Connecting Impact and Quality - Prospective Life Cycle Assessment of recycling Carbon Fibre Composites

ERIK GUNNARSSON

SUVIDHI KASLIWAL

DEPARTMENT OF TECHNOLOGY MANAGEMENT AND ECONOMICS,
DIVISION OF ENVIRONMENTAL SYSTEMS ANALYSIS

CHALMERS UNIVERSITY OF TECHNOLOGY
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www.chalmers.se

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Chalmers Supervisor: Frida Hermansson, IVL Swedish Environmental Research Institute

Volvo GTT Supervisor: Monica Johansson, Technology Strategy and Analysis, Volvo Group Trucks Technology.

Examiner: Magdalena Svanström, Department of Technology Management and Economics, Division of Environmental Systems Analysis.

Master's Thesis 2024
Department of Technology Management and Economics
Division of Environmental Systems Analysis
Chalmers University of Technology
SE-412 96 Gothenburg
Telephone +46 31 772 1000

Gothenburg, Sweden 2024

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Abstract

This thesis investigates the environmental impacts of recycling possibilities of carbon fibre reinforced polymers (CFRP), for which the intended use is carbon fibre tanks in fuel cell electric vehicles (FCEV's). The research, conducted in collaboration with Volvo Group Trucks Technology, IVL Swedish Environmental Research Institute and Chalmers, builds on a previous thesis by Weiszflog and Abbas (2022) that aimed to explore and analyse the implementation of different hydrogen storage systems and compare their environmental impacts.

This study focuses on identifying and evaluating potential commercial viability of the aforementioned recycling methods for CFRP. Each method's potential to produce high-quality recycled carbon fibres (rCF) suitable for second-life applications are examined through mechanical quality indicators, e.g. tensile strength, tensile modulus, length and diameter of the recovered fibre. The different recycling systems are later compared in a Life Cycle Assessment (LCA), where the environmental impacts are quantified and compared to one another based on the impact assessment methods climate change, cumulative energy demand, human toxicity, and resource use.

One of the primary goals of the thesis is to develop a framework for identifying second-life applications for rCF based on the resulting quality indicators after exiting the recycling processes, as well as complementing and adding onto existing inventory data. The study also analyses an exploratory option for recycling of CFRP, comparing the present with a potential 2030 scenario that considers different electricity mixes and their implications for recycling technologies.

Another primary aim for this thesis is to condense the large amount of information available on carbon fibre recycling and its resulting mechanical quality into a table that can be used in future assessments. The thesis also aims to act as inventory data for future work related to CFRP recycling.

The research concludes that effective recycling of CFRP can significantly reduce the environmental impacts associated with the material's production and disposal. By implementing improved recycling technologies, either the same industry or neighboring industries, such as nautical or personal vehicles, can use the rCF instead of virgin carbon fibre (vCF), and through the usage make substantial strides towards decarbonisation and addressing the exponentially growing demand for carbon fibres.

Keywords: **Life Cycle Assessment, Carbon Fibre Reinforced Polymers, Hydrogen Storage, Quality Indicators, Thermal Recycling, Mechanical Recycling, Chemical Recycling, Second-Life Applications, Mechanical Properties, Second-Life applications.**

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We would also like to give our gratitude to the parallel thesis group consisting of Philip Ngo and Anthony Alfred, who were great company throughout the thesis and gave valuable insights into how carbon fibre composite tanks could be manufactured and how the mechanical properties of the composite impact the design aspects of the system.

We express our utmost gratitude to both Volvo GTT and Chalmers University of Technology for this valuable opportunity to deep dive into the world of LCA and have given valuable knowledge in both the technical area as well as preparing us for what is to come in the future.

Finally we would like to thank our families for their unending support throughout the work, this would not have been possible without you.

Erik Gunnarsson and Suvidhi Kasliwal, Gothenburg, June 2024

List of Acronyms

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

CE	Circular Economy
CED	Cumulative Energy Demand
CF	Carbon Fibre
CFRP	Carbon Fibre Reinforced Polymer
EoL	End-of-Life
FCEV	Fuel Cell Electric Vehicle
GWP	Global Warming Potential
HTHP	High Temperature & High Pressure
HTP	Human Toxicity Potential
HTPc	Human Toxicity Potential (carcinogenic)
HTPnc	Human Toxicity Potential (non-carcinogenic)
LCA	Life Cycle Assessment
MR	Microwave Radiation
rCF	Recycled Carbon Fibre
vCF	Virgin Carbon Fibre
SCF	Super-Critical Fluids
SFTT	Single Fibre Tensile Test

Nomenclature

Below is the nomenclature of parameters that have been used throughout this thesis. These are primarily used for the characteristics of the composite used and for the different constituents in either composites, solutions, or emissions.

Parameters

vf%	Volume fraction of solution/composite/emission
w%	Weight percentage in solution/composite/emission

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1

Introduction

The adoption of the Paris Agreement in 2015, aimed at limiting the increase in global temperatures to 1.5° C above preindustrial levels (UNFCC, 2021), has spurred a widespread increase in the global effort to mitigate climate change. This ambitious goal has led all sectors of the economy to reduce their greenhouse gas (GHG) emissions by 40% by 2030 (Erbach, 2016). The transport sector has an important role to play in achieving this climate target. Road transport alone is responsible for around 15 % of the total global carbon dioxide emissions, with long-haul transport contributing to about 30 % (Ritchie, 2020) of these emissions. A rapid switch to electric and hydrogen Fuel Cell Electric Vehicles's (FCEV's) is recommended to enable decarbonisation within the next decade (McDonagh, Connelly, and Teter, 2023). However, the adoption of FCEVs presents its own set of challenges. The highly flammable hydrogen gas is stored under high pressures and should be contained in robust tanks (Weiszflog and Abbas, 2022; Hassan et al., 2023). These tanks, often made from Carbon Fibre Reinforced Polymers (CFRP), are lightweight but durable and very strong. CFRP gives them the ability to meet the safety requirements of stress, strain and thermal conductivity proving them to be the most advanced solution to store hydrogen safely (Gómez and Santos, 2023).

From a life cycle perspective, the production of caron fibres is one of the most energy intensive steps in the manufacturing of CFRP products (Hermansson, Janssen, and Svanström, 2019). In addition, current end-of-life practices involve the landfilling or incinerating of retired CFRP waste, adding to the existing environmental burdens (Meng et al., 2017). However, landfilling is becoming less attractive to industry due to escalating costs, which has increased from 22€/tonne in 2010 (Milios, 2013) to 103.7 €/tonne in 2024 (GOV.UK, 2024) along with a tax on incineration set at 12€ / tonne in 2020 (Milios, 2013; Rybicka, Tiwari, and Leeke, 2016). Carbon fibres have also grown in popularity due to the aforementioned attributes and their demand is projected to exceed supply in the coming decade (Meng et al., 2018). Considering these factors, recycling of CFRP becomes increasingly crucial to reduce the intensive energy demand of producing caron fibres (Hermansson, Janssen, and Svanström, 2019), lower environmental burdens and save substantial costs (Meng et al., 2017). Alternatively, making changes at the product design stage offers another way to reduce resource burden. Exploring targeted second-life applications is yet another way to keep the material in the loop for longer (Weiszflog and Abbas, 2022).

In collaboration with Volvo Group Trucks Technology (GTT) and Chalmers University of Technology, this thesis work builds on the results of a previous thesis by Weiszflog and Abbas (2022) who recommended investigating prospective scenarios for CFRP recycling and studying the resulting quality of recycled carbon fibres (rCF). This thesis thus investigates the various commercially viable as well as promising lab-scale recycling technologies available for CFRP. The technologies were compared on the basis of their environmental performance and the quality of the recycled carbon fibre that they produce. The life cycles were analysed from a prospective point of view to better understand which new technologies would emerge and how their performance would change with the future electricity mix. The study was also challenged with the task of identifying the properties of carbon fibre that indicate its quality after recycling. The goal of enhancing the value of recycled CFRP was further supplemented with the proposal of a framework that aims at facilitating the use of recycled carbon fibre in second-life applications. This thesis is conducted in tandem with another thesis project dedicated to redesigning hydrogen storage tanks to reduce their environmental impact and make them better suited for recycling and/or a second life. The results from this thesis aided us in pointing out the most suitable recycling option in a prospective setting, that retains the most mechanical properties. Additionally, this work feeds into a larger initiative called ”Environmental impacts of recycling and accidents in carbon fibre composite life cycles”, financed by Åforsk, that addresses the need for an inventory with primary and scaled up data for Life Cycle Assessment (LCA) studies on different CFRP recycling options, as well as an inventory of mechanical quality indicators of the respective recycled fibres obtained from the various recycling options.

1.1 Aim

The purpose of the thesis is to assess the environmental impacts of recycling CFRP, exemplified by CFRP that has been used in hydrogen tanks at Volvo Trucks, and thereby comparing different recycling options available for that specific composite. One of the main objectives is therefore to explore suitable CFRP recycling options that produce good quality recycled carbon fibre and identify indicators that help evaluate the quality of the rCF obtained. The consequent aim of the assessment is to develop a framework that helps identify second life opportunities for the rCF based on established quality indicators. The thesis also focuses on comparing and analysing the place for the recycling options in a future setting with a cleaner electricity mix, where the current state of CFRP recycling with a European electricity mix, is compared to a prospective setting in 2030, using a Swedish electricity mix, to find an alternative relevant for both the present and a future.

1.2 Research Questions

The study was conducted in the context of assessing recycling technologies for the the CFRP that is currently being used in hydrogen storage systems at Volvo and the quality requirements for rCF. Through discussions and consultations, the main goal of the thesis would be to answer the following research questions (RQ):

- RQ1) What are the most prominent recycling options for CFRP, and how do they compare to one another based on mechanical quality indicators for recycled carbon fibre?
- RQ2) How do recycling alternatives compare to one another on the basis of environmental impacts?
- RQ3) What are the potential trade-offs between environmental impact and the obtained quality of the recycled carbon fibre for each recycling option?
- RQ4) How can second life options for recycled carbon fibres be determined?

1.3 Limitations to the study

In the thesis, there were limitations that had to be made in order to fit both the systems and the boundaries set for the study. Due to wanting to study the recovery of CFRP, the recuperation of the gases and liquids generated at the end of majority of the recycling processes have not been included. In addition, LCA modeling suggests that the recycling options operate at 100% efficiency. In majority of the cases, it is assumed that 100% of the material going into recycling comes out without losses. In practice, however there will be a range in quality due to degradation and losses in recycling. Additionally, the use phase of the composite has not been modelled in the LCA, mainly due to the fact that the degradation of the composites during the use phase would look alike, and that there was data constraints. Hence, it is assumed that the virgin carbon fibres (vCF) does not undergo any degradation throughout their lifetime and the quality of vCF remains the same until the end of its technical lifetime.

Another limitation that had to be made was excluding the production of the CFRP used in the first application. In preliminary results, production processes dominated the LCA results of the recycling options and skewed them. Therefore, the recycling options were compared without the CFRP production being included to give results that could be compared on an equal level. Another limitation is that the work primarily focused on the recovery of carbon fibres after going through the recycling processes and not on the matrix component, that being, epoxy resin. Finally, the recycling options is selected based on the availability of reliable, good quality data. Consequently, many propitious technologies are mentioned in the literature, and despite their promising outcomes, were not included in the comparative LCA study.

2

Technical Background

This thesis is built on the recommendations made in a previous thesis conducted at Chalmers by Weiszflog and Abbas (2022). They performed an LCA comparing various hydrogen storage solutions, including compressed, liquid, and cryo-compressed hydrogen. The results indicate that compressed hydrogen storage can be the most viable option if the CFRP it utilises is recycled at the end of its technical lifetime. The study thus briefly explores different recycling opportunities for CFRP through an extended LCA, primarily relying on data from an article by Meng et al. (2018) to compare the recycling options. The thesis recommended to consider the maturity of the recycling technologies and scale up the data from new technologies to match that of commercial ones for a fair and relevant comparison. This conclusion also emphasised the need for further LCA studies to improve the inventory data related to CFRP recycling, for more accurate and reliable results. Thus, this thesis, along with the one being conducted in parallel, represented the culmination of their work, aiming to create a comprehensive LCA model of recycling CFRP and manufacturing of CFRP tanks followed by the analyses of potential applications of CFRP after its first life cycle.

2.1 Carbon Fibre Reinforced Polymers

CFRP is a composite material that constitutes of carbon fibres suspended in a polymer matrix. The matrix acts as a binder for the various strands of carbon fibres and helps transfer load between the fibres (Lee and Park, 2013 ; Oliveux, Dandy, and Leeke, 2015). The composite has, since its emergence in the 1960s, seen a gradual to exponential increase in demand in the two previous decades and is projected to increase even more over the next few years. The demand is projected to increase from roughly 80 kt to 130 kt in just ten years between 2020 and 2030 (Isa et al., 2022).

CFRP is a robust material that finds extensive applications in numerous industries ranging from aerospace and defense applications to more novel applications, such as the sporting equipment industry. Their multi functionality can be attributed to their desirable properties such as high tensile strength, high tensile stiffness and low density which makes them very light with high mechanical properties, which makes it stronger than competing metals and alloys, such as steel or aluminium. They are also chemically inert (Oliveux, Dandy, and Leeke, 2015; Chen et al., 2023).

The composite comes in varying quality that depends on the application and the security standards the product has to fulfill. Depending on the mechanical requirements due to safety standards, carbon fibres can range from high performance premium carbon fibres for the space industry to intermediary carbon fibres for applications like sporting equipment (ISO, 2024; Meng et al., 2018). The mechanical performance of the fibres is a direct effect of the length of the fibre and its diameter. Tensile strength has a linear relationship with the length of the fibre while the tensile modulus increases with the increase in length to a certain point (Capela et al., 2017).

2.1.1 Production of Carbon Fibre Reinforced Polymers

The production of vCF is based on a model presented by Benitez et al. (2021), which gives a thorough explanation of the different sub-processes that goes into making vCF. This starts with the first step, where the raw material going in, polyacrylonitrile (PAN), is prepared through polymerisation where the PAN is mixed and made into monomers, which then goes through a spinning process. Afterwards, they are stretched before entering a sizing process, where chemicals coats the PAN to increase adhesion. The PAN fibres are then dried, relaxed, and wound onto a spool to make the fibres into a precursor that can be transported to another facility (Benitez et al., 2021).

This precursor fibre is later turned into carbon fibres through thermal treatments and further processing. This is done by unwinding the already wound precursor and then stabilising the fibres in an oxygen environment at 220 °C to 280 °C. After the stabilisation, the exhaust gases are treated, and the fibre gets carbonised at both low (750°C) and high (1500 °C) temperatures in order to remove unwanted substances still present. This is then followed by electrolysis to improve chemical qualities of the fibre. The fibre is then washed and dried before it goes through a sizing process, in which the fibre is coated to further improve adhesion and increase desired properties (Benitez et al., 2021). The vCF can then be mixed with a variety of different polymers to make CFRP, which depending on the polymer used, can be used in different applications. In this example, the vCF used is Toray T700S, which together with epoxy resin makes a composite that fits the right safety standards set (Toray, 2024). As the system of processes is quite extensive, and require high temperatures and various chemicals, the fibres are quite energy intense to produce, but can be considered as a viable option for CFRP tank manufacturing, as it can reduce the weight of the tank by up to 35% compared to aluminium alloys, and thereby increase fuel efficiency of the vehicle (Niu, 2008).

2.1.2 Recycling of Carbon Fibre Reinforced Polymers

CFRP recycling presents significant challenges due to the complex nature of composite materials, because there is a need to retain properties such as length, tensile strength, and tensile modulus of the fibres, while minimising the environmental impacts of the new material. There is also a need to partially or completely remove the polymer matrix from the fibres before being applied in a second use-phase (Meng et al., 2018; Jiang et al., 2009). Therefore, the following sections explain the most prominent solutions today, and how they are operating.

The main ways to efficiently recycle CFRP are through either mechanical, thermal, or chemical means, which all lead to a range in the quality of the obtained rCF. This is due to the fact the scientific principles behind the types of recycling mentioned above target the fibres and the matrix in different ways (Meng et al., 2018). All recycling technologies except mechanical recycling aim to degrade the polymer while preserving the carbon fibre as much as possible. There are currently many ways to adequately do this, including a variety of methods. The following sections describe the different recycling options and how they compare to one another.

2.1.2.1 Mechanical Recycling

The mechanical recycling technology is a process that utilises grinding and sorting to obtain a coarse, a fine, and a powdered fraction (Qureshi, 2022; Meng et al., 2018). In this recycling option, the polymer matrix is not removed from the carbon fibres, but instead is granulated into fibres of different sizes using an industrial grinder with automatic sorting, resulting in fractions that ranged in both length and fibre proportion (Kouparitsas et al., 2002). The fine and powdered fractions, which contain less resin residue, could be used for lower grade applications such as reinforcement and fillers, while the coarse fraction including more resin and longer fibres are assumed to be sent to an incineration site, where it could be used for energy recovery (Meng et al., 2018).

2.1.2.2 Chemical Recycling

The chemical recycling approach is a group of processes that uses liquid solvents, such as acetic acid, nitric acid, or acetone, to separate the composites into their constituting parts. In the case of CFRP, it is degraded into rCF and polymer matrix residues, which could be recovered and used again (Meng et al., 2018; Piñero-Hernanz et al., 2008). In general, chemical recycling yields non-contaminated rCF that can be used for higher-grade applications (Meng et al., 2018).

The chemical recycling options can be divided into different categories, mainly depending on their operating pressure and temperature. These include subcritical, where recycling is carried out at temperatures below 374°C at normal pressure, and supercritical, which decomposes the matrix at higher temperatures at higher pressures (Shetty, Pinkard, and Novosselov, 2022).

2.1.2.3 Thermal Recycling

Thermal recycling of CFRP is a group of recycling options that utilises high temperatures to decompose the polymer matrix in an inert environment. In general, the temperatures ranges from 450-700°C depending on the method used and the environment created. Inert environments are created using inert gases, such as nitrogen or argon. This then leads to the CFRP being degraded into pyrolytic gases and oil, which in turn presents separate challenges as those are considered dangerous emissions and hazardous waste (Shetty, Pinkard, and Novosselov, 2022 ; Meng et al., 2018). High temperature processes burn the material and thereby create tar and char, which in turn reduces the quality of the carbon fibre. The charring could be removed via a second pyrolysis reaction, but in that case there is a hightened risk of further rCF degradation (Shetty, Pinkard, and Novosselov, 2022).

3

Theoretical Background

3.1 Circular Economy

This thesis relates to the concept of circular economy (CE), which proposes a fundamental shift from the traditional economic model towards a more sustainable approach to resource management. In a more linear model, resources are extracted, processed into goods, used, and eventually discarded as waste, leading to the depletion of natural resources and environmental degradation (Bocken et al., 2016; Bocken, Boons, and Baldassarre, 2019). In contrast, a circular economy aims to close the loop of resource flows by keeping materials and products in use for as long as possible through strategies such as reuse, recycling, and remanufacturing (Ellen MacArthur Foundation, 2013). This transition towards a more circular economy is driven by various environmental, economic, and social aspects. Growing concerns about resource scarcity, waste generation, and climate change have highlighted the need for more sustainable consumption and production patterns (European Commission, 2020). By maximising the value of resources and minimising waste generation, a circular economy offers the potential to reduce environmental impacts and improve resource efficiency (Stahel, 2016).

Key principles of the circular economy include a variety of potential aspects, such as designing products for longevity, ease of repair, and recyclability, as well as promoting strategies such as sharing and leasing to prolong product lifespans (Geissdoerfer et al., 2017). Businesses play a crucial role in driving the transition to a circular economy by adopting circular business models, redesigning products, and rethinking supply chain processes (Kirchherr, Reike, and Hekkert, 2017).

In general, the concept of a circular economy represents a paradigm shift towards a more regenerative and sustainable economic system, with the potential to create value for businesses, society, and the environment, all at the same time (Rizos et al., 2016). This thesis relates to circular economy primarily through recycling, which emphasises the importance of longevity of the material, retention of mechanical quality indicators and the purity of the composite, which makes sure that it can be used in more than one application during its technical lifetime (Qureshi, 2022).

3.2 Life cycle assessment

LCA is a tool used to determine the environmental loads that products or product systems have, throughout their life cycle, from the extraction of virgin materials to when the product is discarded or recycled. The ideas behind the framework on life-cycle orientation were first introduced in the 1960s as a means to address pollution and material scarcity (Hauschild, Rosenbaum, and Olsen, 2018). It has since been further developed and was later in 2006 made into an ISO-standard when ISO 14040 and 14044 was introduced. They were brought forward to standardise the practice of assessing the environmental performance of processes and systems (ISO, 2006b; ISO, 2006a). This original framework can be viewed in Figure 3.1, where it is shown how the different frameworks can be divided into four separate parts; Goal and Scope Definition, Inventory Analysis, Impact assessment and Interpretation. All of these will be described in greater detail in the following sections.

