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Bachelor's thesis

Life Cycle Assessment of Reuse/ Remanufacture End-of-Life Fibre Reinforced Polymer in Composite Industry

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Table of contents

List of figures

List of tables

Abstract-en

Remanufacturing is an important strategy in promoting product circular economy and material efficiency. The increasing demand of fibre reinforced polymer (FRP) composite for lightweight construction has led to high volumes of composite waste after their operational life. Recycling thermoplastic composites via remanufacturing into virgin-like structure and quality can prevent the composite from going into the waste stream and thus reducing environmental pollution. A life cycle assessment (LCA) is crucial in evaluating the environmental performance of a remanufactured product compared to its virgin counterparts. LCA software tool allows modelling of the product life cycle and further investigation of the hotspots together with the potential optimisation to improve the production efficiency and to reduce ecological impacts.

The aim of this thesis was to provide a comprehensive environmental analysis of remanufacturing thermoplastic composite laminate (tp-CL), i.e. Reverse-Thermoforming. The LCA analysis tool, GaBi Software was utilised in this work with the application of ReCiPe(H) 2016 Midpoint method. For a better comparison, the production of virgin composite laminate was conducted with the dataset available in the GaBi pre-installed Database. The results showed that the global warming potential (GWP) for remanufactured polyamide 6-carbon fibre (PA6-CF) composite laminate was 61% less than its virgin counterpart. This indicates that 12.5 kg of CO_2-equivalent greenhouse gas is avoided from being emitted into the atmosphere for remanufacturing 1 kg of PA6-CF composite laminate. For polypropylene-glass fibre (PP-GF) composite laminate, the impact assessment results showed that the water consumption potential for remanufactured CL was only 22.3% of its virgin counterpart.

Keywords: Life cycle assessment (LCA), remanufacturing, thermoplastic composite laminate, fibre reinforced polymer (FRP), recycling

Abstract-de

Die Wiederaufarbeitung von Gebrauchsende-Produkten und -Bauteilen ist eine wichtige Strategie zur Förderung der Kreislaufwirtschaft und der Materialeffizienz. Der steigende Bedarf nach Faser-Kunststoff-Verbund (FKV) für den Leichtbau hat dazu geführt, dass nach der Nutzungsphase eine große Menge an Verbundwerkstoffabfällen anfällt. Das Recycling von thermoplastischen FKV durch Wiederaufarbeitung zu der ursprünglichen Struktur bzw. zu der neuwertigen Qualität kann die Abfallmenge reduzieren und somit die Umweltverschmutzung verhindern. Eine Lebenszyklusanalyse (LCA) ist entscheidend für die Bewertung der Umweltverträglichkeit eines wiederaufbereiteten Produkts im Vergleich zu seinem neuen Gegenstück. Die LCA-Software ermöglicht die Modellierung des Produktlebenszyklus und die weitere Untersuchung der Hotspots zusammen mit der potenziellen Optimierung zur Verbesserung der Produktionseffizienz und zur Verringerung der Umweltauswirkungen.

Das Ziel dieser Studienarbeit war es, eine umfassende Lebenszyklusanalyse der Wiederaufbereitung von thermoplastischen Faser-Kunststoff-Verbunden (tp-FKV), d.h. Reverse-Thermoforming, zu erstellen. Das LCA-Analyseprogramm GaBi Software wurde in dieser Arbeit mit der Anwendung der ReCiPe(H) 2016 Midpoint-Methode verwendet. Zum besseren Vergleich wurde die Produktion eines neuen Organoblechs mit dem Datensatz in GaBi-Datenbank durchgeführt. Die Ergebnisse zeigen, dass das Treibhauspotenzial (GWP) von wiederaufbereitetem Polyamid 6-Kohlenstofffaser Organoblech (PA6-CF) um 61% geringer ist als das seines Neugegenstücks. Dadurch wird der Ausstoß von 12,5 kg CO2-Äquivalent an Treibhausgasen in die Umgebung verhindert, wobei 1 kg FKV material als funktionelle Einheit dient. Bei Polypropylen-Glasfaser Organoblech (PP-GF) lag das Wasserverbrauchspotenzial für wiederaufbereitete Organoblech nur bei 22,3% seines Neugegenstücks, basierend auf den Ergebnissen der Umweltwirkungsabschätzung.

Schlagwörter: Lebenszyklusanalyse, Wiederaufarbeitung, Neufertigung, Organoblech, Faser-Kunststoff-Verbund (FKV), Recycling

Declaration

This is to certify that the work that forms the basis of this thesis with the title "Life Cycle Assessment of Reuse/Remanufacture End-of-Life Fibre Reinforced Polymer in Composite Industry", is original work carried out by the author.

- This thesis has not been submitted in any form at another university for award of degree or examination.

- The thesis does not contain information and writing from other person unless specifically cited or quoted in the work.

I hereby declare that I have prepared the present work without the unauthorised help of third parties and all sources of information and data are fully acknowledged in this thesis work under References sections.

Wolfsburg, 18th November 2021

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Abbreviations

Abbreviation	**Description**
a.k.a.	also known as
ALOP	Agricultural Land Occupation Potential
AP	Acidification Potential
CCM	Continuous Compression Moulding
CDIM	Calender-Direct Impregnation Machinery
CED	Cumulative Energy Demand
CF	Carbon Fibre
CFC	Chlorofluorocarbon
CFRP	Carbon Fibre Reinforced Polymer
DBP	Double-Belt Press
DCB	Dichlorobenzene
DE	*Deutschland* (*engl.* Germany)
DIN	*Deutsches Institut für Normung* (*engl.* German Institute for Standardisation)
el.	electrical energy (electricity)
EN	*Europäische Norm* (*engl.* European Standards)
EOFP	Ecosystem-related Oxidant Formation Potential
EoL	End-of-Life
EP	Eutrophication Potential
eq.	equivalent
etc.	et cetera
ETP	Ecotoxicity Potential
EU	European Union
FDP	Fossil Depletion Potential

Abbreviation	**Description**
FEP	Freshwater Eutrophication Potential
FU	Functional Unit
FRP	Fibre Reinforced Polymer
GaBi	*Ganzheitliche Bilanzierung* (*engl.* Holistic Balancing)
GFRP	Glass Fibre Reinforced Polymer
GHG	Greenhouse Gas
GLO	Global
GWP	Global Warming Potential
HOFP	Human health-related Oxidant Formation Potential
HTPc	Human Toxicity Potential, cancer
HTPnc	Human Toxicity Potential, non-cancer
i.e.	that is (Latin "id est")
IRP	Ionising Radiation Potential
ISO	International Organisation for Standardisation
IWU	*Institut für Werkzeugmaschinen und Umformtechnik* (*engl.* Institute for Machine Tools and Forming Technology)
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
MEP	Marine Eutrophication Potential
ODP	Ozone Depletion Potential
OEM	Original Equipment Manufacturer
OHLF	Open Hybrid Lab Factory
PA6	Polyamide 6
PA6-CF	Polyamide 6-Carbon Fibre composite
PAN	Polyacrylonitrile

Abbreviation	**Description**
Plastics Europe	Plastics Industry Association in Western Europe
PMFP	Particulate Matter Formation Potential
PP	Polypropylene
PP-GF	Polypropylene-Glass Fibre composite
R&D	Research and Development
rCL	recycled Composite Laminate
RER	Region of Europe
SOP	Surplus Ore Potential
therm.	thermal energy
tp	thermoplastic
ts	thermoset
vCL	virgin Composite Laminate
WCP	Water Consumption Potential

Italics represent the terms and definitions in German and the content in brackets represent the terms and definitions for the abbreviations in English.

1 Introduction

This chapter is dedicated to three aspects that provide a brief introduction to the content of this study. The first subchapter provides information regarding the topics of fibre reinforced polymers and life cycle assessment tools involved in the work. The aim and objectives of this study are also included in the following subchapter. This chapter concludes with an outline of this study.

1.1 Motive of Work

Composite materials have been developed to serve the purpose of lightweight construction. These composite materials, in particular carbon and glass fibre reinforced polymers (C/ GFRP) have progressively replaced metals and alloys in order to reduce fuel consumption during transportation. [1] The fibre reinforced polymers (FRP) have also shown great potential in industrial usage due to their excellent mechanical properties and corrosion resistance, as compared to metal. The industries and sectors with an increased use of FRP include aviation, automotive, medical technology, building construction, renewable energy and other applications. [1][2]

Nevertheless, the recycling of the End-of-Life (EoL) composites is complicated and remains a challenge due to its heterogeneous hybrid structure and variety of matrix resin systems. [3] Composite waste treatments such as mechanical grinding and co-processing in cement kilns have reached a relatively high Technology Readiness Level (TRL). However, these treatments have drastically reduced the supply chain value (down-cycling) of the recycled materials due to the significant mechanical property loss. [4] Pyrolysis has shown promising results in retrieving recycled carbon fibre (rCF) as high value recyclate. But due to the high processing costs, pyrolysis is only economically feasible in recycling carbon fibre reinforced polymer (CFRP) composites as the production cost of carbon fibre (€ 20-30/kg) is approximately 10 times higher than production cost of E-glass fibres (€ 2-3/kg). [5][6] Thus, research and development (R&D) on sustainable recycling technologies with maximal property retention has become crucial to meet the industrial legislative and/or the commercial requirements. [7][8]

Down-cycling of materials is a common phenomenon in almost all recycling technologies currently available in the market, where the fibres are shortened and mechanical properties are significantly deteriorated. This study proposes a solution to enhance the current resource-conserving economy using the technology "Reverse-Thermoforming". By retaining the maximum value and length of the fibres, this approach can regenerate flat thermoplastic composite laminates (organo sheets) and then reshape them into new components through reconsolidation and thermoforming process. Reverse-Thermoforming is potentially a simple, cost-effective and sustainable solution to reuse and prolong the service life span of the thermoplastic FRP composites. [9]

In order to effectively evaluate the ecological impacts of this recycling technology for thermoplastic composites, a life cycle assessment (LCA) is utilised in this study. This LCA methodology is structured, comprehensive and globally standardised, which provides detailed information based on the calculation principles and processes involved. [10][11] By including all the input and output flows of the product system, this assessment method provides a true reflection of the potential environmental impacts of this recycling technology. When conducted extensively, the results can be compared to other advanced technologies of a similar purpose and contribute to selection of products and processes and decision-making. [10][12]

1.2 Aim and Objectives

The aim of the thesis is to perform a life cycle assessment (LCA) of the thermoplastic fibre reinforced polymers (tp-FRP) using "Reverse-Thermoforming"[9] technology. This study investigates and evaluates the environmental impacts of the remanufacturing process of thermoplastic fibre reinforced components in automotive industry.

The objectives of this work are:

- to research on valuation of the remanufacturing technology of the End-of-Life thermoplastic composite in regard to the environmental impacts and energy demand.
- to conduct a comprehensive LCA of thermoplastic composite prototype based on available technology and machinery.
- to review published literature and available databases on energy flows and emissions released at the life cycle of the FRP composites (Life Cycle Inventory, LCI).
- to study the environmental impacts of the recycling process for the FRP structures based on the key ecological indicators.

1.3 Structure of Work

The scope of this study is to conduct a life cycle analysis based on recycling process of thermoplastic composites. This also includes the specific production processes and parameters, the manufacturing machinery and tools involved in the experimental investigation and assessment.

Subsequently, this study will discuss the procedure for model development, the datasets used and the methods employed for the systematic evaluation of the LCA model. Based on the models created via the LCA software, key ecological indicators in this remanufacturing technology are listed and a detailed life cycle assessment is performed.

Finally, this study interprets the results related to the carbon dioxide emission and other key ecological indicators based on the constructed scheme. For a better comparison and understanding, the above remanufactured model is compared to a hypothetical model on the production of virgin thermoplastic composite using the same LCA software.

In **Figure 1**, the contents and structure of work are briefly described.

