Circular aviation: A study on recycling strategies in aviation industry

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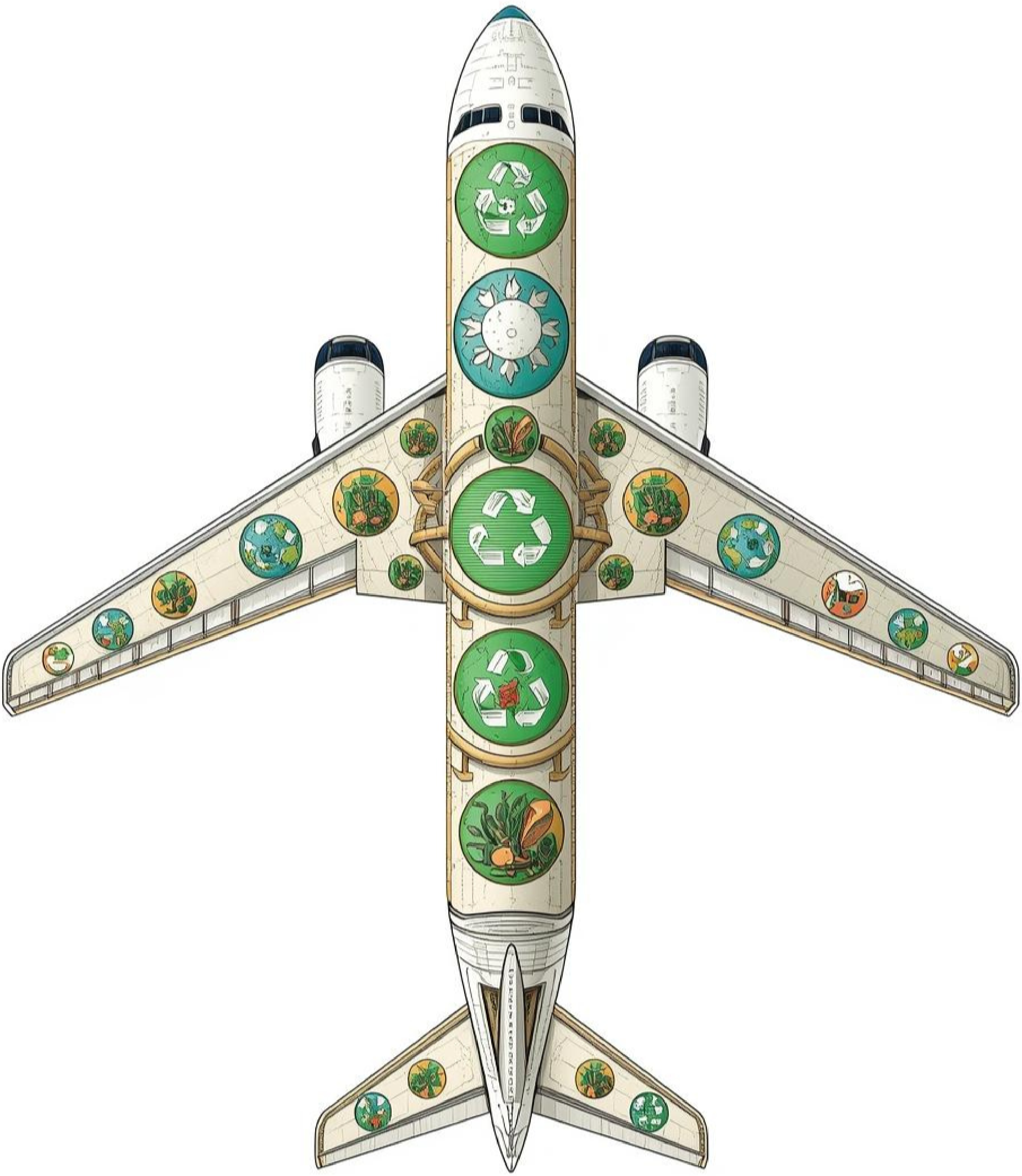

Circular aviation: A study on recycling strategies in aviation industry

by

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to obtain the degree of Master of Science at the Delft University of Technology.

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Preface

This thesis was written as part of the Master's program in Aerospace Engineering at TU Delft. Choosing the topic of circular aviation and recycling strategies was driven by my passion for sustainability. For many years, I have been motivated by the challenge of reducing aviation's environmental footprint, and this thesis offered the chance to turn that motivation into tangible research. It has been deeply rewarding to explore how circular economy principles can be applied in a high-tech field like aerospace, allowing me to contribute to an area that aligns with my values and addresses an urgent industry challenge.

I would like to express my sincere gratitude to my supervisor, Ir. Jos Sinke, for his continuous guidance, patience, and encouragement throughout this project. Further, I am also thankful for the constant support of my family, friends and colleagues throughout this time.

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Summary

This thesis examines how recycling in the aviation industry can be improved by focusing on two key material groups: aluminium alloys and carbon fiber reinforced polymers. Aircraft production and end-of-life disposal generate significant environmental impacts, and circular economy principles offer opportunities to reduce waste and emissions. The research was guided by the question of how to raise the recycling percentage in aviation when considering both environmental and cost factors, supported by sub-questions on material performance, economic thresholds, and future policy effects.

A mixed-method approach was used, combining literature review, comparative materials analysis, life cycle assessment (LCA), economic evaluation, and decision modelling. The LCA quantified the energy and emissions associated with different recycling routes for aluminium and CFRP, while the economic analysis evaluated cost-effectiveness and scale requirements. These findings were synthesized into a decision flow framework to guide stakeholders in selecting optimal end-of-life options based on priorities such as cost, environmental impact, or material quality.

The results show that aluminium recycling is highly efficient: solid-state recycling and remelting can retain material quality with up to 95% energy savings compared to primary production. However, CFRP recycling is more complex. While processes like pyrolysis can recover fibers and save some of the high embodied energy of virgin carbon fiber, the recycled material often cannot always be reused in critical aerospace applications at this moment. Economically, aluminium recycling is already favorable, whereas CFRP recycling requires larger-scale facilities or supportive policies to become viable.

Overall, the thesis concludes that aluminium can be closed-loop recycled profitably and sustainably, making it a clear success case for circularity in aviation. CFRP presents greater challenges but still offers opportunities for material recovery if technological and economic barriers are addressed. The decision flow developed provides a practical tool for aligning recycling strategies with industry goals, showing that with the right choices and scale, higher recycling rates in aviation are both possible and beneficial.

Contents

List of Figures

List of Tables

Nomenclature

Abbreviations

Abbreviation	Definition
AFRA	Aircraft Fleet Recycling Association
AI	Artificial Intelligence
APU	Auxiliary Power Unit
CE	Circular Economy
CFRP	Carbon Fiber Reinforced Plastics
CMAB	Carbon Border Adjustment Mechanisms
EVR	Eco-efficient Value Ratio
EEI	Eco-Efficiency Index
EOL	End-of-Life
EPR	Extended Producer Responsibility
ESG	Environmental, social and governance
ETF	Elongation Till Failure
EU	European Union
FRPC	Fiber-reinforced Polymer Composites
GRI	Global Resource Indicator
HPT	High-Pressure Torsion
IAI	International Aluminium Insitute
LCA	Life Cycle Assessment
LME	London Metal Exchange
MCDM	Multi-criteria Decision-making
MFA	Material Flow Analysis
MRO	Maintenance, Repair and Overhaul
OECD	Organisation for Economic Co-operation and Development
OEM	Original Equipment Manufacturer
OOA	Out-of-autoclave
PAMELA	Process for Advanced Management of End of Life of Aircraft
PAN	Polyacrylonitrile
PM	Powder Metallurgy
R&D	Research and Development
rCF	Recycled Carbon Fiber
RPI	Resouce Potential Indicator
SPD	Severe plastic deformation
SSR	Solid-state recycling
TRL	Technology Readiness Level
UD	Unidirectional
UTS	Ultimate Tensile Strength

Symbols

Symbol	Definition	Unit
T_g	Glass transition temperature	[$^\circ$ C]
T_m	Melting temperature	[$^\circ$ C]

1 Introduction

1.1. Problem statement

Aviation industry is an important global transportation industry, facilitating the movement of goods and people across various distances. It also plays an important role in the global economy, providing millions of jobs across the globe and supporting different industries, such as tourism, logistics and trade.

However, this industry is one of the main contributors to pollution, especially in terms of waste and carbon emissions. For example, one person flying from Lisbon to New York, generates approximately the same amount of emissions as it is necessary to heat up a house for one year [1]. The main cause for this is related to the operational phase of aircraft which emits significantly higher CO2 emissions than the production and recycling phases. Researchers are currently developing methods of reducing this impact by either changing the propulsion system of aircraft to electric systems or hydrogen or by replacing the conventional kerosene fuel with bio-fuels. However, the importance of reduction of the energy consumed in the rest of life cycle phases of an aircraft should not be neglected.

Looking at the process of manufacturing an aircraft, different waste sources can be identified. These sources come from material processing, part manufacturing, maintenance and of course, during retirement of the aircraft, the entire aircraft could potentially become waste, if not properly recycled.

With the increased attention on sustainability, the aviation industry faces pressure into implementing more environmentally friendly actions. Some commonly researched routes in this aspect are the use of lighter weight materials, such as composites for achieving lower weight structures and thus reducing fuel consumption or the use of alternative fuels, such as hydrogen or biofuels. However, another topic worth of investigating is the recyclability of the aicraft materials at the end-of-life stage. This topic has implications on both the economic and environmental aspects. By using a circular economy approach, with a focus on recycling, the environmental footprint is expected to decrease significantly. Looking from an economic perspective, recycling practices can lead to cost savings by recovering valuable materials and reducing the need for pristine materials.

1.2. Research scope

The aim of the present study is to address a gap in the current body of knowledge by identifying possible recycling routes and presenting a strategy to enhance recycling, considering environmental, economic and product quality factors. Using such decision flow chart, stakeholders can make informed decisions on the routes that could potentially be followed at the end-of-life stage of an aircraft for achieving higher recycling rates and greater sustainability.

The main research question which will be answered during this report is:

What strategy can be developed to increase, when looking at environment and costs, the percentage of recycling in the aviation industry?

The answer to the main question will be supported by subquestions as presented below:

1. To what extent can recycled materials be used in aircraft components?
2. What are potentially the most impactful materials to recycle in terms of energy requirements, costs and material availability?
3. What value (price x quantity) is required to make recycling effort affordable?
4. What are current prices and are they expected to change (legislation, subsidies, penalties)?

1.3. Research outline

The report is structured in six chapters, excluding the introduction chapter. In chapter 2, a literature study is performed on various topics related to materials used in aerospace industry, but also to circular economy and sustainability. Chapter 3 offers a comparative study of the properties of aluminium and CFRP when using virgin materials and recycled materials, while in chapter 4, the environmental aspects of these materials are presented by means of a LCA. In chapter 5 economic aspects are discussed, while in chapter 6 the decision flow chart is presented. Chapter 7 offers the conclusion of the present study and presents some recommendations for future work.

2

Literature Study

2.1. Overview of materials

The materials used in the aviation sector need to be of high quality and possess high specific mechanical properties. This is because of the high loads they need to withstand during the operation phase. However, the structures need to be lightweight. A lighter structure leads, undoubtedly, to an overall lower weight of the aircraft which has, for instance, consequences on the fuel consumption. The standard practice is still to use metals in aircraft manufacturing as they are well-known materials, with robust manufacturing and inspection techniques [2]. Aluminium alloys are mainly used in the aircraft airframe. However, initially starting with military applications, where performance was more important than the relatively higher costs of producing, polymer composites have shown a high increase in usage also in commercial aircraft. Therefore, this section aims to provide an overview of these two classes of materials. The processing of raw materials is presented for both materials and some information on specific types of such materials is discussed in section 2.1.1 and section 2.1.2. Further, in section 2.1.3, the material distribution across different types of aircraft is presented.

2.1.1. Aluminium alloys

As a material on its own, aluminium is obtained from bauxite ore. This is first refined into alumina, which is further smelted to obtain pure aluminium. The bauxite ore is refined through the so-called Bayer process [3]. There are five main stages in this process:

- **Grinding:** Bauxite ore is crushed and ground into fine particles to increase its surface area for chemical extraction.
- **Digestion:** The crushed bauxite is mixed with a hot, concentrated solution of sodium hydroxide (NaOH). This is done in a high-pressure vessel called a digester. Impurities such as iron oxides and silica are left behind during this step.
- **Clarification:** The resulting mixture is filtered to separate the solid impurities from the dissolved alumina solution.
- **Precipitation:** Carbon dioxide (CO_2) is introduced into the sodium aluminate solution resulted from the previous step. This leads to alumina to precipitate out as aluminum hydroxide while leaving behind sodium hydroxide in solution.
- **Calcination:** The aluminum hydroxide precipitate is heated during this stage at high temperatures to remove the water, forming alumina (aluminum oxide).

Further, after the Bayer process, the alumina goes through the Hall-Héroult process [3]. During this process, the alumina is dissolved into cryolite (Na_3AlFe_6). After electrical current is applied and passes through this solution, aluminium and CO_2 are produced [3]. This electrolysis process takes place at elevated temperatures, in the range between 950°C and 980°C. Thus, it is an energy-intensive process. Exact values for the energy consumption of the production process of aluminium could not be found in the literature. Therefore, the software EduPack was used to get an indication on the range of energy consumption. For example, for production of a typical aerospace grade alloy, AA2024-T3, the embodied energy ranges between 161 and 178 MJ/kg.

After the electrolysis process, pure aluminium is formed. Further, this is mixed with different components to obtain alloys.

The production of aluminium leads to a division between cast and wrought aluminium. Cast aluminium is intended for the production of castings as a result of solidification of a molten alloy in a cavity. Wrought aluminium is the aluminium produced by rolling, forging or extrusion processes out of a billet. In aerospace applications, wrought aluminium is mostly used. The wrought aluminium alloys are divided into 8 different series depending on their composition and physical properties. Each series has advantages and disadvantages and for this reason, they are used in different applications. Table 2.1 presents an overview of the aluminium alloy series along with a couple of their major properties and usual applications.

Table 2.1: Aluminium alloy series properties [4]

Series	Main alloying element	Properties	Applications
1000	None	- thermally conductive - highly ductile - corrosion-resistant	- chemical tanks - rivets
2000	Copper	- can withstand high temperatures	- military - aerospace - high-performance applications
3000	Manganese	- moderate strength	- automotive parts - construction materials
4000	Silicon	- moderate strength - good machinability - minimal shrinkage when it solidifies	- automotive industry
5000	Magnesium	- moderate to high strength	- vehicles - pressurized vessels
6000	Magnesium Silicon	- good strength - significant resistance to atmospheric corrosion	- aerospace / automotive structural components
7000	Zinc	- high strength	- aerospace applications
8000	Other	-good formability	- 8019 alloy good for high-temperature aerospace applications

2.1.2. Polymer composites

Composites are materials made out of two or more distinct constituent materials that, when combined, create a new material with properties, superior to those of the individual components. For this research, only the fiber-reinforced polymer composites (FRPC) will be looked into.

The fiber-reinforced polymer composites can be categorized based on various properties as presented below. Based on the type of fibers, the FRPC are categorized as follows:

- Carbon-fiber reinforced polymers
- Glass-fiber reinforced polymers
- Aramid-fiber reinforced polymers
- Natural-fiber reinforced polymers

Based on resin, the FRPC are categorized as follows:

- Thermoset polymer composites
  - amorphous
- Thermoplastic polymer composites
  - amorphous
  - semi-crystalline

Finally, based on the fiber length, the FRPC are categorized as follows:

- Continuous: aspect ratio between the length and diameter of the fiber is high. Length is usually larger than 1m
- Long: length is between several millimeters to centimeters
- Short: length is smaller than several millimeters

Based on their usage, carbon and glass fibers are the most used types of reinforcements in the aviation industry. Thermoset resins are predominantly used, however, recent developments show also the benefits and possible usage of thermoplastics in aircraft airframes. Thus, further in the study carbon-fiber reinforced polymers and glass-fiber reinforced polymers will be looked into taking into account both thermoset and thermoplastic resin types.

The method of production of carbon fibers differs from the one of glass fibers, therefore this will be discussed in separate sections. Similarly, thermosets and thermoplastics will be discussed separately.

Reinforcement

Carbon-fiber reinforced polymers

The method of producing the carbon fibers used as reinforcement in composite materials starts with the raw material, named precursor. The majority of carbon fibers are made out of an organic polymer known as polyacrylonitrile (PAN). The first step is called spinning. In this step, the precursor is converted into fibers. Afterwards, the fibers go through a thermal treatment which consists of oxidation, carbonization and graphitization. The oxidation, carbonization and graphitization processes are highly energy-demanding as they take place at elevated temperatures. Typical temperatures are in the range of 200°C-300°C for oxidation, 700°C-1500°C for carbonization, while for graphitization temperatures can reach even more than 2000°C.

To ensure good bonding, surface treatments are necessary. The treatments are typically done by passing the fibers through air or ozone. Because of the reaction with the oxygen, the fibers are oxidized and their surface becomes slightly rougher. The rougher surface ensures a better mechanical bond. The last step required is sizing. It involves covering the fibers in a thin film that protects them during handling and winding. Usually, this layer is a resin such as epoxy that is compatible with the resin the fibers will later be infused with during manufacturing. Further, the fibers are twisted into yarns.

Glass-fiber reinforced polymers
For creating the glass-fibers, minerals such as silica sand, limestone, dolomite, etc. are heated in a furnace until they reach the melting point. This melted compound is then extruded through bushings with different sizes, depending on the requirements. The extrusions are now called filaments and they need to be sized (for similar purposes as in the case of carbon fibers) and bundled into rovings [5].

Resin

Thermoset polymer composites Thermoset resin is the type of resin that forms crosslinks between the polymer molecules. Initially, this type of resin is composed of monomers. Upon exposure to high temperatures and pressures, and by using in most cases a chemical catalyst, named hardener, the resin starts to react and form macromolecules. Subsequently, it becomes rigid [6]. This chemical reaction is called curing and it leads to the polymer having a definite structure and form, which cannot be reversed. Because of this curing process, the production cycle of thermoset composites materials takes a long time, in the range of hours depending on the exact resin used [6].

There are multiple thermoset resins used in the aviation industry, such as phenolics, polyurethanes and polyimides, but the most commonly used type of thermoset resin is the epoxy resin [7]. This particular type of resin has excellent properties: high strength, high adhesion to substrates and high electrical insulation. Furthermore, the low shrinkage and low cost are also important factors [7]. However, epoxy resins also possess low fracture toughness and are brittle, which makes them not suitable for certain kind of applications [7].

When selecting an epoxy resin, one of the main properties investigated is the glass transition temperature [7]. The glass transition temperature is the temperature where the amorphous polymer changes from a rigid state to a softer state. If for thermoplastics, reaching this temperature would mean that the polymer melts considerably, for thermosets, upon reaching this temperature, the components would soften but not loose their shape because of the crosslinks formed during polimerization. However, this temperature is of high importance because it shows whether or not a certain resin can be used for structural or non-structural applications. Above the glass transition temperature, the modulus is several times lower than below the glass transition temperature, thus indicating the range in which it can be safely used [7]. The glass transition temperature depends on the curing temperature of the polymer, which is also related to the hardener type used for curing [7].

In cabin interior applications, phenolic resins are mostly used. This is because the mechanical properties are of less importance, but the fire resistance and smoke emissions are critical [6]. However, the focus of this research is on airframe components, therefore, the phenolic resin is not discussed further. Another matrix material usually employed in the aircraft radomes or antennae is the cyanate ester resin [6]. Their excellent dielectric properties are responsible for being used in such applications [6]. Even though they exhibit properties that would make them suitable for other applications, even replacing the traditional epoxy resins, the cost of cyanate ester matrix is relatively high, thus its usage is limited [6].

Besides the methods of producing the raw material (fibers and resins) the production methods of the components using these materials have high consequences on the energy usage, costs and so forth. The production method influences the costs in terms of energy costs, labor costs, and material costs. The fabrication methods for the thermoset matrix have mainly three main steps: material placement, forming and curing [8].

For the material placement stage, Falzon et al. identified four main techniques: hand lay-up, filament winding, tape laying machines and fiber placement machines [8]. Each of these techniques have different advantages and disadvantages in terms of quality, labor cost and energy cost. For example, hand lay-up involves cutting the plies to size, transporting them and placing them in the mold by a skilled operator [8]. Because the shape of the plies needs to be cut from a wide roll of material, nesting techniques need to be applied for an efficient usage of the material. However, there will always be some waste produced after using this technique. Furthermore, after a certain number of plies, they need to be debulked by applying a vacuum to consolidate and remove the entrapped air, which also leads to energy consumption [8]. Commonly, prepregs are used for such techniques. Prepregs are impregnated fibers in which the resin is semi-cured, in the so-called B-stage. The curing of the resin is paused by having these materials stored in a freezer. This pause is limited, therefore one of the disadvantages of prepregs is that they have a limited shelf life, typically between 3 and 12 months. If we look at this from an energy requirement perspective, it should be noted that also storing the prepregs in the freezer results in the use of energy and therefore, adds up to the energy demand of this type of material.

Going back to processing techniques of thermosets, if we consider the tape laying techniques, this requires less skills of the operators, because it is an automated process. The machine can dispense the UD prepreg tape from rolls while removing the backing film and applying sufficient pressure for debulking and consolidating purposes [8]. Net shapes can be achieved by such a process, therefore the waste produced during this operation is minimal. The fiber placement machines have a similar way of operating, with the difference that they can place up to 32 individually controlled tows in one run. Each tow has a width between 3 and 6 mm [8]. This technique is already implemented in the aviation industry, for the manufacturing of the Boeing 787 Dreamliner fuselage [8].

Looking at the forming and curing phase of composite structures, they can be mainly divided into two categories: autoclave methods and out-of-autoclave (OOA) methods [8]. Autoclave curing is a production method intended to be used with thermoset prepreg materials [8]. In this method, a polymer film is used to cover the composite component and vacuum is drawn to consolidate the plies and remove the air. Additionally, pressure and heat are applied to consolidate and cure the thermoset matrix [8]. The curing cycle is relatively long, therefore this method is not commonly used for large production rates [8]. OOA processes involve also the use of a polymer film, such as a vacuum bag, but the components can be cured at ambient temperatures or in an oven [8]. The methods under this category are mainly used for dry fibers which are later on infused with the resin [8].

At a first glance through the EduPack software, it can be noticed that the energy required to process 1kg of prepreg using an autoclave is between 20 and 23 MJ/kg, while if dry fibers are used and later infused via the resin infusion process, the energy demand is reduced till 12 - 13 MJ/kg. Note that these numbers are indicators and result from assumptions of the energy required to heat up the base material to the processing temperature, maintain this temperature for the entire curing cycle, and also the energy required to deform the material at this processing temperature. Thus, the energy demand can vary based on the material used.

Thermoplastic polymer composites Unlike thermosetting resins, thermoplastic resin can be re-melted. This is because the thermoplastic resin does not undergo chemical reactions, but physical changes in which the structure solidifies by cooling down. The main bonds between the molecules are Van Der Waals forces. Therefore, this leads to the possibility of being re-shaped whenever it is melted. The use of thermoplastic resins opens the doors towards sustainable components as the parts can be re-shaped and used in different applications. Another advantage over their thermoset counterparts is the fact that they do not require a special refrigerated environment during transportation and storage. Therefore, this has an economic impact because there is a reduction in the investment in the storage and cost of transportation [6]. However, if we consider the disadvantages, the lack of drapability and tack of this type of material is lower than in the case of thermoset prepregs. This is a result of the polymer being fully reacted and thus, it does mean that hand lay-up techniques are impossible to implement in the production of thermoplastic composite components [6]. In addition to this, the processing temperatures are higher than in the case of thermoset resins. For example, a PEEK prepreg material needs to be processed at a temperature around 380°C, compared to a standard epoxy resin which can be processed at 120°C or 180°C [6].