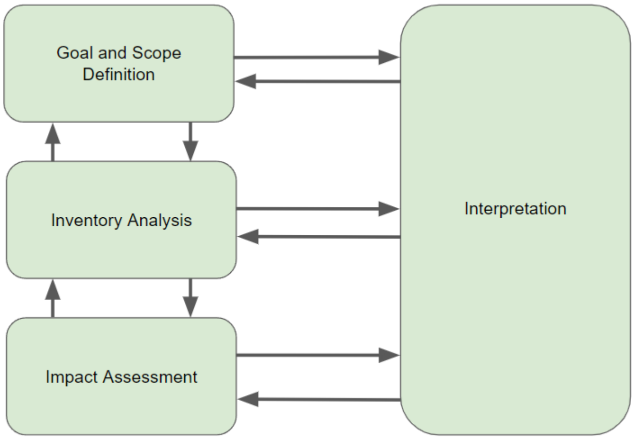


Figure 3.1: The Life Cycle Assessment Framework

3.2.1 Goal and Scope Definition

The goal definition of an LCA raises questions regarding who the intended audience is, what the primary reason for carrying out the study is, what the intended applications for the study is, whether the results are intended to be available to the general public (ISO, 2006a).

The goal is supported further by the scope, where the product or the system is explained in greater detail, and also how the report is intended to work with it. This involves deciding upon a functional unit (F.U.) for the study, which means in which term the results will be expressed, and whether that is sufficient for the intended purpose of the study. Thereafter, the boundaries of the study are further explained; these include the spatial boundaries, e.g., where the system is and what is considered apart of the system, the temporal boundaries, which explains when it is taking place, and the technical boundary, which explains which processes and pathways to include in the study (Tillman et al., 1994).

During the Goal and Scope definition phase, it is crucial to decide which type of modelling approach that is to be used in the study. The ones used primarily are attributional and consequential LCA's. An attributional LCA assumes that all material flows are already defined and are in a steady state within a temporal window, whereas consequential LCA does not assume such things and instead looks into how flows can change depending on decisions or actions by companies within the given system (Hauschild, Rosenbaum, and Olsen, 2018).

The system boundaries in the LCA of recycling options conducted in this thesis determine which processes and life cycle stages are included in the analysis. Common boundaries might involve raw material extraction, manufacturing, use phase, collection, sorting, recycling processes, and the disposal of non-recyclable residues (Baumann and Tillman, 2014). Deciding whether to include or exclude specific activities, such as transportation or secondary processing, can significantly impact the LCA results. There is, although, a cut-off between applicable results and complete system analysis when assessing systems because of availability and the potential large scale of the data.

3.2.2 Life Cycle Inventory Analysis

In Life Cycle Inventory (LCI) Analysis, the data required for the study is gathered and quantified to fit the system's parameters. Both inflows and outflows into the assigned sub-systems are analysed and quantified to understand the product system by analysing the raw materials needed, the different manufacturing steps required, transportation, distribution and storage of goods, usage and end-of-life of the assigned reference flow (Hauschild, Rosenbaum, and Olsen, 2018). The data gathered is then used as inputs and outputs in an LCA software, such as openLCA and Ecoinvent, to connect the different parts of the system to explain the product systems, processes, and flows, to compare and analyse different options and solutions (Wernet et al., 2016).

In the LCI, there is a need to distribute burdens and benefits between the various co-products and life cycles that are in the analysed system with the functional unit that is assigned in the Goal and Scope definition. This is realised via either subdivision, allocation modeling, or system expansion. All LCAs are being done in accordance with ISO 14044:2006, which states that allocation should be avoided if possible, through either subdivision or system expansion (ISO, 2006a). If that is not possible, the primary method for allocating flows in a multifunctional issue is to allocate using physical relationships, such as weight or volume. If that is considered insufficient, the allocation can be made through partitioning based on different relationships, such as economic value (Hauschild, Rosenbaum, and Olsen, 2018; ISO , 2006a).

3.2.3 Life Cycle Impact Assessment

The third step of the LCA is the Life Cycle Impact Assessment (LCIA), which is the part of the LCA where all inventory data are categorised and weighted to one another in different environmental impacts categories. Choosing impact categories in a LCA is a critical step as it directly influences the assessment's relevance to stakeholders and decision-makers. Impact categories represent environmental concerns that need to be evaluated across the product's life cycle (Baumann and Tillman, 2014). The selection of these categories must align with the industry context and the priorities of relevant stakeholders, such as regulators, customers, and investors. For example, industries like manufacturing or energy producers may prioritise categories related to carbon emissions, energy usage, hazardous waste and resource depletion, as these are closely scrutinised in regulatory frameworks and sustainability goals. On the other hand, sectors like agriculture may focus on land use, water scarcity, and biodiversity impacts due to the fact that it directly impacts the surrounding environment. The availability and quality of data also play a crucial role in determining which impact categories are feasible to assess. To ensure that the LCA addresses the most prominent environmental concerns, stakeholders can be consulted early, and thereby enhancing the credibility of the assessment. By carefully choosing the impact categories to industry needs and data constraints, LCA practitioners can produce more actionable insights that support informed decision-making and compliance with sustainability standards (Chevalier, Reyes, and Laratte, 2011).

3.2.4 Interpretation

The Interpretation part of the LCA is the last step in the process that integrates all the different parts of the study. The various information that is of interest is identified and evaluated with regard to their influence on the completeness and consistency of the study. The results of the evaluation are then used to formulate recommendations and conclusions at the end of the study (Hauschild, Rosenbaum, and Olsen, 2018). The main purpose of the interpretation step is to acknowledge that the entire process of conducting an LCA is iterative and that there is a need to go back and forth between the steps in order to continuously assess the sensitivity and uncertainty of the system (Baumann and Tillman, 2014).

3.3 Prospective Life Cycle Assessment

Prospective LCA (pLCA) is an approach where emerging technologies during their initial development stages (e.g., small-scale production) are evaluated based on their potential environmental impacts at a more advanced stage (e.g., large-scale production) (Arvidsson et al., 2018). This approach projects future environmental effects by modeling not just the current processes but also anticipating future technological advancements and changes in production scale. It is especially valuable for assessing technologies that have not yet achieved full market maturity.

CFRP recycling is an emerging technology, with many promising methods still being tested in the lab or at early stages of commercialisation (Rybicka, Tiwari, and Leeke, 2016). These processes are often inefficient and costly at present. To accurately assess its future environmental impact, a pLCA approach would be ideal. Since a prospective LCA analyses the technical system at a future point in time, the inventory requires a scale-up of the data available for the technologies at a lab scale to an industrial scale. Similarly, in the background system, the electricity mix is changed to the one that more accurately represents the ideal future electricity mix to avoid temporal mismatch (Arvidsson et al., 2018).

3.3.1 Technology Readiness Level

First developed by NASA in the 1970s, Technology readiness level (TRL) is a measuring system that evaluates the progress made by a technology from back of the envelope calculations to commercial viability. The scale serves as a point of reference for the progress of a particular technology and is a commonly used communication tool to diverse collaborators and stakeholders that communicates the maturity and validity of that technology (G. Manning, 2023).

The levels range from one to nine, one being the lowest and nine being the highest level representing the most developed technology. Each technology is evaluated against each other, comparing if they are conceptional, on a lab-scale, have a prototype reactor, or are on an industrial scale (G. Manning, 2023). The distance between TRL one and TRL nine is often that of decades of studies. The technology moves from fundamental research to systems research around TRL three or four and thereafter moves from being academia-centric to industry-centric around TRL six. Although knowledge transfer happens between academia and industry at all levels of the technology development (G. Manning, 2023; Banke, 2010). The TRL scale thus provides an overview of the technologies and aid in the potential commercial feasibility in either the far or near future.

3.3.2 Scaling up lab scale solutions for prospective assessment

Scaling up lab scale solutions is integral in the context of pLCA because it bridges the gap and provides pathways of how current experimental data can turn into future industrial processes, and there-through analyse the environmental impacts in a future setting (Arvidsson et al., 2018). Laboratory-scale data often fails to represent the complexities and efficiencies achievable in full-scale operations. For instance, material and energy usage typically improve as production scales increase, significantly affecting environmental outcomes (Piccinno et al., 2016). Furthermore, upscaling facilitates through the use of predictive models and simulations, and enable accurate environmental impact forecasting When working with emerging technologies and more specifically those at lower TRL, scaling up sub-systems becomes extra important for direct comparison with those at higher ones. This was accomplished through utilisation of both a theoretical framework for scaling up chemical processes and direct scaling up through specific process parameters. This was done through the utilisation of an article by Piccinno et al. (2016) for the chemical recycling options, as well as scaling up linearly under specific assumptions for the other technologies.

4

Methodology

The following section outlines the approach in which the concepts and frameworks from Section 3 were applied to answer the RQs defined in the thesis, both for the results presented in the next section to be meaningful and to guide potential future users of the method through the process. The flow of the methodology is illustrated in Figure 4.1 where the color of the dotted boxes indicates the RQ that was addressed by the methodological step in grey above.

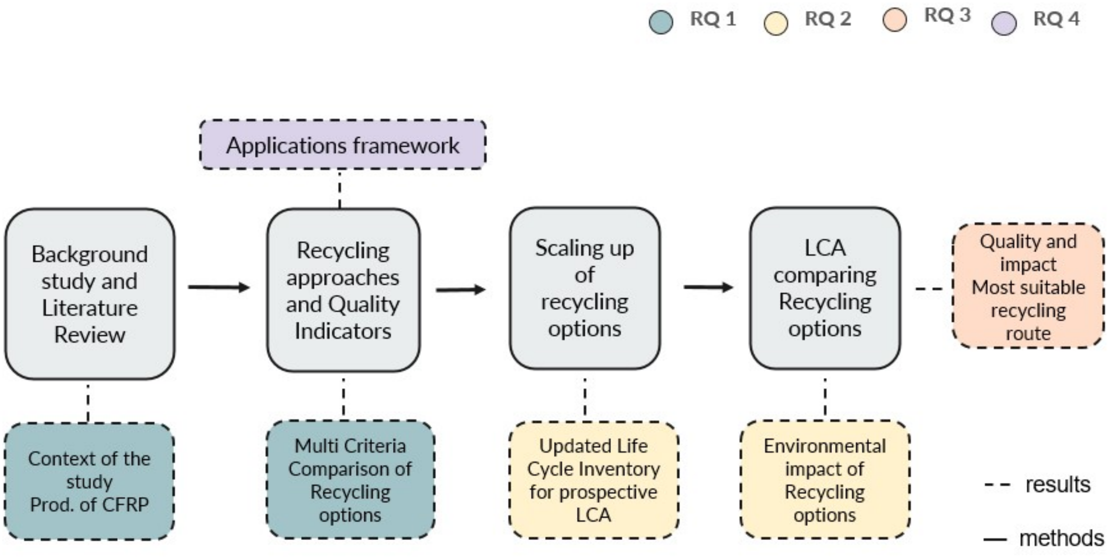


Figure 4.1: General overview of the Methodology

As a first step, a background study as described in Section 2, was conducted to understand the broader landscape of CFRP and give context to the problem statement. This was followed by a review of existing literature on CFRP recycling technologies, analysing their current status, advancements and limitations.

To answer RQ1, data collected on different types of recycling technologies from the literature review was compared and summarised in Table 5.3. The technologies were compared based on various criteria, highlighting the range of energy requirements of each technology and quality of recyclate obtained from them. The process of choosing recycling technologies for comparison and the criteria on which they are compared is explained in Section 4.2 and further in Section 5.1 and 5.2. The comparison revealed that all alternatives were not at the same TRL.

LCA was used as a tool to answer RQ2, however, comparing environmental impacts of technologies with varying TRLs would have resulted in a disproportionate evaluation. The next step thus involved scaling up the technologies with a lower TRL to industrial scale using the frameworks described in Section 3.4. The chemical recycling processes were scaled up using the framework developed by Piccinno et al. (2016) and the thermal processes were scaled up according to reactor volume. The calculations from this step are explained in detail in Section 4.4. The data collected for RQ1, along with results from the scaling up procedure were then used to create the inventory for the LCA which is one of the key results of the thesis. Results from the LCIA presented in Section 5.4 answer RQ2.

Data on quality indicators from Table 5.3 was combined with the LCIA results to create plots that illustrate the trade-offs between environmental impacts and the quality of rCF for each recycling option. These graphs, presented and discussed in Section 5.4, address RQ3 by providing a clearer understanding of the balance between sustainability and product quality.

Finally, to address RQ4, a “Second Life Applications Framework” was developed and proposed in this thesis. This framework positions rCF as a new material by matching its qualities to those of the virgin carbon fibre (vCF) that most closely aligns with its mechanical properties. This approach enables rCF to replace vCF in relevant applications, giving it a second life. The methodology is a developing solution and is detailed in Section 4.6, with an illustrative use case provided in Section 5.5.

The study’s results are discussed and compared to other relevant studies in Section 5.6.1 to provide a broader perspective. The thesis concludes with a section on further research, highlighting the study’s limitations and suggesting important areas for future exploration.

4.1 Data collection

Information for the thesis was collected from a variety of sources. Primary data collection involved consulting experts from Volvo GTT and researchers at Chalmers University of Technology, project-affiliated suppliers, and through study visits. In instances where certain data for the LCA study was not readily accessible such as the background system, the ecoinvent v3.10 database was used, as well as pertinent literature sources (Wernet et al., 2016). In addressing potential data gaps, informed estimations were formulated in collaboration with the guidance of the thesis supervisors. Additionally, for the qualitative analysis, relevant case studies were referred to build on the information gathered from primary sources,

The literature data collection was done between January and April in 2024, using platforms such as Web of Science, Google Scholar, and ScienceDirect with sources being prioritised by date of publication, citation count and relevance to the thesis. To adjust the information found in the literature to the context of the thesis, input from experts and industry contacts at Chalmers University of Technology and Volvo GTT was considered. The data for the quality indicators related to its mechanical properties were collected from the same trusted data bases as above.

4.2 Comparing Recycling Alternatives

Recycling technologies for this study were selected through a systematic approach involving three stages of literature review to ensure relevance and data robustness. The initial search aimed to identify and list all recycling technologies developed for CFRP. The subsequent search was conducted prioritising studies that specifically examined the quality of rCF after recycling. Finally, a third search targeted LCA studies that analysed CFRP recycling technologies. Technologies common to all searches were then narrowed down and selected based on the robustness of data, as well as their promising results in preserving fibre quality.

The recycling technologies selected were mechanical recycling, fluidised bed recycling, pyrolysis, microwave pyrolysis (MR), solvolysis using acetic acid, solvolysis using supercritical fluids (SCF) and superheated steam recycling. However, another promising recycling method using Electrolytic sulfuric acid (Okada, 2024) was excluded due to insufficient data and lack of relevant research on the topic.

The selected recycling alternatives were systematically compared in a table, with the technologies listed in columns and the criteria for comparison in rows. Key parameters for this comparison were established after extensive discussions with experts from Volvo GTT and our supervisor at IVL Swedish Environmental Research Institute. These parameters are further detailed in Section 5.1. An overview of the selected recycling options can be found in Section 5.2. The properties of the resulting rCF from each technology are contrasted to those of vCF type T700S which is type of carbon fibre most commonly used in the transport industry, in Figure 5.1.

The recycling methods differ in their TRLs. Mechanical recycling and pyrolysis are mature technologies, with TRLs greater than 7, while the other recycling methods have only been tested on a lab scale and have TRLs below 5. To ensure a fair comparison in a prospective scenario, data for the technologies with TRLs below 5 were scaled up to match those at the commercial level.

In all of the other recycling methods, except mechanical recycling and the fluidised bed process, it was assumed that the resulting rCF acquired would be able to be unwounded after recycling and therefore would be continuous. The amount of energy required to unwind 1 kg of CF was based on previous assumptions made by Benitez et al. (2021). They modelled the winding of a CFRP tank, which was around 853 MJ of electricity per tank. This was scaled down based on the amount of CFRP that went into the existing Volvo tanks. Due to confidentiality, the amount of CFRP used in these tanks cannot be disclosed. The following sections outline the processes for each recycling option and provide context for the assumptions made in the modeling of the LCA study.

4.2.1 Mechanical recycling

Mechanical recycling is, in comparison to the rest of the recycling options, the most mature technology, and is therefore already up to scale (Zhang et al., 2020). This is mainly due to its commercial viability today and because it is less energy intensive to operate, with 0.17-0.27 MJ being used per kg of CFRP (Meng et al., 2018). In this assessment, the higher range of the two was used, that is, 0.27 MJ of electricity per kg of CFRP.

The assumptions regarding mechanical recycling that were made in the study were primarily based on existing LCA studies being done, where the mechanical recycling option uses only electrical energy to grind down the CFRP and is thereafter separated into a coarse fraction, a fine fraction, and a powdered fraction (Meng et al., 2018). These were assumed to later be either used again in second-life applications or were landfilled, as shown in Figure 4.2.

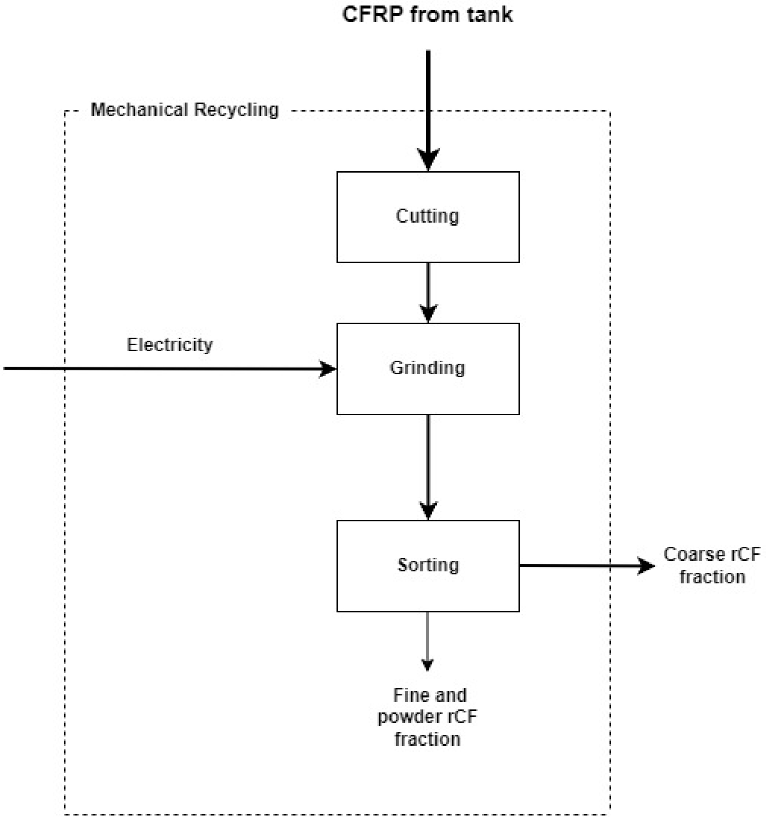


Figure 4.2: Flowchart of the mechanical recycling option

4.2.2 Pyrolysis recycling

The pyrolysis recycling option was another mature technology which was determined to not require any further scaling up, other than scaling up the reactor to fit continuous CFRP entering and continuous rCF exiting the system. Therefore, the modeling was based on previous work comparing different recycling options for CFRP (Meng et al., 2018). They presented the amount of energy that was used, both in terms of electricity, natural gas and what type of emissions that were present within the system. 13.7 MJ energy was carried by electricity and 23.8 MJ was provided by natural gas per kg of CFRP entering the system (Meng et al., 2018). The assumptions that are made for the continuous rCF exiting the system are based on the intended use case of the rCF, where a new CFRP tank gets made through winding of continuous fibres (Benitez et al., 2021).

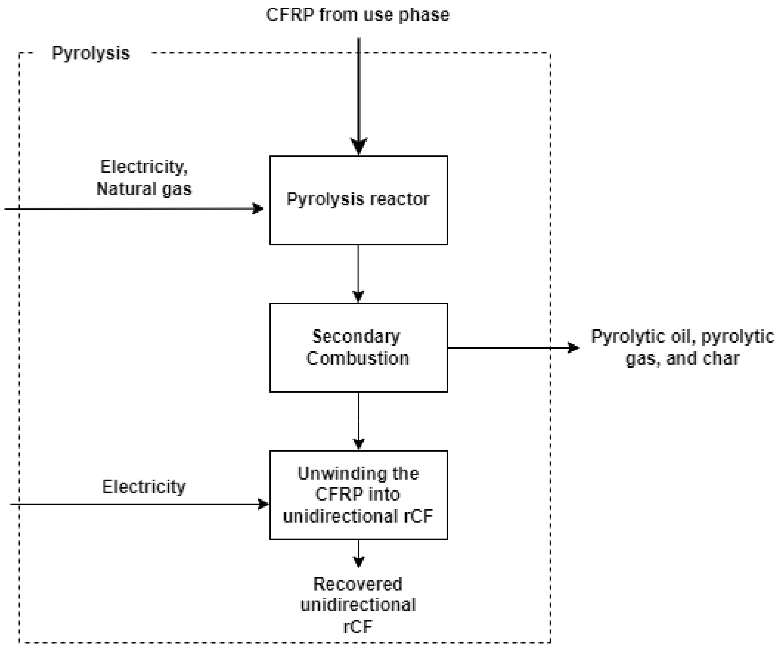


Figure 4.3: Flowchart of the pyrolysis recycling option

4.2.3 Fluidised bed recycling

The fluidised bed recycling of CFRP is not at the same TRL as mechanical recycling, but researchers at the University of Nottingham have built a pilot plant that shows how the recycling can be done on a larger scale (Pickering et al., 2015). This continuous pilot plant was used as the basis for the scaling up, where the energy requirements stayed the same, but the amount of silica sand going into the system was increased on the basis of the reaction vessel becoming bigger. The flowchart of the system can be seen in Figure 4.4, where grinded CFRP enters the continuous reactor that heats up and separates the milled rCF and the polymer matrix residue.