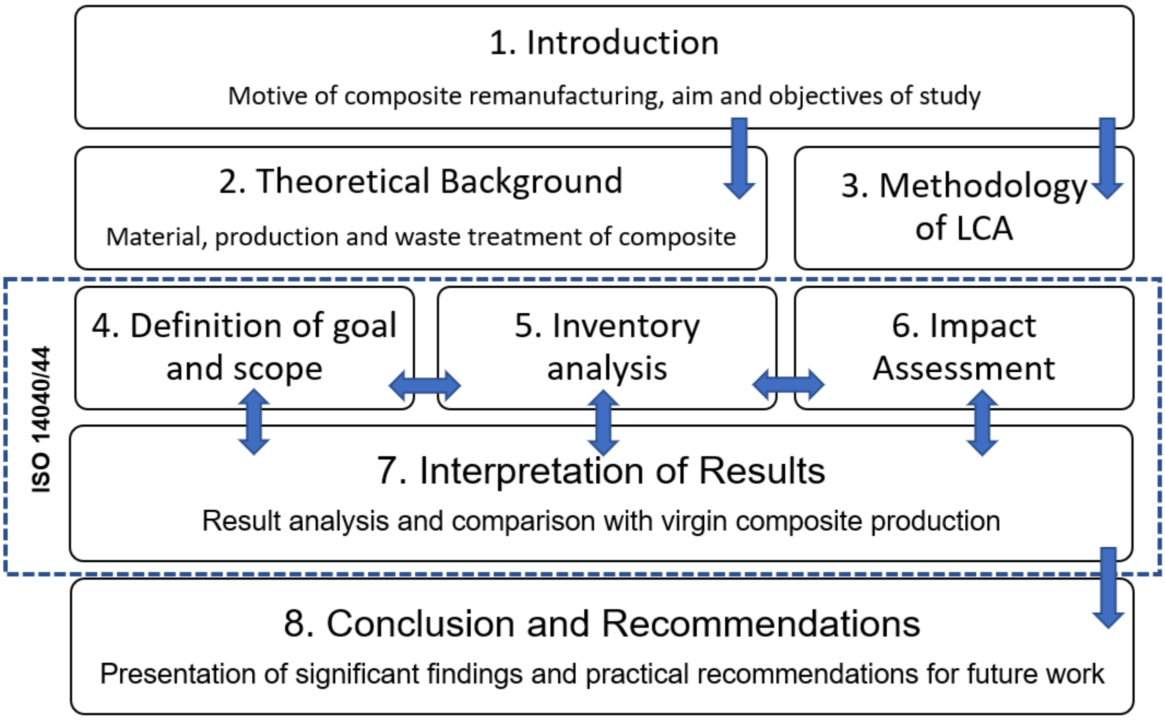

Figure 1: Outline of the thesis structure

2 Theoretical Background

This chapter aims to provide a comprehensive introduction into composite materials, i.e. types of fibre reinforcements, resin systems and the manufacturing processes. The following subchapter looks into the current industrial outlook of the waste treatment methods of the fibre reinforced polymer composites. This chapter concludes with a description of the chosen recycling technology, i.e. Reverse-Thermoforming method for the thermoplastic FRP composites.

2.1 Fibre Reinforced Polymer (FRP)

Composites are a combination of two or more material constituents that can achieve mechanical and material properties superior to those of the single constituents in an overall structure and one of the most significant constructions is fibre reinforced polymer (FRP) [1]. FRPs usually consist of a fibre reinforcement phase, a resin polymer phase and also variety of additives depending on the required properties in the final products, as shown in **Figure 2** [13].

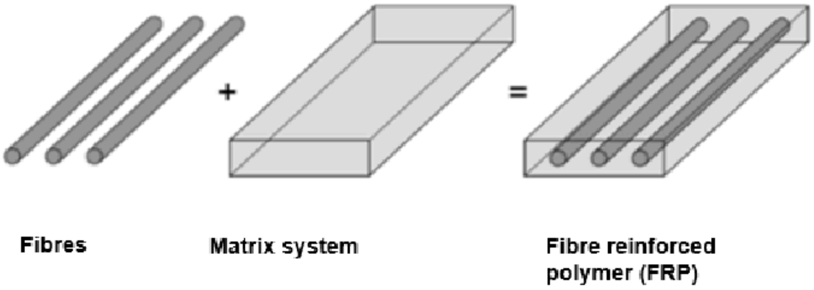

Figure 2: Component and structure of fibre reinforced polymer, reproduced [13]

Fibre provides stiffness and strength to the composite structure while the resin system holds the fibre reinforcements in place and transfer the impact loads along the fibres together with stress distribution throughout the material whilst deforming. In addition to that, the resin system also provides an external protection for the fibre surface against environmental and mechanical degradation such as corrosion, fire, abrasion, wear and tear etc. [14][15][16]

In this work, two constituent combinations for thermoplastic composite laminates are included in the assessment. They are namely Polypropylene-Glass Fibre (PP-GF) and also Polyamide 6-Carbon Fibre (PA6-CF) woven fabric composites, which are produced and supplied by Bond-Laminates GmbH (Birlon, Germany) to Fraunhofer Project Centre Wolfsburg.

2.1.1 Fibre Reinforcements

The fibres are the solid constituent of the composites, which are reinforced into the matrix system. The common fibre types are carbon fibre (CF), glass fibre (GF), aramid fibre (AF) and also natural fibre such as flax, bamboo, hemp, etc. The type of fibres determines the mechanical properties of the composite such as tensile strength and modulus, compressive strength and modulus, fatigue strength and fatigue failure mechanisms. [15] In addition, the architecture of the reinforcement also affects the mechanical performances of the FRP semi-finished or end products. A range of products are available in the composite market such as short fibre, long fibre, unidirectional prepregs, 2-Dimensional (2D) and 3-Dimensional (3D) woven fabrics, braided mats and knitted mats. [1][16] In this work, 2D continuous filament fabrics embedded in thermoplastic resins are selected and utilised.

Glass fibre reinforcements were first produced in the 1890s. Currently, glass fibres (GF) are the most common reinforcement type for FRP composite due to its high performance in terms of tensile strength, good insulation properties, chemical and water resistance and most importantly, low cost [17]. Glass fibres are resistant to high temperatures and corrosive environments. The high level of radar transparency in glass fibres makes them an outstanding material for industrial lightweight construction, especially in automotive parts production. [15] Although GFs have in general high strength-to-weight ratio, but the modulus are only considered as moderate. In addition, GFs are prompted to strain fatigue under constant load over time. These factors have led to the usage of more advanced reinforcements such as carbon fibres. [16]

Carbon fibre reinforced polymers (CFRP) may only take up 1.5% of the total composite market by weight but they are accounted for over 20% of the market value [18]. They are more expensive to produce due to the high raw material costs and also high energy intensity production route. Commercial carbon fibres are mainly produced by extruding organic precursors such as polyacrylonitrile (PAN) into filaments, then these PAN-fibres go through stabilisation treatment, carbonisation and final heat treatment (a.k.a. graphitisation) to become carbon fibre reinforcements. [16] Carbon fibres have several advantages including high stiffness, high tensile strength, excellent weight-to-strength ratio, high chemical and temperature resistance and low thermal expansion [19]. Due to the excellent performances, the demand for carbon fibre composite has a steady annual growth of approximately 12% in global market since 2010 [18].

2.1.2 Resin Matrix Systems

Most of the resin systems used in composites are a combination of several resins and various additives. The term ″resin matrix system″ is more accurate than ″resin″ to reflect such complexity. There are several types of resin systems available on the market. These resin systems include polyesters, polyolefins, epoxies, phenolics, bismaleimides, polyimides, polyacrylic, polyamide, etc. with their corresponding additives. They are categorised into two separate classes of polymers, which are thermoset resin and thermoplastic resin. [16]

Figure 3 illustrates the molecular structure of the thermoplastic polymers (on the left) and thermoset polymers (on the right) with lines representing long chain of molecules and dots representing the cross-links [20].

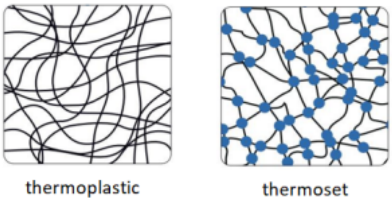

Figure 3: Simplified structure of thermoplastic and thermoset, reproduced [20]

Thermosetting resins are typically resins designed to react chemically (curing process) by cross-linking the polymer chain to form a 3D-network. Once cured, they cannot or seldom be re-melted or reformed. Thermoset plastics with polyester and epoxy resins have in general high dimensional stability and low creep (deformation), and thus are well suited for high temperature applications. [15][16]

In opposite to thermosets, thermoplastic composites enable recycling after a part is retired from service and facilitate thermal joining of multipart structures. Most importantly, the advantages of thermoplastic resin systems are the ability to be post-thermoformed and separated for further recycling processes after the composite constructions have reached the end of their use phase. Thus, thermoplastic composites have gained much attention, particularly in automotive sector, with polyamide 6 (PA6), polypropylene (PP) and acrylonitrile-butadiene-styrene (ABS) as the most widely used polymers. Additionally, the most appealing advantage of thermoplastic over thermoset is the significant reduction of fabrication lifetime, consequently lower manufacturing costs of composite parts and higher production rate. [16][21][22]

Notably, polypropylene(PP)-based composites dominate in thermoplastic structural applications as they are re-malleable and re-processable, posses reliable mechanical and thermal properties after reprocessing and substantially, the lowest ecological impacts and materially cheapest compared to other thermoplastic composites [23]. Generally, these recycled thermoplastic-based composites are dominated by short FRP products, manufactured by injection moulding or compression moulding processes. In terms of performances, these short fibre reinforced composites (discontinuous blends) are less competent than the continuous filaments thermoplastic composites. The short fibre blends are less effective in improving strength of the composites. [22]

2.1.3 Thermoplastic Composite Laminate (Organo Sheet)

Composite laminate is one of the most commonly used structural FRP semi-finished products in the market [24]. The continuous fibre woven textiles are embedded in the thermoplastic resin systems to produce a fully-impregnated and consolidated fibre reinforced thermoplastic laminates, which are also known as organo sheets [25]. Carbon and glass fibres with polypropylene and polyamide matrixes are mainly used for mass production [13].

The common weaving methods of textile fabrics are plain (canvas), twill and also satin weave as shown in **Figure 4** [26]. The thermoplastic composite laminates utilised in this work are fabricated by twill weaving.

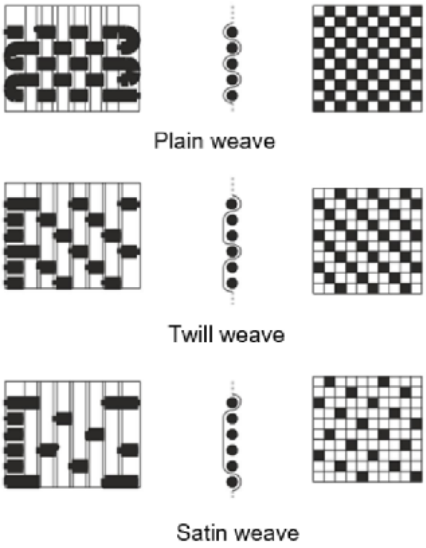

Figure 4: Common weaving methods for fibre woven fabrics, reproduced [26]

In the production of the organo sheet, thermoplastic resins in the form of granulate, fluid or thin film, are fed and applied to the dry woven fabrics, which are then heated above their resin melting temperature for impregnation. Both the resin system and fabric are bonded together via high temperature and a defined haul-off speed to produce this intermediate material. [13]

Currently, continuous film stacking processes such as Double-Belt Press (DBP) and Continuous Compression Moulding (CCM) are designed and deployed for lower-cost manufacturing of organo sheets. [25]

Figure 5 represents the production of organo sheets through a heated DBP system [13].

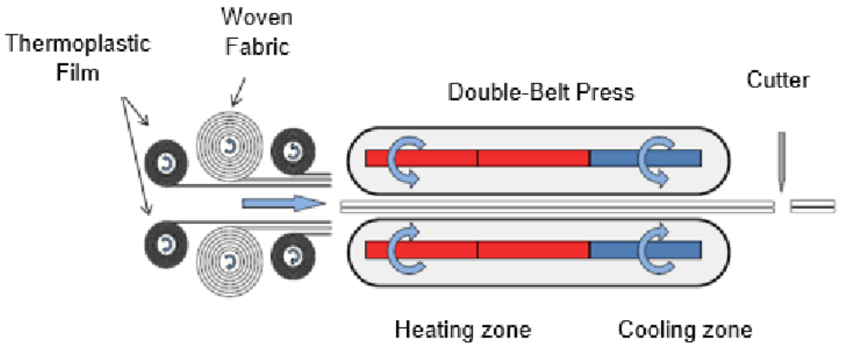

Figure 5: Manufacturing of organo sheets via Double-Belt Press, modified [13][27]

Figure 6 shows examples of semi-finished products of the continuous fibre reinforced thermoplastic composite under the brand name "Tepex®". These product series are owned by Bond-Laminates GmbH, a daughter company of LANXESS AG. [27]

Figure 6: Variety of thermoplastic laminates in Tepex® series, reproduced [27]

These thermoplastic FRP sheets can then be cut into desired shape and dimension according to the component geometry before forming. Heating methods such as infrared (IR), contact, convection and induction heating system can all be applied for thermal forming process. [25] **Figure 7** illustrates the thermal forming process of a thermoplastic component from organo sheet [28].