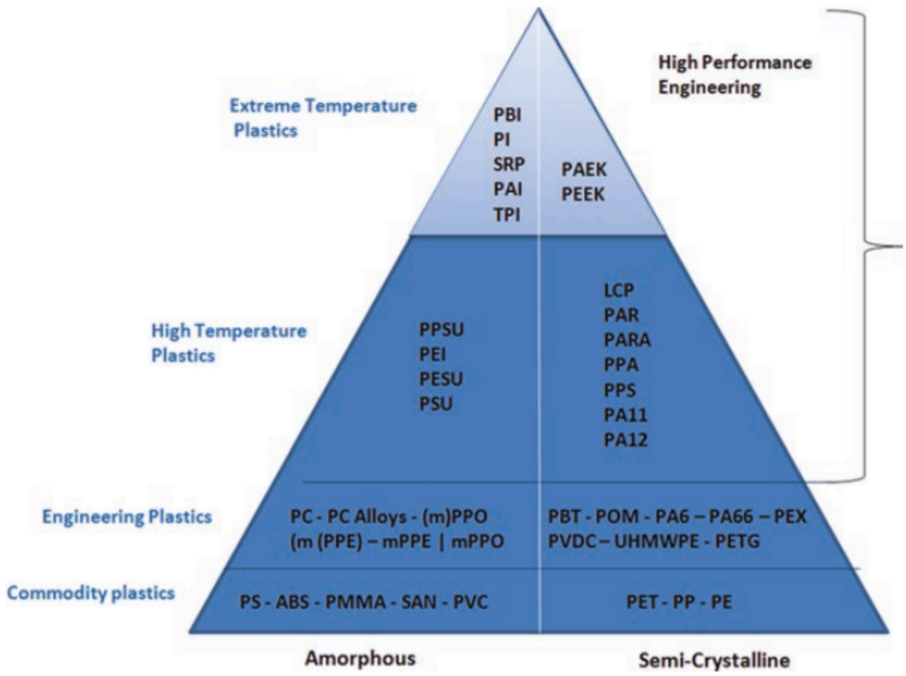

Figure 2.1: Thermoplastic resin pyramid [6]

Fig. 2.1 illustrates the pyramid of thermoplastic matrices divided in two categories based on their chemical structure: amorphous and semi-crystalline and in four categories based on their performance [6]. The difference between the amorphous and semi-crystalline polymers is in their molecular structure. The amorphous polymers have no clear molecular shape or form.

As they have no sharp melt point, the amorphous polymers gradually soften as the temperature increases [9]. Because of their molecular structure, they allow more deformation at higher temperatures, at the cost of having lower mechanical strength and stiffness compared to the crystalline counterparts [9]. On the other hand, semi-crystalline polymers have an ordered structure, however with certain areas of amorphous regions. They do have a sharp melting point, which implies that the polymer is rigid until a specific amount of heat is absorbed and then it softens [9]. This melting point is normally higher than in the case of amorphous polymers. An illustration of the molecular structure can be seen in figure 2.2.

If we take into account, the second division in the pyramid, the ones based on applications and performance, then the thermoplastic polymers are divided into four categories. The lowest category in the pyramid is the one of commodity polymers. These polymers are relatively inexpensive and easy to process [10]. Going higher in the pyramid, the next category is the one of engineering plastics. These have better thermal and mechanical properties than their commodity plastics counterparts [10]. The high-temperature and the extreme-temperature plastics can be combined into one group: the high-performance polymers. The polymers in this category are generally reserved for applications that require excellent durability and mechanical properties [11].

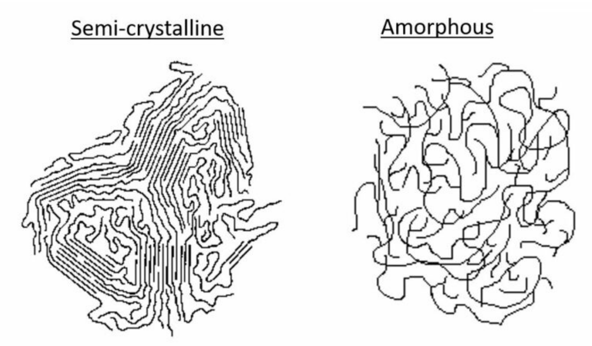

Figure 2.2: Amorphous vs semi-crystalline molecular structure

The most commonly used thermoplastic resin in the aerospace industry is the PEEK resin [6]. PEEK is a semi-crystalline polymer. As explained above, this means that it has a distinct melting point, of 343°C.

Looking at the manufacturing techniques of components with a thermoplastic matrix system, the main trait that all of them share is the use of high temperatures during processing: above T_g in the case of amorphous structures and above T_m for the semi-crystalline ones [6]. The holding time at this elevated temperature can be relatively short because it is only needed for consolidating the plies and not for polymerization reactions [6]. However, as the processing temperatures are significantly higher than in the case of thermosets (in range of 300° to 400° C), the heat-up and cooling stages are also more energy-intensive and could potentially be of importance in determining whether or not thermoplastic composite material have an overall lower energy consumption than the thermoset counterparts.

Thermoforming processes are usually used for transforming a 2D thermoplastic panel into a 3D shape [6]. This process requires the cutting of the plies to the gross shape required for the component and stacking them using a soldering iron to keep the plies together [6]. The consolidation can take place either in an autoclave or in a press [6]. This is a highly energy-intensive process as the temperatures needed are high and also the press cannot be opened until the cooling has finalized [6].

2.1.3. Material usage breakdown structure within the main competitors

The existing fleet of airliners is expected to double in the next 20 years [12]. This is due to the increase in the number of passengers. As some of the airplanes in the existing fleet will be replaced because of reaching the end-of-life, it is important to know how the material distribution varies per aircraft type. For this, a comparison is made between some of the main aircraft types of Airbus and Boeing. These are the two main competitors in the commercial aircraft market today, therefore the selection to elaborate the discussion on them.

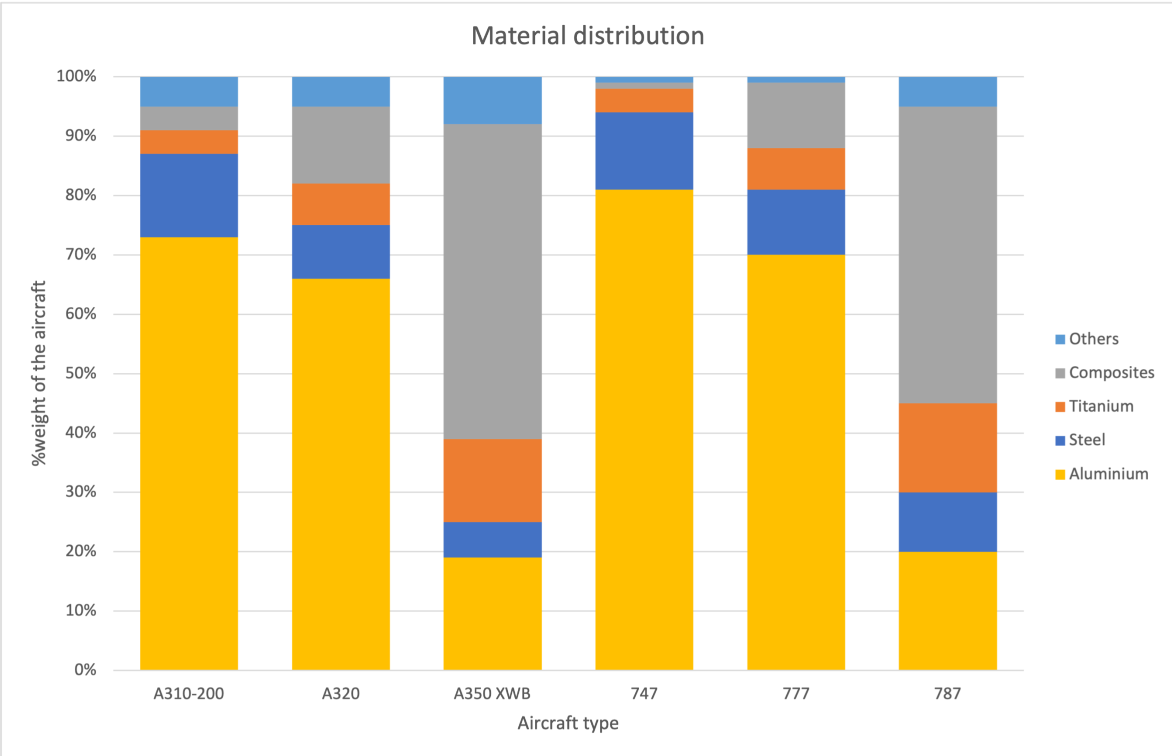

Figure 2.3: Material distribution in Airbus and Boeing most representative aircraft types (adapted from [13])

The first three columns in figure 2.3 represent three aircraft models developed by Airbus. The first type, A310 was developed in the 70s, while the A320 in 80s and the last one, A350 XWB was first produced in 2010. This distribution illustrates that the usage of aluminium decreases over time, while the usage of composite materials is increasing. A similar trend can be observed for the Boeing aircraft, the last three columns in the figure 2.3. While around 80% of the weight of the aircraft was aluminium in the 747 model which was first introduced in 1969, the percentage decreased as the models evolved. Therefore, in the latest Boeing 787, only approximately 20% is aluminium, while composite materials make up half of the weight of the aircraft.

Taking into account that the expected lifespan of an aircraft is between 20 and 30 years, it can be stated that the generation of Airbus A320 is the model that is reaching the end-of-life in this time. Therefore, the focus of this study will be on this type of aircraft.

2.2. State-of-the-art recycling techniques in aviation

This section will provide information regarding the state-of-the-art recycling techniques and ideas available for more sustainable aviation. Section 2.2.1 presents an overview on how the end-of-life phase in the lifecycle of aircraft is dealt with at this moment. This is presented also from a legislative point of view. Section 2.2.2 focuses on the state-of-the-art recycling techniques for aluminium alloys and FRPC.

2.2.1. Aircraft end-of-life phase

Recycling takes place during the end-of-life phase of products. The International Standard ISO/IEC/IEEE 15288 divides the lifecycle of products into six phases [14]:

- Design phase
- Development phase
- Production phase
- Operations phase
- Support phase
- Disposal phase

It is clear that these stages can be adapted and applied to any product and, therefore, also to aircraft. For this research, mainly the disposal phase will be looked into.

Disposal phase, or end-of-life aircraft phase, is the phase where the aircraft operational usage has come to an end and its components are about to be reused, recycled or disposed of [14]. For many years, the retired aircraft have been stored in desserted areas, called scrap yards. These areas provide enough space for aircraft to be stored under convenient climate conditions, such as dry and non-corrosive, and for affordable rates [15]. The storage in such areas takes place until a decision is made regarding the individual components of the aircraft [14]. Deciding if an aircraft gets temporarily taken out of service depends on how the market is and the quality of the aircraft. Bringing it back into service mostly relies on changes in the economy or how competitive it is compared to others [15]. For example, with older aircraft, that are both noisy and fuel inefficient, a reintroduction into market is highly unlikely [15]. However, certain components can still be reused for aftermarket.

As this principle of dealing with retired aircraft is far from ideal, the two largest civil aircraft original equipment manufacturers (OEMs), Airbus and Boeing, have come up with two strategies.

Airbus Strategy was to launch a project named ”Process for Advanced Management of End of Life of Aircraft” (PAMELA). The main goal of this project was to demonstrate that between 85% and 95% of an aircraft can be either recycled, reused, or recovered [14].

Decommissioning phase consists of parking, inspecting, and draining all the liquid and hazardous substances. All parts that could be used as spares are dismantled in the second stage, checked and cleaned. Here, the APU (auxiliary power unit) and landing gears can be included. When the third stage, dismantling, is reached, the aircraft must be handled following the waste regulations. Components should be grouped, sorted and recycled as per their intented application [14]. At the end of the project, it was demonstrated that 85% in weight can be saved as well as up to 90% in energy and mining resources of metallic material [14]. However, there is some unclarity about how this percentage of material recyclability is obtained as there could be two different methods of calculating it as presented in [15]. The first method implies that the final percentage is the combination of the material recycling percentage and the percentage of re-use of components. The second method presents only the percentage of recycled aircraft material by weight of an end-of-life aircraft [15].

As a result of the project, Airbus founded the Tarbes Advanced Recycling and Maintenance Aircraft Company (Tarmac Aerosave) in France. According to their website, since 2007, the company has recycled more than 300 aircraft by applying the results and methodology of the PAMELA project [14].

Taking into account that Boeing fleet is relatively older than of Airbus, there might be some sort of pressure on Boeing to join this new, sustainable movement. Therefore, **Boeing Strategy** was to start, in collaboration with European and American companies, the Aircraft Fleet Recycling Association (AFRA) in 2006. The founding companies have different areas of expertise such as waste management, aircraft maintenance and manufacturing, service providers, etc. The association strives to create a set of rules governing the handling of retired aircraft [15]. As a result, the "Best Management Practice for Management of Used Aircraft Parts and Assemblies and for Recycling of Aircraft Materials" guidelines have been elaborated [14].

As it has been outlined, the two strategies developed by Airbus and Boeing differ. While Airbus focused more on the technical aspects of the end-of-life phase, Boeing was more working towards implementing administrative and legislative changes to this phase. However, both aspects go hand-in-hand and are of importance when discussing recycling strategies.

From a legal perspective, there is no clear rule about handling the aircraft end-of-life. However, there are different approaches used to deal with this. One of them is the use of existing regulations that have an indirect impact on aircraft recycling. For instance, the components are recycled based on their intended purpose in the aircraft [14]. So, for example, regulations such as Directive 2002/96/EC on "Waste Electrical and Electronic Equipment (WEEE) , the Directive 1994/62/EG on "Packaging and Packaging Waste" (Directive Line 94/62/EG), Regulation (EC) No 1907/2006 concerning the "Registration, Evaluation, Authorization and Restriction of Chemicals (REACH)" can be used for recycling different parts used in aircraft [14]. All these directives rely on the so-called principle of Extended Producer Responsibility (EPR) [14]. The Organisation for Economic Co-operation and Development (OECD) defines this policy as "an environmental policy approach in which a producer's responsibility for a product is extended to the post-consumer stage of a product's life cycle including its final disposal" [16]. In other words, this principle indicates that the polluter should pay the cost of pollution. Having this principle in place is considered to make the producers more aware of the products they put on the market and therefore, they would start taking into account more sustainable options in the design phase of any new product [15]. Some researchers consider that this methodology could be useful in the case of aircraft manufacturers as well. However, it is not completely clear if the responsibility would be on the airline or manufacturer itself. In this sense, research has been conducted by Delft University of Technology in collaboration with Erasmus University. The research dates back in 2007 and aims at investigating the efforts related to the EPR in the aviation sector [15]. The research concluded that given there are two major manufacturers in the industry, there could be relatively easy ways to negotiate recovery targets and regulations [15]. On the other hand, provided there are no exact numbers yet on the recovery potential and the associated costs and benefits, a weakness can be faced in the introduction of an EPR policy [15].

A second approach to dealing with end-of-life aircraft is to look at analogies with other transport industries such as train, shipping or automotive [14]. Among these, the automotive industry is the most investigated. Given that there is a large number of cars approaching the end-of-life phase every year and that there is a close relationship between this industry and the citizens, there is a higher pressure on having legislation around it [14]. This industry also works on the principle of EPR, illustrated above. The manufacturers are required to accept the end-of-life vehicles back and the European Directive 2000/53/EC on “End-of-Life Vehicles” provides information on the recycling rates [14].

However, recycling or reusing aircraft components would be impossible without knowing how to recycle the materials they are made out of. Therefore, the next section focuses on the recycling techniques available for aluminum alloys and FRPCs.

2.2.2. Material recycling techniques

Examining the sustainability of materials involves considering life cycle assessment (LCA) or recycling potential. Important to note is the fact that waste in materials can come not only from the end-of-life products or components but also from manufacturing processes where not all the material is used and thus, waste is produced [17].

There are sociotechnical drivers behind the developments of recycling technologies for both aluminium and composites materials. If we look at the composites materials, according to Krauklis et al. starting 2009, there is a ban on landfilling composites in Germany [18]. This leads to other countries wanting to follow the example and set stricter rules for end-of-life handling of these materials. Further, there is a major wave of wind turbines that have reached their end-of-life phase and need to be decommissioned and of course, the same applies to aircraft, especially given the COVID-19 pandemic and decline in the air traffic [18]. Lastly, composites have seen a huge increase in the manufacturing of cars, therefore this also leads to the need of better recycling technologies available for the recycling of these materials [18].

As far as the composite materials are concerned, once reaching the end-of-life phase, there are three different options at this moment on the market: landfill, incineration and recycling [18]. Even though landfilling is the cheapest discarding route, it is also the least preferred option based on the European Union’s Waste Framework Directive [18]. Incineration is a waste management method centered on burning the organic elements present in waste materials [18]. However, after incineration, around 50% of the composite waste is transformed into ash, which still needs to be landfilled [18]. As far as recycling techniques are concerned, they can be grouped into three main categories presented from the least energy demanding to the highest energy demanding [19][18]:

1. **Mechanical processes.** These processes rely on grinding the matrix. An initial crushing or shredding takes place. These are mainly applied to glass fibers and carbon fibers [19]. This type of recycling technique is the least energy demanding of all recycling techniques for FRPC. However, as most of the composite value comes from the high properties which are related to the length and orientation of the fibers used, relatively high percentage of the value of this type of material is lost when shredded. This is mainly caused by the fact that the properties of the material are significantly reduced by the crushing together the fibers and the matrix, without any separation between them [18].
2. **Thermal processes.** The main purpose of this category of processes is to separate

the fibers from the resin [18]. Pyrolysis, fluidized bed pyrolysis, and microwave-assisted pyrolysis are the most known thermal processes in recycling composites [19]. One of the advantages of the pyrolysis process is that the by-products can be used for the production of fuels or oils, which implies a high economic value for this process [18].

3. **Chemical processes.** These types of processes rely on dissolving the resin in a reactive medium [18]. The polymers are chemically converted to monomers through chemical reactions [18]. According to research available, this category of processes is mainly suitable and used for carbon fiber reinforced plastics [18]. The solvolysis process is an example of such a process [19]. Even though the recycled fibers obtained after the solvolysis process are of the highest quality among others, this process is not yet commercially available as presented by Krauklis et al. [18].

Even though these techniques exist and research is currently being conducted on them, these processes have certain commercialization barriers as identified by Yang et al. Some of these obstacles identified are the lack of markets, high recycling cost, and lower quality of the recyclates versus virgin materials [20]. Among them, pyrolysis for carbon fibers is the one that has a technology readiness level (TRL) of 8, while solvolysis which was mentioned to have the highest quality of recyclates has a TRL of 4 [17]. The technology readiness levels measure the maturity level of a certain technology. Companies might use different scales, but the main levels are presented below:

- TRL 1: basic principles are detected and scientific research begins [21];
- TRL 2: basic principles are studied and practical application should be applied to those principles [21];
- TRL 3: checking if the technology is viable by analytical and laboratory studies. Proof-of-concept might be delivered in this stage [21];
- TRL 4: multiple components are tested with each other [21];
- TRL 5: continuation of TRL 4, but with the addition of more rigorous tests;
- TRL 6: fully functional prototype should be delivered at this stage [21];
- TRL 7: the working prototype should be tested in a space environment [21];
- TRL 8: technology has been tested and it can be implemented into an already existing technology [21].
- TRL 9: once the testing is done and implementation takes place [21].

However, when it comes to using recycled composite materials in primary aircraft structures, this is not yet allowed by the regulatory bodies because of the properties not achieving the same values as in the case of virgin materials. Therefore, recycled composites can only be used either in non-structural applications or in other applications where lower properties are required.

Shifting the focus towards the metals, the aluminum used in the aviation industry has the highest quality and manufacturing costs among the rest of aluminium alloys [22]. The traditional method of producing aluminium presented in section 2.1 is highly energy- and cost-consuming. It is believed that by recycling and remelting the scrap aluminium, a cost saving of 90% can be achieved [22]. This cost-saving comes mainly from the less energy-intensive process that happens during the recycling of aluminium compared to the production from virgin materials. According to the Australian Aluminium Council, the recycling of aluminium has in general five steps: collecting the material, sorting it, crushing it, remelting and casting [23]. During the sorting phase, not only the aluminium alloys are sorted based on their composition, but also they are sorted on the presence of coatings [23]. Further, the metal is crushed into small parts and then the uncoated material is placed in a furnace called remelter. If the aluminium is coated, then it goes first in a gas-fired rotary furnace for removing the coatings before going in the remelter [23]. The recycled material is cast in ingots at temperatures around 700°C and thus, new material is produced [23].

2.3. Circular economy

Adopting a circular economy strategy is considered by many researchers and institutions to be the way forward towards a more sustainable economic system [24].

This strategy is supposed to replace the traditional linear economy. In a linear economy, the raw materials are processed and transformed into a finished product. By using this product, it becomes disposable waste at its end-of-life [24]. This type of economy paradigm is also referred to as ”cradle-to-grave” [26] and its main assumption is that there is an unlimited amount of resources existing [27]. On the other hand, by using the circular economy approach, the waste is recovered and brought back into the supply chain [24]. This is the ”cradle-to-cradle” approach [26]. Different definitions are given in the literature studied, however, the core principles of circular economy which are reduce, recycle, and reuse, often referred to as the 3R are always involved in these definitions [27]. Yet, different researchers or industries use even a 9R principle (reuse, rethink, refuse, reduce, repair, refurbish, remanufacture, repurpose, recover and recycle) [27]. Fig. 2.4 depicts these principles going from the least to the most circular, by categorizing them in three groups: useful applications of materials, extending the lifespan of product and its parts and the smarter product use and manufacture.

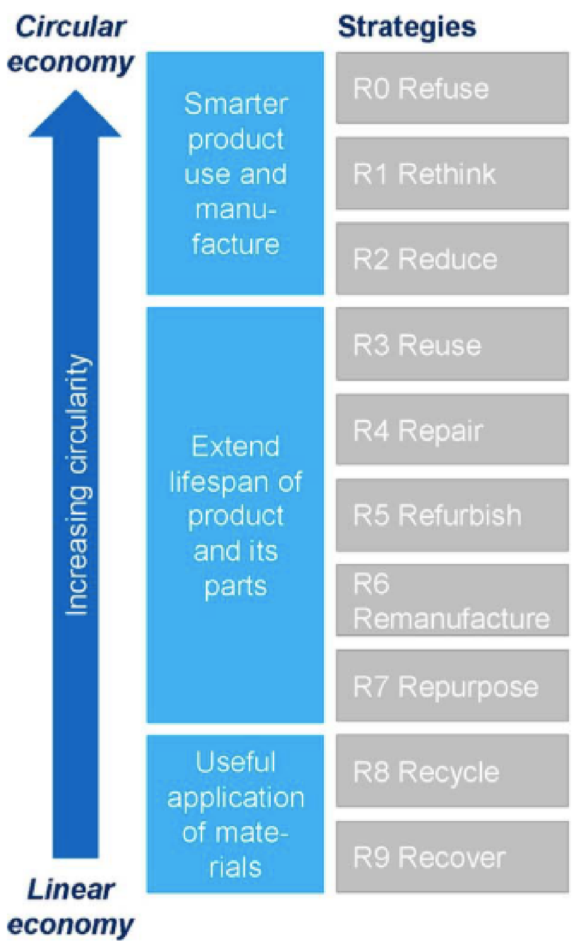

Figure 2.4: Circular economy principles [25]

In the least circular category, we can distinguish 2 principles: recover and recycle. These two principles apply to the end-of-life phase. The products in these categories have been labeled as waste and consequently, need special treatments and processing to enter the value chain again [28]. The Recover principle refers to the incineration of material with the purpose of energy recovery, while the Recycle principle involves the processing of materials to obtain a material with the same grade or lower quality [29].