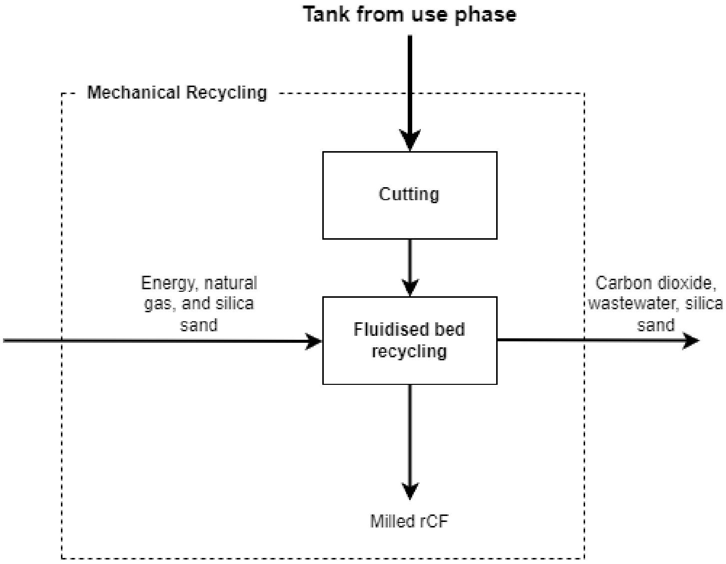


Figure 4.4: Flowchart of the fluidised bed recycling option

Meng (2017), that was apart of the project, stated in his report on the plant that 7 kg of silica sand was used for a smaller scale reactor with 0.33 m diameter, whereas the pilot plant was suggested to have a diameter of 1.4 m (Meng, 2017). The amount of silica sand was therefore based on the correlation between the diameter of the tank and the amount used. Based on the reactor volume, the amount of silica sand that was intended to be used was increased from 7 kg for the 0.33 m diameter reactor tank as specified in the smaller pilot plant to a bigger reactor tank with a diameter of 1.4 meters. This was then calculated using Eq. 5.1. where A_s is the amount used for the smaller tank, D_s is the diameter of the smaller tank, A_b is the amount used for the bigger tank, and D_b is the diameter of the bigger tank.

$$\frac{A_s}{D_s} = \frac{A_b}{D_b} \Longrightarrow \frac{A_s}{D_s} * D_b = A_s = \frac{7 * 1.4}{0.33} = 27.4\text{kg} \tag{4.1}$$

Although this bigger batch reactor being a bigger size that would be able to fit a larger amount of CFRP. The amount of silica sand was scaled up accordingly, but the energy required to recycle the entire CFRP sample was assumed to be the same as in the first pilot plant, which according to Meng et al. (2018), was considered to be about 4.5 MJ of electricity per kilogram of rCF exiting the process. The silica sand was asssumed to only be used for one iteration of recycling before being discarded and be discarded. This would not have been the case in practice as the reactor would be continuous and could be used for many kgs of CFRP, but since the recycling processes needed to be evaluated on the same basis, the same assumption was made as for the chemical recycling options, that the solvent was discarded after its use.

4.2.4 Solvolysis using Acetic acid

Solvolysis using acetic acid is a chemical recycling option that utilises a mixture of acetic acid and water to dissolve the matrix part of the waste CFRP into rCF and dissolved polymers (Meng et al., 2018). The flowchart of the system can be seen in Figure 4.5, where the CFRP waste enters a batch reactor and therein the CFRP is separated into its constituting parts, which could later be handled with or be reused as rCF in a second life. This data was primarily based on a comparative study made by Meng et al. (2018), but was complemented by an experimental study by Shetty, Pinkard, and Novosselov (2022) and was then scaled up on the basis of the Piccinno et al. (2016) article.

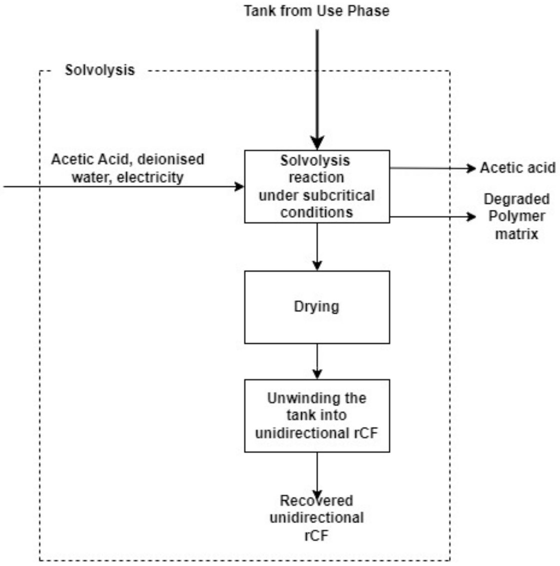


Figure 4.5: Flowchart of the solvolysis recycling option

The scaling up of the recycling option started with finding a reference point for the energy usage, which was based on an article by Meng et al. (2018). This study presented that 6.5 MJ of electricity were used per kg of CFRP waste. This in turn produced 0.55 kg of rCF after recycling, which meant that for 1 kg of recycled rCF, 11.82 MJ of electricity would be used. It was however unclear in the article how scaled up these numbers were, and therefore they had to validated with a scaled up solution based on numbers that were used in Shetty, Pinkard, and Novosselov (2022).

This reference point was then compared to a scaled up version based on an article by Shetty, Pinkard, and Novosselov (2022) in order to understand and evaluate the different parameters for the scaling up model. In this article, they chose to have their chemical reaction run in an experimental batch reactor setup for 1800 seconds at a temperature of 300 degrees in a 50 wt% acetic acid solution in order to dissolve the matrix (Shetty, Pinkard, and Novosselov, 2022). After these numbers had been collected, the article by Shetty, Pinkard, and Novosselov (2022), could be used as input in a framework suggested by Piccinno et al. (2016), where the low TRL technology could to be scaled into a prospective industrial one.

The chemical plant's different processes, which were assumed to be heating and stirring, were scaled up to make a fibre that could be seen as viable rCF to be used in a second application. The equation of heating a reaction vessel is explained in Eq. 4.2, where the energy to heat the reactor, Q_{heat}, and the energy require to maintain the reaction temperature for the reaction time, Q_{loss} explain the total energy required to heat the specific reaction for the set amount of time, including an efficiency of the heating element, η_{heat}. The sub-equations for both Q_{heat} and Q_{loss} are explained in greater detail in Eq. 4.3 and Eq. 4.4, where it becomes apparent that there are more parameters in place to a chemical batch reactor, rather than just the energy required to heat the environment.

$$Q_{react} = \frac{Q_{heat} + Q_{loss}}{\eta_{heat}} \tag{4.2}$$

The central Q_{heat} was itself based on parameters, which are shown in Eq. 4.3 where Q_{heat} depended on the specific heat capacity (C_p) of the mixture, the mass of the mixture (m_{mix}) and the difference in temperature between the outside and inside of the reaction vessel. The specific heat capacity for the acetic acid was directly derived from MatWeb (2024a), which was 2.05 $\frac{J}{kg}$ K, and the specific heat capacity of water was 4.186 $\frac{J}{kg}$ K. The resulting specific heat capacity for the mixture came out to be the mean of the the two values, which was 3.118 $\frac{J}{kg}$ K. The mass of the mixture needed a few more steps to be calculated, starting with the density, which was directly gathered from VWR International (2024), where it was presented that the density for acetic acid was 1.049 g/cm^3, and 0.997 g/cm^3 for water. Because the mixture used was 50 wt% acetic acid and water, the resulting density was assumed to be the mean of the two, which came out to 1.023 g/cm^3. The mass of the mixture was then derived from the density times the volume of the mixture, which was 500 L, due to the fact that the reaction vessel was assumed to be filled by half to account for the displacement of liquids. This came out to 511.170 kg. In this setting, it is assumed that approximately 300 kg of CFRP is recycled. The reaction temperature was, as previously mentioned, 300 °C and the surrounding temperature was assumed to be 25 °C, which was a number already set by Piccinno et al. (2016).

$$Q_{heat} = C_p * m_{mix} * (T_r - T_0) \tag{4.3}$$

To maintain the set temperature throughout the duration of the reaction, Q_{loss} was used, which is presented in Eq. 4.4 The reaction depends on the surface area of the 1000L reactor (A), the thermal conductivity of the insulation material used (k_a), the thickness of the insulation (s), which together represent the rate of heat loss per Kelvin, came out to 3.303, which was already stated in Piccinno et al. (2016). Two more parameters that were used here was the temperature difference between the inside and outside of the reaction vessel, which came out to the difference between 300 and 25, as presented by Shetty, Pinkard, and Novosselov (2022) and Piccinno et al. (2016), and the reaction time (t), which was 1800 seconds, which was was presented by Shetty, Pinkard, and Novosselov (2022).

$$Q_{loss} = A * \frac{k_a}{s}(T_r - T_{out}) * t \tag{4.4}$$

The framework also explains how the stirring can be modeled in a scaled up scenario, where Eq. 4.5 from Piccinno et al. (2016) showed how the stirring of the bigger reactor could be calculated. The stirring happens once the reactor has reached its reaction temperature and thereafter it is stirred throughout its duration. The energy to stir the mixture for the set amount of time, was scaled up on the basis of the type of impeller used (N_p), the diameter of the impeller (d), the rotational velocity of stirring (N), the density of the reaction mixture (ρ_{mix}) and the reaction time (Piccinno et al., 2016). In this article by, both N_p was set to 3.44, d was set to 0.373, and N was set to 1.417 (Piccinno et al., 2016). The density however needed to be calculated, but as that calculation already has been presented above, it was calculated to be 1.023 g/cm^3

$$Q_{stirring}[J] = \frac{N_p * \rho_{mix} * N^3 * d^5 * t}{\eta_{stir}} \tag{4.5}$$

The different energies were thereafter calculated based on the assumptions presented in Table 4.1 and was inserted into the equations for heating and stirring of the reactor, e.g. Eq.4.2, Eq. 4.3, Eq.4.4 and Eq.4.5 (Piccinno et al., 2016).

Table 4.1: Parameters for solvolysis using acetic acid. [1] Piccinno (2016); [2] Shetty, Pinkard and Novosselov (2022)

Parameter	Value	Unit
Specific heat capacity of solvent (C_p)	3.118 [n/a]	$\frac{J}{kg} * °C$
Mass of the mixture (m_{mix})	511.170 [n/a]	kg
Density of the mixture (ρ_{mix})	1.023 [n/a]	g/cm^3
Reaction temperature (T_r)	300 [2]	$°C$
Reactor volume ($V_{reactor}$)	1000 [1]	L
Reaction time (t)	1800 [2]	Seconds
Impeller diameter (d)	0.373 [1]	m
Rate of heat loss per Kelvin ($A * \frac{k_a}{s}$)	3.303 [1]	W/K
Starting temperature (T_0)	25 [1]	$°C$
Power number of the impeller (N_p)	3.44 [1]	
Rotational Speed of agitator (N)	1.417 [1]	$\frac{1}{s}$
Efficiency of the agitator (η_{stir})	90 [1]	%

The results for the calculations are presented in Table 4.2, where Q_{react} came out to be 2.765 MJ/kg of recycled rCF, and $Q_{stirring}$ was calculated to be 0.531 MJ/kg of recycled rCF, which was significantly less than the the numbers presented by Meng et al. (2018), but was expected since the reaction would run on a bigger scale.

Table 4.2: Scaled up energy requirements for the solvolysis per kg of recycled rCF

Solvolysis		Unit
Q_{react}	2.765	MJ
$Q_{stirring}$	0.531	MJ

4.2.5 Solvolysis using Supercritical Fluids

The SCF recycling is like the conventional Solvolysis, based on using chemicals in a reactor to dissolve the CFRP into its constituents, that being rCF and the polymer matrix as monomers, that can either be used in a second life or be handled with through waste disposal. The flowchart of the system can be seen in Figure 4.6, where the CFRP enters the batch reactor and gets treated with an acetone mixture at high temperatures and at high pressures. The flow of the recycling option is based on an experimental study by Keith et al. (2019), which was later used as a base for scaling up into a prospective system, where the recycling is being done on a larger scale.

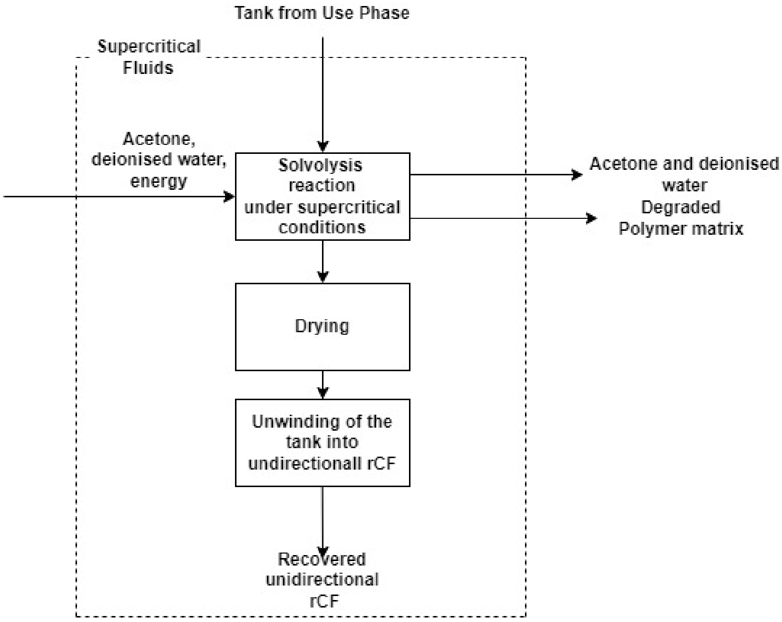


Figure 4.6: Flowchart of the Supercritical fluids recycling option

Like in the other solvolysis reaction, the assumed processes were heating and stirring, which can be seen in the flowchart, but instead of acetic acid, 80/20 v% of acetone solution was used at a slightly higher temperature, 320 °C for 7200 seconds (Keith et al., 2019). With these numbers in mind, the scaling up could commence, with starting to calculate the different parameters needed.

What needed to be done was to follow the same procedure as for the conventional solvolysis, with calculating Q_{heat} for the reaction at hand. This could be done by using Eq. 4.2, which in itself was dependent on both Q_{heat} using Eq. 4.3, and Q_{loss} using Eq. 4.4. As previously mentioned, in doing these calculations it becomes apparent that the reaction is highly variable and require a lot of different parameters.

The parameters used in Q_{heat}, were the mass of the mixture, the specific heat capacity of the mixture and the difference in temperature to the surrounding environment. To start, the mass of the mixture was calculated in the same manner as for the conventional solvolysis, meaning that it had to be derived from the density. This was used by first deriving the density of both the acetone and the water, where the density was derived through MatWeb (2024b) to be 2.15 g/ml, and together with water having the density 0.997 g/ml, the combined density could be calculated using Eq.4.6.

$$\rho_{combined} = \frac{\rho_1 * V_1 + \rho_2 * V_2}{V_1 + V_2} = \frac{0.997 * 0.2 + 2.15 * 0.8}{1} = 1.919 \frac{g}{ml} \tag{4.6}$$

The mass of the mixture was then calculated by multiplying the density with the volume of the mixture, which like the conventional solvolysis was assumed to be 500 L. This led to the mass being 959.5 kg. This then leads to calculating specific heat capacity of the mixture, which was derived using Eq. 4.7, where the specific heat capacity of acetone was gathered from MatWeb (2024a), where it was stated that the specific heat capacity of acetone was, 2.15 $\frac{J}{kg}$ K, and together with the knowledge that the specific heat capacity of water was 4.186 $\frac{J}{kg}$ K, the combined heat capacity could be calculated.

$$C_{pmixture} = (\frac{m_1}{m_{mixture}})C_{p1} + (\frac{m_2}{m_{mixture}})C_{p2} = ... = 2.381 \frac{J}{kg} K \tag{4.7}$$

With these calculations in mind, the scaling up could start, going through the same procedure as for the solvolysis using acetic acid using Eq. 4.2, Eq. 4.3, Eq. 4.4 and Eq.4.5, which numbers could be condensed into Table 4.3, which is shown below. In this example, the same assumptions were made regarding the tank parameters, meaning that the numbers used for tank dimensions, rate of heat loss, and stirring parameters for the reactor were the same as for the acetic acid one.

Table 4.3: Parameters used for supercritical fluids recycling. [1] Piccinno (2016); [2] Keith et.al (2019)

Parameter	Value	Unit
Specific heat capacity of solvent (C_p)	2.560 [n/a]	$\frac{J}{kg} * °C$
Mass of the mixture (m_{mix})	959.5 [n/a]	kg
Density of the mixture (ρ_{mix})	2.035 [n/a]	g/cm^3
Reaction temperature (T_r)	320 [2]	$°C$
Reactor volume ($V_{reactor}$)	1000 [1]	L
Reaction time (t)	7200 [2]	Seconds
Impeller diameter (d)	0.373 [1]	m
Rate of heat loss per Kelvin ($A * \frac{k_a}{s}$)	3.303 [1]	W/K
Starting temperature (T_0)	25 [1]	$°C$
Power number of the impeller (N_p)	3.440 [1]	
Rotational Speed of agitator (N)	1.417 [1]	$\frac{1}{s}$
Efficiency of the agitator (η_{stir})	90 [1]	%

These parameters could then be condensed into Table 4.4, where the amount of energy needed for recycling 1 kg of rCF is presented. This is slightly higher than the amount needed for the acetic acid, but that is because the reaction is heated for longer, and under different conditions.

Table 4.4: Scaled up energy requirements for the supercritical fluids per kg of recycled rCF

Supercritical fluids		Unit
Q_{react}	10.321	MJ
$Q_{stirring}$	7.482	MJ

4.2.6 Microwave pyrolysis

Microwave pyrolysis (MR) is a recycling technology that is not at the same TRL as technologies like conventional pyrolysis or mechanical recycling, and therefore needed to be scaled up as well. Because the recycling option could not be considered as a chemical process, the scaling up framework would not be applicable (Piccinno et al., 2016). Therefore, the recycling option was up-scaled based on the size of the reactor vessel, which was assumed to be 1,000 L, and that the tank would fit within this reaction vessel.

The recycling data was based on an article looking into MR pyrolysis recycling of CFRP and explained every step of the entire process (Ren et al., 2022). This article assumed that the sample is put into a batch reactor, where it is heated to 500° C for 15 minutes using Microwave radiation in an inert environment, where argon is being introduced been introduced. The resulting CFRP is then be oxidised one more time, raising the temperature to 550° C for 30 minutes in an oxygen environment (Ren et al., 2022). The flow of the recycling option can be seen in Figure 4.7.

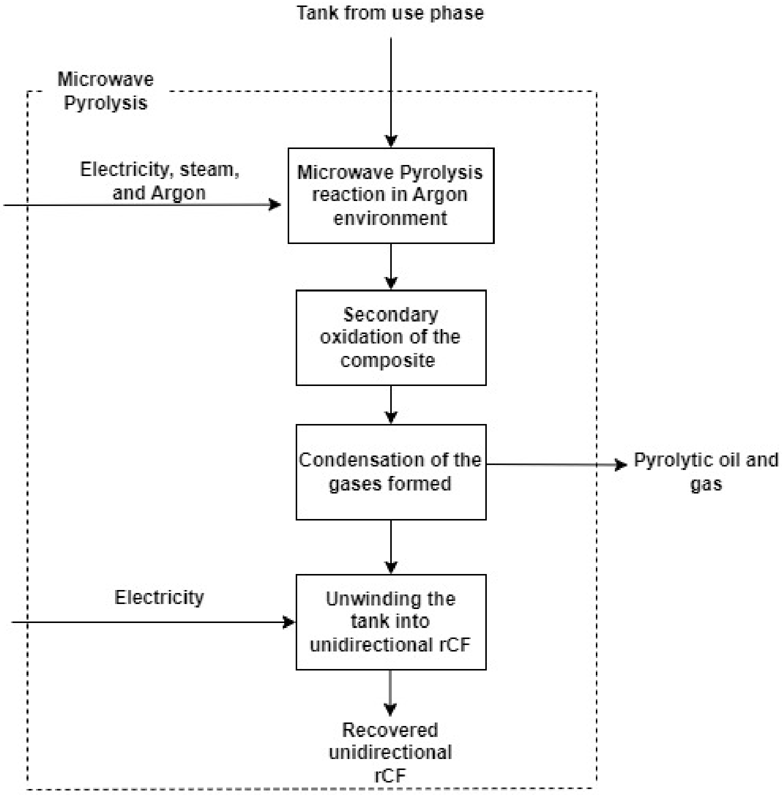


Figure 4.7: Flowchart of the MR Pyrolysis recycling option

The amount of both argon gas and electricity had to be scaled up to fit the 1,000 L prospective reactor. The amount of argon scaled up was based on the size of the reactor, where it in the original experiment used an inflow of 50 ml/min of reaction during its reaction cycle, which meant that for the 15 minute reaction time it used 750 ml of argon gas (Ren et al., 2022). The size of the reactor in the experiment was 26x28x31 mm, and by that the amount of argon gas required could by presented in the unit of ml/m^3, which was 6750 ml/m^3. These calculations were then used to scale up the amount used in a 1000 L tank, which scaled up to become 6.75 L. The energy required in the scaled up scenario was based on using a lower end of the required energy of the current situation, where several articles presented an energy use of 5-10 MJ of energy per kilogram of CFRP recycled (Ren et al., 2022; Job et al., n.d.). Therefore, to scale up the energy requirements, the assumed energy needed was 5 MJ/kg.

