the most extreme values found among the other cases. Which cases these are for each impact category can be seen in Table G.2 and Table G.3.

Table G.2: Overview of the combination of factors with which CFRTP is the most and least favoured **in relation to aluminium alloy** in the generalised break-even analyses.

Impact category	**2020-2050 (SAF and H_2)**		**2040-2070 (SAF and H_2)**	
	CFRTP most favoured	**CFRTP least favoured**	**CFRTP most favoured**	**CFRTP least favoured**
climate change	UE: low; WD: baseline; MF: ALCA	UE: low; WD: circular; MF: CFF	UE: low; WD: linear; MF: ALCA	UE: low; WD: circular; MF: CFF
acidification	UE: low; WD: baseline; MF: ALCA	UE: low; WD: circular; MF: CFF	UE: low; WD: baseline; MF: ALCA	UE: low; WD: circular; MF: CFF
ecotoxicity: freshwater	UE: low; WD: baseline; MF: ALCA	UE: high; WD: circular; MF: CFF	UE: low; WD: baseline; MF: ALCA	UE: high; WD: circular; MF: CFF
eutrophication: freshwater	UE: low; WD: baseline; MF: ALCA	UE: low; WD: circular; MF: CFF	UE: low; WD: baseline; MF: ALCA	UE: high (low for H2); WD: circular; MF: CFF
eutrophication: marine	UE: low; WD: baseline; MF: ALCA	UE: low; WD: circular; MF: CFF	UE: low; WD: baseline; MF: ALCA	UE: low; WD: circular; MF: CFF
eutrophication: terrestrial	UE: low; WD: baseline; MF: ALCA	UE: low; WD: circular; MF: CFF	UE: low; WD: baseline; MF: ALCA	UE: low; WD: circular; MF: CFF
human toxicity: carcinogenic	UE: low; WD: baseline; MF: ALCA	UE: low; WD: circular; MF: CFF	UE: low; WD: baseline; MF: ALCA	UE: high (low for H2); WD: circular; MF: CFF
human toxicity: non-carcinogenic	UE: low; WD: baseline; MF: ALCA	UE: high; WD: circular; MF: CFF	UE: low; WD: baseline; MF: ALCA	UE: high; WD: circular; MF: CFF
ionising radiation: human health	UE: low; WD: baseline; MF: CLCA	UE: low; WD: circular; MF: CFF	UE: low; WD: baseline; MF: CLCA	UE: low; WD: circular; MF: CFF
photochemical ozone formation: human health	UE: low; WD: baseline; MF: ALCA	UE: low; WD: circular; MF: CFF	UE: low; WD: baseline; MF: ALCA	UE: low; WD: circular; MF: CFF
ozone depletion	UE: low; WD: baseline; MF: CLCA	UE: low; WD: circular; MF: CFF	UE: low; WD: baseline; MF: CLCA	UE: low; WD: circular; MF: CFF
particulate matter formation	UE: low; WD: baseline; MF: ALCA	UE: low; WD: circular; MF: CFF	UE: low; WD: baseline; MF: ALCA	UE: low; WD: circular; MF: CFF
energy resources: non-renewable	UE: high; WD: baseline; MF: CLCA	UE: low; WD: circular; MF: CFF	UE: low (high for H2); WD: baseline; MF: CLCA	UE: low; WD: circular; MF: CFF
material resources: metals/minerals	UE: low; WD: linear; MF: CLCA	UE: high; WD: circular; MF: CFF	UE: low; WD: linear; MF: ALCA	UE: high; WD: circular (linear for H2); MF: CFF (CLCA for H2)
land use	UE: low; WD: baseline; MF: CLCA	UE: high; WD: linear; MF: CLCA	UE: low; WD: baseline; MF: CLCA	UE: high; WD: linear; MF: CFF

Table G.3: Overview of the combination of factors with which CFRTP is the most and least favoured **in relation to CFRTS** in the generalised break-even analyses.