Going further towards more circular principles, the second category is the ”extend lifespan of product and its parts” category. This category comprises the following principles: repurpose, remanufacture, refurbish, repair and reuse. The enumerated principles are usually applied during the use or operations phase in the life-cycle of a product. The Repurpose principle refers to the use of a discarded product or part of a product in a new product that has a different function [29]. Remanufacture implies that the discarded products are used in a new product which has the same function [29]. Refurbish refers to updating and restoring an old product [29]. Repair denotes that a defective product is being repaired with the purpose of restoring its original function [29]. Lastly, the Reuse principle implies that another customer is going to use a discarded product that still fulfills the original functions [29].

In the last category, the most circular principles are enumerated: reduce, rethink and refuse. These principles should already be applied at the design stage in the lifecycle of a product. Principle R2, Reduce, implies that the efficiency in product manufacture is increased by using fewer natural resources [29]. Rethink implies that the product use should be more intensive, leading to the strategy of sharing a product. Therefore, this not only has an impact on the product design, but also on the business models of companies. Further, Refuse refers to making a product redundant by offering the same functions with a newer product. This implies that already at the design stage, the circularity of the product needs to be assessed and the product designed and manufactured accordingly [29].

Placing these principles in the aviation context, it is obvious that some of them are easier to implement than others. For instance, the rethink purpose can be considered already implemented in several aspects of aviation: airliners lease their aircraft, and in some cases, companies also lease the engines. However, this principle would be rather difficult to be applied in the context of only a part of the airframe. Further, looking at R4, this could potentially be implemented or improved through predictive maintenance to any component in the aircraft, thus, also to airframe components which are the focus of this study.

Elia et al. have introduced a four-level framework for providing information about the circular economy paradigm. These levels are as follows [24]:

1. **Processes.** The processes that need to be monitored can be divided further into five categories such as material input, design, production, consumption and end-of-life management [24]. By examining these processes, the circularity of the overall system can be evaluated [24].
2. **Actions.** Four ”building blocks” can be looked at when talking about actions that are involved in the development of a CE. These are:
   - Circular product design and production. Actions such as designing and producing the products focusing on re-usability and recycling can be included here [24].
   - Business models. They define the way a business is run. The choice for a certain model has consequences on its methods of doing business and the expansion path of the company [26]. It is rather difficult for a company to change its business model, once the company is established, therefore, going to a circular economy model requires a radical change [26].
   - Cascade/reverse skills. Actions that help with closing the loops and lead to a circular economy [26]. For example, by cascading it is implied that the byproducts of one process are used as input for other processes. Therefore, there is limited to no waste in the process flows.
   - Cross cycle and cross-sector collaboration. Building relationships across the value chain, but also between industries can be included here [24].
3. **Requirements.** As the main focus of CE is to maximize the value, while reducing the amount of materials needed, different requirements can be selected for evaluating the circularity of a system. However, according to Elia et al., they all can be categorized into the following five groups [24]:

   - Reducing the usage of natural resources
   - Reducing emission levels
   - Minimizing the loss of valuable materials
   - Increasing the proportion of renewable and recyclable resources
   - Increasing the durability of products

4. **Implementation.** The implementation of such a paradigm can take place at three different levels:

   - Micro: companies or customers
   - Meso: ecoindustrial parks
   - Macro: from cities to entire countries

Developing on the idea that certain actions are needed for implementing a CE approach, one of the main contributors is product design stage. In traditional product development, if the product specifications are being set, then changing them at a later stage is often impossible or at least very difficult and requires a lot of budget and time [26]. Therefore, different strategies can be implemented in the early stage of product design. These strategies are grouped into two categories by Bocken et al:

1. **Strategies for slowing resource loops.** Slowing the resource loops refers mainly to extending the product's life. As the product's life is increased, the need for newer products is decreasing and therefore, fewer resources are used. Some strategies within this category are: design for reliability and durability, design for ease of maintenance and repair, design for adaptability [26].
2. **Strategies for closing resource loops.** By closing the resource loops, it is understood that the resources are used again at the end-of-life, employing recycling or reusing [26]. Within this category, a distinction between different recycling methods can be made. This distinction is made based on whether or not the products obtained after recycling have or not the same properties as the original material [26]. Thus, an ”upcycling” method refers to reprocessing of the material to obtain a material with the same properties, while ”downcycling” considers that the obtained material is of lower quality and value than the original product [26]. However, there are certain researchers, such as McDonough and Braungart, who consider that downcycling does not involve a cyclical flow of resources. They consider that the recycling techniques involved in this category only delay the linear flow of material, and eventually, the materials still end up being waste [26].

Taking a look at the business models that can be used for implementing a CE approach, they can be divided in the same two categories as above:

1. **Business models for slowing resource loops.** One example of such a business model is called the ”Access and performance model”. It relies on providing the customers the services they need without their need to own the actual products [26]. Representative for this model are the car sharing services or the launderettes. Another model is the ”Extending product value” model which focuses on benefiting from the residual value of products. In this case, the manufactureres are able to give the users an affordable, ”as new” option through remanufacturing or repairing [26]. The ”Classic long-life” model is another model that businesses use when they focus on delivering long-lasting products. These products are usually designed for durability.
2. **Business models for closing resource loops.** These business models are about capturing the value from the ”waste”. They can be either on a micro scale, where the materials are reused within the same manufacturing/production facility, or macro when the

products are disposed of and other companies are recycling them [26]. According to Bocken et al., two different models can be distinguished: ”Extending resource values” and ”Industrial symbiosis” [26]. The first model focuses on extending the value of a product that would be waste by recycling it, while the second model focuses on using the residual output from one process as raw material for another process [26].

If we are to look further at different tools that can be used to assess circularity, they can be divided into assessment frameworks and indicators [27]. According to Vogiantzi et al., the frameworks are based on three methodologies: Life Cycle Assessment (LCA), Material Flow Analysis (MFA) and Input-Output Analysis [27]. LCA is a tool used for the quantification of the advantages and disadvantages of various CE strategies. For a long time, LCA was used to evaluate only the environmental impacts, while in the present it is a framework that evaluates the circular systems, Product Service Systems and recycling mechanisms [27]. MFA is a quantitative method employed to ascertain the movement of materials and energy within the economy [30]. Lastly, the input-output analysis was initially developed to look into economic interdependencies between different sectors. Later, it has been expanded to assess the environmental and socio-economic impacts related to these sectors [27].

Besides these, several indicators can be used for the assessment of the circularity. The first indicator presented by Vogiantzi et al. is the longevity indicator. This indicator looks at how long a certain material remains within a product system. The indicator takes into account the initial lifetime and durability that is gained through recycling or reusing. However, the longevity indicator does not take into account the decrease in quality after the material is recycled [27]. The Resource Potential Indicator (RPI) assesses the inherent value of a material regarding reusability. Taking into account the available technologies, this indicator assesses the feasibility of a material to be recycled [27]. Some indicators are derived from LCA methodologies. The Global Resource Indicator (GRI) is mainly used in LCA for characterizing resource use. It looks at the scarcity of a material, the geopolitical availability, but also the recyclability of the resources [27]. If we want to focus on the monetization of environmental and economic consideration, then we could use the Eco-Efficient Value Ratio (EVR) and the Eco-Efficiency Index (EEI) [27].

As it can be seen, assessing the circularity can become easily a complex task. For this reason, the multi-criteria decision-making approaches (MCDM) are used [27]. In their work, Sassanelli et al. perform a literature review on the available articles related to MCDM. Markatos et al. discuss the impact of selecting materials in the context of circular economy in aviation. In their research, they developed a decision-making tool that would allow the stakeholders to make an informed material selection. Based on their interest, the stakeholders can use the formula developed by the researchers and give a different weight to the quality feature of the material, cost of the material and the environmental footprint [31]. Therefore, this tool takes into account ecological, economic and circularity aspects [31]. Ng et al. designed a framework that combines multi-criteria analysis and process modeling to assess the performance of the CE [32].

Another interesting proposed framework is the ReSOLVE framework developed by the Ellen MacArthur Foundation, one of the key players in advertising the CE as the future in industries. The ReSOLVE framework stands for: Regenerate, Share, Optimize, Loop, Virtualize, and Exchange [33]. Rodrigues Dias et al. performed a literature study in which they reviewed different articles available on initiatives in the aviation industry and categorized them based on the aforementioned framework. The scope of the Regenerate dimension is to use renewable energy for restoring the health of the environment [33]. In this category, most initiatives that strike out concerning the usage of alternative fuel systems such as electric or hydrogen instead of traditional fossil fuels [33]. The next dimension in the ReSOLVE framework is the Share dimension. This aims at the maximum use of products. Such a goal can be achieved by sharing the products among users, using second-hand products and so forth [33]. In the aviation industry, this leads to the initiative of disassembling the aircraft and selling the good quality components as spare parts [33]. Further, the Optimize dimension looks at increasing the efficiency in the use of material resources by eliminating waste in production and/or supply chain [33]. According to Rodrigues Dias et al., some initiatives that could be included in this category are related to the design of structures with reduced weight and, the use of simulation tools to assess the impact of mass reduction [33]. Looking at the Loop dimension, its purpose is to keep the materials in closed loops, by recycling [33]. Therefore, some ideas in the aerospace industry are to recycle the materials and use them in new components, but also to look at how the waste generated during production is managed [33]. Virtualize looks at developing digital solutions that would reduce the production cycles and therefore, the environmental impact, while Exchange aims at replacing the traditional materials with new, sustainable ones [33].

The advantages of implementing a CE approach in the aviation industry, such as improving environmental sustainability and increasing the life cycle of products, are indubitable. However, there are still a lot of challenges that need to be overcome to have a transition from a linear to a circular economy. After interviews with three aerospace companies, Rodrigues Dias et al. noted in their work that cost is one of the obstacles. This is mainly because the development and usage of newer, environmentally friendly materials have a higher cost than traditional materials. Further, issues with certifications are also a barrier. Companies believe that even though adopting a software-based simulation would generate higher material savings, regulatory bodies should encourage this and certify such practices [33]. However, the most severe barrier is related to the quality of the materials resulting from recycling activities. This is due to safety regulations which are very strict about the quality of materials that can be used [27].

3

Comparative analysis of recycled and virgin material properties

Traditionally, aerospace manufacturers prefer the usage of virgin materials for achieving the requirements of aircraft structures. However, with the nowadays focus on more sustainable aviation, the use of recycled materials is gaining momentum.

Despite popular belief, the use of recycled materials is not prohibited by the relevant legislation. In Europe, the EASA legislation has been examined. CS-25 defines the airworthiness standards that airplanes must meet to be certified within the European Union. These specifications apply to aircraft with a maximum take-off weight of more than 5700 kg, used for commercial purposes. The certification specification covers various aspects such as structural integrity, system and equipment requirements, flight performance, and safety features. The specification is divided into 8 subparts, labeled from A to H, each addressing a different subject. The subpart of interest for this project is subpart D: Design and Construction. According to section CS25.603, the use of any approved material is allowed as long as the materials are tested, and it is demonstrated that they meet the standard values of composition and properties. Thus, it is implied that use of recycled materials is allowed as long as they meet the standards for use for the structure they are intended for.

This chapter presents a comparative analysis on the properties between recycled and virgin materials for one type of aluminium alloy and thermoplastic and thermoset carbon fiber reinforced plastic. In this chapter, the first research subquestion presented in chapter 1 is answered.

3.1. Aluminium alloys

3.1.1. Selected recycling techniques for aluminium alloys

Two main recycling techniques of aluminium are identified in the literature: the conventional recycling and the solid-state recycling.

During the conventional recycling the aluminium is melted and subsequently casted into ingots to solidify. This method of recycling is considered to still be energy-intensive and not achieve a high energy efficiency [34]. Along with this, it is considered that metal loss occurs as a result of oxidation and evaporation during remelting and this can be prevented by another recycling method. Therefore, the solid-state recycling (SSR) is also investigated by researchers.

In the SSR method, firstly, chips of different sizes are produced. Then, these chips are compacted in order to form dense samples via cold or hot press processes. This recycling method is considered to reduce the energy needed for the conventional recycling as there is no need to reach a high temperature for achieving the melting point of the metal. The SSR can be further categorized in two sub-categories: powder metallurgy (PM) and severe plastic deformation (SPD) [34]. The severe plastic deformation is looked into in this research. The energy consumption required for each of these processes will be discussed in detail in chapter 4.

3.1.2. Properties comparison for aluminium alloys

The main type of aluminium that is investigated in this chapter is the 7075 alloy.

The 7000 series alloy is used in the aerospace industry mainly for its mechanical properties. It has one of the highest strength-to-weight ratios among all the aluminium alloys, while having good performance in static loading conditions. The main tempers in which this alloy is used are the T6 and T73, which provide higher mechanical properties to the material. T6 temper can be achieved by a solution heat treatment step followed by an artificial aging, or the so-called precipitation hardening. In a similar fashion, the T73 temper is achieved. The only difference being that in the case of T73, two precipitation hardening steps are required. The main alloying element of the 7000 series is zinc, while the standard composition of the 7075 alloy is presented in table 3.1.

Table 3.1: Chemical composition of 7075 alloy [35]

Alloy	Zn	Mg	Cu	Cr	Fe	Si	Mn	Ti	Al	Other
7075	5.1-6.1	2.1-2.9	1.2-2.0	0.18-0.3	<0.5	<0.4	<0.3	<0.2	Rest	<0.05

Different studies have been researched in order to get a better understanding on the properties of recycled 7075 aluminium alloy.

Ruhaizat et al showed that during the hot press forging recycling method, the ultimate tensile strength and the elongation at fracture are dependent on the temperature and holding time. The method of producing the samples is by compacting the chips in a hot press forging machine. The variable parameters during this study are the operating temperature, between $380°C$ and $480°C$, and the holding time, which is between 0 min and 120 min [34].

Several properties, such as ultimate tensile strength (UTS), elongation at failure, density, microhardness and grain size, have been analysed. It was revealed that the ultimate tensile strength and elongation at failure increase with the increasing temperature and holding time during compacting phase [34]. This increase was above 90% when the properties are compared at lowest settings and highest settings. At the highest setting of operating temperature and holding time, $480°C$ and 120min, the UTS and ETF show values of 245.62 MPa and 6.91% compared to the 228MPa and 17% which are the standard for this type of material [34].The increase in tensile strength is also related to the reducing in grain size when the maximum settings are applied. Furthermore, the density between the minimum and maximum settings is increased by approximately 40% [34]. This can lead to the conclusion that the higher the temperature and holding time, the less gaps are between the chips and therefore, the material acts more as one unit [34].

Other study of Khajouei - Nezhad et al, presents the results for the same properties, when a different solid-state recycling technique is used. In this research, the chips were compacted via high-pressure torsion (HPT) method [36]. The parameters that were varied were the number of turns during this process, the weight percentage of chips compared to the weight percentage of pure aluminium powder, and the heat treatment applied to the chips prior to compaction. The study revealed the fact that the pure aluminium powder acts as a binder during the consolidation process [36]. This implies that better tensile properties are exhibited by samples that have a certain weight percentage of pure aluminium powder. Similar to the previous research, it is shown that when there is a weaker bond between the chips in the sample, then the tensile strength is lower. During the research of Khajouei - Nezhad et al, the weaker bond happened in the case of 100% weight percentage of not annealed chips. In this case the tensile strength was only 11 MPa, while with heat treating the chips this value increased to 35 MPa [36]. Among the different weight percentages investigated, it is worth mentioning that the best mechanical properties were obtained in the case when 60% weight percentage of heat treated chips are used. In this particular case, the UTS is 349MPa, for 1 turn and 508MPa, for four turns [36].

The aforementioned studies show that the properties of the recycled aluminium can be compared to a certain extent to those of the virgin 7075 alloy in O temper for example. The ultimate tensile strength of the 7075-O is 228MPa which is comparable to the strength obtained in the research of Ruhaizat et al. However, when looking at the elongation at break of the virgin materials, 16% is expected. This is more than 2 times higher than what was experienced in the studies reviewed. One possible reason for this could be related to the compaction level of the chips during the recycling process.

Another idea suggesting this hypothesis is the fact that during the research of Zhou et al. in which the recycled aluminium is obtained via melting, the elongation at break of the recycled material is higher than that of the virgin material. Zhou et al. have investigated the smelting, extrusion and heat treatments of a recycled 7075 aluminium alloy [35]. The scientists have looked into properties such as ultimate tensile strength, composition, and corrosion resistance to salt spray [35]. The tensile strength and yield strength of the recycled 7075-T6 were tested and the results shown values of 558MPa and 487MPa, which are higher than the ASTM standard of 538MPa and 462MPa. The conclusion of the study is that the recycled 7075 aluminium alloy could potentially be a substitute for the virgin material, given the fact that the properties are higher than the ASTM standard for such an alloy [35].

In the above paragraphs, the focus is mainly on the mechanical properties, but another important aspect is the chemical composition of the alloy. It is of paramount importance that when an alloy is recycled, the composition is maintained. Maintaining the chemical composition is easier in the case of SSR; however, in all the reviewed studies, the chemical composition was within the standards presented in table 3.1.

3.2. Carbon fiber reinforced plastic

3.2.1. Selected recycling techniques for carbon fiber reinforced plastic

Multiple recycling technologies are identified in the literature. These technologies are grouped as presented in section 2.2.2 in three categories: mechanical, thermal and chemical recycling technologies. For the purpose of this chapter, one method per group is selected and investigated. Therefore, the following processes are looked into: grinding, pyrolisis and chemical recycling. A thorough description of them is given further.

Grinding composite materials is a mechanical process and is considered the most cost-effective method. High-speed milling machines are used to reduce composite parts to small sizes. The resulting fragments are commonly used as fillers or reinforcements in new composite materials [37]. However, because it is nearly impossible to recycle individual fibers in this process, comparisons in mechanical properties are typically made at the composite level [38]. One major advantage of this recycling method is that both the resin and fibers can be recovered, and no hazardous materials are produced during the recycling process [38]. Nevertheless, there is a significant degradation of mechanical properties compared to the virgin counterparts, as it will be illustrated in the subsequent section.

Pyrolisis is part of the thermal processes and it is the recycling process in which the decomposition of the organic material takes place at high temperature and in an oxygen-deficit environment [39]. In general, this process is using either an inert gas environment, such as N_2 or it takes place in vacuum [39]. The CFRP is heated up to temperatures ranging from 450°C up to 700°C, and the resin is therefore volatilised into lower-weight molecules, while preserving the fibers intact [38]. According to a study made by Pimenta et al., this is one of the only recycling processes that is used on a commerical scale [38]. The main advantage of this type of process is that the mechanical properties of the fibers are retained to a high percentage [38]. However, this comes at the cost that there might be some char deposited on the fiber surface and that potentially hazardous gasses are emitted in the environment [38].

Chemical recycling processes are based on reactive mediums, such as catalytic solutions or benzyl alcohol. This type of processes take place under temperatures below 350°C [38]. Similar to the pyrolysis, the matrix is the decomposed, but this time in large oligomers, while the carbon fibers remain intact [38]. According to studies, the chemical recycling technologies prove to be the ones where the highest retention of mechanical properties and fiber length takes place [38]. However, the use of chemicals, such as acids, bases and solvents, may have potential environmental impact when employing this method and may also result in reduced adhesion to polymeric resins [37].

3.2.2. Properties comparison for carbon fiber reinforced plastic

The selected material for investigation is carbon-fiber reinforced plastic including both types of resins: thermoplastic and thermoset. Selection for this specific type of fibers is related to the distribution of fibers in airplane structures which is the highest in case of carbon fibers.

The properties investigated are surface quality of the recycled fibers and mechanical properties, such as tensile strength of the fiber. The surface of the fibers is an essential property because it dictates the bonding quality between the fibers and the resin, which consequently has an effect on the stress transfer between the two and further, increases the mechanical properties.

Pyrolisis can be used for both thermoset and thermoplastic materials as illustrated in the studies researched. In their work, Fernandez et al. investigated the properties of commercially available recycled carbon fibers when used in combination with thermoplastic polymer [40]. Interesting results were obtained from the surface analysis of the fibers. In their work, the researchers used a scanning electron microscope which showed that the surface of the fibers is clear from any resin as a result of the pyrolysis recycling process [40]. However, certain residues that still exist on the fiber are attributed to the pyrolytic carbon [40]. A layer of pyrolytic carbon forms as a result of polymer degradation in non-oxidized atmosphere and it may become fragmented in an oxidized atmosphere [41]. Similar results in terms of surface analysis are presented also by Giorgini et al. in their work. The group of scientists observed a correlation between the process temperature and the level of cleanliness of fibers [42]. The higher the process temperature, the higher the number of residues present on the surface of the fibers. The correlation between the temperature of the pyrolysis process and surface quality is also discovered by Yatim et al. They investigated the separation of CF from the epoxy resin in a prepreg material. Besides the relation between the temperature and surface quality, another correlation between the atmosphere in which the process takes place and the quality is observed [43]. In their work, they compared the surface quality between fibers, which were processed in nitrogen atmosphere and in a combined atmosphere of nitrogen and oxygen [43]. It was observed that the separation between the fibers and the matrix is higher in the case of combined atmosphere, which can potentially be linked to the two step degradation process which takes place if there are two inert gases [43]. This is illustrated in figure 3.1.

Generally speaking, it is observed in the literature that the mechanical properties of the recycled fiber could potentially have comparable values with the virgin counterparts when pyrolysis or chemical treatments are used as recycling methods. Pimenta et al. have summarized the research available on different recycling techniques [38]. It is noted in their work, that the tensile strength in the 0 direction of the recycled fiber varies depending on the processing technique and fiber type. For example, it is measured that the tensile strength can be 2% higher in the case of recycled Hexcel AS4 via pyrolysis process than in the case of the virgin fibers. However, for the same processing technique, the strength can be reduced by 20% for the Grafil 34-700 fiber [38]. In this paper, there are also values presented for recycled carbon fibers via chemical techniques. However, in this case the tensile strength of fibers is lower with 9% for the Hexcel AS4 [38]. Thus, it was shown through this paper that the tensile strength of the fibers can be either not affected or reduced to up to 85%, depending on the processing conditions and on the fiber type [38].

However, mechanical recycling of composites leads to the fibres to have properties that allow them to be used mainly as filler [44]. Carbon fiber reinforced PEEK was the subject of a study

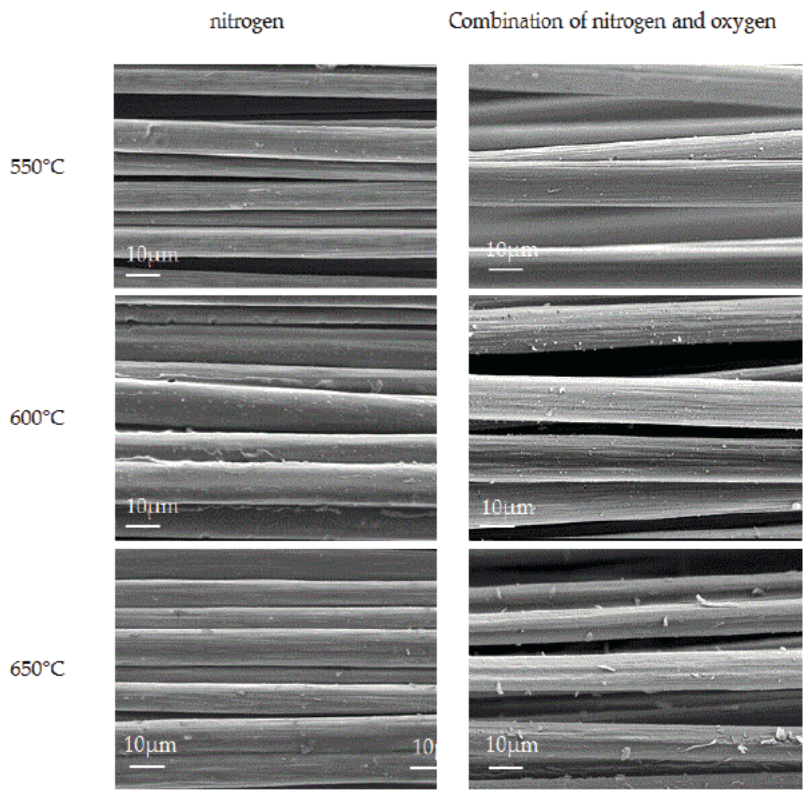

Figure 3.1: Recycled CF after pyrolysis at different atmosphere and heating temperature [43]

made by Schinner et al. in which different milling tool types were investigated. This led to the conclusion that cutting milling tools were better for obtaining a stable fibre length distribution but at the cost of the mills being worn faster. The recycled material was later on incorporated successfully via injection molding into virgin resin [44]. Yet, the incorporation of grounded thermoset material is still a challenge as the bonding between the recyclates and new resin is poor [44].