The gas that had been formed in the reaction vessel was then condensed, and thereafter, the non-condensible gas and the condensed liquids could be separated and collected. The article provided information about the composition of both the gas and the liquid, which was based on the article by Ren et al. (2022), but not about the actual amounts, due to the fact that they only presented those in volumetric fractions. Therefore, an assumption was made that the resulting gas and liquid would be the same amounts as for the conventional pyrolysis, and therefore the percentages were used on the amounts that the conventional pyrolysis resulted in. The argon that was used to make the reaction inert, was assumed to be collected together with the pyrolytic gas and later reused in the process. Although this study only looks at one iteration of the recycling, and therefore assumes that the argon is emitted together with the pyrolytic gas.

4.2.7 Superheated Steam recycling

The superheated steam recycling process is process that decomposes the CFRP into epoxy and rCF by utilising hot steam that gets introduced to the environment in a batch reactor. The reactor gets heated to 550° C and is oxidised during two separate reactions, both reaching 550° C before the gases and liquids formed are condensed and collected as its condensible and non-condensible fraction (Hecker et al., 2023). The flowchart of the system is presented in Table 4.8, which shows the parameters going into the reaction vessel.

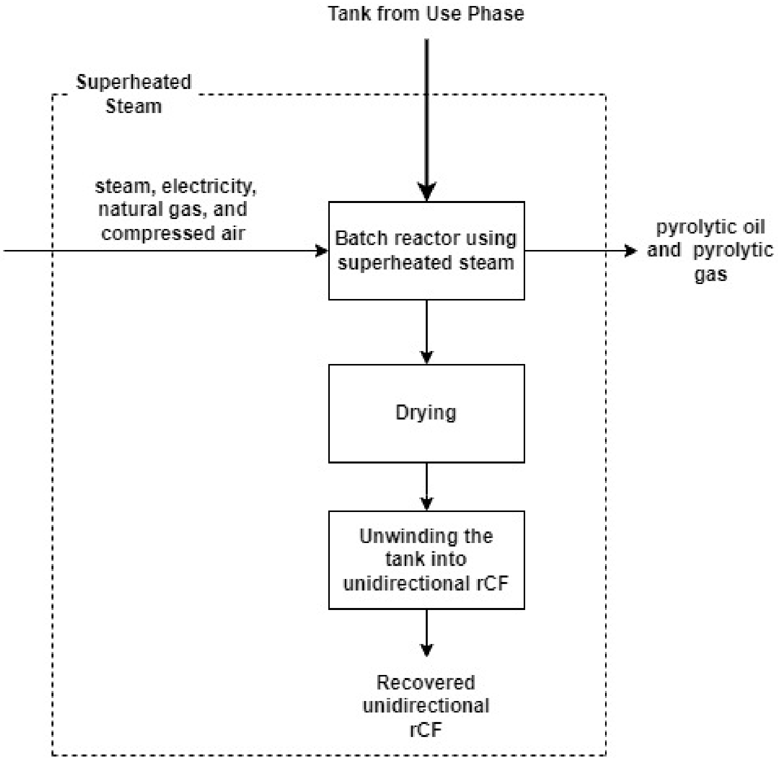


Figure 4.8: Flowchart of superheated steam recycling

This recycling option was like the solvolysis and SCF modeled according to the Piccinno et al. (2016) article, on the basis of Hecker et al. (2023). This reaction was then based on that the water was introduced as steam and was assumed to act like a chemical solvent in the reaction, and therefore could be used in the same manner as the chemical recycling options in a batch reactor. The processes involved in the reaction was therefore heating and stirring like the other two options, before getting unwounded into unidirectional rCF. The amount of steam entering the reactor was assumed to be scaled up based on the size of the reactor, meaning for 1000 L reactor, 1000 L of water vapour would be used.There could be a surplus of water vapour, and therefore the CFRP would not fit, but modeling for a surplus of water vapour ensures a more robust design, reducing the risk of performance variability or sporadic and unintended reactions that might arise from underestimating its dynamic behavior (Jain, Dhodapkar, and Villa, 2016). The specific heat capacity of water changed once it was heated, and therefore was derived from Engineering Toolbox (2024) to be approximately 2147 $\frac{J}{kg}$K at 550 ° C. The density of water remains the same, e.g.

0.997 g/cm^3, and the mass of the mixture is expected to remain the same as well. The entire reaction vessel was assumed to be filled with 1000 L of water, which comes out to 997 kg for the entire reaction vessel. These numbers, together with the already set parameters for a 1,000 L reactor in Piccinno et al. (2016) can be seen in Table 4.5.

Table 4.5: Parameters for superheated steam. [1] Piccinno (2016); [2] Hecker et.al (2023); [3] Engineeringtools (2024)

Parameter	Value	Unit
Specific heat capacity of solvent (C_p)	2147 [3]	$\frac{J}{kg} * °C$
Mass of the mixture (m_{mix})	997 [n/a]	kg
Density of the mixture (ρ_{mix})	0.997 [n/a]	g/cm^3
Reaction temperature (T_r)	550 [2]	$°C$
Reactor volume ($V_{reactor}$)	1000 [1]	L
Reaction time (t)	5400 [2]	Seconds
Impeller diameter (d)	0.373 [1]	m
Rate of heat loss per Kelvin ($A * \frac{k_a}{s}$)	3.303 [1]	W/K
Starting temperature (T_0)	25 [1]	$°C$
Power number of the impeller (N_p)	3.440 [1]	
Rotational Speed of agitator (N)	1.417 [1]	$\frac{1}{s}$
Efficiency of the agitator (η_{stir})	90 [1]	%

The assumptions made in 4.5 were then, like for the two chemical processes, inserted into Eq.4.2 and Eq. 4.5, which together with the equations Eq.4.3 and Eq. 4.4 in Piccinno et al. (2016) gave the results showed in Table 4.6. These energy requirements are quite high, but was expected as there was a need to heat the reactor to significantly higher temperatures and for a longer period of time than the conventional solvolysis.

Table 4.6: Scaled up energy requirements for superheated steam reactor per kg of recycled rCF

Superheated steam		Unit
Q_{react}	1510.878	MJ
$Q_{stirring}$	1.515	MJ

4.3 Goal and Scope Definition of the LCA study

4.3.1 Goal and context

The goal of the LCA study is to compare the environmental impact of all the recycling technologies as discussed in Section 4.2 in a prospective setting when all technologies are at an industrial scale. Furthermore, the impact of decarbonising the electricity grid on the technologies is also aimed to be studied by comparing the use of the current European electricity mix with the current Swedish electricity mix, which has a higher contribution from renewable energy sources on the system. Overall, the aim of the LCA study is to decide which technology alternatives are relevant for the future that minimise environmental impacts while maintaining high quality rCF.

The results of this LCA are intended for use by environmental researchers and academics studying sustainable materials and recycling processes, CFRP manufacturers and recycling companies seeking to understand the environmental implications of their processes, policymakers and regulatory bodies interested in developing guidelines and policies for the recycling of composite materials, investors and stakeholders in the CFRP industry aiming to make informed decisions based on environmental performance coupled with the quality of the obtained rCF.

4.3.2 Scope of the study

The product systems analysed were seven different ways of recycling CFRP, two mechanical recycling options, two chemical recycling methods, and three thermal recycling options were considered for this analysis. The LCA only calculates the burdens from the main recycling process and does not take into account impacts from preceding steps like the production of CFRP as discussed in Section 1.2.1.

It is a gate-to-grave, pLCA. Strong interpretation of sustainability is assumed in this study, meaning benefits of future recycling have not been included in the calculations and a End-of-Life (EoL) cut-off approach is modelled (Hermansson et al., 2022). The rCF only carries the impacts of the recycling processes.

4.3.2.1 Functional unit of the system

The functional unit for this LCA is defined as the recovery of 1 kg of rCF that leaves the recycling process to be used again after either being shredded or unwinded into unidirectional rCF. This unit will serve as the basis for comparison and quantification for inputs and outputs. The CFRP that is used is a 60 w% CFRP composite, which includes 60% carbon fibres and 40 % matrix. The calculations are based on one kg of CFRP from a CFRP tank. Therefore, 1.667 kg is used in a majority of the recycling options, where that amount of CFRP enters the system to recover 1 kg of rCF. This is although not the case for the mechanical recycling, which instead would need 2.326 kg of CFRP as an input due to the different fractions formed during the recycling process (Meng et al., 2018).

4.3.2.2 System boundaries

This section details the boundaries of the study, meaning, when, where and under which circumstances the study is assumed to be performed, where are all seven recycling technologies are assumed to be operated and where the residue is discarded. The technical boundaries of the system are illustrated in Sections 4.2.1 to 4.2.7.

4.3.2.3 Boundaries in relation to the natural systems

The life cycle study begins when the CFRP tank is retired and sent for recycling and ends at landfilling of the waste generated after successful recycling of CFRP. This has been illustrated in the flowcharts in Section 4.2. The emissions to water, air and soil do not go through any waste treatment methods before being released. The waste to landfill remains in the technical system as the temporal boundary is one year. Therefore, the applied temporal boundaries within the system begin from the point the tank leaves its use-phase to the point it became a unwinded unidirectional rCF that could be used again in other applications.

4.3.2.4 Geographical Boundaries

The CFRP is assumed to be manufactured somewhere in Europe, which means that a standard European electricity mix was used for the study. The tanks were assumed to be made at a certain facility, before they were transported and used in Sweden to make tanks that store compressed hydrogen on a Volvo GTT truck. The use phase of the CFRP is not taken into consideration since the degradation would be the same across all cases and would add equal amount of impact to all recycling options, keeping the net comparative analysis the same. The CFRP is assumed to be recycled not far from the Volvo facilities in Gothenburg, either through in-house recycling or having close cooperation with local waste management companies that do it for them.

4.3.2.5 Temporal Boundaries

The prospective setting is assumed to be set in a future where the CFRP tanks being used today would be retired after a estimated technical lifetime of 20 years and would thereafter be sent for recycling (Zhu et al., 2023). It is assumed that the electricity grid would have higher dependency on renewable energy in the future therefore the current Swedish electricity mix is assumed to be used in all operations in the prospective setting. This LCA study also compares the effect of decarbonizing the current electricity system on the recycling technologies for which the study compares the use of the current European electricity mix with the current Swedish electricity mix.

4.3.2.6 Boundaries within the technical systems

Capital goods changing with time or that need to be changed with time are not considered. Similarly, the need for personnel is also not included.

4.3.2.7 Impact Assessment methods used

The environmental impacts of the recycling options will be compared using the midpoint categories Global Warming Potential (GWP), Cumulative Energy Demand (CED), Resource Use, and Human Toxicity Potential (HTP). These purpose of using these impact categories was to analyse the actual impacts of the technical system, on both the surrounding environment and human life. The selection of impact categories was based on those most commonly used in previous studies on CFRP recycling found in the literature.

GWP quantifies GHG emissions of a product and its potential contribution to climate change. CED helps identify opportunities for energy reduction and encourages the use of renewable energy sources. An understanding of GWP and CED allows to make decisions that discourages use of fossil fuels and be more aligned with global sustainability goals. Resource use helps identify critical resources that may be limited or at risk of depletion. It highlights the need for recycling and promotes CE. Finally, HTP was to understand the implications of material choices and emissions from the processes on human health.

The system was analysed using the database ecoinvent 3.10 (Wernet et al., 2016) in the openLCA 2.1 LCA software, which is the most up-to-date version of both the software and the database. Included in the database are various different impact assessment methods, which all have a variety of categorisation factors of the various elementary flows related to emissions from the processes modeled in the software. The impact assessment method chosen in this study was the ReCiPe 2016 v1.03, midpoint (I) method, which analyses midpoint categories from an individualistic perspective, which in practice means looking at the various different impact categories 20 years into the future (Huijbregts et al., 2017).

4.4 Second-Life Applications framework

A framework was developed in this thesis to examine and explore the possibilities of a potential second life for the composite after its initial use. The framework was based on comparing the quality of the mechanical properties, tensile strength and tensile modulus, shown by CFRP after recycling with those of a virgin CFRP.

Data was collected on the quality indicators showcased by the CFRP after recycling. The value of those mechanical properties , tensile strength and tensile modulus, was then compared to the values of virgin CFRP using the fact sheet on different grades of CFRP provided by TORAYCA (Toray, 2024). The rCF was matched to the closest vCF in terms of mechanical properties on the fact sheet. The expected outcome was a new fact sheet that includes information on rCF that can potentially replace vCF in certain applications. This can be seen in Figure 4.9, where, as an example, the properties of higher grade recycled T800H and M46J, that have gone through recycling, match the mechanical properties of lower grade virgin T830H and M55J respectively and can replace them in different applications.

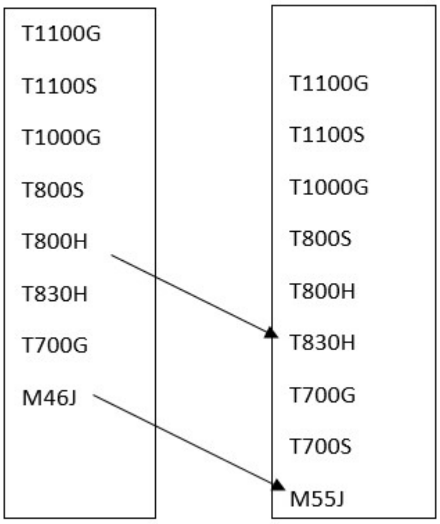


Figure 4.9: Match-making system of swapping virgin carbon fibre with recycled carbon fibre

It should be noted that this is a emerging framework and the match-making system is highly dependant on a wide range of factors other than the ones identified, such as degradation of the composite in its initial application, range of quality after recycling, surface treatment etc., but in an optimal scenario, where degradation is not accounted for and a set quality is assumed, this would be possible. The other factors out of the scope of the study are discussed in detail in Section 5.6.1.

The methodology can be easily recreated using fact sheets from different CFRP manufacturers. It can also be used for different materials to facilitate the use of recycled materials.

5

Results and Discussion

In this section, we present and interpret the findings of our research, combining results from data collection with existing literature to provide a complete understanding of the relationship between the data. The results are organised according to the research questions posed in the introductory chapter, with each subsection addressing a specific aspect of these questions. We begin with the key findings, followed by a detailed solution to the problem of missing data. Graphs are used as means to identify significant patterns and relationships between significant results, which are interpreted and then discussed in the context of previous studies. This discussion integrates the theoretical framework and methodology described earlier, offering insights into the implications of the results.

5.1 Quality of Recycled Carbon fibres

To achieve true circularity, it is not enough to divert efforts solely towards recycling; it is equally important to assess the material's quality after recycling to ensure it can be effectively reused in other applications. A key outcome of the project, thus, was identifying the mechanical properties that indicate the quality of carbon fibre post-recycling.The properties identified are as follows:

- Length: The linear magnitude of any thing as measured from end to end (Oxford English Dictionary, 2024)
- Diameter: Thickness of the fibre (Dai and Li, 2006)
- Tensile Strength: Maximum load a material can withstand under tension (Ismail, Khulbe, and Matsuura, 2019)
- Tensile Modulus: Measure of stiffness of a material, that is, ability of the material to not be deformed under load. The higher the modulus the higher the stiffness.(Vaidya and Pathak, 2019)
- Resistance to Fatigue: Ability of a material to withstand repeated cycles of stress and relaxation. (Scallan, 2003)

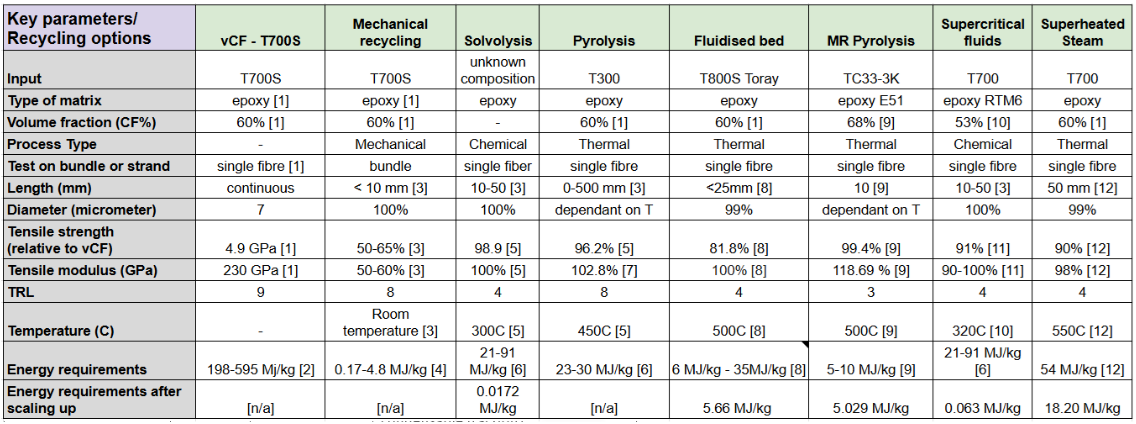
Length and diameter are the primary mechanical properties that directly influence the most sought after properties of CFRP which are tensile strength and tensile modulus. The relationship between tensile strength and length is directly proportional, that is, it increases as the length of the fibre increases. Whereas the stiffness of the fibre which is determined by the tensile modulus increases as the length increases but only up to a certain point after which it either remains the same or decreases with an increase in length (Capela et al., 2017).

Tensile strength and modulus both increase with a decrease in diameter. Carbon fibre has internal and surface defects that influence its strength. As the diameter increases, the concentration of these defects increase which in turn decrease the strength. Thus, a small aspect ratio of diameter to length of the fibre is desired. (Kong et al., 2014; Krishnan, 2019).

A higher length fibre makes for an easy manufacturing process for majority of the applications. Moreover, high length leads to a uniform application of the fibre that improves load distribution on the strand as well as across the matrix (citeantonyphilip). The primary focus in designing a recycling process should thus be to produce fibres with maximum length while maintaining their diameter (Zhang et al., 2020). In addition to the above properties, it is important to measure the fibre's ability to bounce back from repeated stress (Guo et al., 2022). The presence of certain chemical functional groups on the surface of the rCF such as as –OH, –CH, hydrogen bonds, –C= O, and -C-O groups, were also identified as an indicator of fibre health that forms bonds with the polymer matrix, effectively transferring load between the fibre and the matrix (Ren et al., 2022). However, these two properties are out of the scope of the study.

5.2 Comparing recycling alternatives

In this section the key quality indicators established in Section 5.1 are used to compare and contrast the recycling alternatives. Some other parameters such as type of input CFRP, its matrix type and the percentage of CF in the CFRP as the volume fraction, their process requirements, their TRL, if the test for mechanical properties was conducted on a single strand or a bundle of fibre etc are used to provide context. vCF type T700S from (Toray, 2024) is used as a reference against which the recycling technologies can be examined. It should be noted that the energy requirements for vCF T700S represent energy for production. Figure 5.1 gives an overview of the comparison with key parameters in rows on the left and each recycling technology in a column on the right. The percentages noted for the mechanical properties represent the percentage of properties retained after recycling in comparison to the reference, vCF T700S.