Impact category	2020-2050 (SAF and H_2)		2040-2070 (SAF and H_2)	
	CFRTP most favoured	CFRTP least favoured	CFRTP most favoured	CFRTP least favoured
climate change	UE: low; WD: baseline; MF: ALCA	UE: low; WD: circular; MF: CFF	UE: low; WD: linear; MF: ALCA	UE: low; WD: circular; MF: CFF
acidification	UE: low; WD: baseline; MF: ALCA	UE: low; WD: circular; MF: CFF	UE: low; WD: baseline; MF: ALCA	UE: low; WD: circular; MF: CFF
ecotoxicity: freshwater	UE: low; WD: baseline; MF: ALCA	UE: high; WD: circular; MF: CFF	UE: low; WD: baseline; MF: ALCA	UE: high; WD: circular; MF: CFF
eutrophication: freshwater	UE: low; WD: baseline; MF: ALCA	UE: low; WD: circular; MF: CFF	UE: low; WD: baseline; MF: ALCA	UE: high (low for H2); WD: circular; MF: CFF
eutrophication: marine	UE: low; WD: baseline; MF: ALCA	UE: low; WD: circular; MF: CFF	UE: low; WD: baseline; MF: ALCA	UE: low; WD: circular; MF: CFF
eutrophication: terrestrial	UE: low; WD: baseline; MF: ALCA	UE: low; WD: circular; MF: CFF	UE: low; WD: baseline; MF: ALCA	UE: low; WD: circular; MF: CFF
human toxicity: carcinogenic	UE: low; WD: baseline; MF: ALCA	UE: low; WD: circular; MF: CFF	UE: low; WD: baseline; MF: ALCA	UE: high (low for H2); WD: circular; MF: CFF
human toxicity: non-carcinogenic	UE: low; WD: baseline; MF: ALCA	UE: high; WD: circular; MF: CFF	UE: low; WD: baseline; MF: ALCA	UE: high; WD: circular; MF: CFF
ionising radiation: human health	UE: low; WD: baseline; MF: CLCA	UE: low; WD: circular; MF: CFF	UE: low; WD: baseline; MF: CLCA	UE: low; WD: circular; MF: CFF
photochemical ozone formation: human health	UE: low; WD: baseline; MF: ALCA	UE: low; WD: circular; MF: CFF	UE: low; WD: baseline; MF: ALCA	UE: low; WD: circular; MF: CFF
ozone depletion	UE: low; WD: baseline; MF: CLCA	UE: low; WD: circular; MF: CFF	UE: low; WD: baseline; MF: CLCA	UE: low; WD: circular; MF: CFF
particulate matter formation	UE: low; WD: baseline; MF: ALCA	UE: low; WD: circular; MF: CFF	UE: low; WD: baseline; MF: ALCA	UE: low; WD: circular; MF: CFF
energy resources: non-renewable	UE: high; WD: baseline; MF: CLCA	UE: low; WD: circular; MF: CFF	UE: low (high for H2); WD: baseline; MF: CLCA	UE: low; WD: circular; MF: CFF
material resources: metals/minerals	UE: low; WD: linear; MF: CLCA	UE: high; WD: circular; MF: CFF	UE: low; WD: linear; MF: ALCA	UE: high; WD: circular (linear for H2); MF: CFF (CLCA for H2)
land use	UE: low; WD: baseline; MF: CLCA	UE: high; WD: linear; MF: CLCA	UE: low; WD: baseline; MF: CLCA	UE: high; WD: linear; MF: CFF