3.3. Conclusion

Summing up the information researched and providing an answer to the first research subquestion, it can be concluded that while usage of recycled materials is not prohibited in the aircraft structures, it might be relatively difficult to achieve in the case of composite materials. In the case of aluminium recycling, the recycling processing is more straight forward and the option of conventional recycling always gives alloys within the specifications, which is not completely true for the carbon fiber reinforced plastic. In this case, there is no one-method fits all. It is discovered and researched that all processing conditions, fiber type and recycling techniques influence the output performance of the fibers. Thus, the more difficult route towards implementation of recycled composites within aircraft structures.

4 Life cycle assessment

This section intends to answer the second sub-research question as indicated in chapter 1.

Manufacturing of materials is known to be an energy intensive process. Depending on the material, the requirements in terms of energy consumption, CO_2 emissions and material availability are varying. For this reason, in order to assess the environmental impact of several materials, the life cycle assessment methodology is used.

Life cycle assessment is a tool used to assess the environmental impact of a product thoughout its lifecycle.

The stages of a LCA are presented below:

1. **Goal and scope definition.** In this stage, the relevant elements which are required for the analysis are presented. In this step, the functional unit is defined along with the boundaries of the analysis [45]. Based on this stage, two different types of methods for LCA exist: the attributional and consequential LCA [46]. The first type is characterized by its emphasis on detailing the environmentally relevant physical flows to and from a life cycle. In contrast, the purpose of a consequential LCA is to present how these environmentally relevant flows change as a result of certain decisions [46].
2. **Inventory analysis.** During this stage, the data related to the processes involved in the analysis is gathered. This data should reflect the elements stated in the first stage of the LCA. Based on the source of the data, it can be divided into either primary or secondary data. The primary source of data is related to data that is gathered in real time during a process, while the secondary data includes data gathered from databases [45].
3. **Impact assessment.** The environmental inputs and outputs are evaluated in this stage. The impact categories are analyzed and they can include: global warming potential (GWP), acidification potential or resource depletion.
4. **Interpretation of results.** This stage represents a last check of the procedure and the results against the scope and boundaries defined in the first step of the LCA. It may also include a sensitivity analysis, in which the effect of varying a certain input is identified [45].

As in the previous chapter, the present chapter is also divided in two sections: one dealing with aluminium alloys and one with CFRP.

4.1. Aluminium alloys

4.1.1. Scenarios

The present section presents three scenarios that are investigated during the LCA study of aluminium. The first assumption is that production waste is not taken into consideration in any scenario. Using each scenario, the stakeholders can explore potential environmental impacts. The three recycling techniques investigated are: remelting with downgrading of properties and further usage for other application, remelting with upgrading the properties and further usage for same application and solid-state recycling with downgrading and further usage for other application. The scenarios are presented in figure 4.1 up and including figure 4.3. Another assumption is that only one recycling cycle is considered. The transport between the sites where different activities are performed is kept out of the analysis, leading to the third assumption.

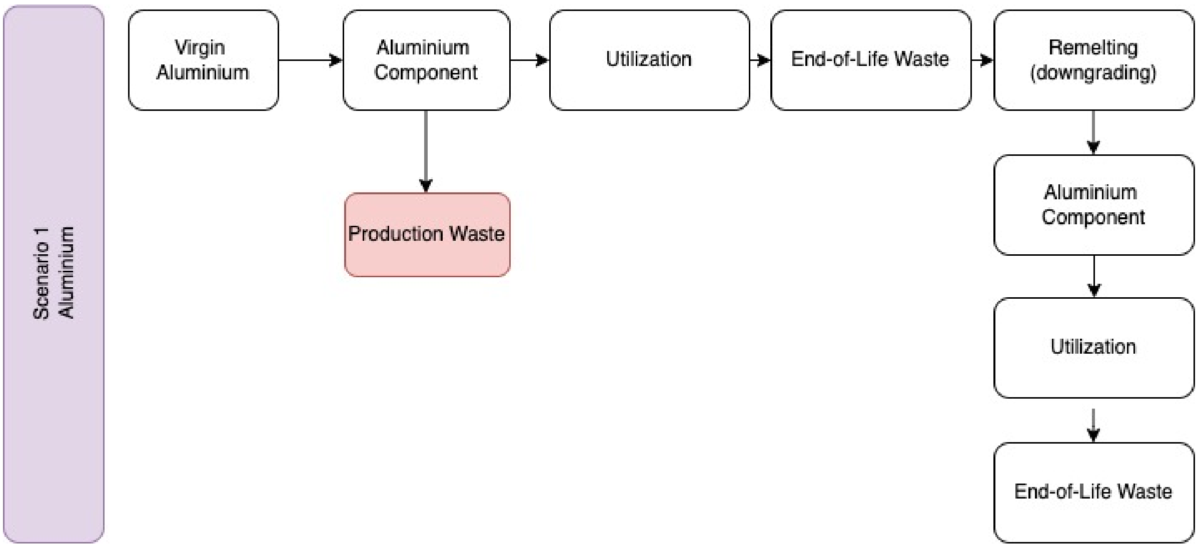

Figure 4.1: Scenario 1 for LCA of Aluminium

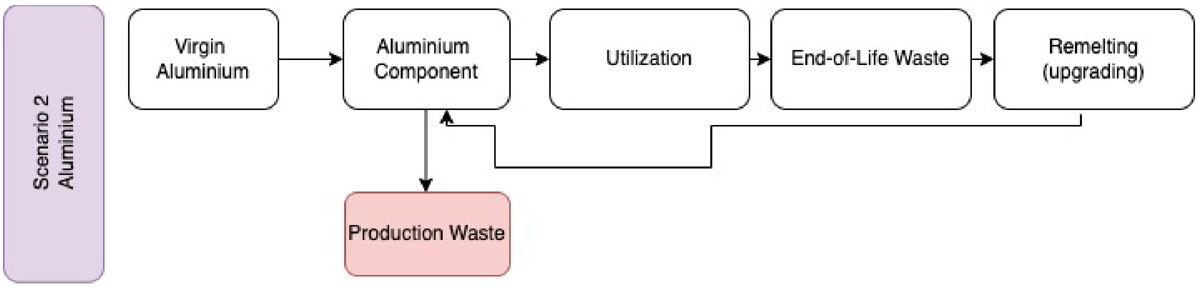

Figure 4.2: Scenario 2 for LCA of Aluminium

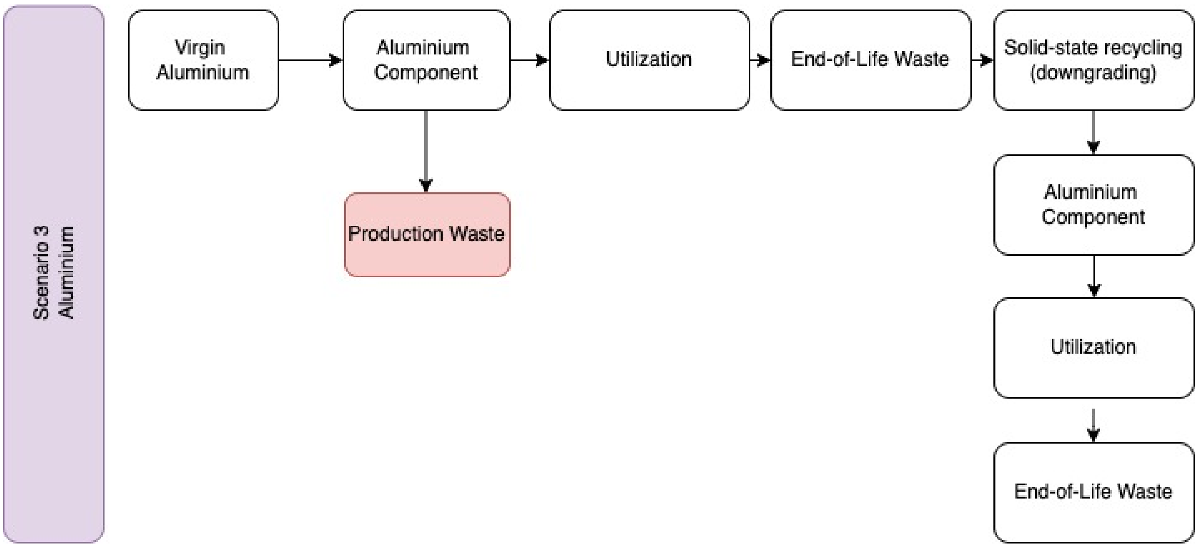

Figure 4.3: Scenario 3 for LCA of Aluminium

4.1.2. Data collection

This section deals with data collection used for the LCA. The data presented in this section is general and applicable for one kilogram of aluminium. In the upcoming sections, this data is to be applied for one fuselage panel which will act as functional unit. Taking into account the previous division of data type, the data collected and used in this section is considered to be secondary data and it is collected from databases such as that of EduPack, as well as other sources such as articles, websites.

Virgin aluminium

As previously mentioned in section 2.1.1, the aluminium is produced from bauxite, which is refined into alumina and then smelted into pure aluminium. The pure aluminium is further mixed with other components to form the alloys used in engineering applications.

The energy consumption per individual step was difficult to find, therefore CES EduPack software package is used for obtaining the data. In this software, the entire process of obtaining the specific alloy is combined into one data entry, referred to as Embodied Energy for Primary Production. This is the energy required to make 1 kg of the target material from its ores. One important note for this data point is that the values appear as a range, which leads to another assumption of this LCA: If a range of data is given, the value that leads to the most conservative study is used. This can be either the largest value of the range or the lowest values, depending on the properties discussed. This value is used in order to obtain the largest values for the energy and CO_2 emitted. Another important aspect about the embodied energy presented in the EduPack software is that there is already a difference made between the production of virgin grade material and typical grade material. The virgin grade material refers to the fact that there is 0% recycled content in the material, therefore, the entire 1 kg of aluminium is produced from new extracted bauxite. Opposite, the typical grade values consider the recycling fraction in the current supply chain. As it is presented that approximately 75% of the aluminium produced in the 1800's is still in the market, it is evident that the current aluminium has a certain percentage of recycled aluminium content which is mixed to the virgin aluminium. However, for this section, the virgin grade value is used.

Besides the energy embodied, the carbon footprint is important to investigate. The carbon footprint is calculated based on the embodied energy and a conversion factor as presented in equation (4.1). The conversion factor depends on the electricity mix. The electricity mix varies per country, depending on the sources of energy. Because the production steps can take place in various countries, it is decided to use the electricity mix of Europe and, therefore, use the associated conversion factor. This conversion factor is 0.114 kg/MJ.

$$\text{CO}_2\ \text{Equivalent} = \text{Embodied Energy} \times \text{Conversion Factor} \tag{4.1}$$

The values used in subsequent chapters for the virgin aluminium production are presented in table 4.1.

Table 4.1: Embodied energy and CO_2 equivalent for primary production

Description	Embodied energy	Unit	CO_2 equivalent	Unit
Virgin aluminium	176	MJ/kg	20.07	kg/kg

Component manufacturing - first life cycle

The aluminium component which is investigated is manufactured using the stretch forming operation. The operation consists in the aluminium sheet being clamped and stretched over a form to result in double curved component. Life-cycle inventory data indicate that stretch forming typically consumes on the order of 3.95 kWh/kg of aluminum formed [47]. This is equivalent to roughly 14 MJ/kg for the stretch forming operation. In same manner as previously, a conversion factor of 0.114 kg/MJ is applied for obtaining the CO_2 equivalent.

Pre and post processing steps include in many occasions, heat treatment of the alloy and surface treatment of the component, prior to paint application. The energy consumed per component for these treatments is typically estimated at around 10–20%, since ovens for heat treatment and baths for surface finishing are operated for multiple components simultaneously, thereby lowering the burden allocated to each individual part. However, for the purpose of this study, these processing steps are not taken into account.

Table 4.2: Embodied energy and CO_2 equivalent for component manufacturing

Description	Embodied energy	Unit	CO_2 equivalent	Unit
Component manufacturing	14	MJ/kg	1.6	kg/kg

Component manufacturing - second life cycle

Scenario 1 involves recycling of aluminium through remelting with downgrading properties. In this case the component that can be produced is typically a non-structural component. Typical non-structural components are fairings. Fairings are components typically used to improve appearance and reduce drag in aircraft. For its production, either stretch forming or bending processes are used and for this report, the press brake bending manufacturing process is investigated.

CNC press brake bending is not an energy-intensive process as it consumes on the order of 0.2–0.3 MJ of electrical energy per kg of aluminium bent. Taking into account the fourth assumption, the value 0.3 MJ is used further for the analysis. Using the conversion factor of

0.114KJ/kg, this implies a values of 0.0342 kg/kg of CO_2 equivalent.

For scenario 2 in which the recycling follows a closed-loop flow, the same manufacturing technique as in the first life cycle is used. Thus, same values as in table 4.2 can be used.

For scenario 3, the component manufacturing energy is included in the recycling step and will be discussed in the subsequent sections.

Similar as in previous case, pre and post processing steps are not included in the analysis.

Table 4.3: Embodied energy and CO_2 equivalent for component manufacturing - second life cycle

Description	Embodied energy	Unit	CO_2 equivalent	Unit
Component manufacturing - second life cycle scenario 1	0.3	MJ/kg	0.0342	kg/kg

Utilization - first life cycle

For the first life cycle, the part under investigation is utilized in an aircraft. Therefore, the energy required during the utilization step is related to the amount of energy needed to carry a kilogram of material over a distance of one kilometer. According to Stefanidi, this energy is 1.72 kJ/(kg*km) [45]. The conversion factor in this case is not related to the electricity mix, but to the fuel used. Therefore, the conversion factor for the utilization phase is 0.072 kg/kg [45].

Table 4.4: Embodied energy and CO_2 equivalent for utilization phase

Description	Embodied energy	Unit	CO_2 equivalent	Unit
Utilization	0.00172	MJ/(kg*km)	0.00012384	kg/(kg*km)

Utilization - second life cycle

The second utilization phase of the material depends on whether or not the material is downgraded. For the upgrading path illustrated in Scenario 2, the same utilization as first life cycle can be used. However, when the material is downgraded, it can be used either in other fields such as packaging or still be used in aerospace industry but for non-structural components. For the purpose of this study, the utilization phase of the second life cycle will still be for aerospace industry but for non-structural component. Thus same information as in table 4.4 can be used.

End-of-Life preparation

The end-of-life preparation phase consists of different activities to make the components ready for recycling. These activities include dismantling, sorting, and stripping organic and inorganic layers. There are multiple strategies for dismantling an aircraft, each of them leading to different scenarios. As there is no information found on the specific energy consumption of this phase, it is decided to neglect these activities. This leads to another assumption: dismantling, sorting and stripping of layers is out-of-the-scope of this study.

Remelting

Recycling by remelting is typically constrained by scrap quality and the alloy composition. Upon remelting, there are two main pathways: downgrading (down-cycling) and upgrading (up-cycling), described below. These affect how the scrap can be reused and whether its original alloy performance is fully recovered. Typically, upgrading the remelt is done by diluting primary aluminium in the product.

Remelting with downgrading implies that aluminium scrap is recycled into alloys of lower grade than the original grade. For example, high-purity wrought alloy scrap might be remelted and used in secondary cast alloys that tolerate higher impurity levels. This is a practical solution to consume mixed scrap, but over time it leads to an accumulation of undesirable elements (like iron) in the recycled pool. Even though, down-cycling maintains the low energy and CO_2 profile of recycling, the material value is somewhat reduced as the metal may end up in products that cannot exploit the original high properties of aerospace-grade aluminium. The LCA per kg is reported to be in the range of approximately 10–18 MJ/kg and approximately 0.6–0.8 kg CO_2/kg [48]. Thus, for conservative study, the value of 18 MJ/kg is used, and, for consistency, the CO_2 equivalent is calculated as in previous sections using the conversion factor of 0.114kg/MJ.

Remelting with upgrading aims to maintain or improve the alloy quality of the recycled aluminium so it can replace primary metal in high-performance uses. Upgrading scrap typically involves diluting or alloying with some primary aluminium to adjust chemistry [48]. Such “closed-loop” recycling can avoid the continual build-up of impurities. The trade-off is potentially slightly higher energy or material input (e.g. extra processing steps for scrap cleaning/refining, and addition of some primary aluminum for dilution). In the work of Ruhaizat et al. it is stated, that by adding the primary aluminium in the mixture, the embodied energy of the recycled aluminium could potentially be increased with up to 30 MJ/kg [34]. This value can be dependent on the amount of pure aluminium required for dilution, however for the purpose of this study, the value of 30 MJ/kg is added to the 18 MJ/kg required for downgrading aluminium, resulting in a value of 48 MJ/kg of energy consumed for this stage.

Table 4.5: Energy embodied and CO_2 equivalent for remelting

Description	Embodied energy	Unit	CO_2 equivalent	Unit
Remelting aluminium (upgrading)	48	MJ/kg	5.5	kg/kg
Remelting aluminium (downgrading)	18	MJ/kg	2.05	kg/kg

Solid-state recycling

Solid-state recycling does not require the metal to reach its melting point. Therefore, this method is believed to be potentially more energy efficient than conventional recycling by remelting. In this case, the main machines that require energy to recycle the aluminium are milling machines, press machines, and potentially ovens for heat treatment of the alloy to a desired temper.

Recent studies report that this method may use only 10 MJ/kg [49]. Using the same conversion factor as before, this implies a value of 1.14 CO_2 equivalent.

Table 4.6: Embodied energy and CO_2 equivalent for solid-state recycling

Description	Embodied energy	Unit	CO_2 equivalent	Unit
Solid-state recycling	10	MJ/kg	1.14	kg/kg

Summary of values

Table 4.7 presents the summary of values for 1kg of target aluminium material. These values are to be used for the further analysis.

Table 4.7: Summary of values to be used for aluminium analysis

Description	Embodied energy	Unit	CO_2 equivalent	Unit
Virgin aluminium	176	MJ/kg	20.07	kg/kg
Component manufacturing - first cycle	14	MJ/kg	1.6	kg/kg
Component manufacturing - second cycle S1	0.3	MJ/kg	0.0342	kg/kg
Utilization	0.00172	MJ/(kg*km)	0.00012384	kg/(kg*km)
Remelting (upgrading)	48	MJ/kg	5.5	kg/kg
Remelting (downgrading)	18	MJ/kg	2.05	kg/kg
Solid-state recycling	10	MJ/kg	1.14	kg/kg

4.1.3. Goal and system boundary of the study

To illustrate the differences between the scenarios presented in section 4.1.1, a typical aircraft fuselage skin panel is considered as the functional unit. A representative aluminium panel is used in a single-aisle passenger aircraft (e.g. an Airbus A320 or Boeing 737). Dimensions vary, but for a rough estimate, a panel of about 2 m by 2 m area, with a thickness of around 1.5–2.0 mm is to be investigated. These values are assumed based on experience and online research. This corresponds to an area of 4 m^2. At 2 mm thickness, 4 m^2 of aluminium equates to a volume of 0.008 m^3. Given aluminium's density (2700 kg/m^3), the panel's mass would be approximately 21.6 kg, which, for convenience, will be rounded to 22 kg.

Table 4.8 illustrates the summary of the dimensions used for the fuselage analysis.

Table 4.8: Dimensions fuselage to be investigated

Length [m]	Width [m]	Thickness [mm]	Area [m^2]	Volume [m^3]	Mass [kg]
2	2	2	4	0.008	22

4.1.4. Inventory analysis

In this section, all energy inputs and associated CO_2 emissions for each life-cycle stage of the 22 kg aluminium fuselage panel are compiled. Table 4.9 summarises the key data for each stage when scaled for a 22kg component. These values are drawn from CES EduPack data and literature sources as noted in section 4.1.2.

Note that for the utilization phase, a typical aircraft is designed for 25 years and by translation this would imply an amount of approximately 84 million miles flown, which is equivalent to approximately 135 million km flown and thus, this is used in the analysis below.

Table 4.9: Values used for a 22kg fuselage panel

Description	Energy used	Unit	CO_2 equivalent	Unit
Virgin aluminium	3872	MJ	441.54	kg
Component manufacturing - first cycle	308	MJ	35.2	kg
Component manufacturing - scenario 1	6.6	MJ	0.7524	kg
Utilization (first and second cycle)	3179e3	MJ	229e3	kg
Remelting (upgrading)	1056	MJ	121	kg
Remelting (downgrading)	396	MJ	45.1	kg
Solid-state recycling	220	MJ	25.08	kg

4.1.5. Impact assessment

In the following section, the energy use and greenhouse gas emissions are aggregated across all life-cycle stages to quantify the panel's total environmental impact as per scenarios described in section 4.1.1. However, as it can be seen in table 4.9, utilization phase is the most predominant energy consuming and emits the most greenhouse gases. Thus, it will be excluded from the next analysis in order to get a better overview on how the recycling activities of structures and materials influence the energy consumption. The total primary energy demand is calculated in MJ and the total CO_2 emissions in kg. The Global Warming Potential (GWP) is the focus as this is dominated by the CO_2 emissions.

For convenience, the scenarios are re-discussed here. **Scenario 1** includes the route where at the EOL of the aircraft, the fuselage panel is remelted with a downgrading in the grade-quality and further used for non-structural components in aerospace industry. **Scenario 2** includes the route where at the EOL of the aircraft, the fuselage panel is remelted with a upgrading in the grade-quality and further used for similar applications. The last, **scenario 3**, includes the route of solid-state recycling where the fuselage panel would be recycled and further used for non-structural components in aerospace industry.

Scenario 1

Using primary aluminium for production, stretch forming as manufacturing process of the component utilized in the first life cycle, bending for second life cycle and remelting the panel for downgraded recycling between the cycles, the total life-cycle energy comes to 4582.6MJ. This is equivalent to 522.2kg of CO_2 emitted.

Figure 4.4 presents the a visual illustration of the energy required per life cycle phase, while figure 4.5 illustrates the CO_2 emissions. The values for each phase in the two graphs are proportional by the conversion factor used. Therefore, for the further scenarios, only the graph representing the energy usage will be provided. Among all categories, the most dominant in this scenario is the production of the primary aluminium. This accounts for approximately 84% of the total energy consumed during the life cycle of the fuselage panel (taking into account the assumptions). The next category is the remelting by downgrading the grade-quality. This is approximately 8.6% of the total energy and 10.2% of the primary production of aluminium. Thus, an advantage of using recycled aluminium, where possible, can be already indicated. Manufacturing in total accounts for 6.8% of the total energy required throughout the two life cycles. However, taking into account that pre- and post-processing activities were not part of the study, this value is expected to be slightly higher.