Key parameters/ Recycling options	vCF - T700S	Mechanical recycling	Solvolysis	Pyrolysis	Fluidised bed	MR Pyrolysis	Supercritical fluids	Superheated Steam
Input	T700S	T700S	unknown composition	T300	T800S Toray	TC33-3K	T700	T700
Type of matrix	epoxy [1]	epoxy [1]	epoxy	epoxy	epoxy	epoxy E51	epoxy RTM6	epoxy
Volume fraction (CF%)	60% [1]	60% [1]	-	60% [1]	60% [1]	68% [9]	53% [10]	60% [1]
Process Type	-	Mechanical	Chemical	Thermal	Thermal	Thermal	Chemical	Thermal
Test on bundle or strand	single fibre [1]	bundle	single fiber	single fibre	single fibre	single fibre	single fibre	single fibre
Length (mm)	continuous	< 10 mm [3]	10-50 [3]	0-500 mm [3]	<25mm [8]	10 [9]	10-50 [3]	50 mm [12]
Diameter (micrometer)	7	100%	100%	dependant on T	99%	dependant on T	100%	99%
Tensile strength (relative to vCF)	4.9 GPa [1]	50-65% [3]	98.9 [5]	96.2% [5]	81.8% [8]	99.4% [9]	91% [11]	90% [12]
Tensile modulus (GPa)	230 GPa [1]	50-60% [3]	100% [5]	102.8% [7]	100% [8]	118.69 % [9]	90-100% [11]	98% [12]
TRL	9	8	4	8	4	3	4	4
Temperature (C)	-	Room temperature [3]	300C [5]	450C [5]	500C [8]	500C [9]	320C [10]	550C [12]
Energy requirements	198-595 Mj/kg [2]	0.17-4.8 MJ/kg [4]	21-91 MJ/kg [6]	23-30 MJ/kg [6]	6 MJ/kg - 35MJ/kg [8]	5-10 MJ/kg [9]	21-91 MJ/kg [6]	54 MJ/kg [12]
Energy requirements after scaling up	[n/a]	[n/a]	0.0172 MJ/kg	[n/a]	5.66 MJ/kg	5.029 MJ/kg	0.063 MJ/kg	18.20 MJ/kg

Figure 5.1: General overview of the Recycling Technologies. [1] Toraycma, 2021. [2] Benitez, 2021. [3] Chen, 2023. [4] Meng, 2018. [5] Kooduvalli, 2022. [6] Job et.al, 2016. [7] Ren et.al, 2023. [8] Pickering et.al, 2015. [9] Ren et.al, 2022. [10] Keith et.al, 2019. [11] Piñero-Hernanz et.al, 2008 [12] Hecker et.al, 2023

There are three main takeaways from the general overview of alternatives presented in Figure 5.1. First, all recycling methods have negligible effect on the diameter of the fibres. As a result of this observation, diameter was deemed redundant as a quality indicator in this study and was excluded from the comparison with LCA results in Section 5.6. Second, there is a variation in how well tensile strength and modulus are preserved after recycling in each alternative. It can be observed that MR pyrolysis retains the maximum tensile strength at 99 % closely followed by solvolysis with a negligible difference. The maximum tensile modulus is also retained by MR pyrolysis at 119 % followed by conventional pyrolysis at 102 %. The increase in tensile modulus can be attributed to the minimal amounts of resin residue left on the fibres (Pickering et al., 2015). The presence of residual epoxy leads to a poor adhesion between fresh epoxy and rCF (Ballout et al., 2022). The bonding remains poor even when a different polymer is used to bind the rCF (Bhandari and Nam, 2024). Mechanical recycling retained the lowest percentage of mechanical properties in the fibre. Due to lack availability of data, the degradation of tensile modulus in mechanical recycling was assumed to be in the same range as Tensile strength as suggested by Chen et al., 2023. It was considered to be a safe assumption as mechanical recycling simply chops the carbon fibre waste without degrading the matrix. Lastly, it should be noted that all recycling technologies except conventional pyrolysis and mechanical recycling are at a TRL less than 5. This means that these technologies have only been experimentally validated in a lab as discussed in Section 3.3.1 and hence had a less energy efficient recycling process compared to the technologies with TRL greater than 7 that have a improved process for commercialisation. Therefore, without bringing all the technologies at the same level of maturity, the less developed technologies show very high energy requirements per kg of recycled carbon fibre. This kind of data, if used directly, does not represent the full context of the study and leads to an unfair comparison. To avoid that, the data was scaled up to that of a mature technology which is further discussed in Section 5.3.

Apart from the mechanical properties, criterion like resin removal rate and contamination on the input vCF affect the surface chemistry of the fibres and in turn their mechanical performance. These are acknowledged in the discussion of the study.

5.3 Life Cycle Inventory analysis

This section presents the modeling aspects as well discusses the development of the current inventory of the studied system. It is a prospective comparative LCA with cutoff EoL modeling to compare the various different recycling alternatives and how the different inputs, processes, and flows relate to one another.

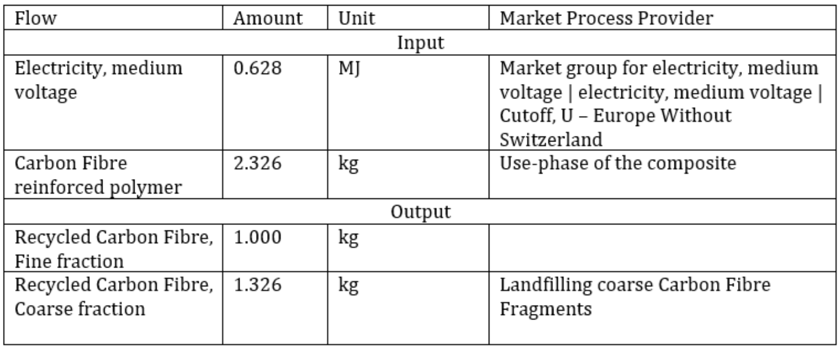
The LCA study relies on datasets of both scaled up solutions presented in Section 5.3 as well as already existing solutions found in literature. The input into the recycling alternatives is variable and is calculated to produce one kg of rCF exiting the reaction vessel where the CFRP going into the reaction is assumed to have a wt% of 60%. All the inputs and outputs for each type of recycling is based on the description in Section 4.3.

The various inputs and outputs that enter or leave the system are dependent on a range of surrounding processes. These are represented in the LCI as "Market Process Providers", which are already existing dependencies and represent sub-systems already modelled in LCA softwares, which are all showed in the following paragraphs. If an output does not have a Process Provider, it is assumed to be modeled as an elementary flow, that acts as a direct emission in the program (Wernet et al., 2016).

5.3.1 Inventory for Mechanical recycling

The mechanical recycling data is modelled based on Meng et al. (2018) as described in Section 4.2.1. Electricity is needed to mechanically shred the CFRP input. 43% of CFRP waste shredded comes out as fine rCF, which can be used again in an industrial application, and 57% of the remaining CFRP is grounded into a coarse fraction which is eventually landfilled or incinerated. The matrix adheres to the cut up fibres as no treatment is done to remove it. Table 5.1 shows how much CFRP is needed to produce one kg of the fine fraction, as that is more widely used in a second life (Kouparitsas et al., 2002).

Table 5.1: Life cycle Inventory of Mechanical recycling, based on data from Meng et al. (2018)

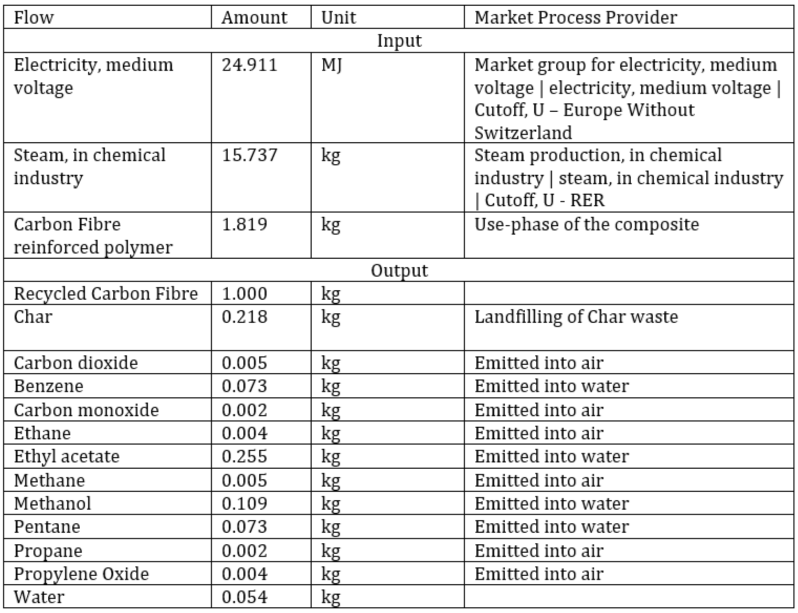


Flow	Amount	Unit	Market Process Provider
Input			
Electricity, medium voltage	0.628	MJ	Market group for electricity, medium voltage | electricity, medium voltage | Cutoff, U – Europe Without Switzerland
Carbon Fibre reinforced polymer	2.326	kg	Use-phase of the composite
Output			
Recycled Carbon Fibre, Fine fraction	1.000	kg	
Recycled Carbon Fibre, Coarse fraction	1.326	kg	Landfilling coarse Carbon Fibre Fragments

5.3.2 Inventory for Pyrolysis Recycling

The life cycle inventory of pyrolysis recycling was modelled on Meng et al. (2018) as described in Section 4.2.2. The matrix from the CFRP waste gets converted into two fractions: pyrolytic gases (non-condensable gases) which are carbon dioxide, carbon monoxide, ethane, methane, propane and propylene (here propylene oxide) and pyrolytic oil (condensable gases) which are benzene, ethyl acetate, methanol and pentane. A small percentage of CFRP gets downgraded to char, a brittle carbon-rich solid also known as pyrolytic-carbon residue.

Table 5.2: Life cycle Inventory of Pyrolysis recycling, based on data from Meng et al. (2018)

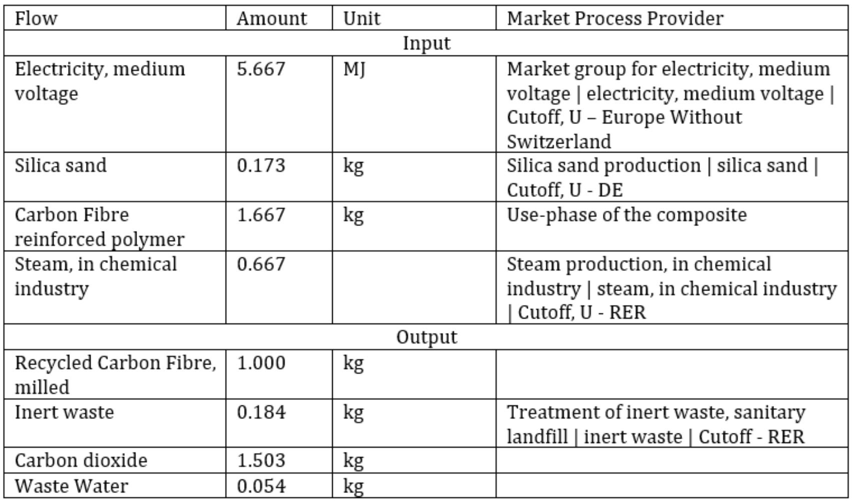


Flow	Amount	Unit	Market Process Provider
Input			
Electricity, medium voltage	24.911	MJ	Market group for electricity, medium voltage | electricity, medium voltage | Cutoff, U – Europe Without Switzerland
Steam, in chemical industry	15.737	kg	Steam production, in chemical industry | steam, in chemical industry | Cutoff, U - RER
Carbon Fibre reinforced polymer	1.819	kg	Use-phase of the composite
Output			
Recycled Carbon Fibre	1.000	kg	
Char	0.218	kg	Landfilling of Char waste
Carbon dioxide	0.005	kg	Emitted into air
Benzene	0.073	kg	Emitted into water
Carbon monoxide	0.002	kg	Emitted into air
Ethane	0.004	kg	Emitted into air
Ethyl acetate	0.255	kg	Emitted into water
Methane	0.005	kg	Emitted into air
Methanol	0.109	kg	Emitted into water
Pentane	0.073	kg	Emitted into water
Propane	0.002	kg	Emitted into air
Propylene Oxide	0.004	kg	Emitted into air
Water	0.054	kg	

5.3.3 Inventory for Fluidised Bed Recycling

As explained in Section 4.2.3, the fluidised bed recycling process is based on inventory data from a paper by Pickering et al. (2015). Silica sand acts as an input is used to make the CFRP particles volatile in the chamber. A small percentage of the matrix melted from the pieces falls down with the sand and is considered inert waste. The remaining matrix is assumed to be converted into carbon dioxide on combustion. Data for amount of silica sand used is taken from Meng (2017). It is assumed that the sand is discarded after each recycling process.

Table 5.3: Life cycle Inventory of Fluidised Bed Recycling, based on data from Pickering et al. (2015)

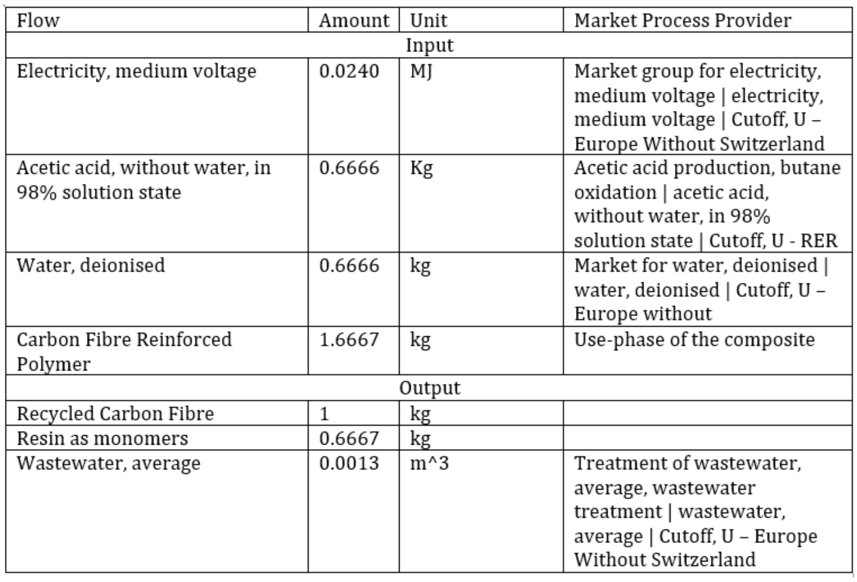


Flow	Amount	Unit	Market Process Provider
Input			
Electricity, medium voltage	5.667	MJ	Market group for electricity, medium voltage | electricity, medium voltage | Cutoff, U – Europe Without Switzerland
Silica sand	0.173	kg	Silica sand production | silica sand | Cutoff, U - DE
Carbon Fibre reinforced polymer	1.667	kg	Use-phase of the composite
Steam, in chemical industry	0.667		Steam production, in chemical industry | steam, in chemical industry | Cutoff, U - RER
Output			
Recycled Carbon Fibre, milled	1.000	kg	
Inert waste	0.184	kg	Treatment of inert waste, sanitary landfill | inert waste | Cutoff - RER
Carbon dioxide	1.503	kg	
Waste Water	0.054	kg	

5.3.4 Inventory for Solvolysis using Acetic Acid

For recycling using solvolysis, inventory data was based on a research paper by Meng et al. (2018) as mentioned in Section 4.2.4. Due to solvolysis being a chemical recycling process, the reaction by acetic acid is very specific and all of the resin is recovered as monomers. The data for electricity is based on the scaled-up calculations presented in the scaling up section of the results. The electricity mentioned in the inventory represents electricity for stirring the reactor vessel and electricity for continuously maintaining the temperature of the reactor vessel for the set reaction time.

Table 5.4: Life cycle Inventory of Solvolysis recycling, based on data from Meng et al. (2018)

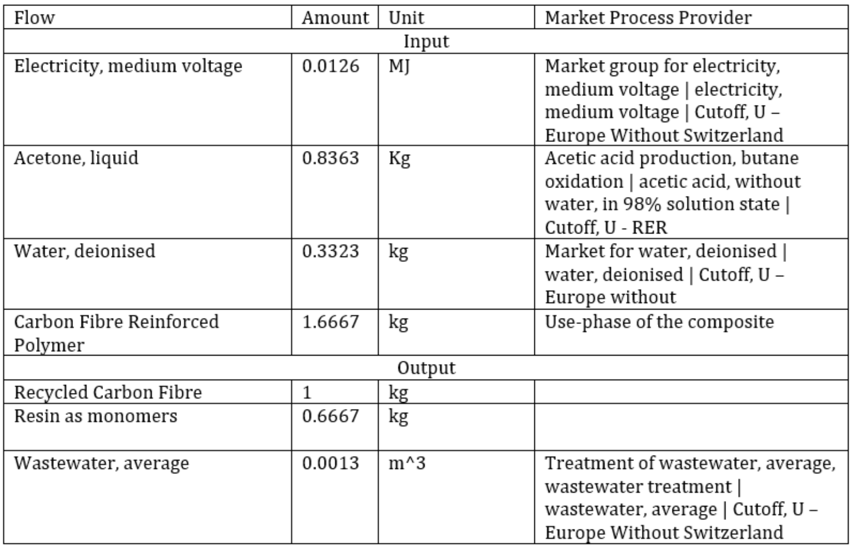


Flow	Amount	Unit	Market Process Provider
Input			
Electricity, medium voltage	0.0240	MJ	Market group for electricity, medium voltage | electricity, medium voltage | Cutoff, U – Europe Without Switzerland
Acetic acid, without water, in 98% solution state	0.6666	Kg	Acetic acid production, butane oxidation | acetic acid, without water, in 98% solution state | Cutoff, U - RER
Water, deionised	0.6666	kg	Market for water, deionised | water, deionised | Cutoff, U – Europe without
Carbon Fibre Reinforced Polymer	1.6667	kg	Use-phase of the composite
Output			
Recycled Carbon Fibre	1	kg	
Resin as monomers	0.6667	kg	
Wastewater, average	0.0013	m^3	Treatment of wastewater, average, wastewater treatment | wastewater, average | Cutoff, U – Europe Without Switzerland

5.3.5 Inventory for Solvolysis using Supercritical Acetone

For recycling using supercritical fluids, inventory data was based on a research paper by Keith et al. (2019), as depicted in Section 4.2.5. As seen in solvolysis, recycling using supercritical fluids is also a chemical process, thus the reaction by acetone is very specific and all of the resin is recovered as monomers in this case as well. The data for electricity is based on the scaled-up calculations presented in previous results for scaling up. The electricity mentioned in the inventory here represents electricity for stirring the reactor vessel and electricity for maintaining the temperature of the reactor vessel.

Table 5.5: Life cycle Inventory of Supercritical Fluid Recycling, based on data from Keith et al. (2019)

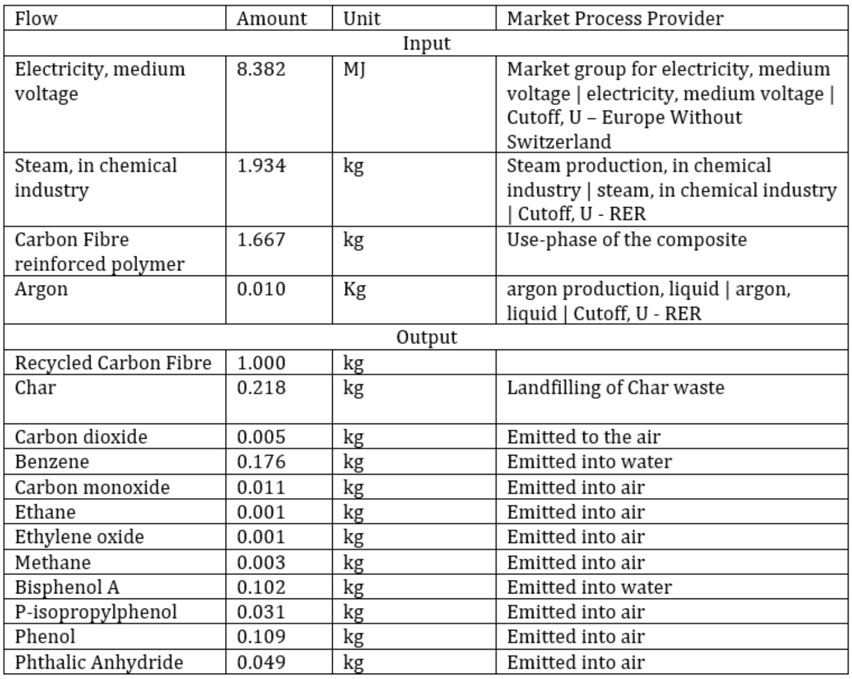


Flow	Amount	Unit	Market Process Provider
		Input	
Electricity, medium voltage	0.0126	MJ	Market group for electricity, medium voltage | electricity, medium voltage | Cutoff, U – Europe Without Switzerland
Acetone, liquid	0.8363	Kg	Acetic acid production, butane oxidation | acetic acid, without water, in 98% solution state | Cutoff, U - RER
Water, deionised	0.3323	kg	Market for water, deionised | water, deionised | Cutoff, U – Europe without
Carbon Fibre Reinforced Polymer	1.6667	kg	Use-phase of the composite
		Output	
Recycled Carbon Fibre	1	kg	
Resin as monomers	0.6667	kg	
Wastewater, average	0.0013	m^3	Treatment of wastewater, average, wastewater treatment | wastewater, average | Cutoff, U – Europe Without Switzerland

5.3.6 Inventory for Microwave Pyrolysis Recycling

As aforementioned in Section 4.2.6, this recycling option is modeled on the data found in a research paper by Ren et al. (2022). The input data for the amount of energy and argon gas was further scaled up according to the reactor size and added to the inventory here. Similar to the process of pyrolysis, the matrix from the CFRP waste gets converted into pyrolytic gases and pyrolytic oil. Carbon dioxide, carbon monoxide, ethane, ethylene oxide and methane make up the pyrolytic gases, which are assumed to be emitted into the air, whereas the benzene, bisphenol A, p-isopropyl phenol, phtalic anhydride and Phenol are the constituents of the pyrolytic oil, which is assumed to be emitted into surrounding water around the plant.