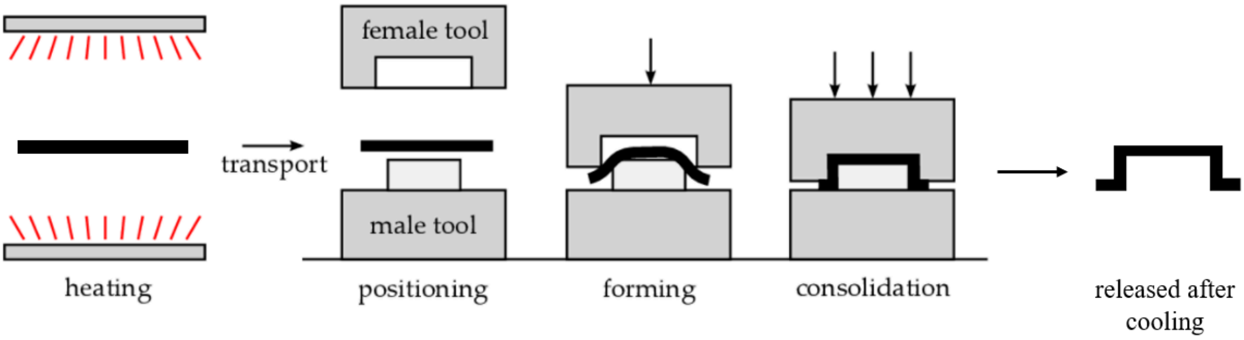

Figure 7: Stamp forming of thermoplastic composite, modified [28]

2.2 Waste Management of Polymer Composites

Due to their lightweight properties, FRP composites have been used in manufacturing sport cars and electrical vehicles to achieve great performances and low energy consumptions. As vehicle manufacturers are striving towards sustainable mobility, lightweight vehicles will satisfy the longer ranges between recharging (electrical cars and buses), which leads to the enormous growth in composite production.[2] As these composite components come to the end of their operational life, recycling these composite wastes has become pivotal for the original equipment manufacturers (OEMs) in their approach towards material circularity [3][29].

Therefore, more efficient solutions for treating the End-of-Life (EoL) composites are required to promote Circular Economy in the transportation sector by integrating these wastes into the value chain for composite production [7]. Several technically and economically feasible circular routes, comprising prevention, remanufacture, recycling, energy recovery and disposal at landfill are discussed.

Figure 8 gives a general idea on the waste management hierarchy for composite waste, ranked from the most preferred (top) to the least preferred (bottom) according to European Union 2008/98/CE Directive [30].

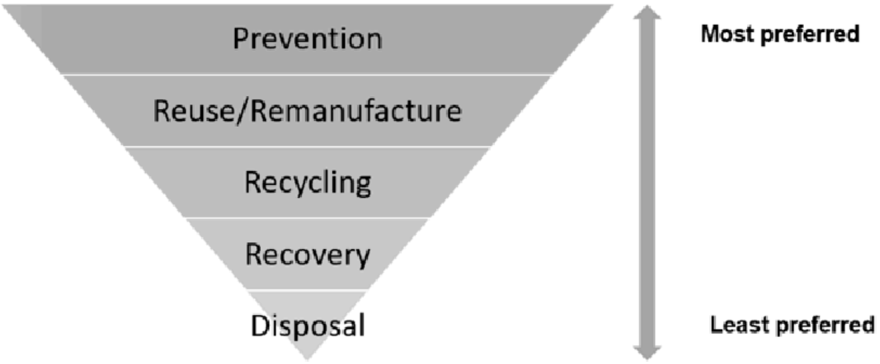

Figure 8: Waste management hierarchy for composite waste, modified [30]

2.2.1 Prevention

Preventing or avoiding waste generation are the most preferred options in the waste management hierarchy [30]. Regular maintenance and routine service can prolong the service life of the composite parts. This can ensure the maximum value for both fibres and resins is retained during the operational phase of the composite parts before being declared as retired components or waste. [31] Better Research and Development (R&D) on composite design and material minimisation together with pre-defining the second life usage of the composite components can further reduce waste being generated. Thus, End-of-Life (EoL) phase should also be considered in product design to ease the dismantling process and also material separation to achieve better product circularity and material acquisition. [32]

2.2.2 Reuse/Remanufacture

The Reuse and Remanufacture methods tackle the value-degraded composite components which have not yet become waste, such as disqualified parts during component production and worn-out products. With minimal reprocessing efforts, these parts can be restored into like-new condition, which allows the remanufactured parts to serve their original purposes (with potentially subpar performances in comparison to virgin products). [33] This method can prevent them from being discarded as waste and facilitate their integration into the material value chain. Remanufacturing can be defined as the rebuilding of a product to specifications of the original manufactured product by repairing, refurbishing and reutilising for whole items or spare parts. [33] The thermoplastic composites used in this study will undergo Reverse-Thermoforming and turn into thermoplastic composite laminate (organo sheet), which can form similar or other composite parts [4].

2.2.3 Recycling

Recycling refers to transforming the EoL composites into high quality secondary raw materials, which can used as input for composite production with the same or different functional use. Energy and other resources might be required to convert the composite waste into useful materials. [31] This subchapter briefly discusses how the available recycling technologies are used to treat the composite waste in three recycling processes namely, physical, thermal and chemical recycling shown in **Figure 9**. [2][3][34]

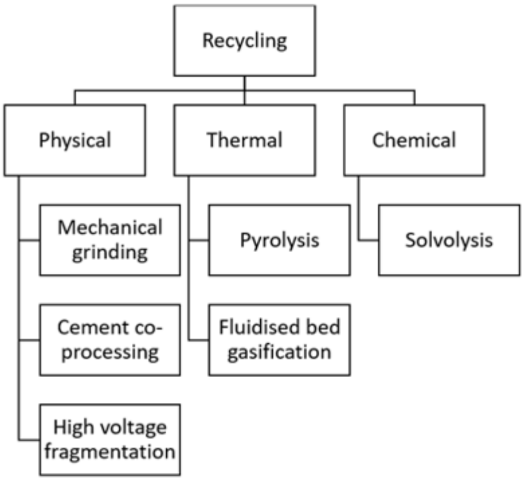

Figure 9: Summary of recycling technologies for composite waste

2.2.3.1 Physical Recycling

The composite materials undergo physical transformation to be reintegrated in another product without alteration of their chemical structure. In mechanical grinding, co-processing in cement kilns and high voltage fragmentation, the scrap composites are initially reduced in material size. They are then treated under mechanical processes (including solely mechanical, thermo-mechanical and electro-mechanical processes) before being re-incorporated with other constituents for secondary production. [34][35]

2.2.3.1.1 Mechanical Grinding

Through shredding, crushing, milling, cutting and other grinding process, the composite waste is broken down into smaller pieces denoted as recyclates (size of 0.05 to 100 mm). These recyclates are classified as coarse (high fibre content) and fine (high resin content) recyclates using sieves and cyclones, which are often used in low-value applications such as fillers or reinforcements. [34] [36] Sheet Molding Compounds (SMC) and Bulk Molding Compound (BMC) processes are typically used methods to reintroduce the chopped glass or carbon fibres back into short fibre reinforced composite materials using compression moulding with compatible resin systems. [21][36]

2.2.3.1.2 Co-processing in Cement Kiln

Cement co-processing or cement kiln route is a thermo-mechanical process for recycling glass fibre reinforced polymers (GFRP). The shredded composite pieces are fed into a cement-kiln reactor. The organic resin system is burnt for energy production (as alternative fuel) and the inorganics are used as feedstock for cement production. Treated with very high temperature (up to 1500 °C), these composites are burnt into ashes and then mixed with other calcinated materials (limestone and clay) to produce the clinker. The clinker is then mixed with gypsum to produce cement of industrial grade for concrete construction. [5][18][31]

2.2.3.1.3 High Voltage Fragmentation (HVF)

HVF is an electro-mechanical process to separate the resin system from the fibres using high voltage pulses. High voltage creates pressure waves along the plasma channels to disintegrate the composite materials in ionised water. Residual resin content of the reclaimed fibres depends on the electrical pulses (range of 50 to 200 kV). Longer and cleaner fibres can be obtained compared to mechanical grinding. [31][37]

2.2.3.2 Thermal Recycling

In thermal recycling processes, the FRP composites are processed with high operating temperature in the range of 450 to 700 °C under various conditions to recover fibres and resins. Unlike incineration and cement-kiln route where only ashes are left behind, pyrolysis and fluidised-bed gasification allow complete fibre recovery using thermal recycling processes. [18][38]

2.2.3.2.1 Pyrolysis

With pyrolysis, the composite waste is heated to high temperatures (about 700 °C) in absence of oxygen to obtain valuable materials. The resin systems and other organic constituents are converted into gas or vapour which can then either be distilled to obtain desired hydrocarbon compounds or feed back to the heating reactor as additional fuels. [35] The glass fibre can be retrieved and processed into secondary products such as glasswool mat and fibreglass blanket for insulation. Temperature is an important parameter for this process as unsuitable temperature can lead to formation of char on the fibre surface (undercooked) or a reduction in the diameter of the recovered fibres (overcooked).[5] CFRP composite is better suited than GFRP for pyrolysis process as high temperature condition causing significant damage on glass fibre surfaces, resulting in poor mechanical properties. But due to the low supply of carbon fibre composite waste, this recycling technology is not yet economically viable.[29][34][36]

2.2.3.2.2 Fluidised Bed Gasification

Fluidised bed gasification is a complex thermal process involving oxygen rich air to decompose the resin system in composite material. The shredded composites are fed in bed of silica sand and react with controlled hot air flow of 450 to 550 °C. The resin systems are decomposed, which then released the fibres and composite fillers particles. Oxygen is required to minimize the char formation.[38] The separation of high value fibres from the relatively low value filler particles can be done using a rotating sieve separator and cyclone. This gasification method usually operates under 550 °C, which the decomposition products can oxidise for energy recovery and also leaving clean fibres with lesser degradation on fibre properties. Heat is recovered from the gas stream to pre-heat fresh air input before being released as flue gas.[5][34][39]

2.2.3.3 Chemical Recycling

In chemical recycling process, the composite waste is treated with various solvents to disintegrate the resin systems of the FRP into the chemical solutions. The chemical recycling processes are often classified into two main categories based on temperature and other process conditions, namely solvolysis with milder conditions and solvolysis with supercritical conditions. [2][3][40]

2.2.3.3.1 Solvolysis with milder conditions

Solvolysis is a chemical process, where the reactive solvents break down the resin system to release the fibres. The suitable chemicals and solvents are chosen based on the nature of the polymer substrate and the conditions are usually below 100 °C with atmospheric pressure. After the resin system is dissolved, the recycled fibres are washed with organic solvent such as acetone to remove the remaining residue. [3] Compared to the pyrolysis and fluidized bed methods, the low temperature solvolysis process is more efficient as it recovers useful chemicals from the resin systems and fibres with very high mechanical properties and fibre length [34][40].

2.2.3.3.2 Solvolysis with supercritical conditions

As some solvents can be aggressive and sometimes toxic to the environment. Thus, new reaction medium is needed in order to reduce the ecological impact of the process. Solvolysis using supercritical fluids has emerged for chemical recycling technology of composite materials. A solvent adopts a high ability to diffuse a soluble substance when its critical temperature and pressure has been met. It can perform new chemical reactions for decomposition and partial oxidation. [41] The commonly used reactive mediums are water and alcohol in their subcritical and supercritical conditions. High temperature solvolysis involves using supercritical fluids such as water and alcohols at temperatures above 374 °C and pressures above 22.1 MPa. [3][31][40]

2.2.4 Recovery

Composite materials can be incinerated for energy recovery. Incineration should only be carried out after removing all useful materials from the composite waste. There are several drawbacks for this waste treatment process[29][42][43]:

- Carbon and glass fibres are not combustible and can be problematic during incineration
- Fibre residues in flue gas may hinder the gas cleaning system

- The ashes after incineration still need to be treated but often goes into landfill
- Most incinerator cannot accommodate very large composite components, so they generally need to be cut into smaller pieces before feeding into the combustion reactor

In order to extract the maximum value out of the composite waste by combustion, waste incineration with combined heat and power (CHP) system (in german *Kraft-Wärme-Kopplung*) should be adopted rather than a conventional incinerator. CHP is an energy efficiency technology that simultaneously generates electricity and captures the heat that would otherwise be discharged to the atmosphere. The heat recovered can be used for district cooling and heating system for household and office buildings. The supply of high-temperature heat from waste combustion first drives a steam turbine-powered generator. The resulting low-temperature waste heat is then used for water and space heating. This co-generation plants often operate at 50—70 % higher efficiency rates than single generation facilities. [44][45]

2.2.5 Disposal

In Europe, the legislation on the disposal of composite waste is mainly regulated by the waste framework and the landfill directive. Since 2009 Germany has banned landfilling waste with a total organic content higher than 5%. [30] Considering these composites contain an organic part (due to the resin that glues together the carbon and glass fibres), they cannot be landfilled. Thus, landfilling or disposal which represent a total loss of resources should always be avoided. [2][5]