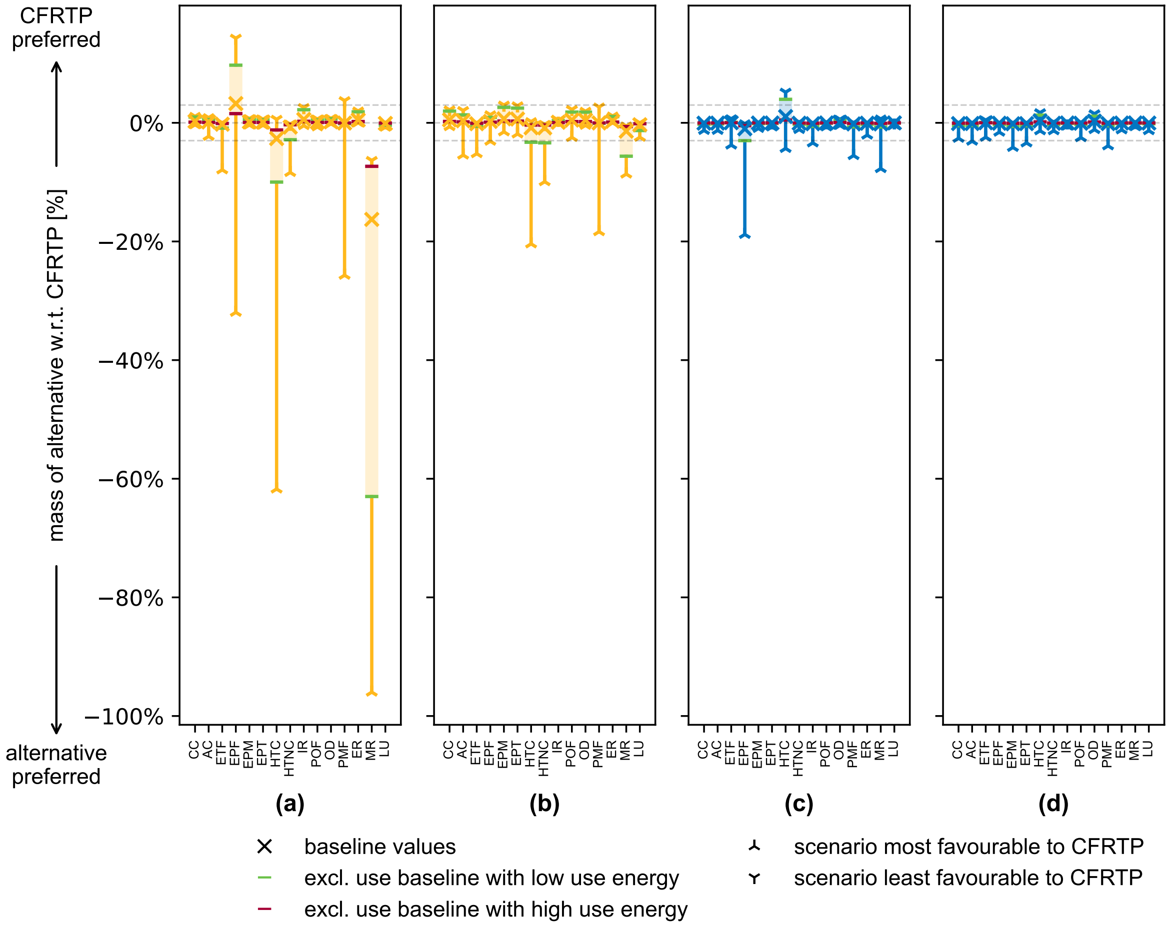


Figure G.3: Generalised break-even masses using the 2020-2050 temporal scope and NDC pathway for **(a)** aluminium alloy using the SAF scenario; **(b)** aluminium alloy using the hydrogen scenario; **(c)** CFRTS using the SAF scenario; and **(d)** CFRTS using the hydrogen scenario for a variety of cases. Dashed lines indicate a mass difference of $+3\%$, 0%, and -3%, respectively, from top to bottom. Consult Figure 9.5 for a version of this graph focused on y-axis values close to 0%.