Table 5.6: Life cycle Inventory of Microwave Pyrolysis recycling, based on data from Ren et al. (2022)

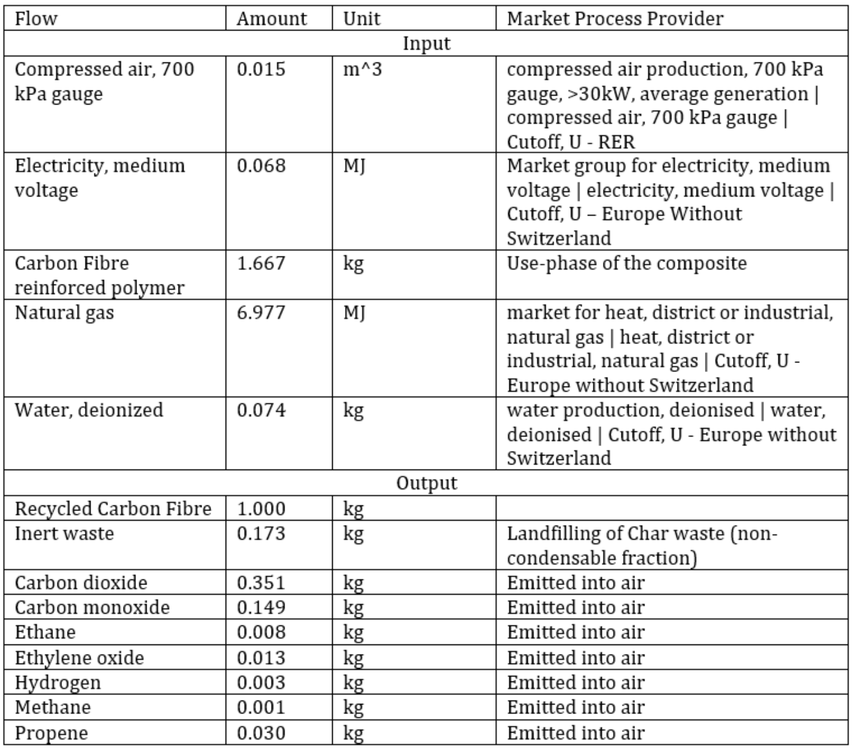


Flow	Amount	Unit	Market Process Provider
Input			
Electricity, medium voltage	8.382	MJ	Market group for electricity, medium voltage | electricity, medium voltage | Cutoff, U – Europe Without Switzerland
Steam, in chemical industry	1.934	kg	Steam production, in chemical industry | steam, in chemical industry | Cutoff, U - RER
Carbon Fibre reinforced polymer	1.667	kg	Use-phase of the composite
Argon	0.010	Kg	argon production, liquid | argon, liquid | Cutoff, U - RER
Output			
Recycled Carbon Fibre	1.000	kg	
Char	0.218	kg	Landfilling of Char waste
Carbon dioxide	0.005	kg	Emitted to the air
Benzene	0.176	kg	Emitted into water
Carbon monoxide	0.011	kg	Emitted into air
Ethane	0.001	kg	Emitted into air
Ethylene oxide	0.001	kg	Emitted into air
Methane	0.003	kg	Emitted into air
Bisphenol A	0.102	kg	Emitted into water
P-isopropylphenol	0.031	kg	Emitted into air
Phenol	0.109	kg	Emitted into air
Phthalic Anhydride	0.049	kg	Emitted into air

5.3.7 Inventory for Superheated Steam Recycling

The inventory data was modelled on the LCA study conducted by Nunes et al. (2018) as described in Section 4.2.7. The data for electricity needed to produce steam obtained from the LCA study was scaled up in Section 5.3.3 and used here. The matrix was converted into pyrolytic gas, which is assumed to be released into the surrounding air, e.g. carbon dioxide, carbon monoxide, ethane, ethylene oxide, methane, propene and hydrogen. The pyrolytic oil is however assumed to act as inert waste, which is later landfilled.

Table 5.7: Life cycle Inventory of superheated steam recycling, based on data from Nunes et al. (2018)

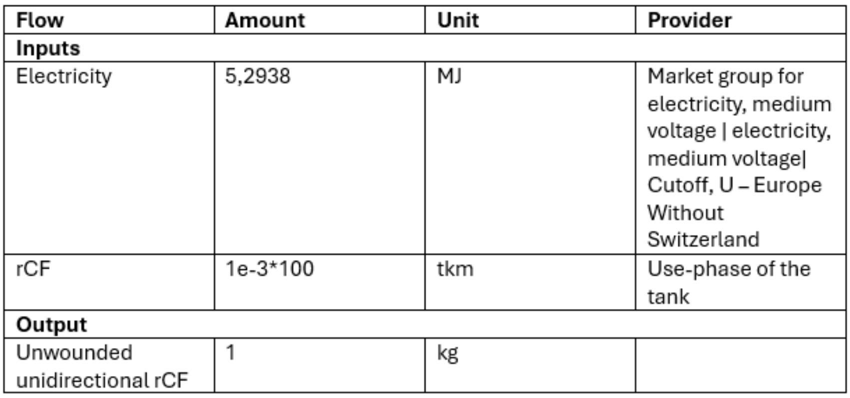


Flow	Amount	Unit	Market Process Provider
Input			
Compressed air, 700 kPa gauge	0.015	m^3	compressed air production, 700 kPa gauge, >30kW, average generation | compressed air, 700 kPa gauge | Cutoff, U - RER
Electricity, medium voltage	0.068	MJ	Market group for electricity, medium voltage | electricity, medium voltage | Cutoff, U – Europe Without Switzerland
Carbon Fibre reinforced polymer	1.667	kg	Use-phase of the composite
Natural gas	6.977	MJ	market for heat, district or industrial, natural gas | heat, district or industrial, natural gas | Cutoff, U - Europe without Switzerland
Water, deionized	0.074	kg	water production, deionised | water, deionised | Cutoff, U - Europe without Switzerland
Output			
Recycled Carbon Fibre	1.000	kg	
Inert waste	0.173	kg	Landfilling of Char waste (non-condensable fraction)
Carbon dioxide	0.351	kg	Emitted into air
Carbon monoxide	0.149	kg	Emitted into air
Ethane	0.008	kg	Emitted into air
Ethylene oxide	0.013	kg	Emitted into air
Hydrogen	0.003	kg	Emitted into air
Methane	0.001	kg	Emitted into air
Propene	0.030	kg	Emitted into air

5.3.8 Inventory of unwinding the composite

After the CFRP has gone through either solvolysis, SCF, superheated steam, pyrolysis, or MR pyrolysis, it was assumed to go through a process of unwinding, where the rCF in its current state is unwounded to a spool to be used again. This can be shown in Table. 5.8, where the rCF enters the system, and where it gets unwounded to spools to be used in a second life.

Table 5.8: Life cycle Inventory of Unwinding the composite (Benitez et al., 2021)



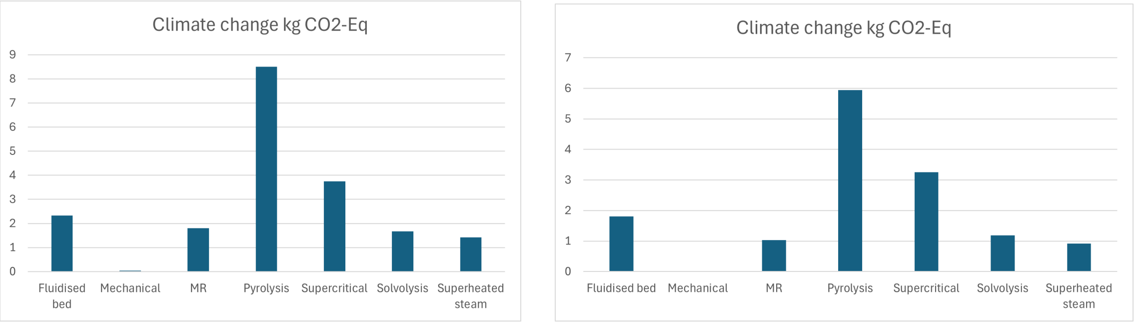
Flow	**Amount**	**Unit**	**Provider**
Inputs			
Electricity	5,2938	MJ	Market group for electricity, medium voltage | electricity, medium voltage| Cutoff, U – Europe Without Switzerland
rCF	1e-3*100	tkm	Use-phase of the tank
Output			
Unwounded unidirectional rCF	1	kg	

5.4 Life Cycle Impact Assessment results

This section presents the LCIA results of the LCA study comparing the different recycling options. The impact categories selected are climate change, global warming, Resource use, toxicity and cumulative energy demand. The calculations are based on the inventory analysis results presented in Section 5.3 which show a mass balance of inputs and outputs related to the recovery of recovering 1 kg of CF after recycling. The results are first compiled with the assumption that the recycling processes use a European electricity mix (EU) for their operation. The results are then compared to a future setting where a Swedish electricity mix (SE) is used to understand the impact of introducing a higher percentage of renewable energy on the system.

In the case of the impact assessment results, they are in the following section presented as absolute numbers, without presenting the contribution of the different sub-processes. This can instead be seen in Appendix A, where the various sub-processes are mentioned and their contribution are shown in graphs.

5.4.1 Climate Change results



(a) EU Climate Change results (GWP20)

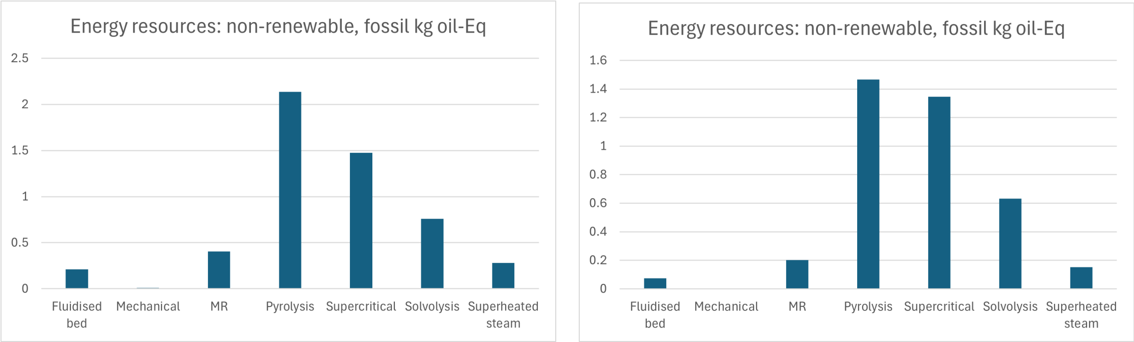
(b) SE Climate Change results (GWP20)

Figure 5.2: Global Warming Potential results for (a) a European Electricity mix, and (b) a Swedish electricity mix

Figure 5.2(a) illustrates the climate change impacts of the various CFRP recycling routes in kilograms of CO_2 equivalent (CO_2-eq) based on the European electricity mix. Amongst all the processes, the mechanical recycling method stands out as having the lowest climate change impact, mostly due to it utilising a small amount of electricity with values close to 0 kg of CO_2-eq. This indicates that mechanical recycling produces minimal GHG emissions, making it the best option solely from a climate perspective. The pyrolysis process, in contrast, shows the highest climate change impact, with a value reaching up to 8 kg CO_2-eq per kg of CF recovered. This significant difference is because pyrolysis is an energy intensive process that requires maintaining high temperatures for long durations and thus uses a substantial amount of natural gas along with electricity for its operation. The supercritical fluid process also exhibits a considerable climate impact, placing it in the middle range of the spectrum. This is mainly due to the use of acetone in the recycling process which is very energy intensive to produce.

On shifting to a Swedish electricity mix, all processes demonstrate a reduced impact as can be seen in Figure 5.2(b) and follows the same trend of highest to lowest impact processes as in Figure 5.2(a). Pyrolysis shows the highest reduction in impact of 2.5 kg CO2-eq from 8.5 kg CO2-eq with a European electricity grid to 6 kg CO2-eq with the Swedish electricity grid. Mechanical recycling has no negative impact on climate change while all the other recycling options reduce their impact in range of 0.5-1 kg CO2-eq when the grid is decarbonized.

5.4.2 Cumulative Energy Demand results



(a) EU Cumulative Energy Demand Results

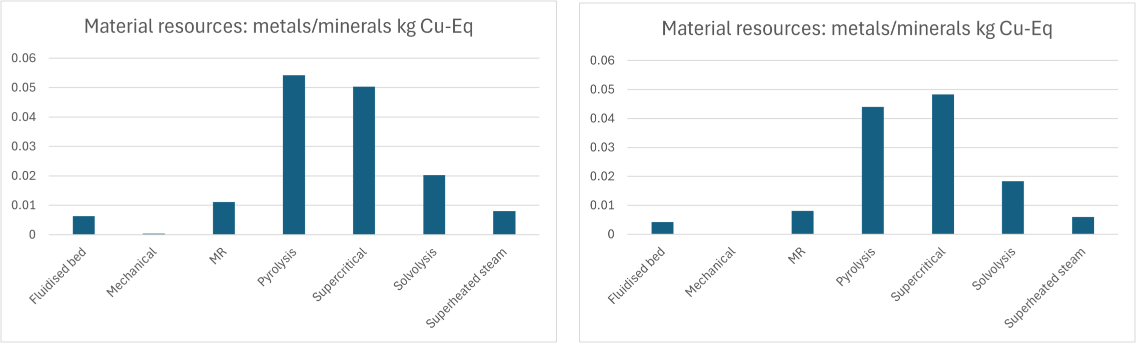
(b) SE Cumulative Energy Demand Results

Figure 5.3: Cumulative Energy Demand results for (a) a European Electricity mix, and (b) a Swedish electricity mix

Figure 5.3(a) illustrates the impacts from energy resources used by the various CFRP recycling processes in terms of kilograms of fossil oil equivalent (kg fossil oil-eq) used using a European electricity mix. Mechanical recycling has the lowest energy requirement amongst all the different processes. This could be attributed to the use of simple machinery to grind the CFRP using close to 0 kg fossil oil-eq. The technology is mature and thus energy efficient. On the other end, the pyrolysis process shows the highest energy demand with almost 2.2 kg of fossil oil-eq used per kg of CF recovered. The majority of energy is spent in maintaining very high operating temperatures. The supercritical fluid process also exhibits considerable demand for energy placing it in the middle range of the spectrum. This is mainly due to the energy needed for the production of acetone used in the recycling process.

Figure 5.3(b), which is based on a future setting using the Swedish electricity grid shows a lowered range of values for energy demand for all recycling processes. The order of highest to lowest impact processes remains the same with the use of the Swedish electricity grid, as seen in Figure 5.3(a). The highest reduction in impact is shown by pyrolysis with a reduction of 0.7 kg of fossil oil-eq from 2.2 kg to 1.5 kg fossil oil-eq. All the other processes show a change in energy demand in the range of 0.1-0.2 kg fossil oil-eq. Despite a positive change, pyrolysis still shows the highest cumulative energy demand and mechanical recycling shows the lowest cumulative energy demand when the electricity grid resembles the mix of the current Swedish electricity system.

5.4.3 Resource Use results



(a) EU Resource Use Results

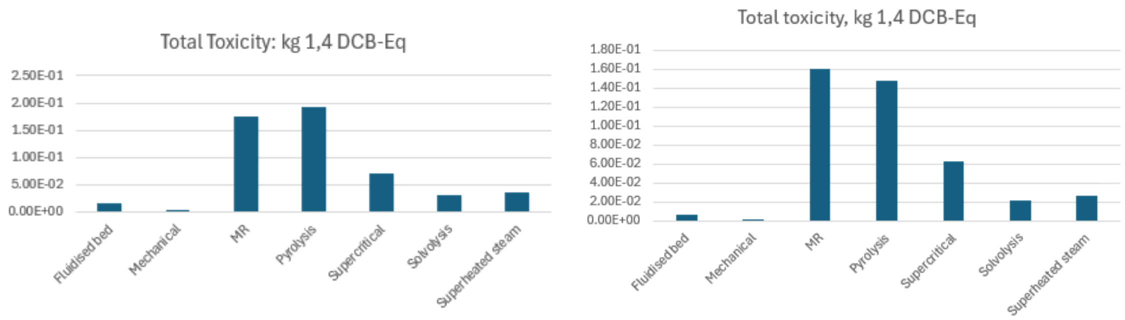
(b) SE Resources Use Results

Figure 5.4: Resource Use results for (a) a European Electricity mix, and (b) a Swedish electricity mix

The category represents the environmental burdens caused by the use of metals and minerals required in the process and is expressed in kilograms of copper equivalent (Cu-eq). Figure 5.4(a) presents the impacts from resource use based on a European electricity mix. Mechanical recycling does not require any inputs of supplementary metals or minerals in its operation, the only input is fuel for electricity. Thus, mechanical recycling shows the lowest impact with near 0 kg of resources used per kg of CF recovered. Pyrolysis and recycling using supercritical fluids have the highest impact on resource consumption. 55 g of Cu-eq is consumed to recover 1 kg of CF using pyrolysis and 50 g on using the supercritical fluids route. While pyrolysis consumes resources mainly for its intensive heat requirements, majority of the impact in supercritical fluids recycling comes from the production of acetone.

In the setting where the Swedish electricity grid is being used to operate the processes, the impact is dropped across all recycling options albeit very slightly Figure 5.4(b). Pyrolysis is the only process that showed a reduction in resource use greater than 2 g Cu-eq at 9 g Cu-eq. For this setting, recycling using supercritical fluids showed the highest impact on resource use while mechanical recycling remained as the lowest contributor. This could be due to the fact that for the production process of acetone, the electricity grid was not switched to the Swedish electricity mix. Since majority of the energy demand for supercritical fluids recycling comes from the production of acetone it shows very little change making it comparable to pyrolysis which has a significantly larger energy demand.

5.4.4 Human Toxicity Potential results



(a) EU Human Toxicity Potential results

(b) SE Human Toxicity Potential results

Figure 5.5: Human Toxicity Potential Results for (a) a European Electricity mix, and (b) a Swedish electricity mix

Total toxicity results here show levels of both carcinogenic and non-carcinogenic toxicity combined. They are expressed in terms of kilograms of 1,4-dichlorobenzene (1,4 DCB- eq) equivalents which is a known carcinogen for human beings. For the first setting using European electricity mix shown in Figure 5.5(a), the mechanical route being a simple method to recycle CFRP has the lowest HTP with close to 0 kg of 1,4 DCB-eq per kg of CF recovered. Pyrolysis and MR pyrolysis exhibit the highest levels of HTP. Emissions from the process and the large amount of heat required for pyrolysis contribute to the toxicity whereas in the case of MR pyrolysis the toxicity is solely a contribution of emissions to air, water and soil from the process itself. Pyrolysis causes human toxicity equivalent to exposure to nearly 0.2 kg or 200 g of 1,4 DCB- eq per kg of CF recovered and for MR pyrolysis the figure is close to 175 g of 1,4 DCB-eq per kg of CF recovered.

In the second setting using a Swedish electricity mix, all recycling options show lowered total toxicity levels. However, in this case MR Pyrolysis showed the highest impact instead of pyrolysis that came down to 0.141 kg 1,4 DCB-eq from 0.180 kg 1,4 DCB-eq. Mechanical recycling had the lowest impact.

5.4.5 Comments on impact assessment results

In the above impact assessment, all recycling technologies were compared to one another for their environmental performance under two settings. In the first setting, all technologies were assumed to be operating on a European electricity mix representing the current context. In the second setting, the electricity mix was changed to a Swedish electricity mix to model a future scenario where there is a higher percentage of renewable energy in the electricity mix and to understand its effect on the performance of the recycling technologies in a prospective setting.

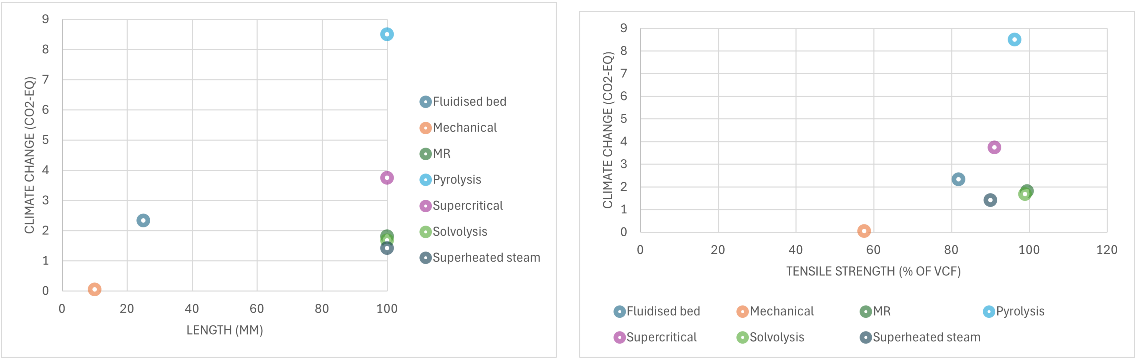
Mechanical recycling showed the lowest impact across all impact categories in both the settings. Pyrolysis performed the worst in the first setting across all categories while in the second setti it had highest impact for climate change and energy demand potential. All recycling technologies, however, showed a better environmental performance overall on switching to a Swedish electricity mix. The impact for worst performing recycling technology in the current context, pyrolysis, improved by 29% for GWP, 32% for CED, by 19% for resource use and 24.1% for HTP. Predictably, GWP turned out to be the most sensitive to a change in electricity mix followed by CED as decarbonisation of the electricity grid reduces GHG emissions and dependency on fossil fuels. These results further substantiate the transition to renewable energy.

5.5 Connecting Impact Category Results to the Quality Indicators

This section connects the environmental performance of each recycling option discussed Section 5.4 to the quality of the recycled carbon fibre they produce while comparing all recycling options.

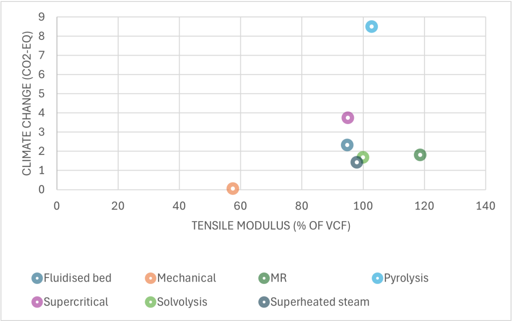
Different recycling technologies provide different quality of recycled carbon fibres. It is not necessary that a recycling process that has a low environmental impact produces rCF that meets the quality needed to close the loop. There is often a trade-off. The following section therefore compares the impact assessment results from each impact category to the quality indicators, namely, length, tensile strength and tensile modulus identified in Section 5.1 respectively for each of the recycling technologies. Each of the graphs presented below have the impact category in its respective unit on the y-axis and the quality indicator in terms of percentage of virgin quality preserved is on the x-axis.