2.2.6 Summary on Composite Waste Management

Landfilling has been the most adopted disposal route for FRP waste as it is comparatively economical since composite polymers are difficult to recycle and landfill can easily handle large waste quantities [17]. Incineration has been an alternative to landfill disposal as there is a potential on energy recovery based on the net calorific value of the composite polymers [46]. But both landfilling and incineration represent a total loss on material and/or the embodied energy of the FRP composites. Nonetheless, restrictions and legislative actions have pushed the composite industry to develop effective and sustainable solutions to treat the ever-increasing composite waste.[7]

Recycling of the End-of-Life (EoL) composites can give these composite waste a second life in another product system of lower property demand such as filler materials, Sheet and Bulk Moulding Compounds (SMC and BMC), non-woven fibre reinforced mats, etc. At this stage, the mentioned recycling technologies are mostly applicable treatments for waste thermoset composites, as most of the thermoplastic composite are shredded into flakes or processed into granulates.[21][46]

Table 1 presents a summary of process-related energy consumption and the global warming potential (GWP) of different composite waste treatments extracted from published articles. [37][43][47]

Table 1: Energy use and carbon emission of FRP recycling technologies

Process	**Energy consumption** **MJ /kg FRP**	**Carbon emission** **kg CO_2-eq. /kg FRP**
Landfill	0.97 [a]	0.13 [a]
Incineration	1.17 [a]	3.09 [a]
Incineration with energy recovery	(-)7.5 to (-)34 [b]	0.09 to 3.4 [b]
Mechanical grinding	0.69 [a]	0.03 [a]
High voltage fragmentation	4 [c]	-
Pyrolysis	37.09 [a]	2.88 [a]
Fluidised-Bed Gasification	9.88 [a]	1.54 [a]
Solvolysis	38.12 [a]	1.51[a]

[a] Based on process related data from [47]. [b] Literature value based on composite calorific content [43]. [c] Data extracted from [37]

2.3 Reverse-Thermoforming

The reuse method involving reshaping of rejected or End-of-Life thermoformed composite parts has gained notable attention in composite industry. Thermoformed parts can be reshaped for several cycles depending on the thermal stability of their respective resin systems.[3][9]

This recycling method has been carried out by Kiss et al. to turn the thermoplastic composite waste into high performance sheet materials as shown in **Figure 10**. As described in this study, the thermoformed part made of 250 x 250 x 1 mm composite sheet were clamped, heated and reshaped into its initial flat form with the aid of tension force. Based on the melting temperature of polypropylene (165 °C) and polyamide 6 (220 °C) resin systems, the PP-GF composite parts was heated to 220 °C and PA6-CF parts was heated to 260 °C by an infrared (IR)-radiator during the reforming process. The method is found effective as it only takes up a short process cycle (60 to 90 seconds) and the material still possessed high value as it demonstrates a direct reuse potential for thermoplastic composite laminate. [9]

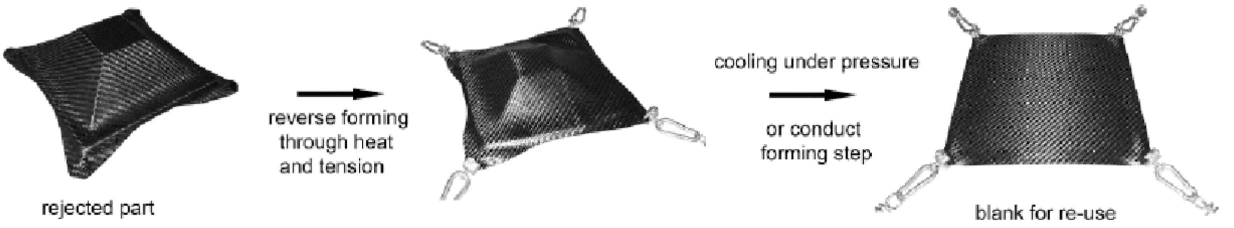

Figure 10: Process route for converting rejected parts back to composite laminate, modified [9]

Division of Fraunhofer Institute for Machine Tools and Forming Technology (Fraunhofer IWU) at Open Hybrid Lab Factory (OHLF) Wolfsburg has been working on Reverse-Thermoforming technology with the infrastructure and machinery available in-house. A remanufacturing process flow for the EoL thermoplastic component that includes heating, calendering, second heating and thermal forming is designed and performed.

In order to investigate the feasibility of the remanufacturing technology, the composite laminate is first thermoformed into the prototype as shown in **Figure 11**. This composite prototype is considered as "End-of-Life composite component" and it will undergo Reverse-Thermoforming based on the four process steps as mentioned above. These thermoplastic parts are made of Polypropylene-Glass Fibre (PP-GF) and Polyamide 6-Carbon Fibre (PA6-CF) consolidated composite laminate with the original dimension of 280 x 280 x 1 mm, which are produced by Bond-Laminates GmbH in Brilon, Germany under product series of "Tepex® Dynalite". [27]

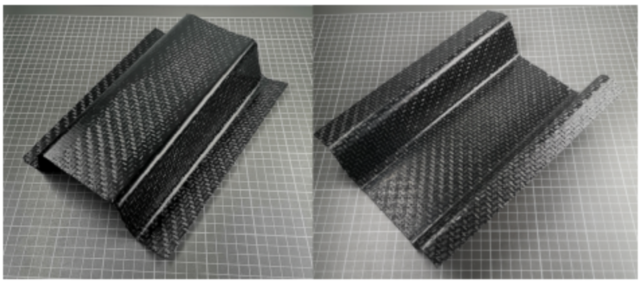

Figure 11: Thermoformed composite component from Tepex® organo sheet

These EoL thermoplastic components are cleaned and inspected before being heated (PP-GF for 190 °C and PA6-CF for 250 °C) by an air-circulating chamber furnace (heating oven) model KU 279/04/A (THERMCONCEPT GmbH in Bremen, Germany) for 4 and 7 minutes respectively. The softened thermoplastic components are then placed on a customised Calender-Direct Impregnation Machinery (CDIM) system (ThermoPre® Machine by ERMAFA Sondermaschinen und Anlagebau GmbH in Chemnitz, Germany) as shown in **Figure 12** to undergo temperature- and pressure-assisted calendering and consolidation processes. The temperatures of the machine are set at 210 °C for PP-GF composites and 260 °C for PA6-CF composites with pressure at 30 bar during the consolidation process. This process usually takes up approximately 6 to 8 minutes for each component and these flatten composite sheets are considered successful when no visible voids or deformations such as obvious wrinkles or yarn slippage is observed.

Figure 12: Calendar-Direct Impregnation Machinery system in OHLF lab

These calendered composite sheets are brought again to the oven and heated based on their constituents (PP-GF for 190 °C and PA6-CF for 250 °C). Meanwhile, the hydraulic stamp press (by Röcher GmbH & Co. KG, Netphen, Germany) is switched on and the heat-assisted forming tools are heated up to 90 °C for PP-GF and 150 °C for PA6-CF composites. The softened thermoplastic sheets are then positioned in between the heated male and female forming tools of the hydraulic press to be thermoformed. The process time for thermoforming is approximately 120 seconds (2 minutes) with pressing force of 800 kN and closing pressure of 30 bar.

Each composite component was subjected up to 5 remanufacturing cycles. The investigation on mechanical performance of the composites was carried out by a colleague from Fraunhofer IWU. The test specimens of each remanufacturing cycle were taken after the calendering process for mechanical properties such as tensile modulus, tensile strength and tensile elongation at break. The physical appearance of the remanufactured thermoplastic composite laminate and the results of mechanical property tests can be found in Appendix C under Experimental Data. **Figure 13** represents the process scheme for remanufactured component from EoL thermoplastic composites based on Reverse-Thermoforming.

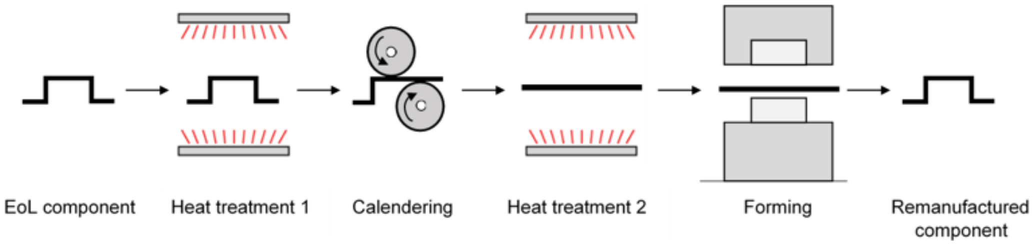

Figure 13: Process scheme of remanufactured thermoplastic component

3 Methodology of Life Cycle Assessment (LCA)

This chapter provides a background to the Life Cycle Assessment (LCA) Framework and the application of the methodology to the case study of remanufacturing of thermoplastic composite. This chapter focuses on the perspectives that can be adopted in the goal and scope definition stage of a LCA for remanufactured composite products together with the functional unit, system boundaries and also impact categories.

3.1 Framework of LCA

The increasing awareness surrounding resource depletion and the potential environmental impacts associated with manufacture and consumption of products have prompted to the development of assessment tools to evaluate such impacts. This has led to the emergence of Life Cycle Assessment (LCA), which is a analytic tool to determine the potential environmental impacts associated with a product or service. [10][19] The LCA tool allows the users to qualify and characterise the inputs and outputs of the specific system associated to the product throughout its life cycle. With the resulted impacts, user can identify the hotspot within the investigated system which can be very useful in supporting decision-making and product designing. Typically, the LCA of a product is conducted with "cradle-to-grave" principle, which includes raw material acquisition, process and manufacture, transportation, use phase and disposal. [10][11]

The efforts to standardise the principle and foundations of life cycle assessment has been ongoing since the 1990s. The result is the published standardisation of ISO 14040 and ISO 14044, which were developed by the CML (Centrum voor Milieukunde Leiden) and the SETAC (Society of Environmental Toxicology and Chemistry). [10] The ISO-standards 14040/44 describe the principles and requirements that must be fulfilled for the performance of life cycle assessment studies and for the preparation of environmental and sustainability reports. In a LCA, the life cycle of a product can be modelled as a product system that performs at least one defined function. [48][49] LCA tools can then be applied to quantify the amount of energy used, the consumption of raw materials, the emissions to the atmosphere and also the volume of waste generated within the defined system. **Figure 14** shows the basic structure of a LCA product system according to DIN EN ISO standard [48].

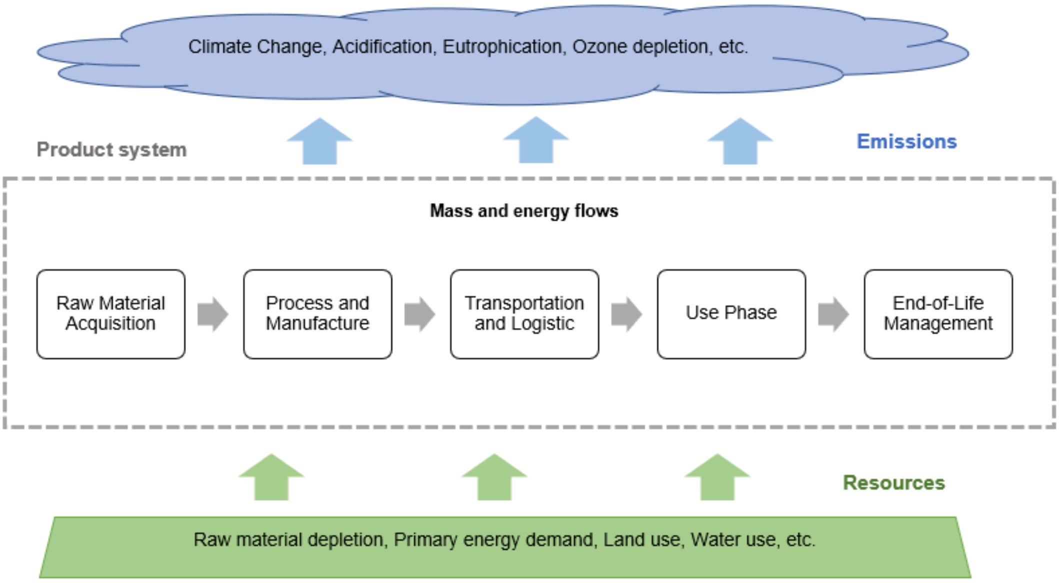

Figure 14: Product system according to ISO 14040 (2006) [48]

LCA is to be subdivided into (i) Definition of goal and scope, (ii) Life cycle inventory (LCI) analysis, (iii) Life cycle impact assessment (LCIA) and (iv) Interpretation of the results, as illustrated in **Figure 15** [48]. Based on the LCA framework, the requirements of the DIN EN ISO 14040/44 standards are described in more detail, broken down by the individual components in following subchapters. A LCA study also provides insights into the complexities of the research product and a more accurate overview of the environmental trade-offs and improvement opportunities. [10][33]