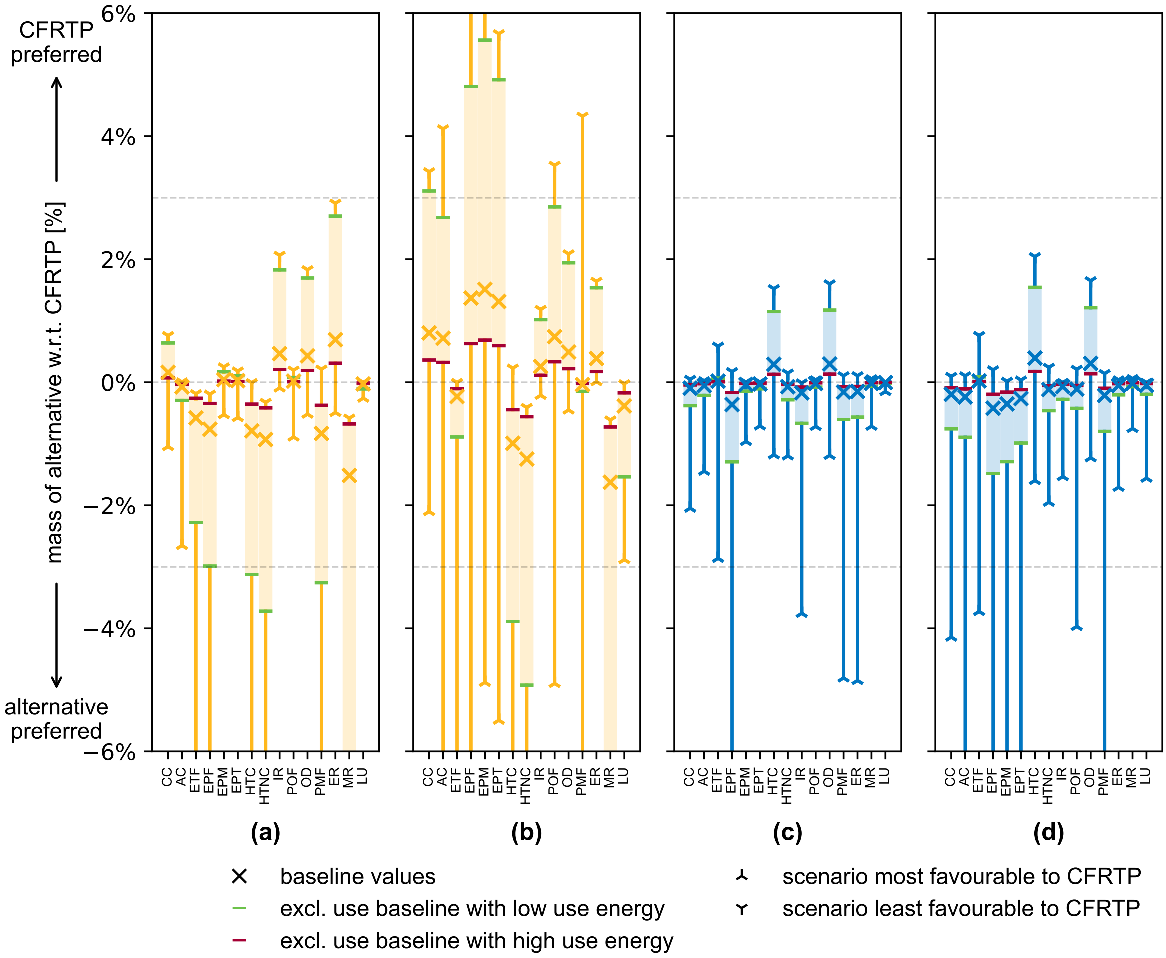


Figure G.4: Generalised break-even masses using the 2040-2070 temporal scope and NDC pathway for **(a)** aluminium alloy using the SAF scenario; **(b)** aluminium alloy using the hydrogen scenario; **(c)** CFRTS using the SAF scenario; and **(d)** CFRTS using the hydrogen scenario for a variety of cases. Dashed lines indicate a mass difference of +3%, 0%, and −3%, respectively, from top to bottom. The y-axis is limited to improve readability, but an alternative visualisation is presented in Figure G.5.