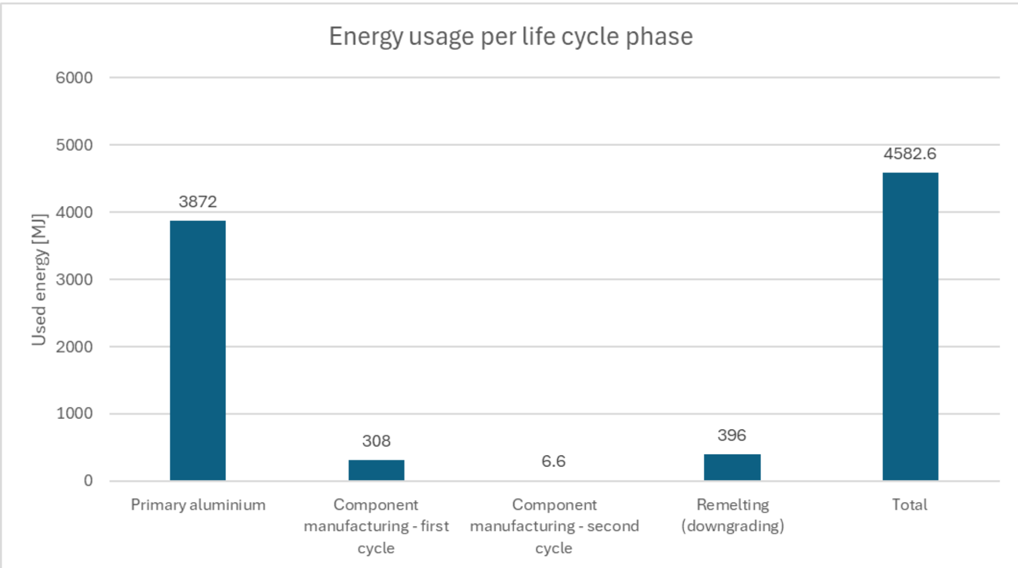

Figure 4.4: Energy consumption vs phase for scenario 1

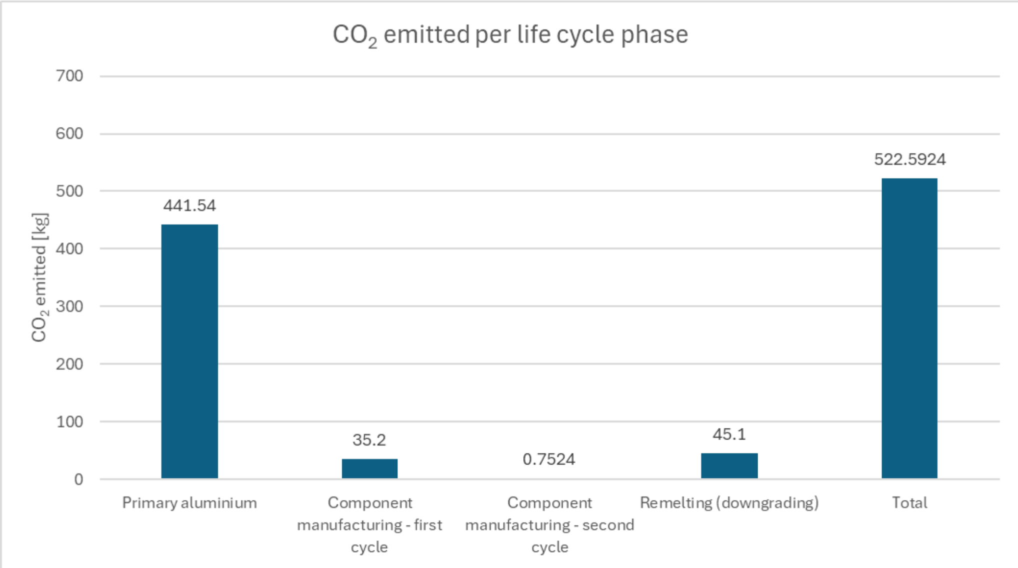

Figure 4.5: CO_2 emitted vs phase for scenario 1

Scenario 2
As the component can be used for the same application, in this scenario, the energy required for the component manufacturing via stretching forming process is doubled and added to the primary and secondary aluminium production via remelting with upcycling. This results in 5544MJ of energy necessary, which is equivalent to 632kg of CO_2.

Similar to previous case, the primary production of aluminium accounts for the most energy consumed as illustrated in figure 4.6. However, in this case the percentage is lower (approximately 69%) as upcycling the remelt adds additional energy compared to Scenario 1. Based on the data, the energy required for recycling the 22kg of aluminium with upcycling the grade-quality is equivalent to approximately a third of producing this quantity from primary aluminium. Thus, taking into account that the usage can be the same as in the case of primary aluminium, remelting in a closed-loop scenario looks promising in terms of energy reduction, while maintaining the same properties.

Scenario 3
The amount of energy required for the solid-state recycling stated in table 4.9 accounts for the energy used for the component manufacturing, thus the total amount of energy consumed in this scenario is 4400MJ. This is equivalent to 501.6kg of CO_2 emitted.

In Scenario 3, the energy required for component manufacturing for the second life cycle is assumed to be implemented in the energy needed for the solid-state recycling. The chart in figure 4.7 reveals a clear dominance of the primary aluminium production relative to the total energy required, with a percentage of more than 85%. The component manufacturing for the first life cycle and the recycling of it are relatively similar in terms of energy consumption, accounting each for less than 10% of the total amount.

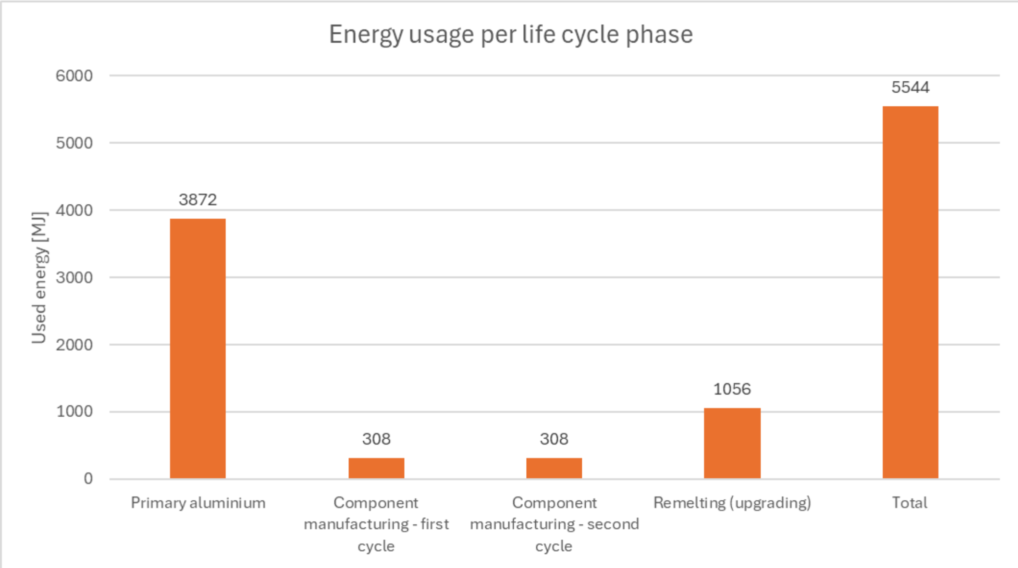

Figure 4.6: Energy consumption vs phase for scenario 2

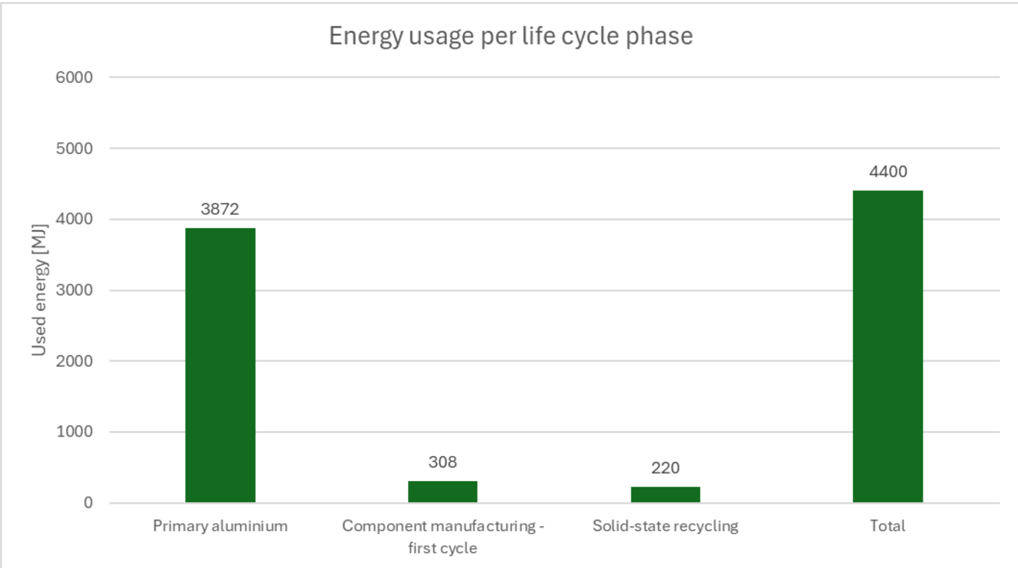

Figure 4.7: Energy consumption vs phase for scenario 3

4.1.6. Discussion

In figure 4.8 the overall values for the energy consumption is illustrated per scenario.

In all three scenarios, the most predominant component is the production of the primary aluminium, which accounts for more than 60% of the total energy consumption in each case. Even though scenario 2 might potentially look to have a higher energy required for two life cycles, it is important to note that this is the only scenario in which a closed-loop recycling methodology is applied. Although EOL processing is a small fraction of the life-cycle impact, it is still important from a resource sustainability perspective and for incremental improvements in energy efficiency. The analysis shows that Scenario 3 offers the most sustainable outcome in terms of immediate energy and emissions as it uses the least energy (220MJ vs. 396MJ in Scenario 1 and 1056MJ in Scenario 2). In percentage terms, solid-state recycling can reduce recycling-stage energy demand by 40%–55% compared to remelting. This is because no high-temperature phase change is needed as processes like chip formation, compaction and extrusion are far more efficient. Moreover, avoiding re-melting means about 95% energy savings relative to primary production, aligning with literature that recycled aluminum takes only approximately 5% of the energy of virgin metal.

Even though the CO_2 emissions are proportional to the energy consumed by the conversion factor. As previously stated, the conversion factor is related to the energy mix of the country. Thus, if 100% green energy were used, taking into account only the emissions generated without considering the production of the energy plants themselves, the conversion factor would approach 0, thus significantly lowering the emissions. Conversely, if the energy mix were to consist only of fossil fuels, the conversion factor would increase, and consequently, the greenhouse gas emissions would also rise.

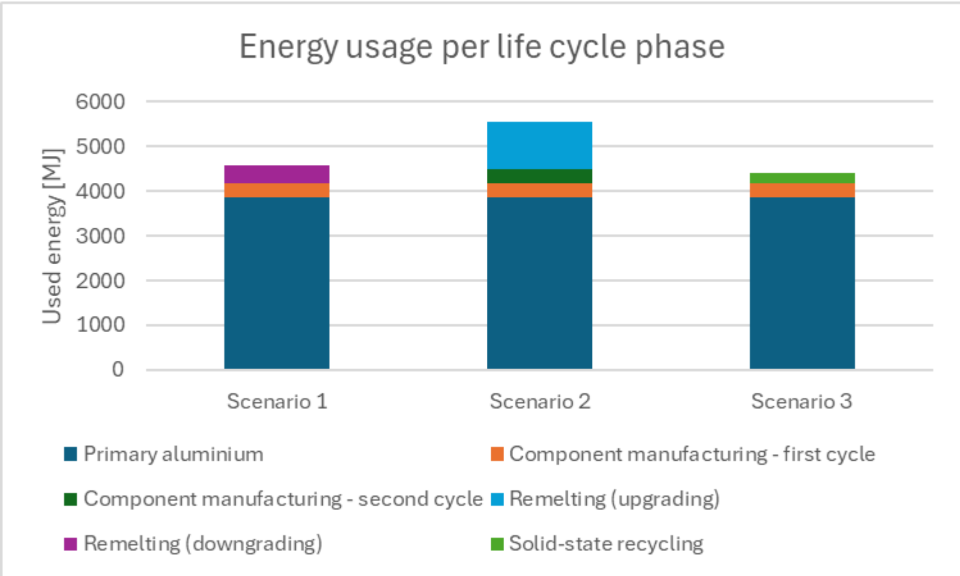

Figure 4.8: Total energy consumption per scenario

4.1.7. Assumptions summary

This section presents a summary of all the assumptions used during the LCA.

1. **Production waste is not taken into consideration.** As the stretch forming process is the manufacturing process for the first cycle, it is expected that the production waste is relatively low, in terms of 5% of the raw dimension of the sheet.
2. **Only one recycling cycle is considered.** However, in the case of aluminium alloys, the recycling can theoretically take place for an unlimited number of times.
3. **Transport between sites is not considered.**
4. **If a range of data is given, the value that leads to the most conservative study is used.** This can be either the largest value of the range or the lowest values, depending on the properties discussed.
5. **Processing steps such as heat treatment, surface treatment, painting are out-of-the-scope of this study.** As previously stated, this is expected to account for approximately 10-20%.

6. **Dismantling, sorting and stripping of layers during recycling phase is out of the scope of this study.**

4.2. Carbon fiber reinforced plastic

4.2.1. Scenarios

Similar to the case of aluminium, different scenarios are used for the carbon fiber case. There are six different scenarios based on different resin types (thermoplastic or thermoset) and based on different EoL strategies. The EoL strategies investigated are: landfilling, mechanical shredding with downgrading of fibers and further usage in different applications, pyrolysis with downgrading of fibers and further usage in different applications and remelting with downgrading of fibers and further usage in different applications. The scenarios are presented in figure 4.12 up to and including figure 4.14. Some of the assumptions used for the analysis of aluminium are also used in the case of CFRP analysis. For convenience, they are repeated here: only one recycling cycle is considered and the transport between production sites is not considered.

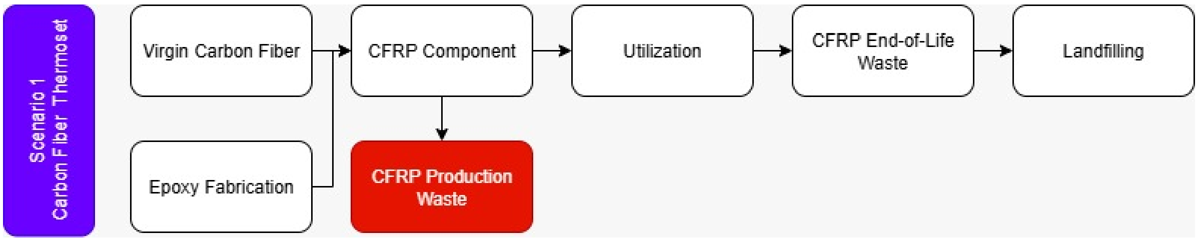

Figure 4.9: Scenario 1 for LCA of CFRP (thermoset)

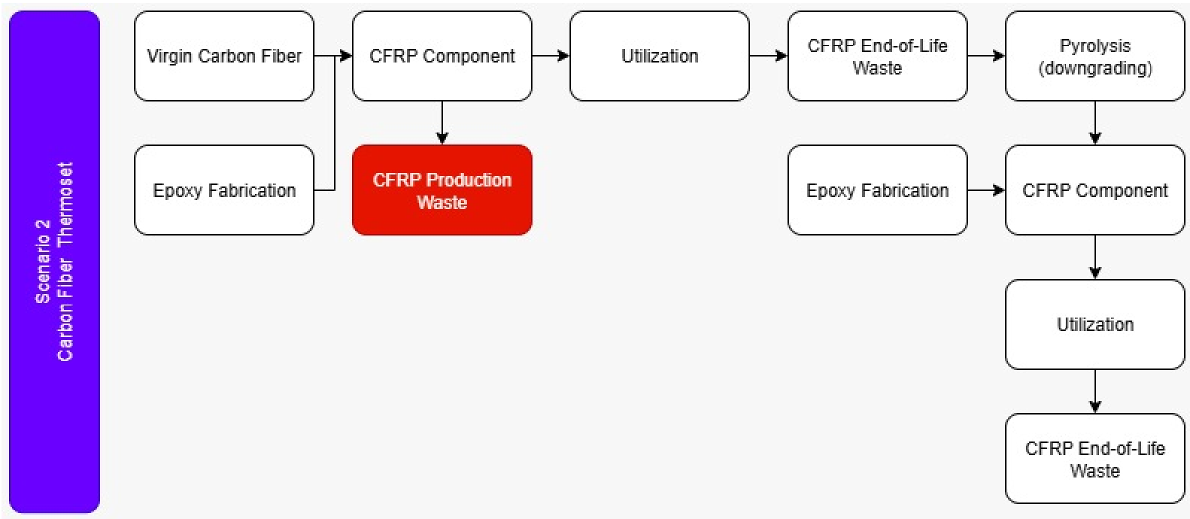

Figure 4.10: Scenario 2 for LCA of CFRP (thermoset)

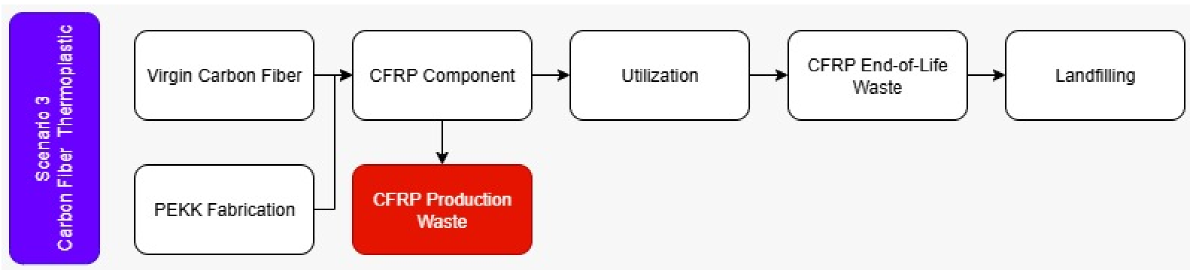

Figure 4.11: Scenario 3 for LCA of CFRP (thermoplastic)

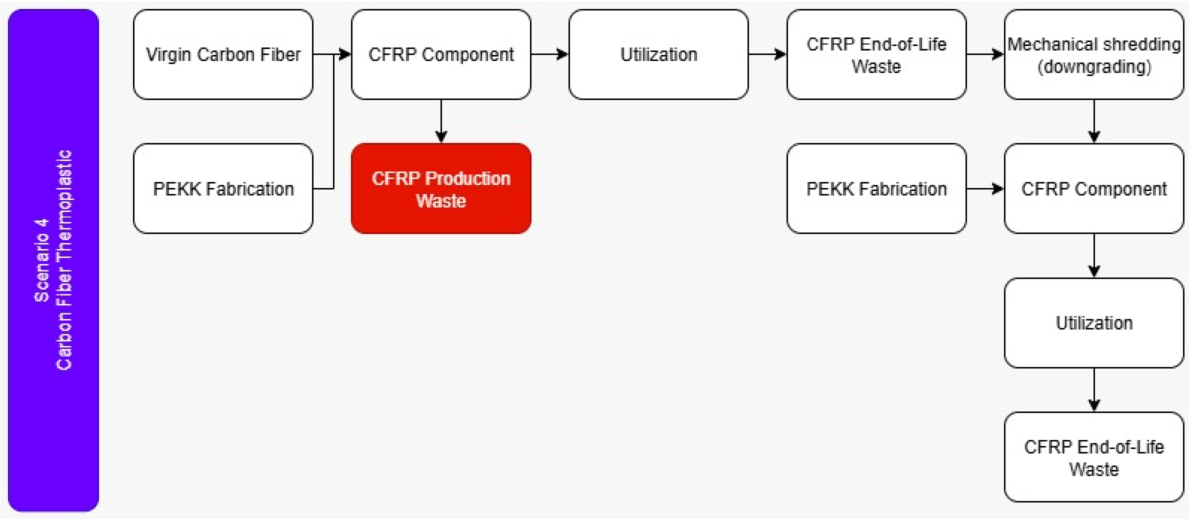

Figure 4.12: Scenario 4 for LCA of CFRP (thermoplastic)

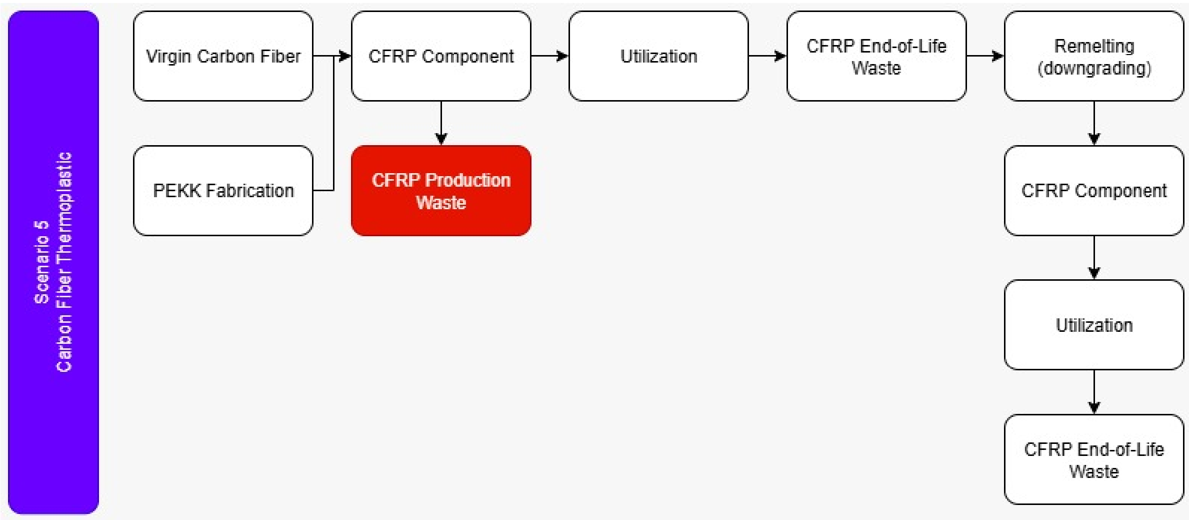

Figure 4.13: Scenario 5 for LCA of CFRP (thermoplastic)

4.2.2. Data collection

LCI data for this study was obtained from various literature sources. Different articles related to LCA of carbon fiber material have been investigated. One of the assumptions as in the case of aluminium is that if a range or multiple values are given, then the value which gives a conservative study is used. The same conversion factors as in the case of aluminium are used: 0.114 kg/MJ for the processes utilizing the electricity provided by the electricity grid of Europe and 0.072 kg/MJ for the utilization phase of the first life cycle.

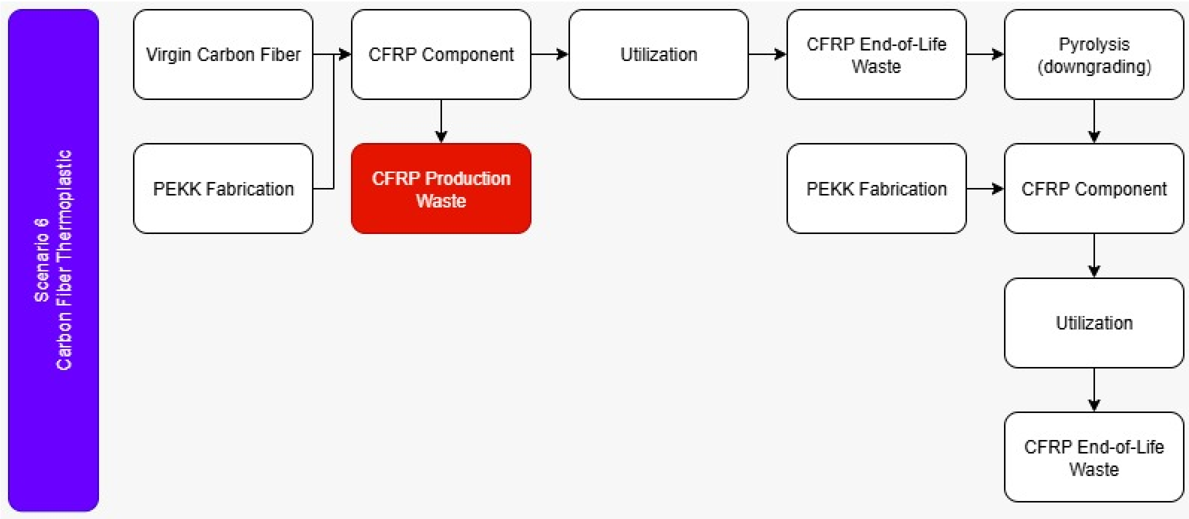

Figure 4.14: Scenario 6 for LCA of CFRP (thermoplastic)

Virgin carbon fiber

Production of virgin carbon fibers is considered to be an energy-intensive process. However, for this process, there is no common agreement of values describing the energy consumption. More than 5 values or ranges have been identified in literature. The highest one identified by Tapper et al. is 771 MJ/kg in one of the European databases [50]. Yet, for the purpose of this study, a derogation from the assumption of most conservative study if applied, and a value of 286 MJ/kg as the one identified in the work of Howarth et al. is used [51]. This is used as it is observed to be an average value and thus, it would be relevant for a typical fiber type.