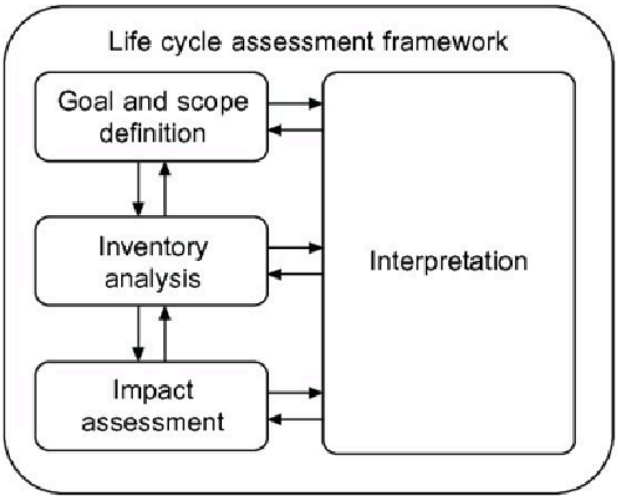

Figure 15: LCA framework according to ISO 14040 (2006), reproduced [48]

3.1.1 Definition of Goal and Scope

In the goal and scope definition stage of a LCA, the purpose and intended application of the assessment should be clearly stated and consistent as this effort forms the basis of the study. This stage also determines the product system in terms of the system boundaries and functional unit. The scope definition also covers aspects such as assumptions, limitations, geographical and technology coverage that could potentially affect the result of the assessment. Particular attention should be given to the definition of the functional unit (FU) as it represents the quantified reference in the comparison of LCA results. In general, the FU is a reference unit that forms the baseline for comparing product substitutions. In relation to FU, reference flows are often included to ensure the equivalence of alternative product systems, which are necessary to deliver the performance described by the functional unit. [10][50]

Depending on purpose of the LCA study, the reference flow of a remanufactured product system may include (i) materials and processes for the original (virgin) product, and/or (ii) materials and processes for multiple remanufacturing cycles. This decision is known as the system boundaries selection and allocation method. Although remanufacturing is practically a form of closed-loop recycling, but it is essential to determined whether the environmental impacts of the first use of the materials are fully allocated to that initial life cycle, a.k.a. ″cutoff approach″, or they are being allocated to the future life cycles, a.k.a. ″avoided burden approach″. [33][40]

In ″cutoff approach″, materials that are used in the next or future life cycle do not bear any environmental burdens from the initial life cycle (virgin product). Thus, the second use of the materials only bears the environmental burdens of collecting, cleaning, processing and further treatments for the recycled materials. In another hand, the ″avoided burden approach″ assumes that recycling or remanufacturing can avoid the production of virgin material, thus the environmental burdens will be credited (rewarded) to the initial life cycle due to its recyclability. [33]

3.1.2 Life Cycle Inventory (LCI) Analysis

The next phase of a LCA involves the compilation and collection of all input and output flows from the processes within the system boundary that is necessary to meet the defined goal and scope. Life cycle inventory (LCI) analysis gives the inventory data of input and output flows as well as formulation of calculation procedures based on experimental results or published literatures to quantify the material usage, energy consumption and also environmental emissions. [11]

The operational steps outlined in **Figure 16** are performed when conducting a LCI analysis according to ISO 14044 on requirements and guidelines [49]. Certain measures should be taken in order to achieve consistent outcome, which includes the construction of the process flow diagrams that outlines all relevant unit processes with data based on operating conditions. Ideally, a number of sources should be compared and analysed during the data collection phase for best characterised results. In cases that such data is not available, calculation should take place and all assumptions should be clearly stated and explained. If the system involved multiple products and recycling processes, allocation of the inventory flows will be performed. [10][50]

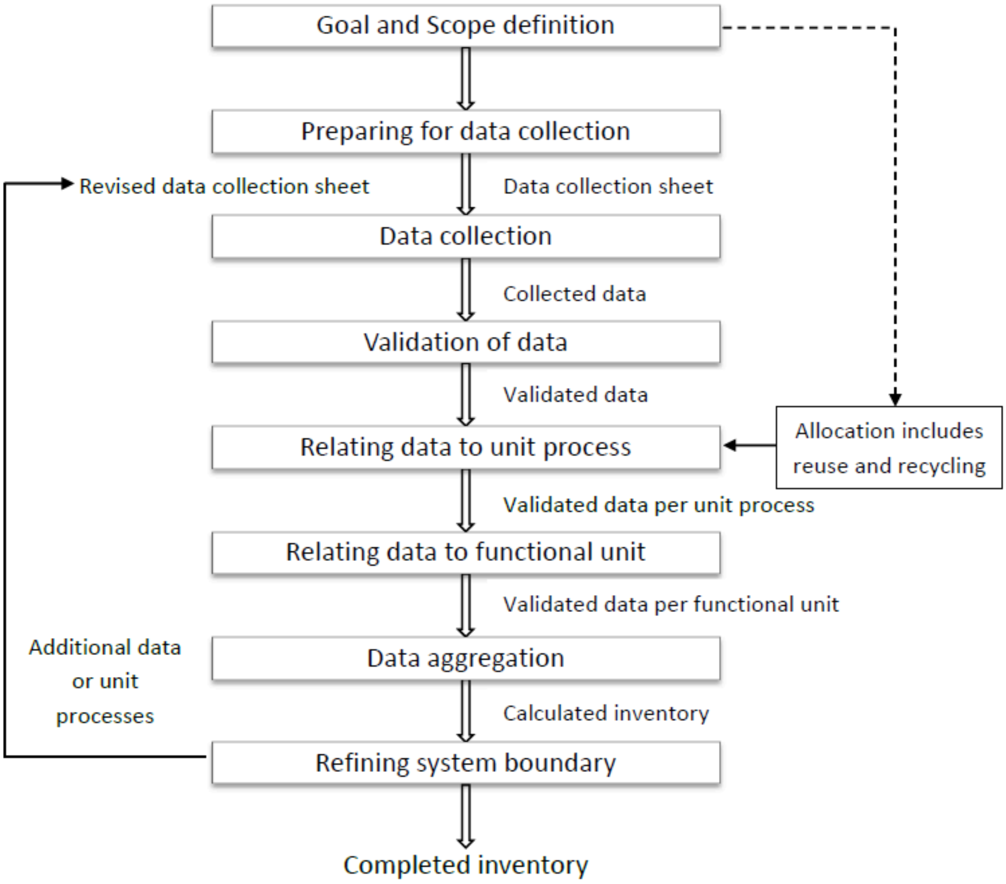

Figure 16: Data collection and calculation procedures for inventory analysis, reproduced [49]

3.1.3 Life Cycle Impact Assessment (LCIA)

The third phase of a LCA is life cycle impact assessment (LCIA). The data collected in the inventory analysis (LCI) are assigned to impact categories such as climate change, eutrophication, acidification, ozone layer depletion, etc. The impact categories and characterisation models should be specified earlier in scope definition. This phase consists of following steps [10][49][51]:

- Selection of impact categories and its respective category indicators

- Classification (assigning the elementary flows to respective impact categories)
- Characterisation (modelling potential impacts using conversion factors based on the impact category)

Optional:

- Normalisation (expressing potential impacts related to a common reference for comparison)
- Grouping (sorting and ranking the impact indicators)
- Weighting (determine relative weightage of impact categories for reporting)
- Data quality analysis (investigate the significance, uncertainty and sensitivity of data obtained)

Table 2 shows some categories commonly assessed in LCA and their respective inventory flows, category indicators together with reference in Kilogram equivalents (kg Reference-eq.).

Table 2: Examples of Impact categories in LCIA methodology [49]

Impact Category	**Inventories**	**Category Indicator**	**Ref.-eq.**
Climate change	CO_2, CH_4, N_2O, CFC	Global Warming Potential (GWP)	CO_2
Ozone depletion	CFC, HFC, Halons	Ozone Depletion Potential (ODP)	CFC
Eutrophication	PO_4, NO_x, NH_4^+	Eutrophication Potential (EP)	P or N
Acidification	SO_x, NO_x, HCl, NH_4^+	Acidification Potential (AP)	SO_2

As an example, global warming (a.k.a. climate change) is selected as an impact category. Inventory data such as $CO_{2,}$ $CH_{4,}$ N_2O and CFCs are classified into their related impact category as global warming. In characterisation, the carbon dioxide emission has a characterisation factor of 1 kg CO_2-equivalent, whereas the methane emission has a factor of 25 kg CO_2-eq. based on GWP_{100} indicator. [10] In another word, 1 kg of methane(CH_4) emission has contributed to similar impact of 28 kg of carbon dioxide emission over a period of 100 years. In practice, LCIA is usually carried out with the LCA Software with selection options of LCIA methods such as ReCiPe, CML, TRACI and Environmental Footprint based on the need or preference of practitioner. **Figure 17** illustrates the process scheme on evaluation of impact assessment based on the resulted inventory flows of functional unit. [10][11]

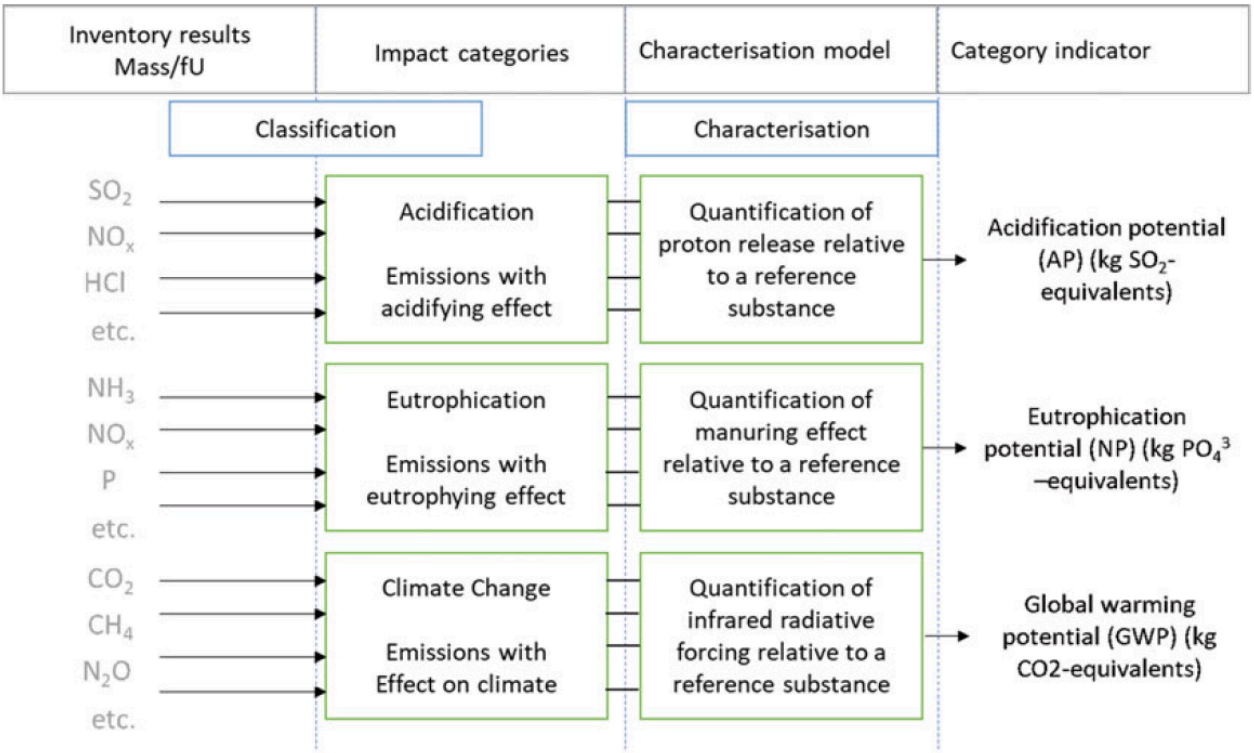

Figure 17: Evaluation method for LCIA, reproduced [10][11]

In addition to the mandatory elements in assessment phase, the four optional features namely normalisation, grouping, weighting and data quality analysis, can contribute to the reliability of the results and better transparency of the data and assumptions employed in the assessment. [11]

3.1.4 Interpretation

In the final phase of a LCA study, life cycle interpretation aims to condense the amount of quantified results from the inventory analysis (LCI) and impact assessment (LCIA) phases to several key findings. The outcome will be utilised with relevant input such as economical and social aspects to facilitate a decision-making process. During the interpretation phase, all assumptions, including the system boundary conditions and specific parameters, should be once again critically assessed. In the phase, the data quality and reliability together with the applied method leading to the ultimate results need to be examined and documented. Uncertainties and limitations should be reviewed to ensure the comprehensive assessment containing all necessary elements and fulfilling the research requirements. [10][11]

3.2 LCA Software Tools

Currently, there are a wide variety of software tools and modelling packages available on the market for conducting a life cycle assessment. LCA tools such as GaBi, SimaPro, openLCA and Umberto are the most widely used software tools associated with composite industry. For this work, GaBi Software is chosen for modelling a LCA due to the relevant datasets available and flexibility to include experimental data into unit processes.