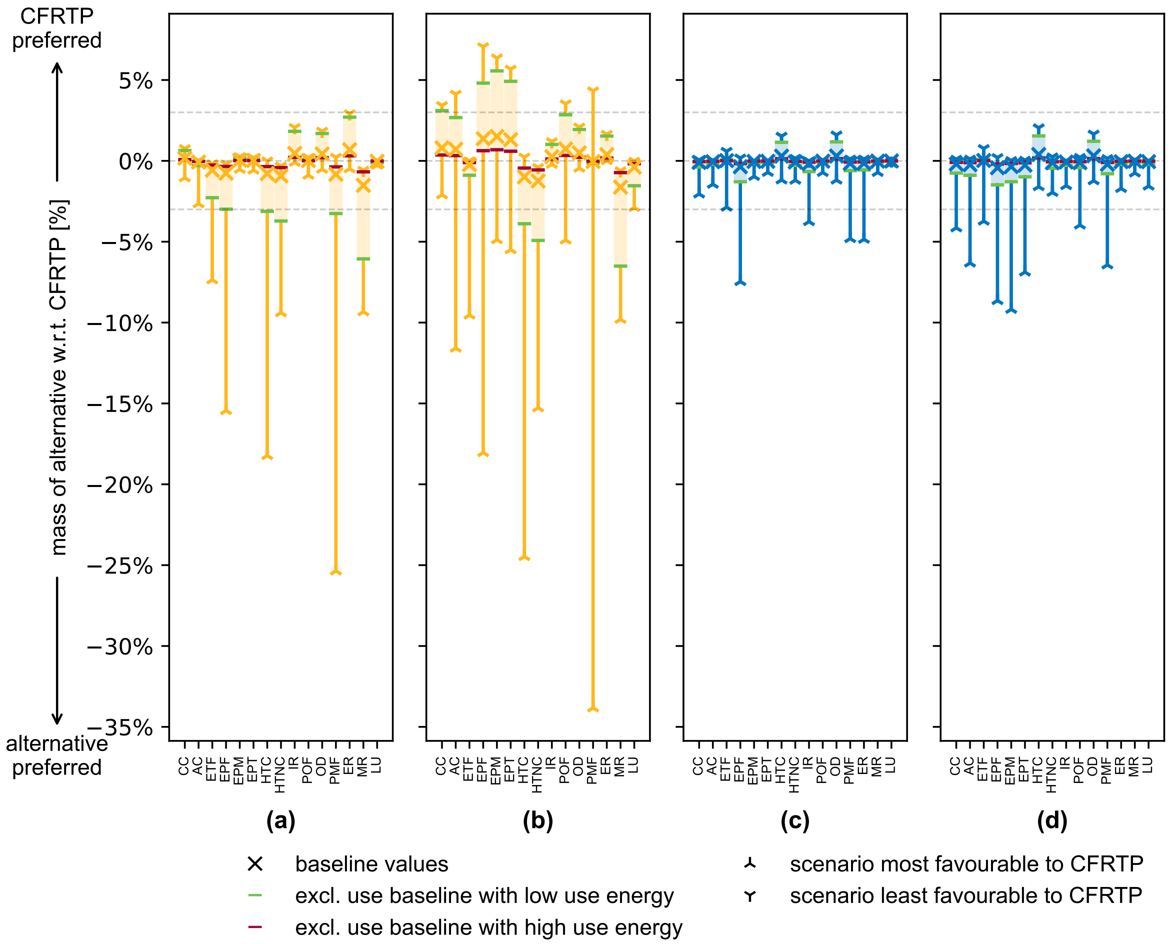


Figure G.5: Generalised break-even masses using the 2040-2070 temporal scope and NDC pathway for **(a)** aluminium alloy using the SAF scenario; **(b)** aluminium alloy using the hydrogen scenario; **(c)** CFRTS using the SAF scenario; and **(d)** CFRTS using the hydrogen scenario for a variety of cases. Dashed lines indicate a mass difference of $+3\%$, 0%, and -3%, respectively, from top to bottom. Consult Figure G.4 for a version of this graph focused on y-axis values close to 0%.