5.5.1 Connecting Climate Change to quality indicators



(a) Climate Change compared to length

(b) Climate Change compared to tensile strength



(c) Climate Change compared to tensile modulus

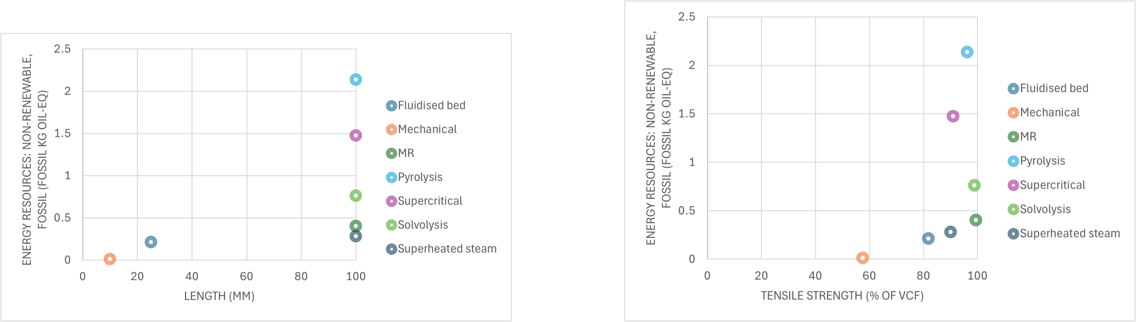
Figure 5.6: Climate Change compared to the different quality indicators: (a) Length, (b) Tensile Strength and (c) Tensile Modulus

Figure 5.6(a) compares the GWP results to the length of the recycled carbon fibre and compares it to the climate impact. As discussed in Section 5.1, the desirable quality is very high length of rCF with a low climate change impact. From Figure 5.6(a) it can be seen that both the mechanical and fluidised bed recycling options that require shredded CFRP waste as an input cannot be recommended. The remaining recycling options all provide an output of continuous rCF and were therefore compared on their climate change impact. This implies that the three overlapping coloured dots on the x-axis, that is, superheated steam followed by solvolysis then MR pyrolysis, are all viable options when considering the length of the rCFs.

Figure 5.6(b) compares the climate change impact to the tensile strength of the rCF. In this case, the recycling options that retained the highest tensile strength were solvolysis and MR pyrolysis. Conventional pyrolysis was a close third. However, it became apparent that the most viable option considering climate impact was solvolysis.

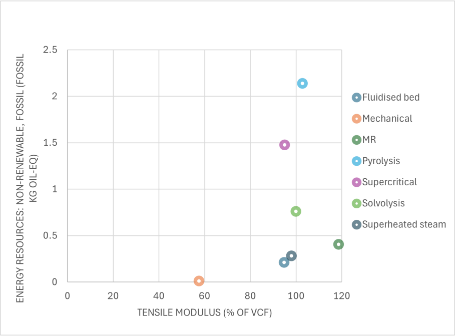
Figure 5.6(c) displays the climate impact in comparison to the tensile modulus of the rCF. The desirable combination of results is maximum modulus with minimum the environmental impact. Solvolysis retains 100% of tensile modulus while pyrolysis and MR Pyrolysis provide rCF with higher tensile modulus than that of vCF (Pimenta and Pinho, 2012). Superheated steam was also considered a good contender being close to 100 %. This increase in modulus can be attributed to the residual resin on the fibres and microwave irradiation. On comparing with the environmental impact, MR pyrolysis, solvolysis, and superheated steam are the most suitable options in that order.

5.5.2 Comparing Cumulative Energy Demand to Quality Indicators



(a) Cumulative Energy Demand compared to length

(b) Cumulative Energy Demand compared to tensile strength



(c) Cumulative Energy Demand compared to tensile modulus

Figure 5.7: Cumulative Energy Demand compared to the different quality indicators (a) Length, (b) Tensile Strength and (c) Tensile Modulus

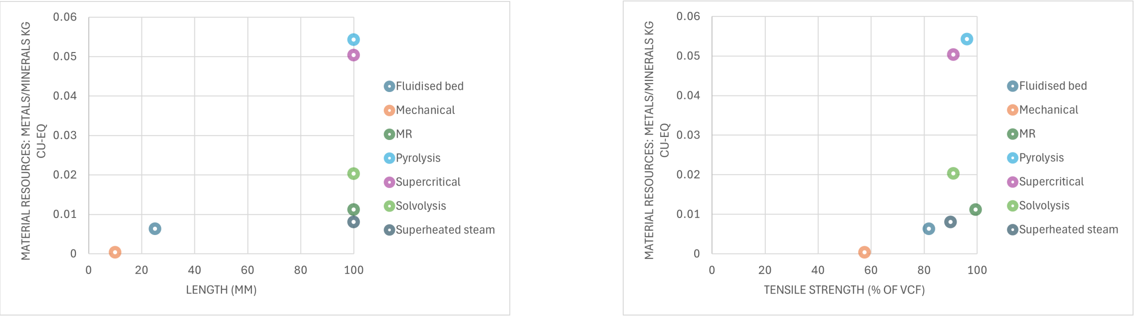
All recycling options except mechanical and fluidised Bed recycling were able to retain the continuous length of rCF as shown in Figure 5.7(a). The results for length retained are compared to the CED of the recycling options in the graph. Since all options performed equally against length, they were eliminated based on CED results solely. Superheated steam comes up as the best option when CED and length are the two criteria.

Figure 5.7(b) next compared the CED to the tensile strength of the rCF. It can be clearly observed that MR Pyrolysis and solvolysis showcase a 100% preservation of the tensile strength followed by superheated steam and supercritical fluids retaining close 90 % of the tensile strength. Based on CED, Solvolysis is the best route.

Figure 5.7(c) compares the CED results with the tensile modulus of the rCF. MR pyrolysis and pyrolysis show values greater than vCF with an 18.6 % increase in modulus for MR pyrolysis and 2.4% increase for conventional pyrolysis. This is due to the residual resin left on the fibres (Pimenta and Pinho, 2012). Solvolysis and superheated steam retain almost 100 % of the tensile modulus after recycling.

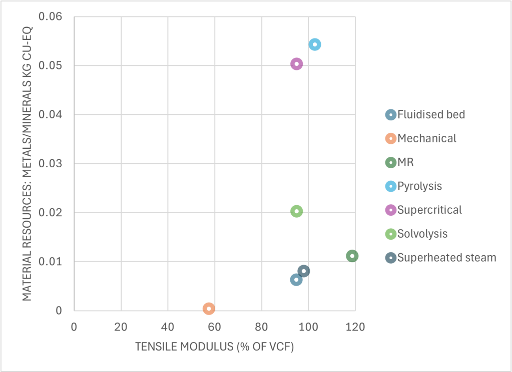
Looking at what minimises the environmental impact as well as retains the original modulus, MR pyrolysis and solvolysis perform the best.

5.5.3 Comparing Resource use to Quality Indicators



(a) Resource Use compared to length

(b) Resource Use compared to tensile strength



(c) Resource Use compared to tensile modulus

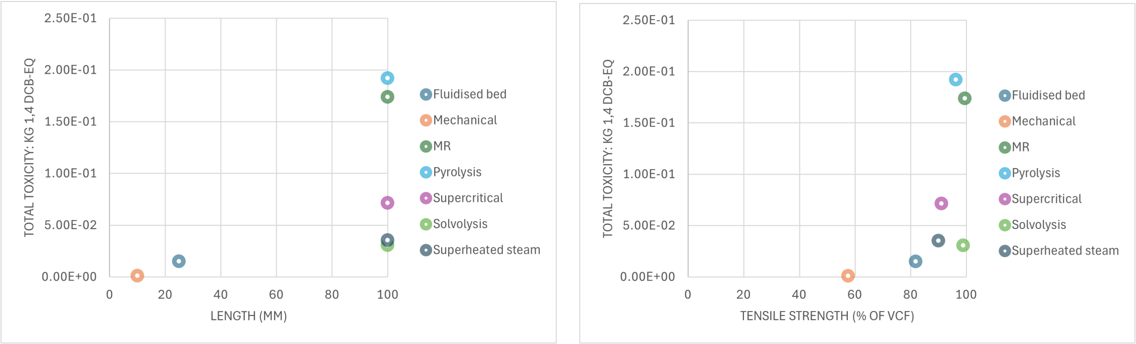
Figure 5.8: Resource Use compared to the different quality indicators: (a) Length, (b) Tensile Strength and (c) Tensile Modulus

Figure 5.8(a) shows the resource use in comparison to the length of the rCFs. Similar to previous results, all recycling options except mechanical and fluidised bed recycling provide continuous rCF. However, amongst all recycling routes, superheated steam and MR pyrolysis are the most suitable options that require the least amount of resources for their operation.

MR pyrolysis clearly stands out as the only route that retains 100% of the tensile strength in Figure 5.8(b). It is closely followed by conventional pyrolysis. As it has been observed in other cases, pyrolysis carries a large impact on resource use and should be discounted as a choice. This implies that MR pyrolysis will provide the desired quality with low environmental impact.

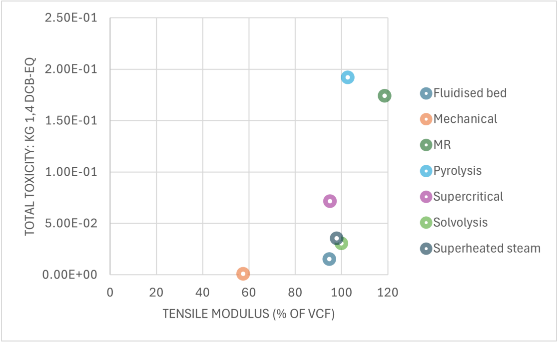
Lastly, Figure 5.8(c) compares tensile modulus with resource use results. On close observation, it can be seen that superheated steam, pyrolysis and MR pyrolysis retain 100 % or more of the tensile modulus in rCF while fluidised bed, solvolysis and supercritical fluids come very close. In this case, the two options with low environmental impact, superheated steam and MR pyrolysis, create comparable impact on resource use and thus were judged based on the percentage of quality of they retained in the rCF. MR pyrolysis with holding 18 % more modulus than vCF arose as the most suitable option (Pimenta and Pinho, 2012). The higher than 100% tensile modulus obtained after recycling is due to residual resin and effect of microwave irradiation.

5.5.4 Comparing Human Toxicity Potential to quality indicators



(a) Human Toxicity Potential compared to length

(b) Human Toxicity Potential compared to tensile strength



(c) Human Toxicity Potential compared to tensile modulus

Figure 5.9: Human Toxicity Potential compared to the different quality indicators (a) Length, (b) Tensile Strength and (c) Tensile Modulus

Here results from HTP are compared against length, tensile strength and tensile modulus in Figure 5.9 (a), (b) and (c) respectively. Similar to previous results, all recycling options are able to produce continuous rCF except mechanical and fluidised bed recycling. superheated steam and solvolysis having the least influence on human toxicity, come up as the most viable options that produce good length rCF. Most tensile strength was retained by solvolysis and MR pyrolysis. However, solvolysis was the clear choice as it caused the least total toxicity. Finally, when comparing tensile modulus results, MR pyrolysis, superheated steam and solvolysis retain 100 % or more of tensile modulus. solvolysis becomes the most viable option here despite MR pyrolysis producing rCF with higher modulus than vCF. This is due to its much lower HTP than MR pyrolysis.

It should be noted that mechanical recycling and fluidised bed recycling options require shredded CFRP waste as an input. Therefore, across all impact categories they exhibited the lowest retention of length and consequentially tensile strength and modulus.

To summarise, out of the seven recycling technologies assessed, show promising results for low environmental impact and high quality rCF. MR pyrolysis retained close to 100 % of length and tensile strength and showed 20 % increase in tensile modulus with a low impact on GWP, CED and resource use. However, it scored the highest for HTP. Solvolysis recycling came close MR pyrolysis and also retained close to 100 % of all mechanical properties. It performed well for the impact categories of GWP and HTP and moderately for CED and resource use. Lastly, superheated steam recycling showed one of the lowest impacts across four categories however it only retained close to virgin quality for length and tensile modulus but close to 90 % tensile strength.

5.5.5 Interpretation of Results

When considering the use of recycled materials for a second life, it is crucial to reflect on the specific performance requirements these materials must meet. The intended application, whether it be for automotive, aerospace, or industrial storage systems, will dictate the standards for mechanical properties and thermal stability. This reflection should also consider regulatory and safety standards, such as ISO-standards (ISO, 2024), ensuring the recycled material can reliably and safely replace virgin materials without compromising the application's integrity or performance.

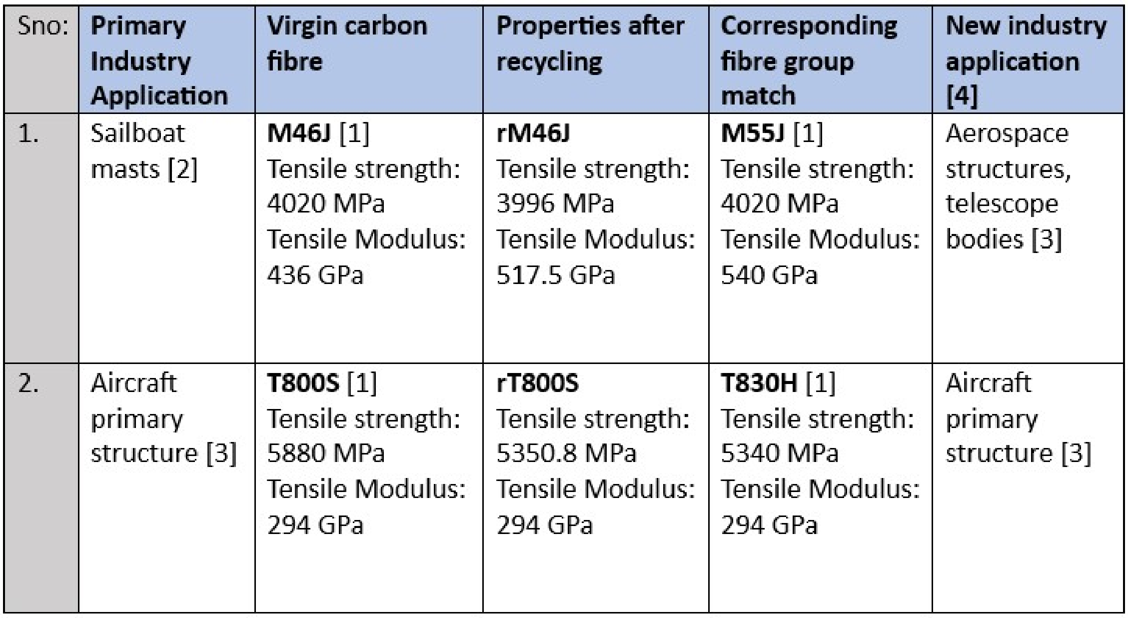
Solvolysis emerged as the most viable recycling option due to several compelling reasons. First, it effectively breaks down composite materials into their constituent components using acetic acid, allowing for the recovery of high-quality fibres and resins. This method is advantageous because it preserves the mechanical properties of the recovered fibres, making them suitable for high-performance applications. Additionally, solvolysis can be tailored to target specific resin types and contamination levels, enhancing the purity and usability of the recycled materials by using different chemicals. The environmental benefits of solvolysis also played a critical role in its selection. Compared to other methods, it typically generates less emissions while minimising the quality degradation. Lastly, the study analysed the recycling option on the basis that the chemicals were used once before being discarded, which is quite a pessimistic assumption. The chemicals could potentially be used for many kgs of CFRP, which would decrease its impacts dramatically, looking at all of the impact categories analysed.

5.6 Second-Life Applications framework

Due to both high impact and high energy requirements related to the production of CFRP, it becomes imperative to find continued applications for CFRP after its use-phase. To overcome resistance associated with the use of recycled materials in applications and simplify the process of replacing vCF with rCF, a framework is proposed in this thesis that compares them on the basis of their mechanical properties. This section aims to explain the use of the "Second-Life Applications framework" methodology developed in detail with illustrated examples.

The applications framework aims to match the rCF to the vCF closest in mechanical properties. This would facilitate finding a fitting replacement for the energy intensive vCF with rCF. The mechanical properties compared are the ones recognised in Section 5.1, that is, the tensile strength and tensile modulus.

Figure 5.10 explains the framework with examples. In example 1, the TORAYCA M46J carbon fibre after being utilised as a sailboat mast, if recycled using MR pyrolysis, will have mechanical properties equivalent to those of virgin M55J carbon fibre (Toray, 2024). This is because MR pyrolysis, as observed from Figure 5.1, reduces the tensile strength by only 0.6% but increases the modulus by 19%. Thus, the recycled M46J can be viewed as a new material and replace M55J in the applications its used for.



Sno:	**Primary Industry Application**	**Virgin carbon fibre**	**Properties after recycling**	**Corresponding fibre group match**	**New industry application [4]**
1.	Sailboat masts [2]	**M46J** [1] Tensile strength: 4020 MPa Tensile Modulus: 436 GPa	**rM46J** Tensile strength: 3996 MPa Tensile Modulus: 517.5 GPa	**M55J** [1] Tensile strength: 4020 MPa Tensile Modulus: 540 GPa	Aerospace structures, telescope bodies [3]
2.	Aircraft primary structure [3]	**T800S** [1] Tensile strength: 5880 MPa Tensile Modulus: 294 GPa	**rT800S** Tensile strength: 5350.8 MPa Tensile Modulus: 294 GPa	**T830H** [1] Tensile strength: 5340 MPa Tensile Modulus: 294 GPa	Aircraft primary structure [3]

Figure 5.10: An example fact sheet of the Applications framework that includes properties of recycled carbon fibre represented with "r" in the carbon fibre grading. [1] Toray, 2024. [2] Marine, n.d. [3] Aeronautics, n.d. [4] Onishi, 2012.

Different recycling methods can also be suggested to obtain desired qualities from the recycled carbon fibres. For instance, by using supercritical fluids as the recycling route for T800S where the tensile strength decreases by 9 % but the tensile modulus remains the same, we get a fibre with mechanical properties similar to virgin T830H as seen in example 2 of Figure 5.10. This approach can be further extended to include the length of the rCF as another point of comparison when making a choice. Different recycling methods give different lengths. Thus, for example, applications requiring chopped vCF can benefit from using rCF obtained from mechanical recycling or fluidised bed recycling.

5.7 Discussion

This section critically evaluates the assumptions, results, and limitations with data encountered in this study, drawing comparisons with other relevant studies. By examining the methodologies and approaches of similar research, the discussion highlights areas of convergence and divergence, offering insights into how the results from the thesis align with established work and in a practical context.

5.7.1 General discussion of the study

The thesis deals with CFRP recycling technologies that aim to preserve the properties of the fibre post recycling to the greatest extent possible. However, all the studies referenced are conducted on virgin CFRP, meaning the fibres have not undergone any degradation from prior use, as they would in real-world applications. Experiments were conducted on either vCF (Kim et al., 2017; Ren et al., 2022) or on scraps from manufacturing CFRP which technically are termed as waste, but have not been degraded from use (Pickering et al., 2015; Oliveux, Dandy, and Leeke, 2015; Stergiou, Konstantopoulos, and Charitidis, 2022). The measure of mechanical properties of these recycled CFRP would be more complete if the studies were supplemented with data from fatigue tests (Guo et al., 2022). Fatigue tests indicate the stress enduring capacity of the fibre, response to stress and ability to bounce back (Scallan, 2003). Oliveux, Dandy, and Leeke (2015) state apart from fibre length, fibre performance, that is, tensile strength and modulus and fibre architecture, that is, uniform alignment of fibres in the matrix, are two other important characteristics if the CF is to be reused in the same high performing application. Apart from mechanical properties, the surface properties of the recycled fibres are just as crucial for their successful induction in a second-life application (Jiang et al., 2015).

All studies referenced in this thesis only use single fibre tensile tests (SFTTs) to measure mechanical performance. While SFTTs provide precise measurements of individual fibre properties, they fail to capture the variation in properties especially found in rCFs, which may have undergone damage during use or recovery. (Calard and Lamon, 2004; (Chi, Chou, and Shen, 1984); Sugimoto et al., 2021) Bundle testing, in contrast, evaluates the collective behavior of fibre groups, capturing the influence of fibre interactions. They offer better insights into real-world manufacturing conditions. Integrating bundle testing into future research could complement SFTTs by bridging the gap between material-level analysis and practical application.

The prospective LCA conducted in this thesis focused on recycling technologies' environmental impact, excluding the production and use phases, similar to approaches by Meng et al. (2018), Ren et al. (2022) and Keith et al. (2019) who argue that the production phase is consistent across recycling methods, and including could shadow the results, making the relevant stages of the LCA negligible. Stergiou, Konstantopoulos, and Charitidis (2022)'s findings further validate this approach, highlighting that while the use phase may reduce impacts (e.g., fuel savings from lightweight materials), the significant environmental burden of CFRP production often dominates the life cycle. The impact categories chosen for this study match those chosen by Stergiou, Konstantopoulos, and Charitidis (2022) that chose to look at GWP, human health, ecosystem quality and resources to look at the life cycle of a CFRP rocket addressing social and environmental aspects of sustainability in the automative sector and those of by He et al. (2023) who also state that GWP and Primary Energy Demand (PED), also called CED, are important categories for the automotive industry.