3.2.1 GaBi Software

GaBi is a software package developed in Europe by PE International and now operated by Sphera Solutions, Inc. (in Stuttgart, Germany). GaBi is one of the leading software tools in the market to fulfill objectives such as sustainability assessment, energy and resource efficiency analysis and also Environmental, Health and Safety (EHS) evaluation. The analysis is carried out with GaBi Education Software, which is accessible for academics to perform an entry-level of LCA reporting for education purposes. [52]

The material flow networks can be used to visualise, quantify and mathematically link the incoming and outgoing material and energy flows as well as elementary flows within a defined investigation area. In addition, implemented data libraries with processes from different areas can be accessed. GaBi Databases provide the life cycle inventory data for several of the raw and process materials obtained from the upstream and downstream systems. The long list of life cycle inventory results can be transformed and categorised by LCIA methods such as ReCiPe, TRACI or CML into a limited number of indicator scores, such as carbon footprint, resource and energy consumption and other relevant ecological impacts. [53]

4 Definition of Goal and Scope

4.1 Goal of the Study

The goal of this study is to evaluate the environmental impacts of a remanufacture process of thermoplastic fibre reinforced polymer (tp-FRP) with the "Reverse-Thermoforming" technology. The results of this study are intended to give an insight on the carbon footprint and also energy consumption with this remanufacturing technology and later be used as a reference to do a comparison with virgin composite production.

4.2 Definition of Assessment Scope

In scope definition, the aspects such as functional unit and system boundary that defines the product system together with allocation, cut-off criteria and also assumptions that could potentially influence the result of the assessment are discussed in detail.

4.2.1 Functional Unit

The functional unit (FU) defined in this LCA is **1 kg of EoL thermoplastic composite components treated**. This per-kilogram basis provides a clear picture of the environmental intensity of composite waste treatment as a good deal of published literature [7][19][43][46][54] had chosen "1 kg of fibre reinforced composite waste" as their reference or functional unit to be compared with conventional treatments such as landfilling and incineration.

There are two thermoplastic composite materials used in this work, namely polypropylene-glass fibre (PP-GF) composite laminate and polyamide 6-carbon fibre (PA6-CF) composite laminate.

4.2.2 System Boundary

The system boundary of this LCA study is shown in **Figure 18**. "Cutoff approach" is adopted in this study. The environmental impacts of virgin production are allocated to the initial life cycle. Thus, only the processes and elementary flows for the remanufactured product are taken into account in the LCA. This analysis is therefore considered as a **Grave-to-Gate** methodology as the EoL composites are considered as waste after their service life (grave) and will be further processed to a product with similar functionality as its virgin component before leaving factory gate and to be transported to the customers (gate). One of the limitations of this study is that it does not include the transportation, logistics and the use phase of the remanufactured products.

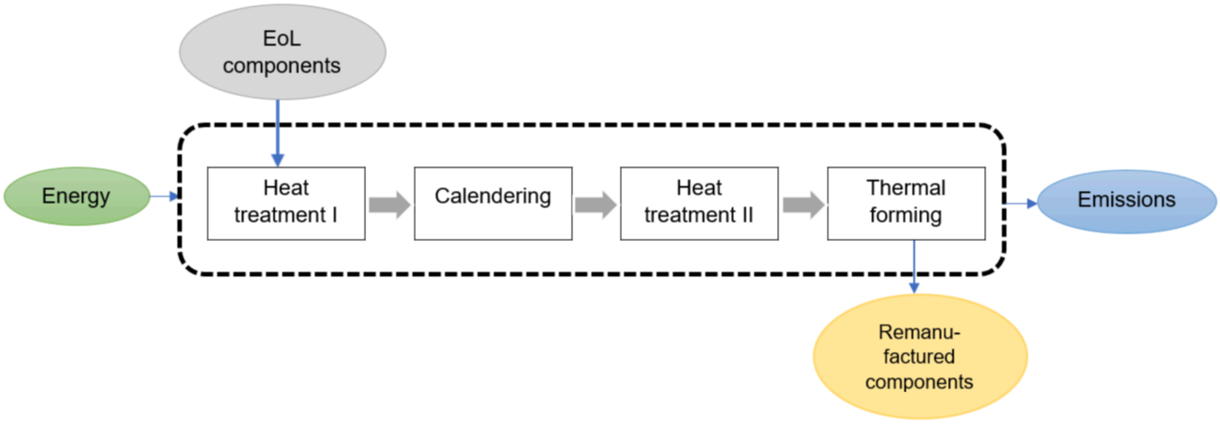

Figure 18: Product system of remanufactured composite components

4.2.3 Allocation and Cut-off Criteria

Allocation is required when there are multiple product-outputs leaving the system (co-product). In this study, the EoL composite components are remanufactured into new components without additional material being added into the system and no additional co-product is formed. Thus, allocation is avoided as this remanufactured process only results in single product.

Cut-off criteria are the areas that are not being considered or appeared to be less relevant to this study. Some operations are also excluded as their contribution to the overall impact is considered as minor. In this study, the following steps have been neglected:

1. Transportation of the composite laminate from the supplier to the research laboratory (production site for remanufacturing)
2. Labour work of handling and inspection of EoL components
3. Logistic and storage of the EoL components and finished products
4. Production and maintenance of the infrastructures (oven, calender and hydraulic press and other machinery involved)
5. Data contributing to less than 1% of mass per module of the input and output flows associated to a unit process. The same goes to energy-related data per module.

In addition, based on mass and energy and the environmental significance, a cut-off rule of 95% is applied. All the known elementary flows of environmental effect have been kept in each inventory for data completeness, which are aided with application of software.

4.2.4 Assumptions

Various process-related assumptions have been made throughout this study. These assumptions will be critically discussed and explained in the next chapter alongside with the process data within the product system. The inventory data and energy sources in this study are predominantly selected from Germany (DE) as geographical boundary, which can be extensive to Europe (EU) depending on the datasets available in GaBi LCA Software.

4.3 Impact Assessment Method

Impact assessment method is often understood as a set of LCIA impact indicators. The widely utilised LCIA methods are TRACI in the United States; Eco-Indicator 99, IPCC 2013 and ILCD 2011 in Europe; together with CML (baseline and non-baseline), ReCiPe 2016 and World and IMPACT 2002+ in general. Midpoint and Endpoint assessment methods are often included in this context as it is important to clarified at which stage the environmental burdens are integrated. [11][52]

4.3.1 ReCiPe (H) Midpoint 2016

ReCiPe is a methodology to conduct life cycle impact assessment (LCIA) based on its characterisation models and the substance coverage for individual impact categories. LCIA translate emissions and resource extractions into limited number of environmental impact scores by means of characterisation factors. ReCiPe distinguishes two levels of categories[53][55]:

- Midpoint categories such as climate change or ozone depletion (a.k.a. impact categories)
- Endpoint indicators with the following categories: damage to human health, damage to ecosystems and damage to resource availability (a.k.a. damage categories)

As an example, the emission in CFC to air will contribute to the depletion of stratospheric ozone layer (midpoint category). As more ultraviolet rays and radiations pass through the ozone layers and enter the atmosphere, the higher the damage on human health due to the higher rate of suffering skin cancer (endpoint category).

All the midpoint and endpoint indicators are available in three different cultural perspectives (timeframes), namely Individualist (I) which is based on short term interest of 20 years, Hierarchist (H) which is based on general assessment timeframe of 100 years and Egalitarian (E) that is based on longest timeframe available of 1000 years with Global warming potential

(GWP) as reference. For this study, ReCiPe midpoint (Hierarchist) is chosen for this study as it is the most common policy principles with regard to time frame and characterisation methodology. This LCIA method has adopted the standard timeline e.g., 100-year impacts for global warming, GWP_{100} for evaluation.[53][55]

A summary of impact categories used in ReCiPe 2016 (Hierarchist) at midpoint level are listed in **Table 3** together with the respective characterisation factors and reference units. [55] These midpoint indicators can be calculated with their characterisation factors based on the damage pathways to form the three areas of protection at endpoint level as following[10][55]:

- Human health
- Ecosystem
- Resource availability

Figure 19 shows the relations between the midpoint impact categories (environmental mechanisms) and the endpoint damage categories (area of protections) as implemented in ReCiPe 2016 methodology[55].

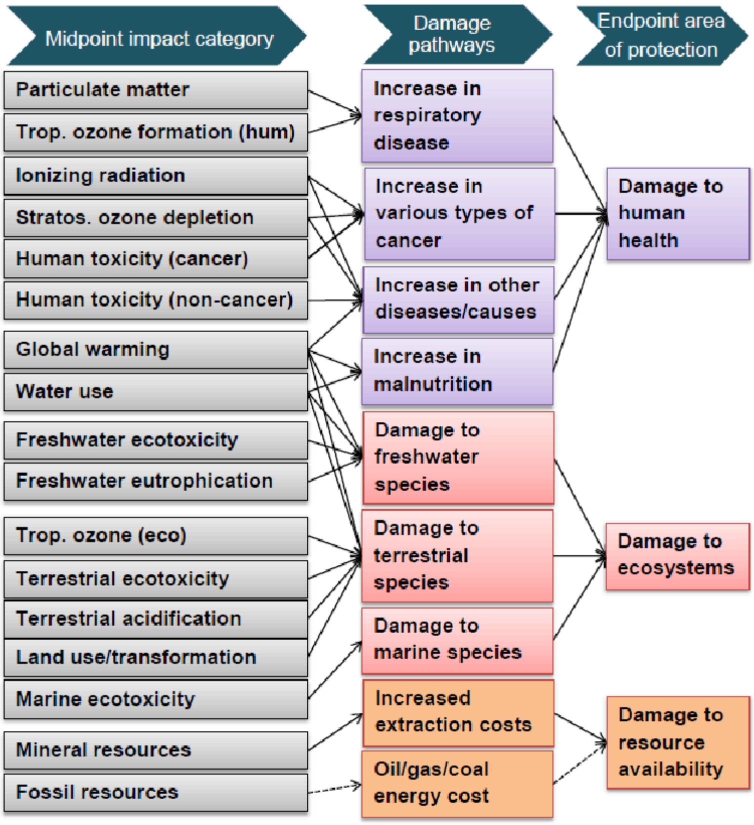

Figure 19: Relation between environmental mechanisms and the areas of protection based on damage pathways, reproduced [55]

Table 3: Overview of midpoint impact category based on ReCiPe(H) 2016 [55]

Impact category	**Characterisation factor**	**Abbr.**	**Unit equivalent**
Climate change	Global Warming Potential (for 100 years)	GWP_{100}	kg CO_2 to air
Terrestrial acidification	Acidification Potential	AP	kg SO_2 to air
Stratospheric ozone depletion	Ozone Depletion Potential	ODP	kg CFC-11 to air
Ionising radiation	Ionising Radiation Potential	IRP	kBq Co-60 to air
Fine particulate matter formation	Particulate Matter Formation Potential	PMFP	kg PM 2.5 to air
Photochemical ozone formation, ecosystem	Ecosystem Oxidant Formation Potential	EOFP	kg NO_x to air
Photochemical ozone formation, human health	Humans Oxidant Formation Potential	HOFP	kg NO_x to air
Freshwater eutrophication	Freshwater Eutrophication Potential	FEP	kg P to water
Marine eutrophication	Marine Eutrophication Potential	MEP	kg N to water
Water consumption	Water Consumption Potential	WCP	m^3 water used
Human toxicity, cancer	Human Toxicity Potential	HTPc	kg 1,4-DCB to urban air
Human toxicity, non-cancer	Human Toxicity Potential	HTPnc	kg 1,4-DCB to urban air
Ecotoxicity (terrestrial, freshwater, marine)	Ecotoxicity Potential	ETP (TETP, FETP, METP)	kg 1,4-DCB to industrial soil, freshwater, and marine water

Impact category	**Characterisation factor**	**Abbr.**	**Unit equivalent**
Agricultural land use	Agricultural Land Occupation Potential	ALOP	m^{2*}yr annual crop land
Mineral resource scarcity	Surplus Ore Potential	SOP	kg Copper (Cu)
Fossil resource scarcity	Fossil Depletion Potential	FDP	kg crude oil (42 MJ per kg, in ground)

5 Life Cycle Inventory (LCI) Analysis

As the second stage of the LCA, the inventory analysis consisted of data collection of process and environmentally related data as well as formulating equations in order to quantify the inventory flows of the product system. In this chapter, process schemes of remanufacturing thermoplastic components are modelled with GaBi Software. For better understanding, LCA modelling on production of virgin composite laminates for both PP-GF and PA6-CF composites and their ecological impacts are compared and discussed with the remanufactured models in the following chapters, Impact Assessment and Interpretation.