G.5. ReCiPe LCIA models

The global warming impact category constructed here is compared to other methods in Section 9.2. For other impact categories, the EF method was chosen, as motivated in Section 7.1. To evaluate how sensitive the conclusions of the work are to this family in particular, the lifecycle inventory results are evaluated with another commonly used method for midpoint indicators: ReCiPe. This family was conceived to harmonise several LCIA methods in the LCA community of the Netherlands. The family in fact includes several sets of LCIA models, each with a consistent philosophy for the time horizon of long-lasting pollutants [139]. Here, the Activity Browser is used to apply ReCiPe v1.13 characterisation models, using the hierarchist (H) perspective. The results of this assessment are illustrated in Figure G.6.

Comparing Figure G.6 to Figure 7.1 and Figure 7.2, the two families are largely in agreement, but there are a few exceptions. The ReCiPe method appears to weigh the environmental flows associated with the aluminium alloy rib comparatively more than those of the composites ribs in the impact categories for marine eutrophication and freshwater ecotoxicity. The former appears to be driven by how the two methods each treat nitrogen compounds differently, meaning that the relatively high nitrate emissions associated with aluminium alloy come through – this can also be noticed in the eutrophication impacts of the energy carriers. The difference in freshwater ecotoxicity cannot be pinpointed to a single flow. The EF method classified aluminium emissions themselves (to air, water, and soil), which form the dominant contribution, not only for the aluminium alternative, but also the composite ones. Using the ReCiPe model, copper emissions (larger for the aluminium alloy alternative) and beryllium emissions (almost exclusive to the aluminium alloy alternative) play an important role. This difference also means that, while all energy carriers have a considerable contribution from aluminium according to the EF method, copper dominating freshwater ecotoxicity would mean that the hydrogen energy scenario comes out a lot less favourable (although it already had the highest impact using EF). Another large difference can be seen in particulate matter formation, where the aluminium alloy alternative saw the highest impact by quite a margin using the EF method, due to the high characterisation of particulates; using ReCiPe, the composite alternatives come to the forefront, due to the higher characterisation of NO_x. This also means that, according to the ReCiPe method, the impact of the lifecycle excluding use is a much lower part of the whole in terms of particulate matter formation. However, this also means that ReCiPe interprets the hydrogen energy scenario as having a much lower impact (as no NO_x is emitted in flight), while using EF the opposite was true, and it had a higher impact than the other energy sources. These are important factors to take into the discussion of the results. There are also some minor shifts which do lead to alternatives being judged differently between the two methods. For example, the CFRTS RTM rib was favoured over the CFRTP rib in freshwater ecotoxicity and non-renewable energy resources impacts, which becomes reversed when using ReCiPe. This reinforces that minor differences between alternatives should be recognised as an indication of similar impacts, rather than one alternative being superior to another. This is also clear from uncertainty in the inventories themselves, discussed in Section 9.1.