The values presented above are mostly used for the production of dry carbon fibers. However, prepreg carbon fiber is mostly utilized in industry. Therefore, the embodied energy for making fabrics and later on, prepregs is also considered in this study. This value is taken out of the EduPack database and it is 2.73 MJ/kg , respectively 42 MJ/kg.

Table 4.10: Embodied energy and CO_2 equivalent for virgin carbon fiber

Description	Embodied energy	Unit	CO_2 equivalent	Unit
Virgin carbon fiber	286	MJ/kg	32.61	kg/kg
Fabrics	2.73	MJ/kg	0.31	kg/kg
Prepreg	42	MJ/kg	4.79	kg/kg

Epoxy resin

For production of epoxy resin, the data from EduPack is used. This data is presented in table 4.11, using a conversion factor of 0.114 kg/MJ.

Table 4.11: Embodied energy and CO_2 equivalent for epoxy resin

Description	Embodied energy	Unit	CO_2 equivalent	Unit
Epoxy resin	135	MJ/kg	15.39	kg/kg

PEKK resin

Similarly, the embodied energy for the PEKK resin is taken from the EduPack database. This embodied energy is considered to be 333 MJ/kg, and using a conversion factor of 0.114 kg/MJ, the CO_2 equivalent value is 37.97 kg/kg.

Table 4.12: Embodied energy and CO_2 equivalent for PEKK resin

Description	Embodied energy	Unit	CO_2 equivalent	Unit
PEKK resin	333	MJ/kg	37.97	kg/kg

CFRP component (thermoset)

The manufacturing process selected for the thermoset component is the resin transfer moulding process. In RTM, dry carbon fiber preforms are placed in a closed heated mold and resin is injected under pressure to impregnate the fibers, followed by curing. This process avoids the need for a high-pressure autoclave, but still requires energy for heating the mold and maintaining vacuum/pressure. Reported specific energy consumption for liquid composite molding processes, such as RTM varies widely, from about 15 MJ/kg up to 100 MJ/kg of composite, depending on factors such as mold heating, injection pressure, and part size and complexity [52]. For conservative reasons, a value of 100 MJ/kg of composite for the RTM process is used. Using the European electricity mix, this corresponds to 11.4 kg CO_2 per kg of composite.

For the case of thermoset presented in Scenario 2, the same manufacturing process can take place for the second life cycle as well. This is because after pyrolisis, the fibers have the same length, thus can be produced using conventional manufacturing processes.

Table 4.13: Embodied energy and CO_2 equivalent for RTM manufacturing

Description	Embodied energy	Unit	CO_2 equivalent	Unit
CFRP manufacturing RTM	100	MJ/kg	11.4	kg/kg

CFRP component - first life cycle (thermoplastic)

For the thermoplastic component, the chosen manufacturing process is the press consolidation. In this method, carbon fiber reinforcement is stacked and heated in a press to melt the matrix, then cooled under pressure to consolidate the laminate. This out-of-autoclave process is generally more energy-efficient than thermoset curing, since no long chemical cure is required, but only melting and cooling of the resin. Reported energy requirements for hot press consolidation was found to be approximately 6.2 MJ/kg for press molding a high-performance thermoplastic composite [53]. We adopt 6.2 MJ/kg as the energy for thermoplastic consolidation, with a CO_2 intensity of 0.7 kg CO_2/kg.

Table 4.14: Embodied energy and CO_2 equivalent for press consolidation

Description	Embodied energy	Unit	CO_2 equivalent	Unit
CFRP manufacturing press consolidation	6.2	MJ/kg	0.7	kg/kg

CFRP component - second life cycle (thermoplastic)

For the second life cycle presented in Scenario 4, the fibers are shredded, thus they can be used in lower quality products, such as the ones resulting from injection moulding. Consequently, the energy required for this process is looked into.

Life-cycle inventory data indicate a specific energy consumption around 5.4MJ/kg of thermoplastic molded [54]. Reported values span roughly 2.88–7.56 MJ/kg, reflecting different polymers and machine conditions [54]. For the purpose of this study, the value of 7.56 MJ/kg is going to be used for a conservative study. Correspondingly, the greenhouse gas emissions associated with the moulding step are 0.86 kg/kg CO_2 equivalent.

Table 4.15: Embodied energy and CO_2 equivalent for injection moulding

Description	Embodied energy	Unit	CO_2 equivalent	Unit
CFRP manufacturing injection moulding	7.56	MJ/kg	0.86	kg/kg

Utilization first life cycle

The operational life for the first life cycle does not change, therefore the same values as for aluminium will be used in the case of CFRP. The values are presented in table 4.4.

End-of-life preparation

All assumptions stated in section 4.1.2 are applicable.

Landfilling

Tapper et al. offer an overview of energy consumption of different processes. Among this, the processes of interest for this study are also included. For landfilling, the values given are between 0.11 and 0.4 MJ/kg [50]. Thus, the energy consumption is set to 0.4 MJ/kg for the purpose of this study.

Table 4.16: Embodied energy and CO_2 equivalent for landfilling

Description	Embodied energy	Unit	CO_2 equivalent	Unit
Landfilling	0.4	MJ/kg	0.05	kg/kg

Mechanical shredding

In the same article, Taper et al. evaluate the energy required for mechanical shredding. This has a bigger range of values between 0.14 and 51 MJ/kg [50]. For this, the study of Howarth et al. is investigated. This study presents the relation between the recycling rate expressed in kg of material processed per hour and the energy necessary expressed in MJ/kg. It is discovered that the higher the recycling rate, the lower the energy necessary per kilogram. This makes sense as the milling machine would be used for processing higher quantities, therefore decreasing the operational cost and energy required per kilogram. For this case, a derogation from the assumption of using the largest value for the conservative study is applied. This is the case as the values presented in more studies are on average around 0.27 MJ/kg, as shown also in the work of Hedlund-Åström et al [55]. Therefore, this value will be further used in calculation and analysis.

Table 4.17: Embodied energy and CO_2 equivalent for mechanical shredding

Description	Embodied energy	Unit	CO_2 equivalent	Unit
Mechanical shredding	0.27	MJ/kg	0.03	kg/kg

Pyrolysis

The pyrolysis process is considered to be more energy demanding than the previous two processes. Most researchers agree for a value of 30 MJ/kg of material processed [56].

Table 4.18: Embodied energy and CO_2 equivalent for pyrolysis

Description	Embodied energy	Unit	CO_2 equivalent	Unit
Pyrolysis	30	MJ/kg	3.42	kg/kg

Remelting

Remelting refers to a recycling route applicable only to thermoplastic-matrix CFRP, since thermoplastic polymers can be re-melted. In this pathway, end-of-life composite pieces are heated to re-melt the thermoplastic resin, allowing the material to be reformed into a new component, typically of lower performance. Both the carbon fibers and the thermoplastic matrix are thus partially retained in the loop, though the fibers may be damaged. Remelting a CFRP involves heating the scrap to the resin's melting point and applying pressure to form a new part. This process is considerably less energy-intensive than pyrolysis, since the polymer is not fully decomposed. While specific LCA data for composite remelting are limited, polymer processing energies on the order of around 10 MJ/kg are typical [57]. In this study, a value of 10 MJ/kg for the thermoplastic remelting process including the energy to melt and re-mold the material. This yields about 1.14 kg CO_2/kg.

Important note is that in this case it is assumed that the component is already formed in the required shape during the remelting process. Thus, there is no need for an additional component manufacturing step for second life cycle in Scenario 5.

Table 4.19: Embodied energy and CO_2 equivalent for remelting

Description	Embodied energy	Unit	CO_2 equivalent	Unit
Remelting	10	MJ/kg	1.14	kg/kg

Summary of values

Table 4.21 presents the summary of values for 1kg of target CFRP material. These values are to be used for the further analysis.

Table 4.20: Summary of values to be used for CFRP analysis

Description	Embodied energy	Unit	CO_2 equivalent	Unit
Virgin carbon fiber	286	MJ/kg	32.61	kg/kg
Fabrics	2.73	MJ/kg	0.31	kg/kg
Prepreg	42	MJ/kg	4.79	kg/kg
Epoxy resin	135	MJ/kg	15.39	kg/kg
PEKK resin	333	MJ/kg	37.97	kg/kg
CFRP component - RTM	100	MJ/kg	11.4	kg/kg
CFRP component - press	6.2	MJ/kg	0.7	kg/kg
CFRP component - injection moulding	7.56	MJ/kg	0.86	kg/kg
Utilization	0.00172	MJ/(kg*km)	0.00012384	kg/(kg*km)
Landfilling	0.4	MJ/kg	0.05	kg/kg
Mechanical shredding	0.27	MJ/kg	0.03	kg/kg
Pyrolysis	30	MJ/kg	3.42	kg/kg
Remelting	10	MJ/kg	1.14	kg/kg

4.2.3. Goal and system boundary of the study

The goal is similar to the one presented in section 4.1.3, only that in this section the component at hand is made out of carbon fiber reinforced plastic. The scenarios investigated are presented in section 4.2.1.

The functional unit is similar to the one presented in the case of aluminium: one CFRP fuselage panel section of an aircraft.

Given that studies suggest that CFRP structures often achieve around 20% weight reduction compared to aluminium equivalents, it is assumed that the panel of interest is approximately 18 kg, thus roughly 20% lighter than the 22 kg aluminium counterpart.

4.2.4. Inventory analysis

In this section, the life-cycle inventory data for the 18 kg CFRP fuselage panel, is compiled for both the thermoset and thermoplastic cases. The material and process data collected in section 4.2.2 are applied to the full panel. Table summarizes the energy inputs and corresponding CO_2 outputs for each stage of the life cycle for the thermoset and thermoplastic CFRP panels. Similar to the case of aluminium, these values are secondary data as they are collected from literature and databases. Assuming a fiber mass fraction of 60% which is typical for aerospace-grade CFRP laminates, this would result in 10.8 kg of carbon fiber and 7.2 kg of resin.

Table 4.21: Summary of values to be used for CFRP analysis

Description	Embodied energy	Unit	CO_2 equivalent	Unit
Virgin carbon fiber	3088.8	MJ	352.2	kg
Fabrics	29.5	MJ	3.3	kg
Epoxy resin	972	MJ	110.8	kg
PEKK resin	2397.6	MJ	273.3	kg
CFRP component - RTM	1800	MJ	205.2	kg
CFRP component - press	111.6	MJ	12.6	kg
CFRP component - injection moulding	136	MJ	15.48	kg
Utilization	2861e3	MJ	326e3	kg
Landfilling	7.2	MJ	0.9	kg
Mechanical shredding	4.86	MJ	0.54	kg
Pyrolysis	540	MJ	61.56	kg/kg
Remelting	180	MJ/kg	20.52	kg/kg

4.2.5. Impact assessment

In this section, the energy use and greenhouse gas emissions are aggregated over all life-cycle stages to quantify the total environmnetal impact as per scenarios described in section 4.2.1. For convenience, only the embodied energy graphs are shown as the CO_2 equivalent graphs would show the same trends because of the conversion factor.

The six scenarios are repeated here for an overview. **Scenario 1** deals with the thermoset component which would only be used for one life cycle and then disposed by landfilling. **Scenario 2** deals with the thermoset component which would be recycled via pyrolisis process and the fibers resulted would be later combined with new epoxy resin for a new component. Further scenarios deal with thermoplastic resins. **Scenario 3** takes into account the landfilling method when a thermoplastic panel is involved, while **scenario 4** looks at mechanical shredding and further injection moulding as possible routes for recycling of the component. **Scenario 5** identifies the remelting of the resin as potential recycling route, while **scenario 6** looks into pyrolisis and further combination with new resin.

Scenario 1

In figure 4.15, it can be seen that landfilling consumes a very low amount of energy compared to the production of virgin CF and epoxy resin. However, if we are to think that landfilling implies that the component is disposed of without recovering any materials, it is obvious that this method is not environmental beneficial as for a new component, one would need to go through the first stages again.

Scenario 2

For scenario 2, a significant amount of energy consumed during the scenario is part of the production of virgin carbon fibers as seen in figure 4.16. This accounts for a third of the overall energy consumption. However, given that the production of recycled fibers accounts for approximately 15% of the production of virgin fibers, this scenario demonstrates the overall benefits of recycling the fibers.

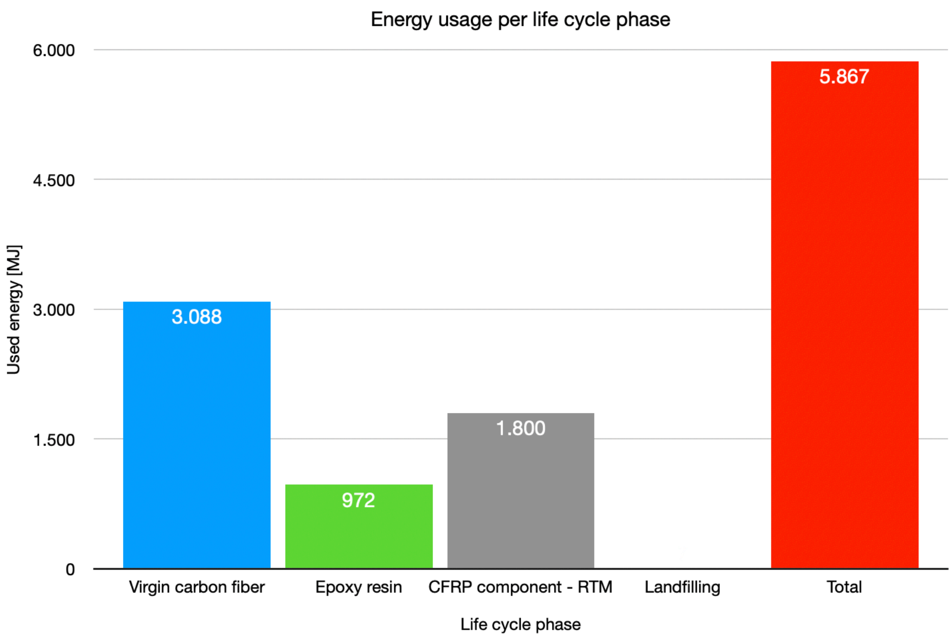

Figure 4.15: Energy consumption vs phase for scenario 1

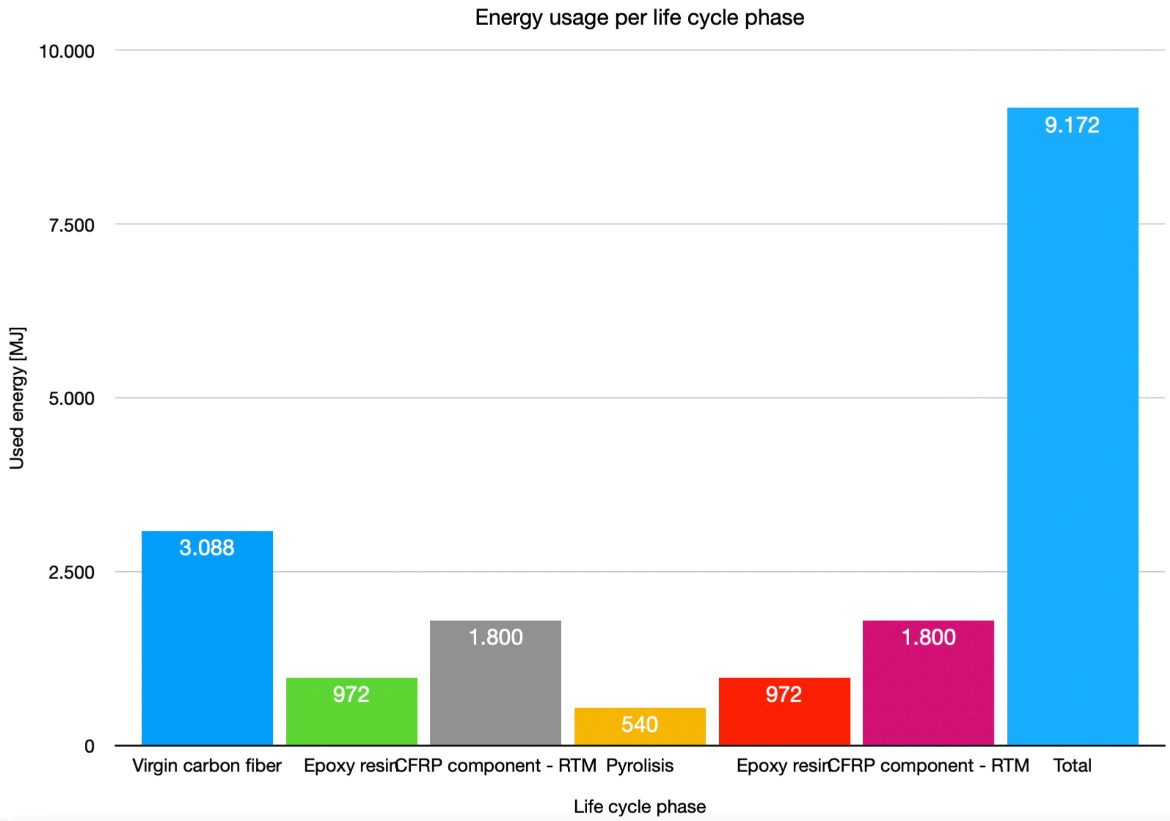

Figure 4.16: Energy consumption vs phase for scenario 2

Scenario 3

Similar to the first scenario, in this scenario the landfilling of the component shows a very small percentage of the overall energy consumption as illustrated in figure 4.17. However, given that a new cycle would imply making new primary carbon fibers and resin, this scenario is not satisfactory from an environmental point of view.

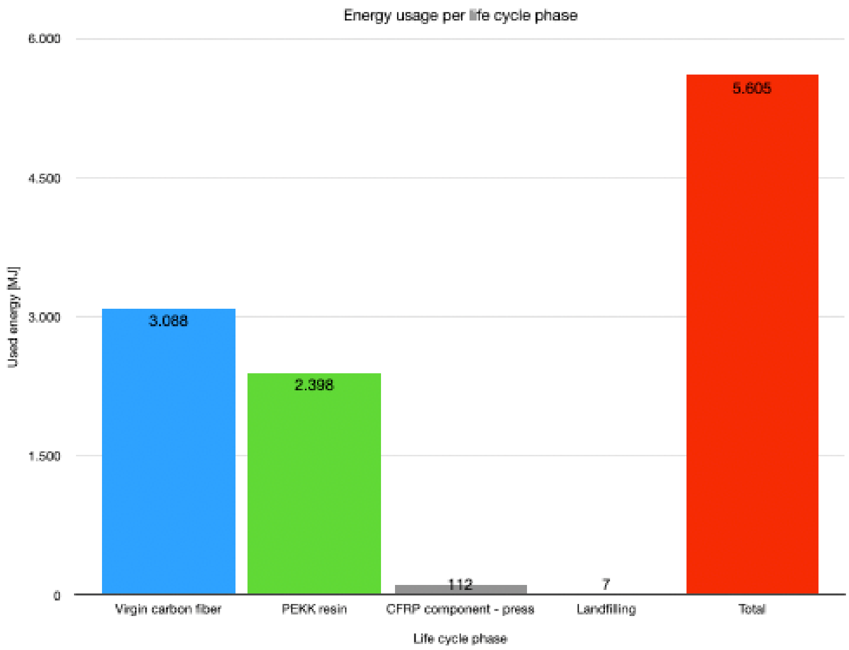

Figure 4.17: Energy consumption vs phase for scenario 3

Scenario 4
Scenario 4 represents the scenario where the recycled material could not be used in the same applications as the primary material because of loss of properties due to mechanical shredding. However, observing figure 4.18, one could argue that the benefits of using recycled fibers as fibers for injection moulding components are undeniable. As it can be observed, the energy required for mechanical shredding accounts for less than a sixth of the energy consumed for producing virgin fibers which would be necessary in case a new injection moulding product would be manufactured. Thus, by recycling the existing fibers and downgrading their use towards applications where the components can be manufactured via injection moulding, the environmental benefits are proven.

Scenario 5
In this scenario, the environmental benefits of recycling the thermoplastic components via remelting the resin are even more obvious as presented in figure 4.19. It can be observed that remelting is using around 3% of the energy required for producing new virgin carbon fibers, resin and producing a component via press consolidation. Thus, as the remelting stage includes the recycling and moulding of the component for a new life cycle, this recycling route proves to be promising.

Scenario 6
When pyrolisis is involved, the benefits are against the production of new carbon fibers as there is still need for new resin to be manufactured and used for a new component. However, the pyrolisis process account for approximately 15% of the production of new fibers, thus the benefits.

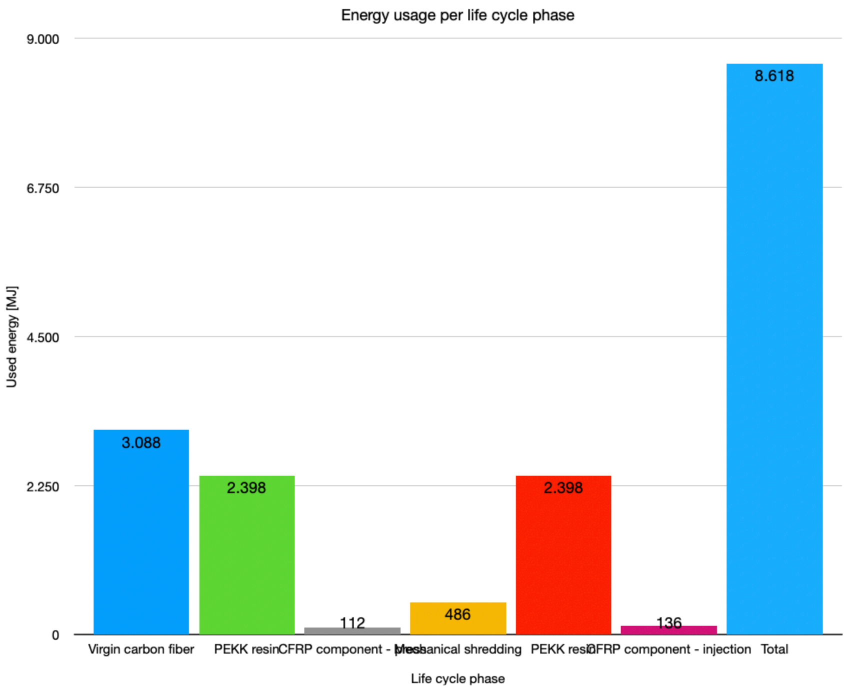

Figure 4.18: Energy consumption vs phase for scenario 4

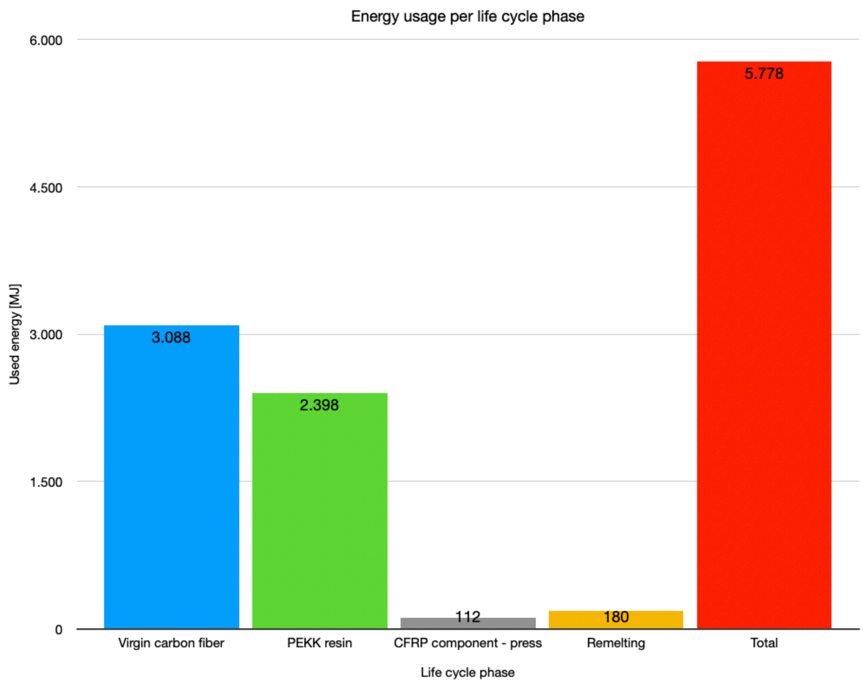

Figure 4.19: Energy consumption vs phase for scenario 5

4.2.6. Discussion

Looking at figure 4.21, the differences in energy consumption per stage per scenario is investigated.