5.1 Modelling of Remanufactured Components

In this subchapter, process flow diagrams are constructed with GaBi Software with the pre-installed database and reference data to provide an outline of all the relevant unit processes together with identified parameters for the operating conditions. Calculations are performed according to the process parameters and experimental results. Assumptions applied in the relevant unit processes are stated and explained. For an effective assessment, the data collected had to be scaled down in accordance with the functional unit (1 kg of composites). GaBi Software allows practitioners to construct the product system by connecting the unit or system processes through intermediate product flows.

5.1.1 Reverse-Thermoforming of PP-GF Components

Figure 20 illustrates the schematic flow of 1 kg remanufactured composites components (FU). In this modelling, four unit operations, namely heat treatment (pre-and post-calendering), calendering and thermal forming are constructed with appropriate inputs and outputs.

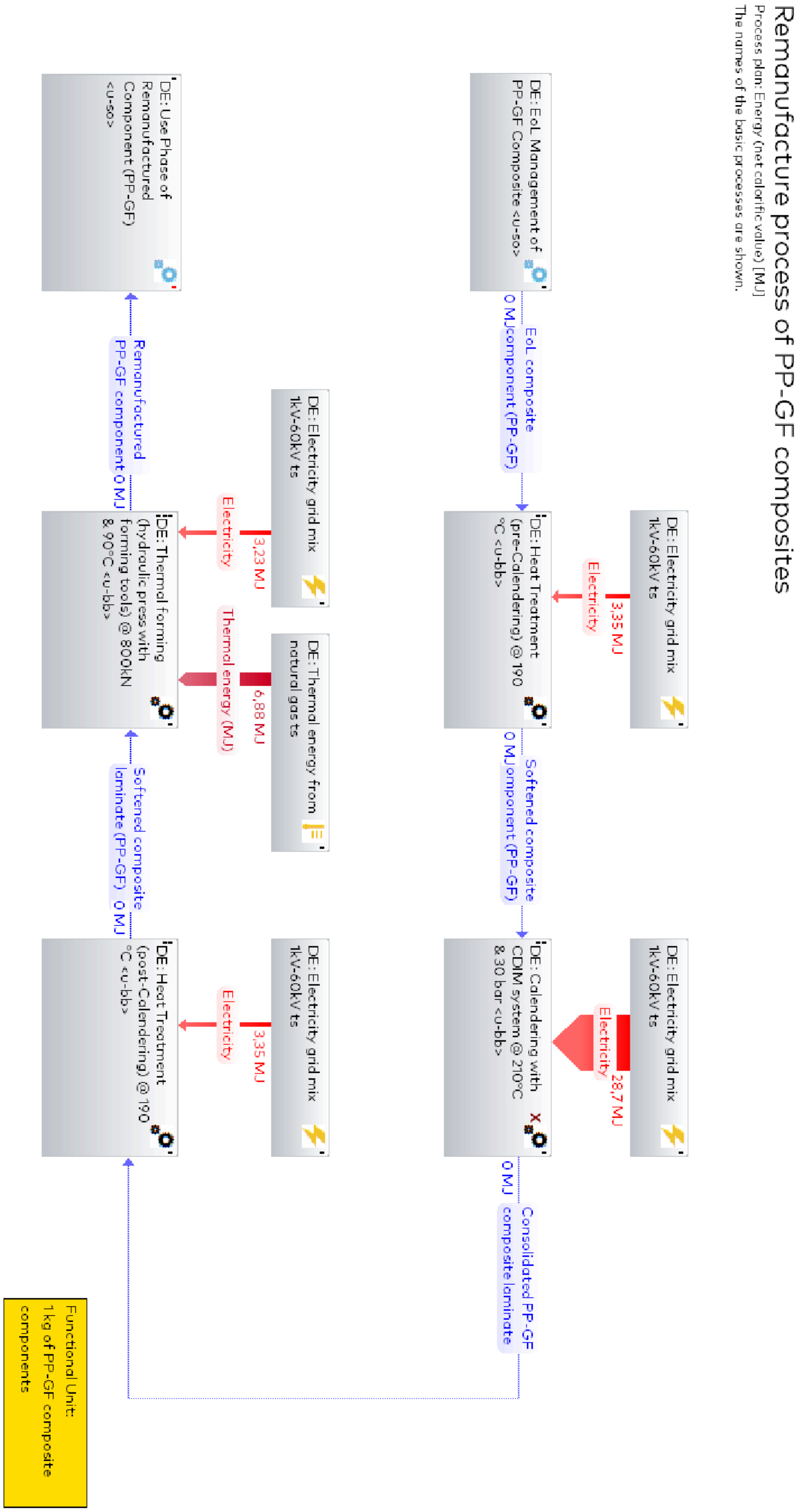

Figure 20: Product system of PP-GF remanufactured components

5.1.1.1 Heat Treatment (pre- and post-Calendering)

Heat treatments were conducted to soften the thermoplastic composites by heating them slightly over the melting point of the resin polymer, so that they can be processed and consolidated back into their original form (composite laminate sheets) or being thermoformed into desired shapes. During this operation, 10 pieces of PP-GF composites (total weight of 1.31712 kg) were heated in the ThermConcept Oven (9.8 kW with maximum heating temperature of 450 °C) for approximately 4 minutes. The melting point of PP resin polymer is at 165 °C, hence the process temperature was set at 190 °C. The oven was pre-heated to reduce the temperature gradient within the composites and resulted in more even heat distribution.

Table 4 summarises the energy input and process parameters for heat treatment of PP-GF.

Table 4: Inventory data of heat treatment (PP-GF)

Heat treatment	Value	Remark
Heating duration	4 minutes	measured
Pre-heating and handling time	15 minutes	estimated
Oven temperature	190 °C	measured
Heating power rate	39.5%	calculated
Weight of composites (10 pieces)	1.317 kg	calculated
Electricity used	1.227 kWh	calculated
Process energy	0.9316 kWh/kg	calculated
	3.354 MJ/kg	calculated

As a result, 3.354 Megajoules (MJ) of electricity per FU (1 kg of composites) was needed for heat treatment based on calculation. The heat treatment after the calendering process (post-calendering) had the same process parameters as pre-calendering.

5.1.1.2 Calendering with CDIM System

After heating, the softened PP-GF components were manually transferred to the Calender-Direct Impregnation Machinery (CDIM) system for calendering and consolidation. The CDIM system was adjusted to temperature of 210 °C and operating pressure of 30 bar and heated from room temperature to its process temperature. The components were loaded continuously into the machinery and flattened as composite laminate sheets. The process time for one composite component was recorded at 8 minutes with an interval period of 3 minutes before inserting the following components.

The energy consumption was recorded with an electricity metering device (electrical network analyser Qualistar$^+$ model C.A 8335, Chauvin Arnoux Group), which can be analysed with PAT (Power Analyser Transfer) software. Temperature profile and energy consumption were constructed based on the extracted data. The inventory data collected from the electricity mater are listed in **Table 5**.

Table 5: Inventory data of calendering process (PP-GF)

Calendering	Parameter	Value recorded in kWh	Conversion to MJ
Heating phase	from 20 to 210 °C 105 minutes	8.122	29.239
Process phase	210 °C 35 minutes	2.371	8.536
Electricity used	for 10 composites (1.317 kg)	10.493	37.775
Process energy per FU	per kg	7.967	28.68 MJ/kg

The process energy required for entire calendering process, including heating and cooling phases were recorded at 10.493 kWh, which is equivalent to 37.775 MJ. The value is then scaled to its functional unit, standing at approximately 28.7 MJ/kg.

5.1.1.3 Thermal Forming

After second heating (post-calendering), the softened, consolidated composite laminates were placed in between the heat-assisted forming tools and thermoformed with the help of a hydraulic press (Röcher press with maximum pressing force of 1600 kN). The forming tools were heated at 90 °C and the hydraulic press was set at 800 kN pressing force. The consolidation period was about 2 minutes with a closing pressure of 30 bar. The electrical power for hydraulic press is 4.73 kW based on calculation and assumption from the work of Hohmann [25][56]. The interval period between the opening and closing of the thermal forming equipment was estimated at 1 minute.

In addition, the heating energy for the stainless steel forming tools was calculated at 8.715 MJ based on the estimated weight of tools at 259 kg and specific heat capacity of steel at 500 J/kgK. This operation was conducted for 10 composites as a batch.

Table 6 represents the process parameters and energy consumptions of the hydraulic press and steel forming tools during the thermal forming operation.

Table 6: Inventory data of thermal forming (PP-GF)

Thermal forming	**Parameter**
Hydraulic press	
Pressing force	800 kN
Operation duration	30 minutes
Electricity used	1.182 kWh
Process energy per FU	0.897 kWh/kg
	3.230 MJ/kg
Heat-assisted forming tools	
Dimension	300 x 550 x 200 mm
Density of steel	7850 kg/m³
Mass of tools	259 kg
Specific heat capacity of steel	500 J/kgK
Temperature difference	70 Kelvin (from 20 to 90 °C)
Thermal energy used	9.065 MJ
Process energy per FU	6.882 MJ/kg

The remanufactured composites were inspected before a repetitive remanufacturing cycle was taken place, subjected to a total of 5 remanufacturing cycles and test specimens of each cycle were tested for its mechanical properties.

5.1.2 Reverse-Thermoforming of PA6-CF Components

The EoL thermoplastic PA6-CF components were treated similar to the process operations as explained but with slight alteration in parameters. **Figure 21** represents the process flow diagram of PA6-CF remanufactured components per FU with electricity needed for each process operation. The PA6-CF components were heated at elevated temperature compared to PP-GF components as polyamide 6 had a higher melting temperature (220 °C) than that of polypropylene polymer (165 °C). 10 pieces of PA6-CF laminate with dimension of 280 x 280 x 1 mm were weighted at 1.11328 kg.

In heating phase, the PA6-CF composites were heated to 250 °C for 7 minutes at 53.5% of oven heating power with additional 15 minutes for pre-heating the oven. The process condition for heat treatment before and after calendering remained unchanged.

As for CDIM system, the machinery was adjusted to process temperature of 260 °C with pressure of 30 bar. The duration for the heating phase in calendering operation were estimated at 135 minutes in accordance with the heating rate of the CDIM system. The process time for one component was 8 minutes with insertion interval of 3 minutes. The entire operation was recorded at 170 minutes. The cooling phase of the CDIM system was not taken into account as the system is capable of processing in larger scale. The inclusion of cooling energy for only 10 components may result in higher energy demand and resulted in high level of uncertainty in the data acquisition. Data on energy consumption were collected with Qualistar electricity meter for calendering.

For thermal forming, the tools were preheated to 150 °C before inserting the components. The pressing force and consolidation time remained unchanged (800 kN and 2 minutes).