The results for mechanical and solvolysis recycling are based on data from Meng et al. (2018)'s findings and report GWP values of 0.11 kg CO_2-eq/kg and 1.53 kg CO_2-eq/kg of CFRP recycled, respectively. However, the results deviate with pyrolysis and fluidised bed recycling , where energy recovery credits and allocation methods significantly influence results. Pyrolysis, for instance, demonstrates improved GWP values in Meng et al. (2018)'s analysis due to the assumption of rCF replacing vCF and energy recovery during the process. These differences underscore the influence of allocation approaches in LCAs for consistent comparisons. CED is reported in MJ/kg CFRP by Meng et al. (2018) therefore is difficult to compare with the results of CED in this thesis. Stergiou, Konstantopoulos, and Charitidis (2022) that uses the same impact categories as this study uses eco points as a unit of measurement which makes it difficult to compare the results from this thesis. Recycling using supercritical fluids and MR pyrolysis lack LCA studies conducted on them.

Impact assessment in LCA typically measures environmental impacts through a variety of methods and does not account for the achieved quality after recycling. Therefore, quality indicators, could be used as a complementary measure to shed light on the usability of the recycled material and assess whether the technology aids in circularity of the material while assessing its environmental impacts. Plots were used to integrate quality indicators with environmental impact in this thesis. This is believed to add another relevant layer to the recycling and usage of materials, and how they can be accounted for in a second life cycle. Stergiou, Konstantopoulos, and Charitidis (2022) uses aggregate environmental impact scores expressed in ecopoints to make the results easily comparable for different recycling routes and future studies. Eco points provide a single score and could have made the comparative analysis of recycling technologies in this thesis less complex (Singh, Dincer, and Rosen, 2018). There, however, would be a need for further research, analysing the potential implications of varying credits gained, depending on the quality of the material, from replacing vCF with rCF in a LCA.

A significant methodological choice in this thesis is the scaling up of data for emerging technologies like MR pyrolysis, solvolysis, superheated steam and supercritical fluids before conducting an LCA. Kawajiri and Kobayashi (2022) state that more studies are needed that use scaled up lab scale processes data before conducting a LCA validating the approach taken in this thesis. They state that using lab scale data for an analysis gives misleading results as there is an overestimation of power consumption from equipment as efficiency increases with scale. However, Pimenta (2013) notes that pilot-scale plants often yield better results in terms of fibre surface quality and mechanical properties compared to industrial processes, highlighting the need for caution when extrapolating findings which could be a limitation of this thesis. Chen et al. (2023) work covers the practicalities of the scaling up different categories of recycling techniques commenting on their drawbacks and advantages which can supplement this thesis in decision making.

5.7.1.1 Connecting Impact Assessment Results with Quality Indicators

This study assumes a set quality after recycling, but in reality there will be a range in the material's mechanical quality indicators (Zhang et al., 2020) influenced by factors such as contamination levels, processing efficiency and treatment conditions (Pimenta and Pinho, 2011). Instead of assigning a fixed quality to the materials, acknowledging variability can inform better utilisation of recycled materials across diverse applications. Implementing standardised quality indicators in recycling LCAs is also critical for can level the playing field for different recycling technologies. By adopting consistent criteria, emerging methods that yield higher quality fibres may receive better recognition and support over cost-effective solutions. Kawajiri and Kobayashi (2022) also emphasises the need for industry-wide standards to enhance the usability of rCF.

Implementing standardised quality indicators in recycling LCAs can level the playing field for different recycling technologies. This ensures that all options are evaluated based on comparable criteria, leading to more objective decision-making, leaving the floor to various recycling options. Often, the most cost-effective or technically feasible solution receives the majority of attention and resources. However, by standardising quality measures, other innovative or emerging recycling methods that yield higher quality fibres may be better recognised and supported. This would although need further research in the future. Kawajiri and Kobayashi (2022) also states that despite promising use for rCF in various applications, a quality standard needs to be established in an industry wide scale.

Lastly, Hecker et al. (2023) in their work conclude that most influential parameters in LCAs are the type of electricity being used or modelled , the scale of the process being described and the quality of the rCFs that dedcide the amount of vCF that can be replaced which further validates the approach taken in this thesis to answer research questions. Similarly, Oliveux, Dandy, and Leeke (2015), state that classifying rCF based on fibre grade in order to optimise fibre use which indicates that the second-life applications framework proposed in this thesis is a suggestion in the right direction. The findings of this thesis align with Gosau, Wesley, and Allred (2006)'s conclusions, which favor pyrolysis and solvolysis as preferred recycling methods. Solvolysis avoids char formation, improving fibre-matrix interaction, while pyrolysis offers energy recovery, making it more economical.

6

Conclusion

This study has provided an extended knowledge base concerning the recycling of energy intensive CFRP and aspects related to its circularity. It looked into seven recycling technologies: mechanical recycling, fluidised bed, pyrolysis, solvolysis using acetic acid, supercritical fluids recycling using acetone, MR pyrolysis, and recycling using superheated steam. The research highlighted that while the recycling processes can successfully recover carbon fibers, the challenge lied in preserving their quality post recycling, which is critical for their reuse in high-performance applications. Length, diameter, tensile strength, tensile modulus and resistance to fatigue were identified as key indicators to assess the quality of the rCF. The thesis also aimed to address the gap in inventory data of emerging recycling technologies for pLCA studies by scaling up lab scale data to a commercial scale. Based on the results established, Solvolysis was the most promising recycling route that retained the mechanical properties of the fibre while leaving a low impact on the environment. MR Pyrolysis and superheated steam recycling were a close second choice.

A second-life application's framework, connecting the principles of circularity, was also developed in this thesis. It aimed to remove the inertia of using rCF by suggesting a catalogue that makes it easy to replace vCF with the closest rCF that matches in quality. If used widely, it can increase the life cycle of CFRP and discourage new production, adding both environmental and economic benefits with growing demand for CFRP.

6.1 Further research

This study investigated seven different CFRP recycling technologies each with distinct advantages and drawbacks. Further research could explore integrating these recycling approaches to leverage their respective advantages to produce the optimum quality of rCF. An example of this approach has been explored by Oliveux, Dandy, and Leeke (2015) where they developed a three-step process which included a thermal pre-treatment under pyrolysis conditions followed by two solvolysis steps to completely strip the resin off the fibre with no char, enhancing their reuse potential. Additionally, further studies could investigate other recycling techniques, such as electrochemical recycling or solvolysis with alternative chemicals like nitric acid or catalysts, to broaden the range of feasible technologies.

While this study used LCA to compare recycling technologies based on four impact categories namely GWP, CED, resource use and HTP, these categories do not capture the risks of working with a composite material that can, in a fibrous form, resembles a structure similar to asbestos, a proven carcinogen (Wang, Schlagenhauf, and Setyan, 2017). Due to lack of a characterisation factor for asbestos-like fibres, the negative impacts on human health remain unquantified (Pini et al., 2021). Future research should prioritise developing inventories and methods to account for such substances. The results of this study can be supplemented by including the USEtox 2.0 impact assessment method proposed by Pini et al. (2021) that provides a characterisation factor for asbestos fibers released both in outdoor air and in occupational setting, once the update is available. Additionally, UseTox has been identified as one of the key indicators that enable the assessment of the environmental impact of CFRP recycling along with GWP, acidification and resource impact assessment (Pillain, Gemechu, and Sonnemann, 2017).

Another critical area for further investigation is the use phase of CFRP, which remains underrepresented in recycling studies. Currently, no experiments include degraded CFRP, leading to an overestimation of recycled material quality .This research gap hinders the acceptance of rCF in new application in industry. Research on fiber and resin degradation mechanisms during use could provide insights to refine recycling technologies, reducing fiber damage during recovery. Additionally, it can help tailor solvents to specific resin types and optimise recovery processes reducing the need for extreme conditions and lowering environmental impacts (Chen et al., 2023). In the absence of real-world data on the CFRP use phase, deterioration modeling could serve as an interim solution, allowing researchers to simulate fiber degradation. This approach could also facilitate dynamic LCA studies, enabling the tracking of material quality over successive life cycles.

Currently, the reuse of rCF is still in its early stages and requires further exploration. While research has largely focused on macroscopic mechanical properties, challenges like fiber re-alignment remain significant barriers to rCF adoption (Zhang et al., 2020). Studies by Pimenta (2013), as well as Oliveux, Dandy, and Leeke (2015), also highlight the need for improved techniques to align fibers effectively and ways to produce discontinuous fiber yarns (Oliveux, Dandy, and Leeke, 2015). In order to further benefit from the reinforcement capabilities of the fibre, the characterisation of fibre surface and of the fibre-matrix adhesion also requires attention (Oliveux, Dandy, and Leeke, 2015). Knowledge of surface properties of the fibres can lead to new ways of reusing rCF, for example, properties of some matrix polymers such as polypropylene are better enhanced with introduction of rCF compared to vCF due to differing surface properties (Jiang et al., 2015).

Comprehensive exploration of second-life application pathways requires studying the full life cycle of products, including re-manufacturing steps. Most LCA studies do not account for the impacts from re-manufacturing processes before modeling rCF in its second life (Tapper et al., 2020). Incorporating these into future analyses would provide a more complete picture of the environmental benefits of reusing rCF over multiple cycles. Additionally, LCA models can be improved by introducing calculations with a quality factor to account for the differences in performance between virgin and recycled materials or by adding allocation methods that capture quality changes.

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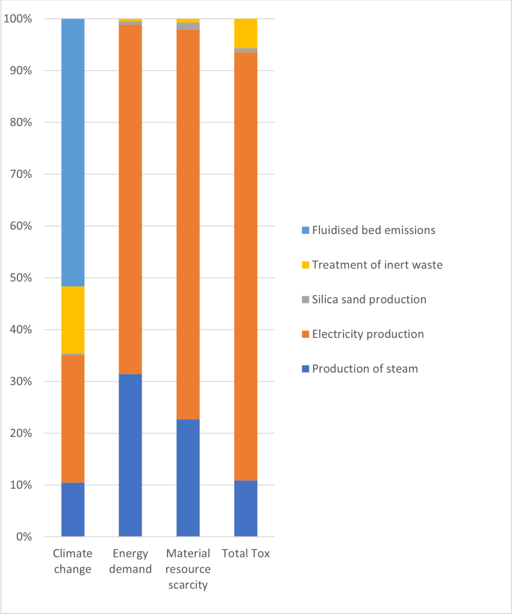
A

Contribution analysis of the various recycling options

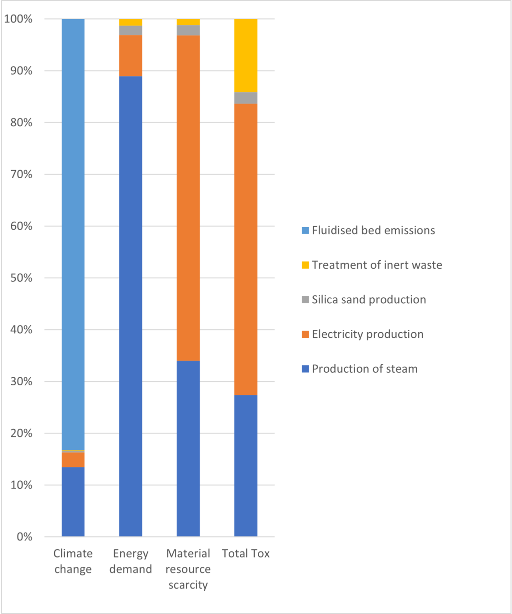
A.1 Contribution analysis of Mechanical recycling

Due to the mechanical recycling only having electricity as an input, and having the different fractions as outputs that all are either handled with or are sent forward to different processes the contribution of the different processes in the mechanical case would only be contributed by the electricity consumption, and therefore this table is not included

A.2 Contribution analysis of Fluidised bed recycling

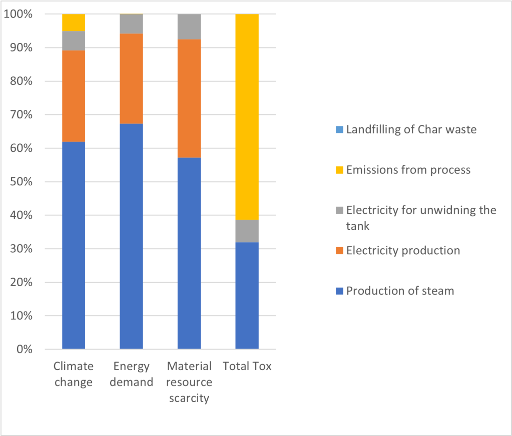


(a) Contribution EU electricity mix

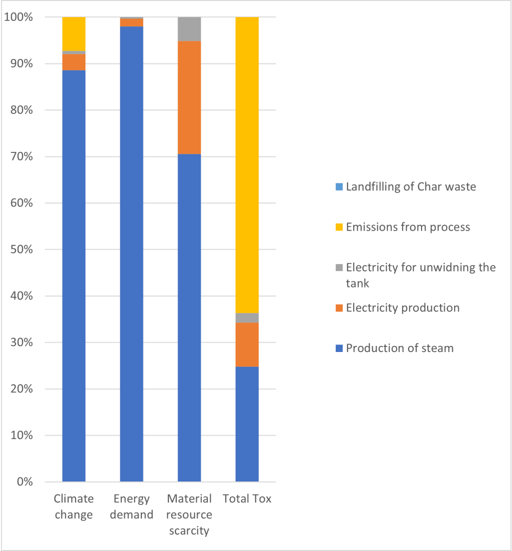


(b) Contribution SE electricity mix

A.3 Contribution analysis of Pyrolysis recycling

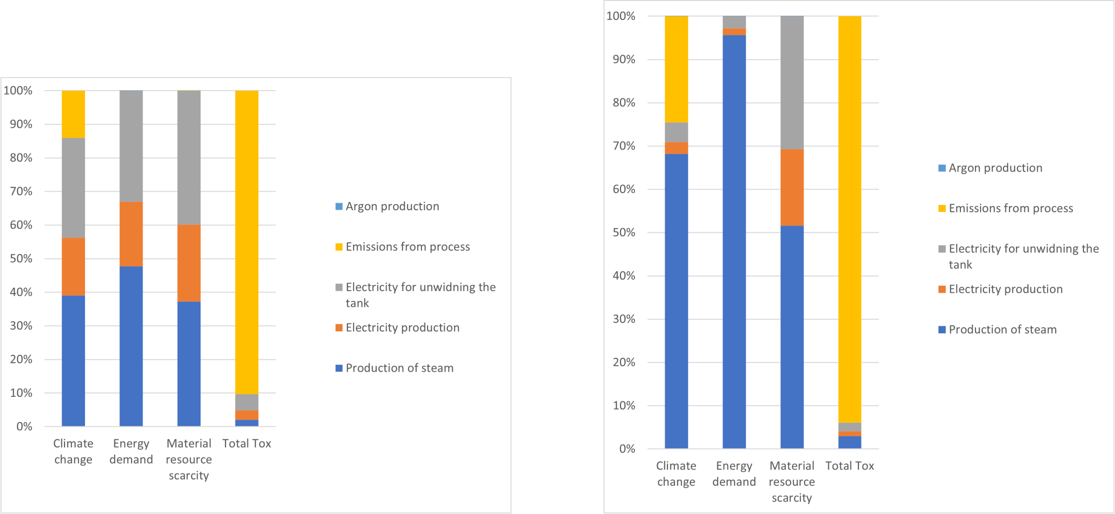


(a) Contribution EU electricity mix



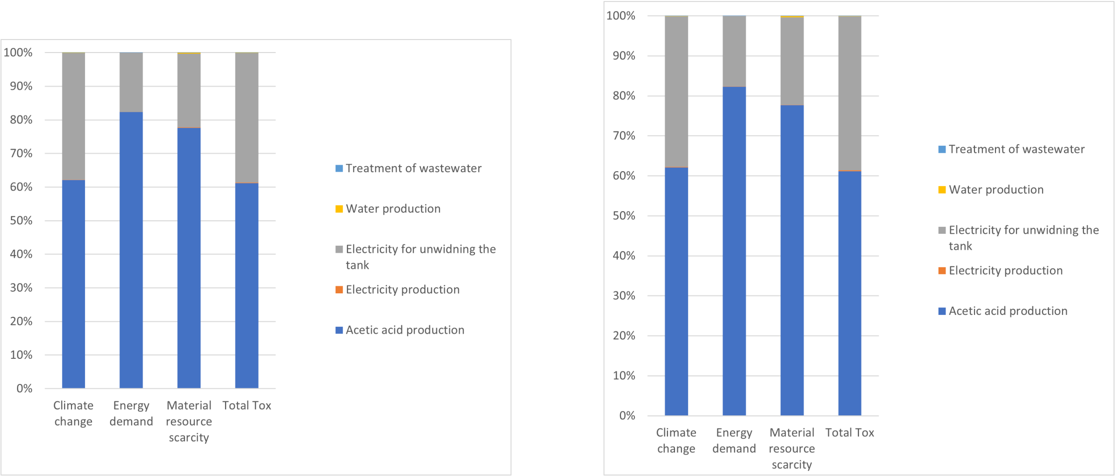
(b) Contribution SE electricity mix

A.4 Contribution analysis of Microwave Pyrolysis



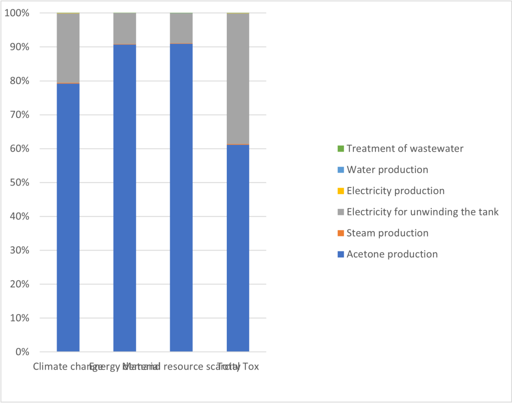
(a) Contribution EU electricity mix **(b)** Contribution SE electricity mix

A.5 Contribution analysis of Solvolysis using acetic acid

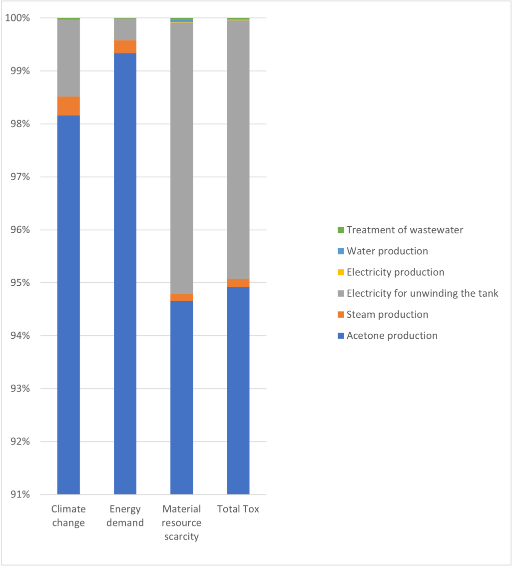


(a) Contribution EU electricity mix **(b)** Contribution SE electricity mix

A.6 Contribution analysis of Solvolysis using supercritical fluids

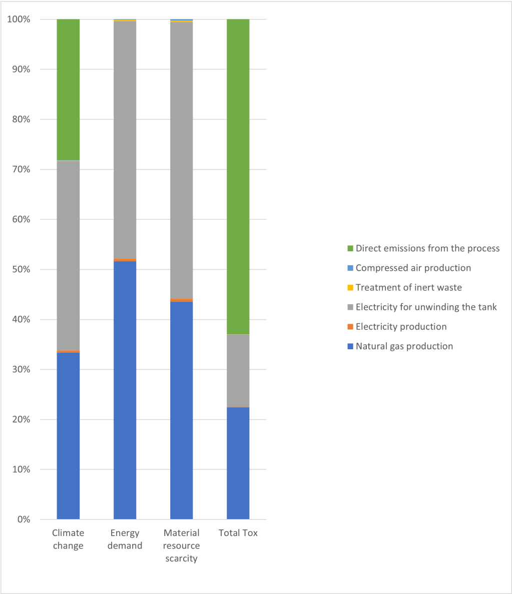


(a) Contribution EU electricity mix

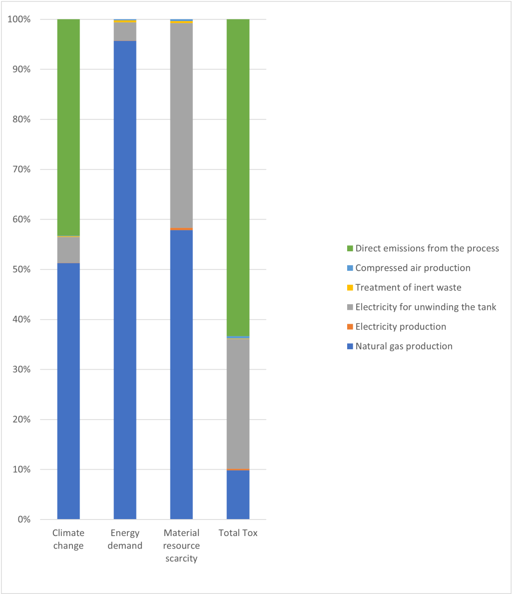


(b) Contribution SE electricity mix

A.7 Contribution analysis of Superheated steam



(a) Contribution EU electricity mix



(b) Contribution SE electricity mix

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