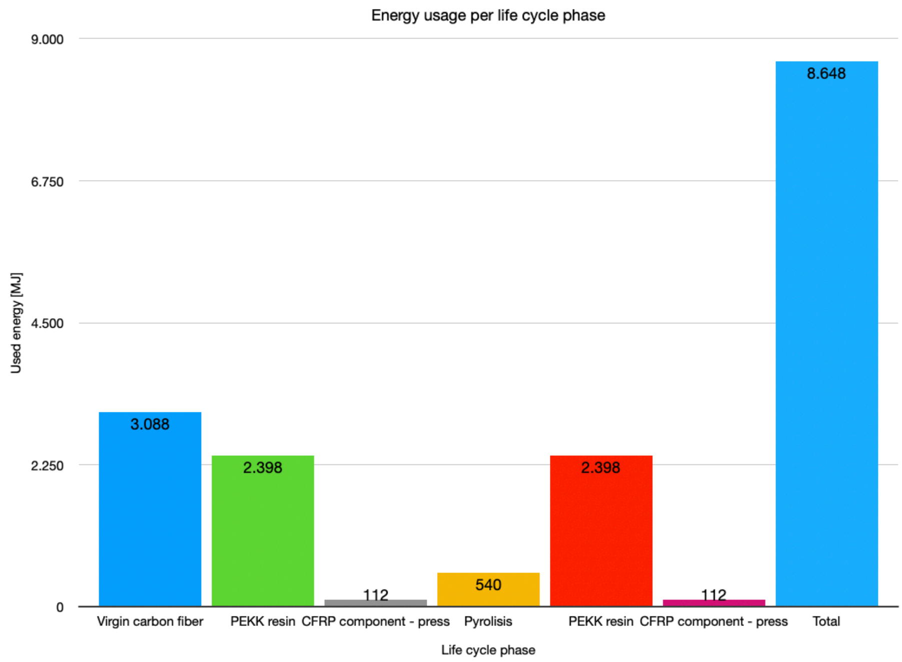

Figure 4.20: Energy consumption vs phase for scenario 6

If one is to compare the differences in using a thermoset or thermoplastic material for a component for only one life cycle, then scenario 1 and 3 should be compared. What is interesting about these two scenarios is that the total energy consumption is very similar, however the distribution across the stages is different. If in the case of thermoset, the component manufacturing stage accounts for the most energy consumption because of the longer times and pressures required, in the case of thermoplastic component, a significant amount of energy goes into the production of the resin. Thus, from such comparison, it can be easily indicated which stages should be of focus for reduction in a second life cycle.

For this reason, in the case of thermoplastic composites, a beneficial method is the remelting method, where both the fibers and the resin can be reused, without the need of producing new materials. This is illustrated in scenario 5. However, if this method is not optimal for the component at question, then the mechanical shredding or pyrolisis can be chosen. However, in both cases, there is need for new resin production which was previously shown to be of significant importance in terms of environmental burden. However, both mechanical shredding and pyrolisis reduce the need for new virgin carbon fibers which require high energy-intensive process.

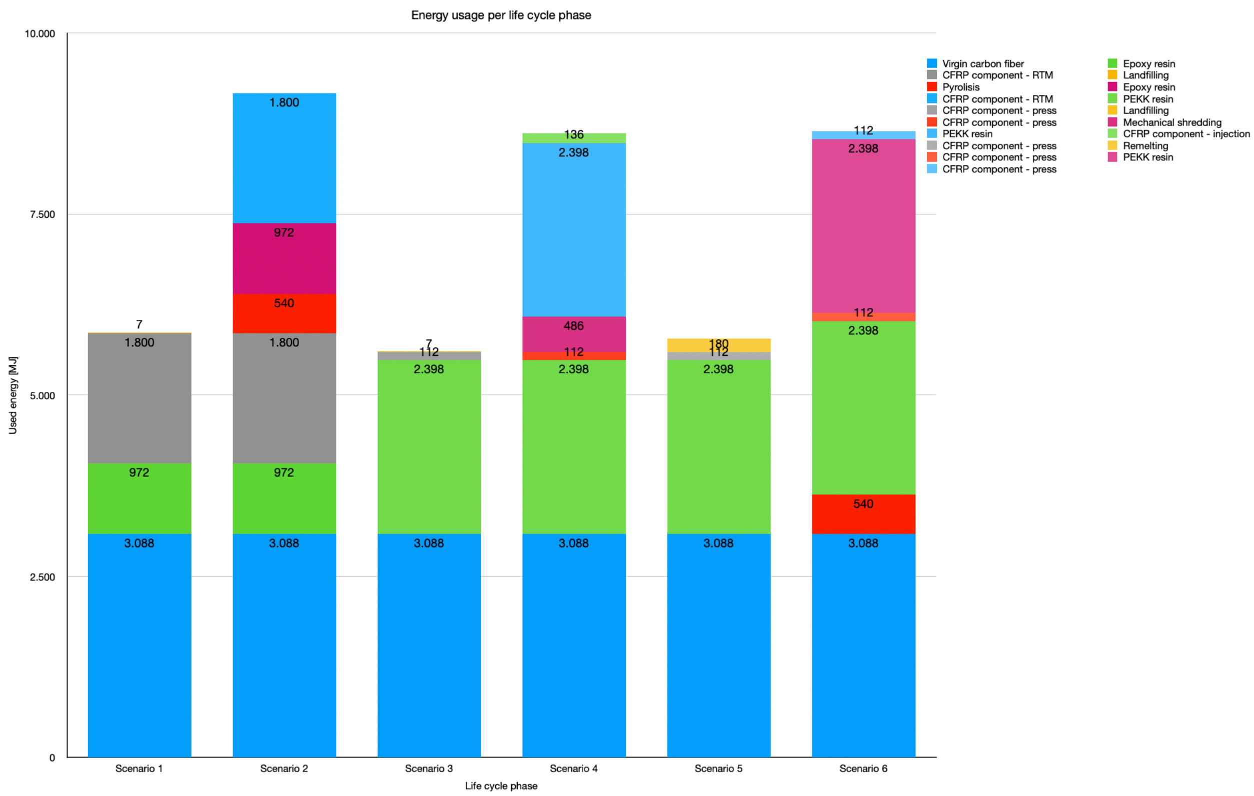

Figure 4.21: Total energy consumption per scenario

4.2.7. Assumptions summary

1. Only one recycling cycle is considered.
2. Transport between sites is not considered.
3. If a range of data is given, the value that leads to the most conservative study is used. This can be either the largest value of the range or the lowest values, depending on the properties discussed.
4. No energy recovery from the pyrolysis is considered.
5. For second life cycle, the same utilization phase is considered. Thus, the components are used in airplanes, as secondary structures.

5 Economic analysis

The economic aspects behind the costs of materials are various. Production costs, scarcity of raw material components, delivery costs and the demand and supply are all influencing the economics of a material. Production costs of raw material are mainly related to the energy consumed during extraction and production, but also to the labour costs involved. While demand determines the amount of material needed in the market, supply determines the amount of material being available to be delivered. Both these concepts are closely linked to the scarcity of a material, which determines how much material is actually available in the world and can actually be produced. Delivery or distribution costs are also an important factor nowadays, and they can also be linked to the scarcity of materials and geopolitical aspects.

5.1. Aluminium alloys

5.1.1. Aluminium Waste Volumes in the Aviation Sector

Economies of scale are critical in aluminum recycling, particularly for the high-grade alloys used in aircraft. The processes and technologies required to recycle aerospace aluminum efficiently often involve substantial fixed costs, for instance, setting up automated sorting lines (using X-ray to distinguish alloys) or operating a remelting furnace with precise alloying controls. One of the most important aspects in the recycling of aluminium aircraft components is the sorting stage in which different alloys are categorized. This can be a rather labour intensive process, however, as the industry evolves and the use of AI is increasing in all aspects of life and technology, one could argue the potential use of AI in such sorting activities. Given that each aircraft component gets an identification label for tracebility purposes, as long as the correct relation is introduced between the ID label and the material in an automated system, the sorting activities could potentially become way less labour intensive. Such investments only make economic sense if there is a large enough throughput of scrap. A key concept is the minimum volume threshold needed for a recycling operation to be cost-effective. While exact thresholds vary per process and region, industry analyses suggest that dedicated aluminum recycling facilities need feedstock on the order of tens of thousands of tonnes per year to achieve low unit costs. This is in part due to high capital costs: even a medium-sized secondary aluminum smelter might have a capital cost in the tens of millions of dollars, but its operating cost per tonne is low if run near full capacity. In contrast, a small-scale operation processing just a few hundred tonnes would have much higher unit costs and likely be uneconomical.

In the context of aerospace scrap, considering manufacturing scrap first: a single large aircraft factory can generate several thousand tonnes of aluminum scrap annually, as evidenced by the Boeing closed-loop programs (3600 tonne/year with Alcoa and expanding further with Kaiser) [58]. This volume is sufficient to justify dedicated logistics and even investments like Boeing and Alcoa's $90 million expansion of a recycling facility with 20000 tonne/year capacity for aerospace alloys [58]. By aggregating scrap from multiple plants (including for example Boeing's suppliers), the program ensured a steady stream of material to keep the recycling loop running efficiently. The economy of scale here means the cost to collect, ship and remelt the scrap is spread over a large mass, reducing the cost per-tonne. Moreover, large volume allows maintaining alloy segregation. For example, by collecting enough 7075 alloy scrap to do a dedicated melt, the high value of the alloy is maintained. If volumes were too low, different alloy scraps would likely have to be mixed for the sole purpose of getting a melt of sufficient size, resulting in a lower-grade output.

Thus, this is a crucial point: to enable closed-loop recycling, one must have sufficient volume of scrap in each alloy group. The German "OptiMet" project highlighted that advanced sorting can enable high selectivity recycling of alloys to reduce downcycling, but sorting technology and its cost is justified only if enough scrap can be processed. For airlines and MROs dealing with EOL aircraft, this means channeling retired planes to specialized recyclers rather than ad-hoc local scrap yards. Indeed, the formation of AFRA and specialized firms is itself a response to the need for scale and standardized best practices.

On the end-of-life side, volume consolidation is key to profitability. The teardown of a single aircraft might yield in the order of 15–50 tonnes of aluminum. To economically remelt that into secondary ingots, recyclers typically combine material from multiple aircraft or stockpile until a sufficient batch size is reached. High-capacity furnaces (for secondary aluminum) might have batch sizes of several tonnes up to 50+ tonnes. If scrap is processed in suboptimal batch sizes, energy and labor costs per tonne rise. Additionally, larger operations can achieve higher recovery rates. For example, shredding an aircraft airframe yields a mix of aluminum and other metals; large-scale processors can employ eddy current separators, density separators, and custom chemistry adjustments to recover more aluminum from the shred. Smaller-scale operations might simply recover the bulk aluminum and let more mixed residuals go to waste or lower-value use. Studies show that advanced processes can improve metal recovery and shorten payback times. One analysis found that an optimized recycling plant for composite-rich aircraft waste could recoup its investment in 1–2 years if running at large scale [59].

There is also a geographical aspect to economies of scale. In Europe, regulations require environmentally sound handling of hazardous materials and proper waste management, which adds compliance costs to aircraft dismantling. Only substantial, well-run facilities can meet these requirements cost-effectively. The European Waste Framework Directive and other regulations mandate permits, pollution controls, and traceability in the dismantling process [60]. Tarmac Aerosave, for instance, operates large dedicated sites in France and Spain and has processed over 300 aircraft since its inception, benefiting from standardized processes and economies of scale. By 2022, Tarmac's Tarbes facility had taken in its 100th aircraft for dismantling; a milestone indicating growing volume [59]. AFRA's best practices followed by its members also facilitate economies of scale by creating uniform methods that can be replicated across many aircraft, reducing the "learning curve" cost for each teardown [58].

Volume thresholds also influence whether recycled aerospace aluminum can be kept in closed loops. For instance, to directly recast scrap 7075 alloy into new 7075 billets, a recycler needs enough scrap of that alloy to fill a furnace while also controlling impurities. If only a small quantity of 7075 scrap is available, it might instead be mixed into a general secondary alloy melt, essentially going towards an open-loop recycling path. Some emerging technologies aim to lower the volume threshold for high-grade recycling, for example, solid-state recycling techniques like hot forging of scrap chips or spark plasma sintering can consolidate small batches of scrap without full remelting, potentially allowing economically viable recycling at smaller scales. This process is explained in the previous chapters.

In summary, the cost per tonne of recycled aluminum decreases significantly as volume increases, due to spreading fixed costs and enabling more efficient processing. Large-scale recyclers can achieve lower operational cost per unit mass and can afford better separation technology, which in turn yields higher quality secondary aluminum as there is more quantity of the same alloy and thus, the melting is done with similar alloy, resulting in less metal loss. On the flip side, insufficient volume leads to higher costs and often to downcycling of the material. One practical implication is that industry collaboration is essential: manufacturers, airlines, and dismantlers may need to pool resources or create centralized recycling hubs to reach the necessary scale. The European context, with relatively high concentration of retired aircraft in certain hubs (e.g., in Spain, France) and strong policy support, has seen movement toward such centralized approaches.

5.1.2. Market dynamics: recycled vs virgin aluminium costs

While the technical possibility exists to recycle nearly all aluminum from aircraft, whether this happens in practice often comes down to market economics. The relationship between recycled aluminum and primary aluminum in the marketplace is complex. Unlike some materials where recycled products are vastly cheaper, aluminum's global market tends to keep secondary and primary prices closely linked. This is because aluminum is a fungible commodity: if secondary aluminum is significantly cheaper, manufacturers will substitute it wherever possible, driving its price up. Conversely, if primary aluminum is cheap, it puts downward pressure on scrap prices. In fact, in recent years scrap aluminum prices are close to primary aluminum prices [61]. According to a 2025 analysis by Norsk Hydro, secondary aluminum (especially when imported into the EU) often enjoys cost advantages due to regulatory loopholes, but fundamentally the scrap is valued not far below primary metal [61].

To put some numbers in context, the London Metal Exchange (LME) price for primary aluminum averaged around $2250 per tonne in 2023 [62], with spikes above $3000/tonne in 2022 amid supply disruptions. Scrap aluminum prices vary by grade and region, but clean sorted aerospace alloys can fetch a high fraction of LME. U.S. scrap yard data in 2024, for example, showed clean extruded aluminum scrap selling for around $1100–$1540 per tonne, roughly half to two-thirds of the primary ingot price at that time [63]. However, that is the price at collection yards; secondary ingot made from scrap often sells closer to primary. An anecdotal data point: in early 2024 the U.S. spot price of primary aluminum ingot was $2580/tonne, while secondary aluminum ingot (for casting, known as A380 alloy) was around $1984/tonne. This suggests an approximate 15–25% discount for secondary metal used in less demanding applications. But for high-grade scrap, the discount can be smaller. In Europe, scrap importers have even been able to undercut primary producers significantly by exploiting carbon cost differences. Hydro warned that under the new EU Carbon Border Adjustment Mechanism (CBAM) rules, foreign producers using "scrap-based" aluminum (counted as zero emissions under CBAM) could sell into Europe at essentially primary aluminum price but without the carbon cost that European smelters must bear, pocketing the difference [61]. By 2035 this loophole could make European recyclers input costs €200/tonne higher than those of non-EU competitors if not fixed [61]. This illustrates how policy and market pricing intertwine: Europe's carbon pricing (via EU ETS) adds about €150–€200 per tonne to primary aluminum cost, which in theory makes recycled aluminum more attractive. Yet, if that policy is not applied equally to imported semi-recycled aluminum, it can hurt domestic recyclers.

Furthermore, as the metal ores vary in their global distribution, they are more susceptible to spatial and geopolitical-related availability [64]. Focusing on aluminium and considering the most critical bauxite ore reserve countries, it is noted that the top three countries with the most reserves of useable bauxite are Australia, Guinea and China [65]. Because of this, the European Council included bauxite as a critical raw material in the latest report on this topic, published in March 2024. The critical raw material act contains all the raw materials with high supply chain risk and are necessary for the proper functioning of industrial ecosystems. In order to cope with the risks associated with the supply of critical raw materials relying on a single country, the EU proposed several objectives for the year 2030. Two of the most important and relevant for this study are that at least 25% of the EU's annual consumption must come from domestic recycling and that not more than 65% of the Union's annual consumption of a critical raw material at any relevant stage of processing should come from a single third country [66]. With this aspect in mind, the recycling of aluminium becomes of even higher importance.

From a cost structure standpoint, primary aluminum production is far more energy- and capital-intensive than secondary. The capital equipment for secondary production is also cheaper as the U.S. Department of Energy estimated secondary aluminum requires only approx. 10% of the capital investment per tonne of capacity compared to primary smelting [67]. These factors mean that, if scrap is available at reasonable cost, secondary producers can produce aluminum at lower marginal cost than primary producers. Indeed, some aluminum companies focus on recycling for exactly this economic edge. However, high-quality scrap is not free as it must be bought and its price tends to be bid up to a point where using scrap is only moderately cheaper than making new metal.

Another dynamic is demand for low-carbon aluminum. In recent years, automotive and packaging industries have sought aluminum with lower carbon footprints. Recycled aluminum is much less carbon-intensive, so it is attractive for sustainability goals. Some buyers are even willing to pay a premium for certified recycled content or low-carbon primary aluminum. This trend can make secondary aluminum price competitive or even at parity with primary despite any quality differences, especially in Europe with strong ESG mandates.

5.1.3. Challenges

One challenge in aviation aluminum recycling is the grade mismatch: secondary aluminum is abundant and cheap when used for cast alloys or non-critical parts, but reusing it for aircraft-grade material entails extra steps (refining, alloy adjustments, stringent quality testing) that add cost. Thus, primary high-purity aluminum and master alloys are still needed to dilute and adjust recycled content for new aerospace alloys. Studies by Hatayama et al. have pointed out that millions of tonnes of high-alloy scrap could remain unrecycled by 2030 because their alloying element concentrations are too high to easily reuse [68]. In practice, this means scrap from 7075 or 2024 alloys, rich in zinc or copper, often must be blended with pure aluminum to make a useful composition or else it gets downcycled to applications where those elements are tolerable. That blending requires primary metal, incurring additional cost. If advanced sorting techniques, such as AI use for identification, could isolate specific alloys, recyclers could directly re-melt scrap into the same alloy, reducing the need for dilution. This is an area of current R&D and could alter cost dynamics in the future: if closed-loop recycling becomes widely feasible, the cost of aerospace-grade secondary ingots might drop and displace more primary metal in new planes, as the need to add expensive pure aluminum decreases.

5.1.4. Recent trends and outlook

The period from 2020 to 2025 has been turbulent yet illuminating for aluminum recycling in aviation. In 2020, the COVID-19 crisis led to an unprecedented number of older aircraft retirements as air travel demand plummeted. An estimated 612 airliners were retired in 2020 alone by early December, roughly double the typical retirement rate [69]. This surge temporarily flooded the market with aircraft aluminum scrap. Initially, one might expect an oversupply of scrap to reduce prices, but global aluminum prices actually rose in 2021–2022 after an initial dip, driven by recovering demand and supply chain disruptions (including energy crises and sanctions on major producers). By 2022, LME aluminum reached decade-high prices ($3800/tonne in March 2022) amid tight supply, which kept scrap prices elevated as well.

Europe's situation during this time underscored the strategic value of recycling. With energy prices spiking in late 2021 and 2022 (partly due to the war in Ukraine), Europe temporarily lost about half of its primary aluminum smelting capacity as plants curtailed or shut down due to exorbitant electricity costs [70]. This made Europe more reliant on imports and on secondary production. Recyclers, who use far less electricity, became relatively more competitive. However, European recyclers also faced high gas prices and a constrained scrap market. Notably, European industry raised alarms that scrap was being exported or imported as "low-carbon" aluminum, bypassing carbon costs, which could undermine local secondary producers [71]. In response, there is growing pressure to adjust policies to ensure scrap is recycled under environmentally equivalent standards, essentially to prevent unfair cost advantages for non-EU scrap-based metal.

From a cost perspective, the gap between primary and secondary aluminum costs in the mid-2020s has been relatively narrow. Primary ingot prices have moderated in 2023–2025 (hovering in the mid-$2000s per tonne), and scrap prices likewise softened from 2022 peaks. However, both remain higher than their 2010s averages due to factors like inflation and higher energy costs. Industry experts forecast aluminum prices will stay firm through 2025, with one outlook projecting an average of $2,575/tonne in 2025 for primary metal [72]. If so, scrap and recycled ingot prices will likely also remain robust. For airlines retiring aircraft, this means scrapping yields decent returns; for manufacturers, it means no big cost relief on input material from using scrap unless they can truly create closed-loop efficiencies. The real cost benefit for manufacturers might come instead from avoided carbon costs and from marketing low-carbon products.

In conclusion, the 2020–2025 trend has been toward greater recognition of the value of recycling both for cost stability and environmental reasons. Europe's regulatory context, from strict dismantling rules to carbon pricing, has made it a leader in pushing the envelope for high rates of aircraft recycling and potentially in using recycled aluminum. The industry still faces technical and logistic hurdles, especially in closing the loop so that recycled aviation aluminum can re-enter new airplanes. But as economies of scale improve (with larger numbers of aircraft being processed and scrap being centrally collected) and as market dynamics (energy prices, carbon costs) tilt in favor of secondary aluminum, the business case for recycling in aviation strengthens.

5.2. CFRP

Economic viability of CFRP recycling is highly sensitive to scale. The fixed costs of setting up and running a recycling operation can only be amortised over sufficient volume throughput. In the aerospace sector, which historically generated relatively modest composite waste volumes, achieving the necessary scale has been a challenge. This section examines the volume of CFRP waste arising from aviation and identifies thresholds at which recycling becomes cost-effective. It also explores how economies of scale are being realised through consolidation of waste streams, multi-industry recycling, and larger-capacity facilities, with developments mostly emerging in the 2020–2025 timeframe.

5.2.1. CFRP Waste Volumes in the Aviation Sector

Manufacturing Scrap: A significant source of CFRP waste in aviation is the scrap generated during aircraft production. Carbon fiber components (like wingskins, fuselage sections, spars, etc.) are typically laid up from pre-preg or textile, then trimmed and machined, resulting in off-cuts and scrap material. Scrap rates in aerospace manufacturing can be quite high, often around 30% of the material by weight is scrapped during part fabrication [73]. In the case of Boeing's production system, the volume is substantial: as of 2020 Boeing reported that about 454 metric tonnes of carbon fiber composite scrap per year were being collected from its 10+ production sites for recycling rather than landfilling [74]. This partnership with UK-based ELG Carbon Fibre has effectively created a supply chain for recycling aerospace-grade prepreg scraps and cured excess material. Similarly, Airbus and its suppliers generate large quantities of composite off-cuts in producing A350 XWB and A220 components, among others, and have initiated recycling programs. For example, in Europe the materials supplier Hexcel partnered with startup Fairmat in 2021 to recycle carbon prepreg cut-offs from Hexcel's prepreg plants, with Hexcel expecting most of its European prepreg scrap (several hundreds of tonnes annually) to be recycled by end of 2022 under this program [75]. These manufacturing scrap streams are relatively clean and consistent (often unused prepreg or cured trimmings), making them ideal feedstock for recycling processes and they are generated continuously, providing a relatively steady volume.