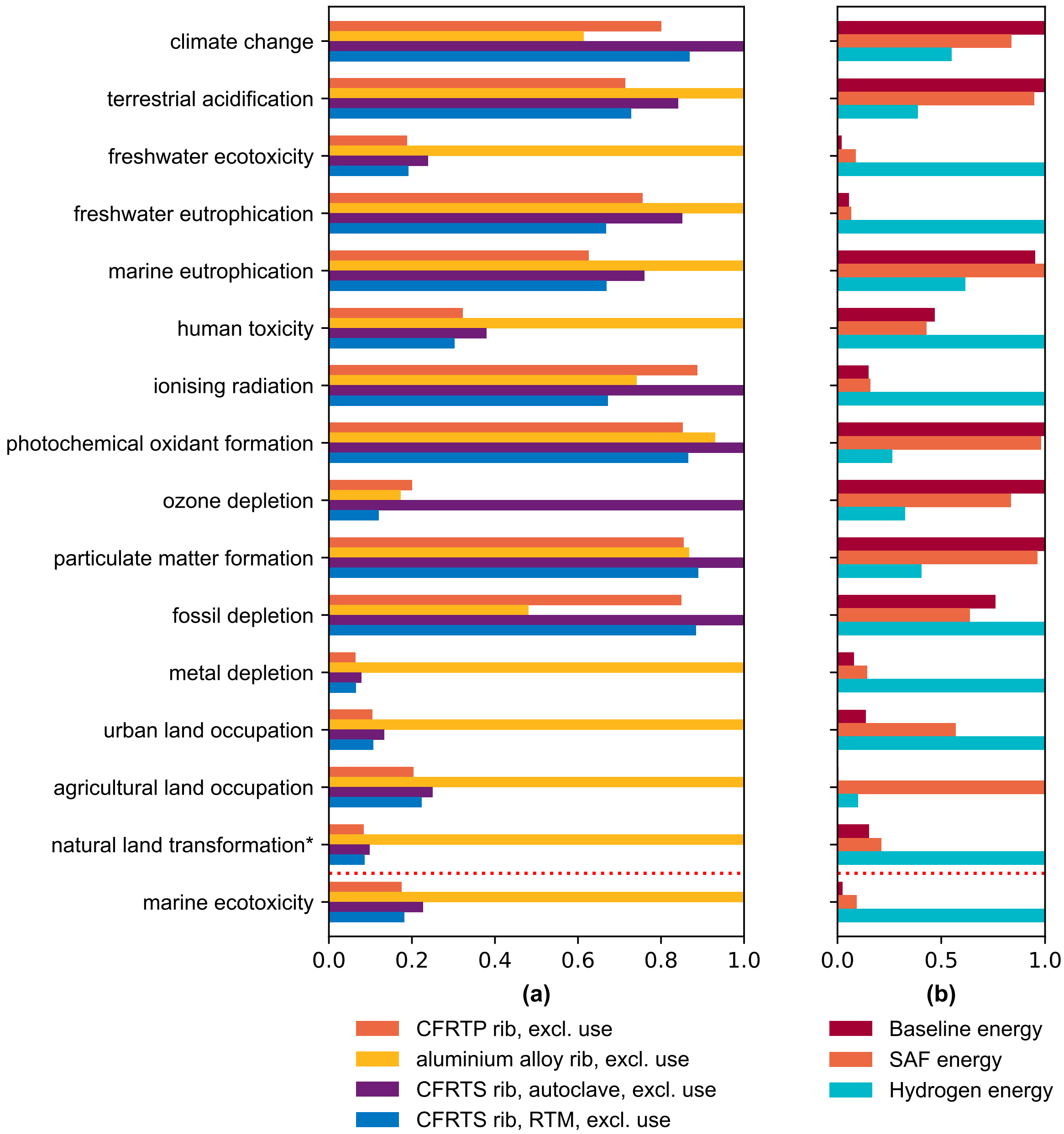


Figure G.6: Characterisation results determined using ReCiPe (H) v1.13 mid-point models, scaled to the highest impact per subfigure, shown for **(a)** the lifecycle excluding use of the alternatives, scaled to 1 wing rib; and **(b)** 1 MJ of mass-induced energy in the three energy scenarios, covering well-to-wake. ReCiPe impact categories are ordered analogously to counterparts in the EF method (compare to Figure 7.1 and Figure 7.2). There is no analogous counterpart for marine ecotoxicity. **Natural land transformation change impacts are negative; the x-axis values should be interpreted as negative values for this impact category.*

H

Data spreadsheets

Inventory results, characterisation results, environmental flows lacking characterisation, and contribution analysis results are reported for selected reference flows in the attached spreadsheet file. The file also includes several Sankey diagrams (see Section E.1).