End-of-Life Aircraft: Previously, composite usage in aircraft was low (limited to small fairings, control surfaces, etc.), so EOL disposal of retired aircraft did not contribute towards significant CFRP volume. But this is changing as newer composite-intensive jets begin to retire in the upcoming decades. The first big wave will be the decommissioning of early Airbus A320s, Boeing 737NGs, etc., which still had limited composite content, but shortly after, aircraft like the Boeing 787 (in service since 2011) and Airbus A350 (since 2015) will reach end-of-life in the 2030s. As noted earlier, each such aircraft contains on the order of 20–50 tonnes of CFRP [76]. Industry forecasts already account for this: one analysis projects 6000–8000 commercial aircraft retirements by 2030, which will "flood the market with recyclable materials" [73]. A considerable portion of that will be aluminum, but also a growing amount of composites. By this year, it is expected that annual CFRP waste (from all sources, not just aerospace) to reach 20000 tonnes and this will climb higher by 2030 as those aircraft retirements ramp up [73].

Crossover from Other Sectors: It is important to note that dedicated CFRP recycling facilities often service multiple sectors, including automotive, wind energy, sporting goods, to achieve higher throughput. For example, a recycling plant might process waste from both aerospace manufacturing and automotive part production, since carbon fiber waste is chemically similar. Many recycling companies have targeted automotive and wind sectors first for recycled fiber applications (due to their larger volume and less critical performance requirements), effectively subsidizing the viability to also take aerospace scrap. For instance, Boeing's scrap material sent to ELG Carbon Fibre was ultimately used by other industries, "from carbon fiber to car parts," as Boeing described it [74]. This inter-sector volume aggregation is a key strategy: aerospace alone might not produce enough steady waste at a single location to justify a large recycling plant, but combined with other industries, the volume can reach economic thresholds.

5.2.2. Economies of scale and break-even analysis

Defined as cost advantages realized by companies when production becomes more efficient, economies of scale are critical in CFRP recycling. Because the initial capital investment and baseline operational overhead of a recycling plant are high, unit costs drop dramatically as throughput increases. Recent techno-economic analyses have quantified these scale effects, providing guidance on volume thresholds needed for profitability.

A comprehensive financial model of a fluidized-bed recycling process (developed by Meng et al. at University of Nottingham) illustrates the scale dynamics clearly. In their analysis, they varied plant capacity from 50 tonnes per year up to 6.000 tonnes per year and computed the minimum selling price of recycled carbon fiber (rCF) required to break even [77]. The results showed a significant difference between small and large scales as follow:

- At a small plant with a capacity of 100 t/yr, the required selling price for recycled fiber was extremely high. The model indicated rCF would need to be sold for up to $15 per kg to make the operation financially feasible [77]. This price is about half the cost of virgin fiber, which might be achievable in niche markets, but it leaves a slim margin and assumes there is a willing buyer at that price for all the output. The reason for such a high break-even price at 100 t/yr is that fixed costs (capital depreciation, basic staffing) are spread over a small product volume, and thus per-unit costs are high [77].
- In contrast, at large scale (≥500 t/yr), the economics improve significantly. Once the plant capacity exceeded roughly 500 tonnes per year, the model predicted that a selling price below $5 per kg of rCF could be achieved [77]. In fact, at 1000 t/yr (which might be considered a mid-size industrial plant), the minimum selling price was in the range of only a few dollars per kilogram for the recycled fiber. At these scales, the fixed capital cost per unit is much lower and operational efficiencies (like energy recovery, bulk purchasing of inputs, automation) can kick in.

For the aviation sector, this analysis raises an important question: Can aerospace composite waste supply sustain a more than 500 t/yr recycling plant? Most likely, some years ago the answer would have been "not by itself" because of the few hundred aircraft worth of scrap per year were not being retired and manufacturing scrap at any single company site was in the low hundreds of tonnes (Boeing's 454 t/yr being an outlier case where they aggregated multiple sites' waste) [74]. However, by pooling sources (as mentioned in previous section) and by the projected growth of waste, the outlook is improving. Some examples are shown further:

- Regional or Global Hubs: One strategy is to establish recycling facilities that take in waste from multiple aircraft manufacturers, maintenance centers, and even other industries. For instance, Europe, has been moving in this direction. The startup Fairmat's facility in France, supported by Hexcel and others, aims for 5000 tonnes per year capacity for recycled composite material in its first phase [75]. This scale far exceeds aerospace scrap alone in the region, so it will most likely handle automotive and wind materials as well. If realized, a 5000 t/yr plant would very comfortably hit the economy-of-scale sweet spot, theoretically driving recycling cost down near the $5/kg level or below.

- Linking with Automotive: The automotive sector is projected to generate large CFRP scrap volumes as use of carbon fiber grows in luxury and electric vehicles. For example, BMW's i-series production had significant carbon scrap which they internally recycled for secondary parts. By aligning aerospace recycling with such automotive efforts, the volume threshold can be met sooner. In one market forecast, the global recycled carbon fiber market of all sectors was valued at only approx. $96 million in 2024, but is projected to grow to $264 million by 2033 [73]. This implies a substantial increase in volume transacted. If we assume an average recycled fiber price of $10–20/kg, that market size corresponds to thousands of tonnes of rCF being traded annually by the 2030s.

- Government and Industry Initiatives: Recognizing the scale issue, some governments and large OEMs have initiated programs to consolidate waste. For instance, the EU's Horizon programs have funded projects to create composite recycling networks where waste from multiple aerospace companies is centrally processed. Japan's aerospace industry, led by companies like Toray, has also looked into establishing recycling plants to handle scrap from aircraft manufacturing and end-of-life, with capacity sizing to also serve non-aerospace demand.

What these developments mean is that volume thresholds that were problematic a few years ago are being overcome by collaborative and cross-industry approaches. As more composite-intensive aircraft enter service and subsequently, exit service, the aerospace sector's composite waste supply will naturally increase, making dedicated aerospace recycling more viable. Until then, interim solutions often involve sending aerospace scrap to multi-purpose recyclers who combine feeds.

From a cost perspective, one can define a rough threshold: on the order of a few hundred tonnes per year of CFRP waste is needed for a recycling operation to be self-sustaining. Below that, either the recycling must be subsidized (for environmental reasons) or the recycler must charge different fees or get exceptionally high prices for the rCF to cover costs. Indeed, in current practice, some composite recyclers do receive fees for taking waste (similar to how metal recyclers might pay or charge depending on scrap value). In Europe, landfill taxes on composite waste can be high, so an aircraft manufacturer might pay a recycler a certain amount per tonne to take the waste, improving the recycler's economics. This effectively means that even if selling the fiber does not fully pay off, the service of waste disposal provides income. As volumes and efficiency improve, however, the model shifts to one where the value of the recovered fiber itself drives profitability.

In summary, economies of scale in CFRP recycling are decisive: larger plants and aggregated waste streams dramatically lower the cost per kg of recycled fiber, enabling it to compete with virgin fiber. By working jointly with other industries, the aviation industry is reaching the scale needed for economically sound recycling.

5.2.3. Challenges

While scaling brings down the costs, it also introduces practical challenges which should be addressed by the industry.

One of these challenges is the **logistics of collecting widely dispersed waste**. Unlike metals (aluminum, steel), which are ubiquitous and have established scrap dealers everywhere, composite waste is relatively specialized. Aerospace composite scrap, in particular, may be generated in a handful of manufacturing centers and aircraft teardown sites globally. Ensuring a steady supply to a central recycling plant means organizing logistics over long distances (potentially international). This can reduce the economic and environmental benefits if not managed efficiently. Innovative approaches are being tried, such as regional collection points and compacting.

A second challenge is the **consistency of feedstock**. Large-scale recycling prefers a consistent, homogeneous feed for optimal operation. Aerospace CFRP waste can be heterogeneous because of different resin systems (epoxy, BMI, phenolic), different fiber types (high strength, high-modulus, sometimes glass fiber mixed in sandwich structures) and varying shapes/sizes. Scaling up means the recycler will inevitably get a mix of materials, which can complicate process settings and quality control. One mitigation is sorting or batching waste by type. Some facilities have started to specialize: one line might handle primarily uncured material (which yields clean fibers easily and even allows recovery of uncured resin for reuse), while another handles cured thermoset parts.

Thirdly, **capital investment and risk**. Building a large recycling plant requires millions of dollars upfront. Investors have to be confident that sufficient feedstock volume and offtake market exist for the plant's output. The failure of some early composite recyclers in the 2010s because of lack of steady feed or customers has made investors cautious. However, the aforementioned partnerships (Hexcel-Fairmat, Boeing-ELG) mitigate this by essentially guaranteeing supply or purchase agreements. In the last five years, we have seen established materials companies (Toray, Mitsubishi, etc.) either acquire recyclers or form joint ventures, signaling confidence in scaling up.

In conclusion of this section, the volume aspect of CFRP recycling is both a challenge and a key to success. The 2020–2025 period has demonstrated that by aggregating waste and building larger facilities, the composite recycling industry can achieve cost reductions that make recycling economically attractive. The aviation industry is moving from small pilot programs to larger collaborative recycling ecosystems.

6

Decision flow

To translate the combined LCA and economic analysis into actionable choices, a decision flow framework for EOL is proposed. When making a decision regarding the end-of-life operations of the aircraft, the stakeholders need to set an objective and thus, the question that should be answered is what the main goal of the end-of-life route is. Potential answers and routes are presented below:

- Minimize costs
- Minimize environmental impact (CO_2, energy)
- Maintain high material quality
- Balance the costs with the environmental impact and quality of material

6.1. Aluminum alloys

The framework presented in figure 6.1 for the aluminium alloy starts by asking whether high material quality must be preserved in the recycled output. This first decision is pivotal: if quality retention is **not required**, the path of **remelting with downgrading** could be favoured. In this route, the components would be melted and cast into a lower-grade alloy. This lower-grade alloy is to be used either in non-structural components similar to the analysis made in chapter 4 or can potentially be sold and used in other fields. Environmentally, this method is more efficient than producing the lower-grade alloy from primary aluminium as illustrated in chapter 4.

On the other hand, if high quality **is required**, the decision shifts towards other options. The further decision is guided by the stringency of the environmental constraints as well as cost considerations. Two alternatives presented in this reports are solid-state recycling and remelting with upgrading of the alloy. Both processes aim to produce a recycled aluminium that matches the original alloys̡ performance, but they differ in process and impacts.

If the priority is to **minimize environmental impacts**, then the solid-state recycling emerges as the preferred route. Solid-state recycling bypasses the melting stage entirely, thus reducing the environmental burden. As per analysis made in chapter 3, the resulting material of the solid-state recycling techniques can potentially have similar properties as primary material. However, solid-state recycling can require significant processing and upfront preparation such as cleaning or degreasing to remove oils, and thus significant mechanical work might be required. These extra steps can increase the processing costs relative to the remelting operations. Thus, SSR provides the lowest environmental footprint and good material quality preservation, however the processing costs might be higher.

If **material quality must be retained**, but **without** meeting significant environmental reduction targets, then the remelting with upcycling is suggested. In this strategy, alloying adjustments are necessary to ensure the recycled metal meets the original specifications. Even though, the environmental impact is slightly higher than for other cases, this process is usually moderate in costs. Factories are already available to process and remelt aluminium, thus the initial costs are in most cases already covered.

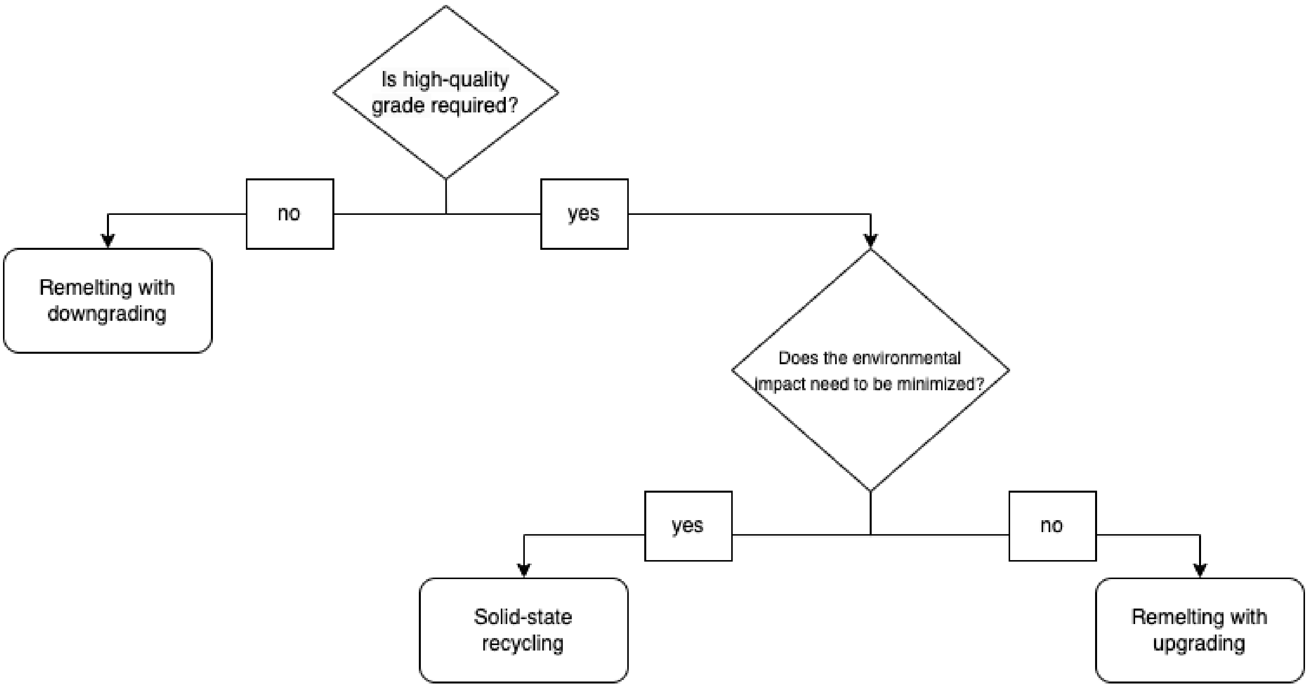

Figure 6.1: Decision flow for the aluminium alloy recycling

6.2. CFRP

Figure 6.2 presents the framework to be used for CFRP materials. The first decision is highly important as the material is selected between thermoset and thermoplastic.

If the CFRP is **thermoset**, the next question that should be asked is whether or not the environmental impact needs to be minimized. When deciding upon this, several aspects should be taken into account such as applicable legislation, energy availability, raw material availability. If the answer is no, then the emphasis can be shifted toward minimizing cost or complexity and thus, disposal via **landfilling**. However, if the legislation does not allow this, or the environmental burden needs to be reduced, then recycling via **pyrolisis** needs to be followed.

However, when it comes to **thermoplastics**, there are multiple routes that can be taken given different decisions. The first decision that needs to be made is related to the environmental impact, similar to the case of thermosets. If this does not need to be reduced, then landfilling is a potential option. However, if the environmental impact needs to be minimized, then the next question is related to whether or not the fibers need to be intact in terms of length.

If the fibers can be chopped, then the mechanical shredding is a viable options to reduce the environmental burden, while being able to use the material in components manufactured via injection moulding for example. Thus, even though the properties and quality would degrade, there would not be a need for production of new fibers. However, if the length of the fibers should be recovered, then pyrolisis and remelting can be the options to follow. The choice between them is related to whether or not the properties of the fibers can be downgraded and the costs involved as the pyrolysis can be a rather cost-intensive process compared to remelting.

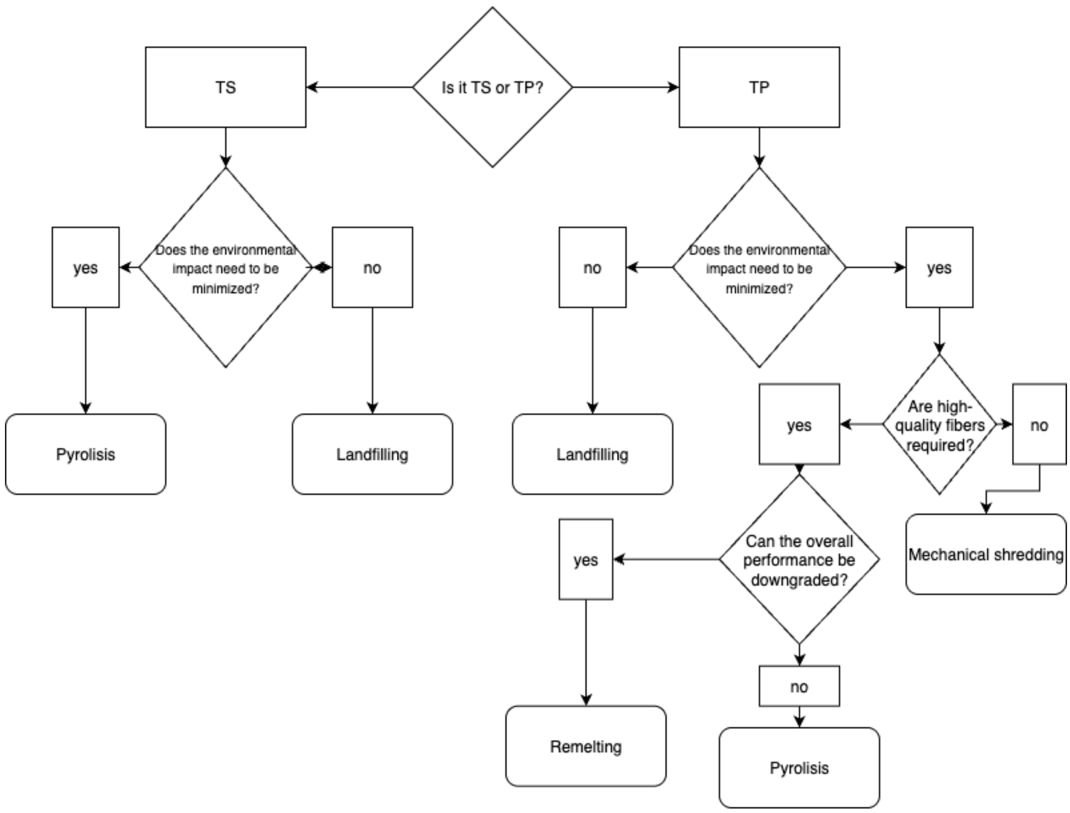

Figure 6.2: Decision flow for the CFRP recycling

6.3. Discussion

Taking into account all the information described in this study, it is clear that while CFRP could potentially reduce the weight of structures compared to aluminium and thus, delivering a clear benefit in the use phase due to this weight saving, at this point in time, there is no process that can fully recover the properties of the fibers while reducing the environmental burden completely. On contrary, the sustainability strength of aluminium lies in its inheritant and established recyclability as it can be repeatedly recycled with relatively low energy input compared to primary aluminium production.

However, among the recycling options explored, pyrolysis process stands out as a viable route for CFRP. It allows recovery of fibers with a majority of their mechanical properties recovered. Thus, if this process would be industrialized, it is potentially a game-changer in industry as it would allow the environmental burden to be reduced from both a recycling route, and from utilization phase as more composite materials could potentially be produced and used. At the same time, for thermoplastics, the remelting options shows significant advantages as illustrated in the LCA performed in chapter 4. From an environemntal impact standpoint, one cannot ignore that by landfilling the CFRP is the worst option. While this method has minimal immediate emisssions, it also implies that all the embodied energy is thos materials is effectively lost. Further, this method also poses the long-term issue that landfill space is finite and the carbon fiber plastic mix does not biodegrade, thus, it only accumulates until there is no physical space left for depositing.

Thus, comparing the two materials (aluminium and CFRP) from a circular economy perspective, a clear difference emerges: aluminium can be relatively easily kept in a closed material loop, while for the CFRP this is currently very difficult. Looking at aluminium and at the fact that recycling it yields roughly 95% energy reduction compared to primary production, it can be stated that even a one-time recycling loop for aluminium yields significant environmental gain. In the case of CFRP, this is not very clear, as there is either the need for new resin to be produced, or the properties are downgraded such that the material cannot be recycled more than one or two times.

Considering the economic and practical implications, one could argue that in order to maximize the sustainability of CFRP by achieving multiple life cycles, new practices would be required. One potential approach would be designing the aircraft components for ease of recycling, thus using thermoplastics for instance, that can be remelted and reshaped or using simpler lay-ups that can be easier separated. Further, even though this report focuses mainly on recycling technologies, there are other ways to extend the life of a components as illustrated in chapter 2.

7 Conclusion and recommendations

7.1. Conclusion

This study set out to develop a strategy for increasing the percentage of aircraft materials that are recycled at end-of-life, with an emphasis on both environmental and cost considerations. Through a comparative analysis of aluminium alloys and carbon fiber reinforced polymers, material properties in virgin versus recycled states were examined, a detailed life-cycle assessment was performed and economic factors were evaluated.

The output of this work is a decision flow chart that synthesizes these findings into a practical end-of-life strategy for stakeholders. In essence, the strategy tailors the recycling route to the material type and the stakeholder's priorities: for each major aircraft material, one must consider whether the goal is to minimize environmental impact, minimize cost, preserve material performance, or achieve an optimal balance. The decision framework then guides the choice of recycling or reuse pathways accordingly. By following this structured approach, the aviation industry can make more informed decisions that significantly increase recycling rates while managing trade-offs between ecological benefit, quality retention, and economic viability. Several key findings of the project are enumerated further.

The most energy consuming part of the life cycle was discovered to be the utilization phase. However, in the context of this thesis, this was not looked further into. Thus, for the scope of the thesis, the consuming part of the life cycle was discovered to be the virgin material production, for both aluminium and CFRP.

In terms of recyclability, the aluminium is leading as it theoretically can be recycled for a very large number of cycles, while for the composite materials, the thermoplastics are better prepared than their thermoset counterparts.

Economic feasibility depends on the scale and economic stability. Aluminium recycling is already cost-effective, whereas CFRP recycling becomes viable only when processes are scaled and markets for secondary fibres develop.

Policy measures can accelerate adoption of recycling activities within the aviation field. Carbon pricing, recycling mandates, or material incentives can shift cost balances in favour of recycled materials, promoting circularity in the aviation industry.

7.2. Recommendations

The present study has explored strategies to increase recycling in the aviation industry, considering both environmental benefits and cost implications. While the findings provide practical recommendations for industry stakeholders, it is equally important to recognize the limitations of the current research and identify areas that require further investigation. This chapter outlines key directions for future research that can contribute to deepening the understanding of recycling in aviation and inform evidence-based policymaking and industrial practice.

One aspect is related to the economic models for circular aviation. Further research is needed to develop comprehensive economic models that capture the full range of costs and benefits associated with recycling initiatives. These should include direct costs (e.g., infrastructure investments, labor, transport), indirect benefits (e.g., reduced landfill fees, resource recovery), and externalities such as avoided emissions. Quantitative models that integrate financial, environmental, and social dimensions could provide decision-makers with clearer incentives to adopt circular practices.

The life-cycle assessment performed in this study takes into account only one recycling cycle. However, it is recommended to perform assessments when multiple recycling cycles are involved. These should take into account degradation of the properties and under which conditions the materials can still be used.

As AI usage is increasing in the modern world, additional research could be performed on improving the methods for waste sorting taking into account AI.

The role of regulations in shaping recycling practices deserves more systematic exploration. Future studies could focus on the effectiveness of policy tools such as Extended Producer Responsibility, mandatory recycling tarrgets and market-based instruments such as, carbon credits and tax incentives. A comparative research across different regions, but also across different industries could provide to be helpful in determining the effectiveness of the regulatory mechanisms.

Thus, further research can be used to quantify even more the benefits of recycling activities within the aviation industry.

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