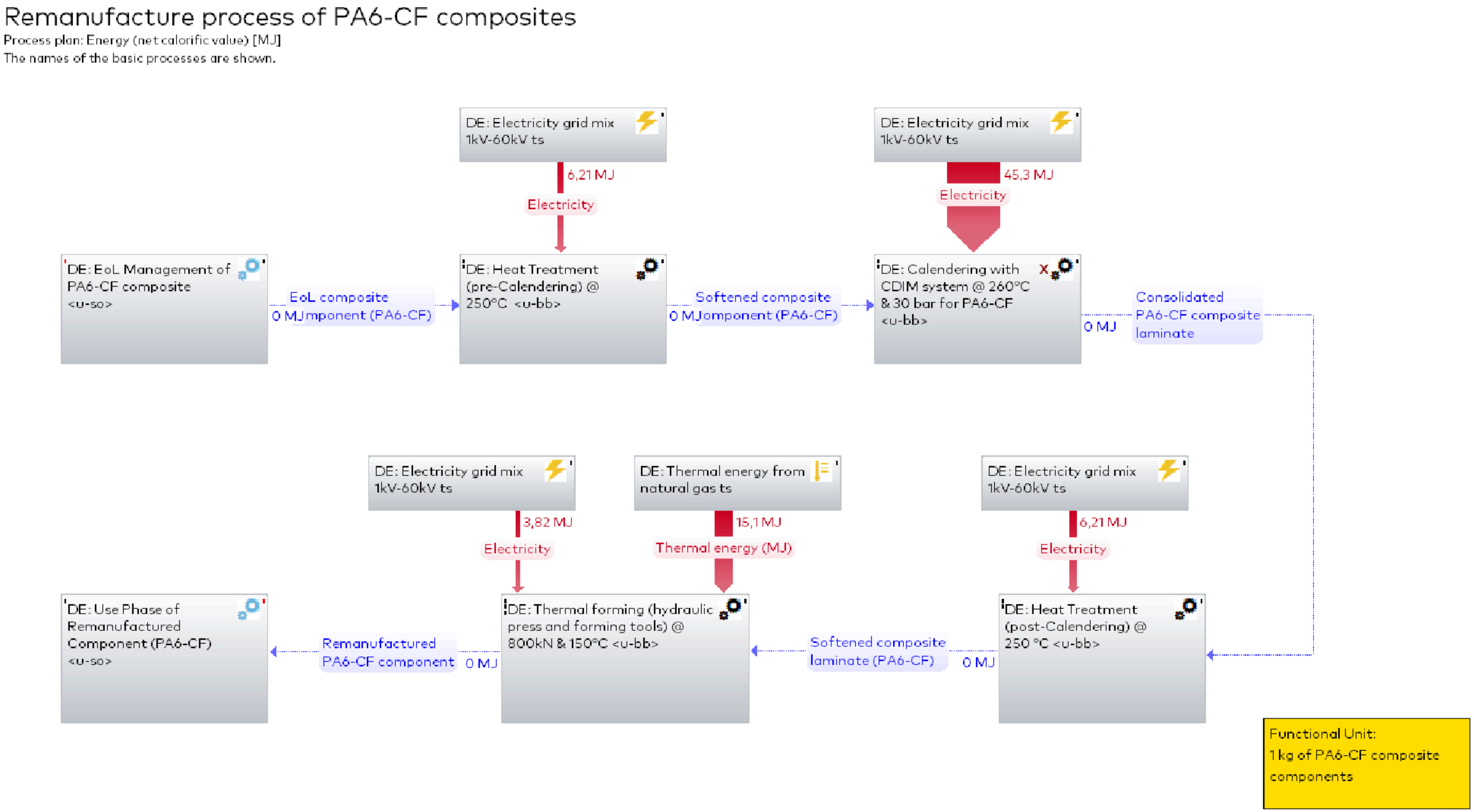

Figure 21: Product system of PA6-CF remanufactured components

Table 7 summarises the process-related inventory data for modelling of remanufactured PA6-CF composite components.

Table 7: Inventory data of remanufacturing PA6-CF composite

Process	Parameter	Remark
Heat Treatment (pre- & post calendering)		
Heating duration	7 minutes	measured
Pre-heating and handling time	15 minutes	estimated
Oven temperature	250 °C	measured
Heating power rate	53.5%	calculated
Composite weight (10 pieces)	1.113 kg	measured
Electricity used	1.922 kWh	calculated
Process energy per FU	1.726 kWh/kg	calculated
	6.215 MJ/kg	calculated
Calendering with CDIM system	**Value recorded in kWh**	**Conversion to MJ**
Heating phase (from 20 to 260 °C; 135 minutes)	11.306	40.702
Process phase (260 °C; 35 minutes)	2.700	9.721
Electricity used	14.006	50.423
Process energy per FU	12.581 kWh/kg	45.29 MJ/kg

Thermal Forming	**Parameter**	**Remark**
Hydraulic press		
Pressing force	800 kN	calculated
Operation duration	30 minutes	estimated
Electricity used	1.182 kWh	calculated
Process energy per FU	1.0614 kWh/kg	calculated
	3.821 MJ/kg	calculated
Heat-assisted forming tools		
Mass of forming tools	259 kg	calculated
Specific heat capacity of steel	500 J/kgK	material data sheet
Temperature difference	130 Kelvin (from 20 to 150 °C)	measured
Thermal energy used	16.835 MJ	calculated
Process energy per FU	15.122 MJ/kg	calculated

5.1.3 Summary on Modelling of Remanufactured Components

In this study, the environmental burdens of the original composite component were not taken into consideration as mentioned in section 4.2.2 under system boundary as the ''cutoff approach'' was adopted. Thus, the EoL components were considered as material input and the focus was to determine the energy needed of bringing the used component back to its original form. The quality of the secondary product should match or just slightly lower than its virgin component in terms of mechanical properties.

As the energy inputs of all four unit processes are electricity, it is crucial to understand the source of electricity supply. In this study, GaBi dataset ''DE—Electricity grid mix of 1kV to 60 kV to consumer'' was applied in the LCA modelling. The electricity is generated by primary energy from renewable and non-renewable sources in the region of Germany. To generate 1 MJ of electricity as process energy, 2.4 MJ of non-renewable primary energy (natural gas, uranium, lignite and other fossil fuels) and 0.5 MJ of renewable primary energy (solar, wind, biomass etc.) are required based on GaBi dataset. [52][56]

Table 8 summarises the process-related energy consumption of the four unit operations in remanufacturing of thermoplastic FRP components.

Table 8: Summary of energy demand for Reverse-Thermoforming

Unit operation	Process energy MJ/kg PP-GF	Process energy MJ/kg PA6-CF	Remarks
Heat treatment (pre-Calendering)	3.354	6.215	calculated [57]
Calendering with CDIM system	28.685	45.288	measured
Heat treatment (post-Calendering)	3.354	6.215	calculated [57]
Thermal forming -Electricity -Thermal energy	 3.230 6.882	 3.821 15.122	literature [25][58]
Total process energy	42.15	76.66	—

5.2 Modelling of Virgin Composite Laminates

In order to make plausible and meaningful comparison in terms of the resulted potential ecological impacts, a modelling of production of virgin thermoplastic composite laminates (vCL) was conducted based on the datasets available in GaBi database and published literature. Material data sheets (MDS) of Tepex dynalite® PP-GF and PA6-CF composite laminates were obtained from the supplier together with some relevant process data required to conduct this modelling of vCL (also referred to as organo sheet).

5.2.1 Production of PP-GF Organo Sheets

Table 9 provides a summary of process chain for production of 1 kg virgin PP-GF organo sheets, which was coherent with the FU of the remanufactured composites. This modelling of virgin production was performed to be compared with the baseline results obtained from the modelling of remanufactured composites. Therefore, the outcome of this study may vary from previously published studies for production of vCL given the different assumptions and system boundaries considered in each study. Significant difference in the modelling is anticipated, especially when the transportation and labour work are not taken into account.

Table 9: Process-related information for production of PP-GF organo sheet

Process operation	**Parameter**	**Specification**	**Data source**
Production of glass fibre	Fibre type	E-glass roving DE	GaBi dataset
Weaving of GF fabric	Electrical energy	Electricity-mix DE	GaBi dataset
		0.11 kWh/m²	Stiller [59]
	Fabric type	Twill 2/2 weaving	Tepex® MDS
	Area weight (dry)	600 g/m²	
Production of resin polymer	Resin type with polymer form	Polypropylene film	GaBi dataset (Plastics Europe)
Production of organo sheet (merging PP film and GF fabric)	Electrical energy	Electricity-mix DE	GaBi dataset
	Type	DBP or CCM	Supplier
	Fibre content	47 vol-%	Tepex® MDS
	Laminate density	1.86 g/cm³	
	Pressing temperature	230 °C	Supplier, Kroemer[13]
	Processing pressure	40—50 bar	
	Process time	8—10 mins	

Four individual process operations were constructed in the LCA modelling of PP-GF organo sheet fabrication. For production of glass fibre, dataset from GaBi Database "Glass fibres, from mineral components, Borosilicate glass /E-glass (DE)" were adopted. This dataset were designed as a system process which is essentially one process that contained a set of unit processes. In this case, unit process data such as electricity mix, limestone flour($CaCO_3$), kaolin, lubricants, clay, natural gas etc. were included in this operation dataset in GaBi Database. Weaving of glass fibre as process operation were constructed based on the work of Stiller [59]. The published report had included the process energy needed for weaving of glass and carbon fibre into fibre woven fabric.

Dataset "Polypropylene film (RER)" was utilised for the production of resin polymer. The source of inventory data was from Eco-profiles of the European plastic industry (Plastics Europe), where survey was conducted among the members of the European trade that produce over 90% of plastics in EU countries according to ISO standards. [60] The manufacturing of PP-GF organo sheet was basically the embedding process of PP resin into the glass fabric with elevated temperature and high processing pressure. The process parameters mentioned in Table 5 were collected from the manufacturer of Tepex® composite laminates (Bond-Laminates GmbH) and also dissertation of Kroemer [13].

Based on the data available, a modelling of virgin PP-GF organo sheet was conducted with GaBi software and presented in **Figure 22**. The glass fibre content of organo sheet is constituted of 47-vol% (volume percentage) according to Tepex® material data sheet (MDS). The weight ratio of fibre and resin polymer can be converted with composite calculation tools (NetComposites calculator [61]) based on the laminate density and the theoretical density of the fibre reinforcements and resin polymer. The fibre and resin densities are referred as 2.56 and 0.90 g/cm^3 accordingly, which resulted the fibre content of 71.61 wt-% and resin content of 28.39 wt-% in terms of weight percentage. The percentage rates stated in the respective unit processes represent their contribution in terms of energy demand in the entire product system. To prevent bias towards remanufactured components, the material loss from the organo sheet fabrication and the production waste of both fibres and resin were excluded in this LCA model.

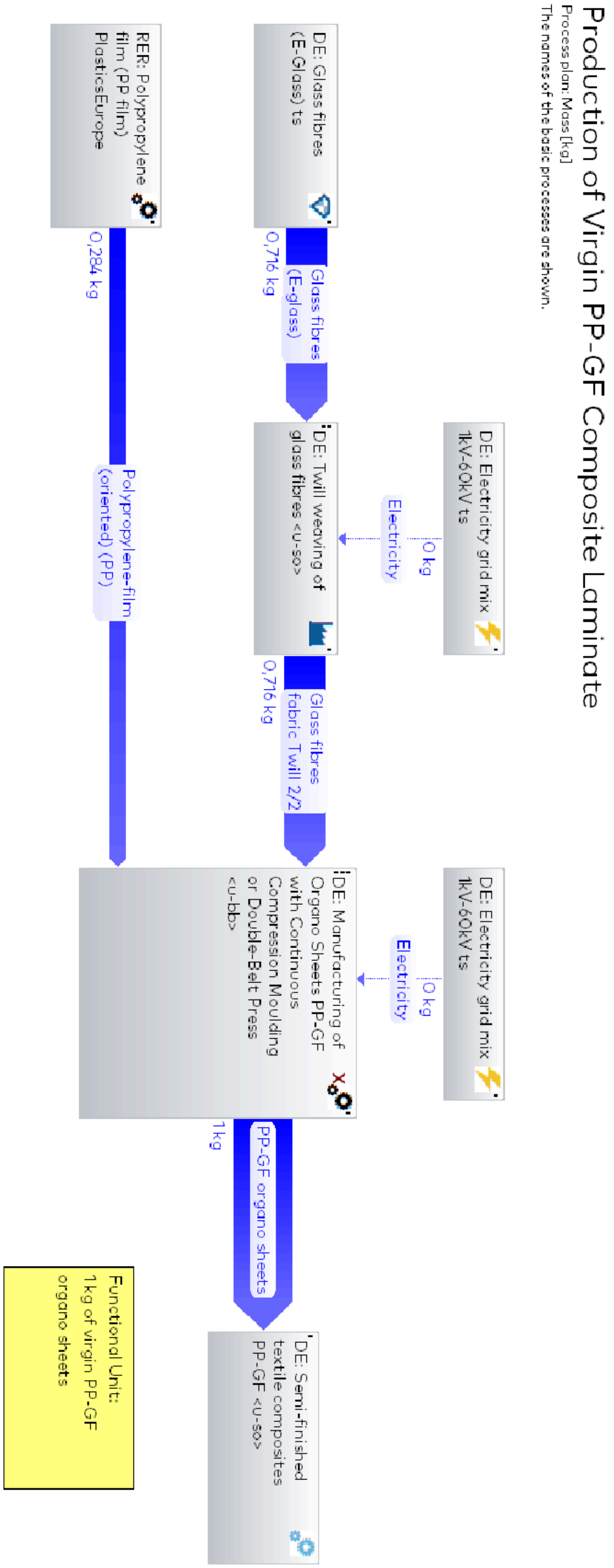

Figure 22: Product system of virgin PP-GF organo sheets production

5.2.2 Production of PA6-CF Organo Sheets

For production of PA6-CF organo sheet, the inventory data gather from the manufacturer and various literature were included in the process operation as stated in **Table 11.** The inventory data for this modelling were collected from various reports and studies on CFRP production chains, contributed mainly by dissertation of Hohmann[25], a published report from Fraunhofer-Institut with MAI Carbon Cluster Management GmbH [56] and GaBi Database.

Table 10: Process-related information for production of PA6-CF organo sheets

Process operation	**Parameter**	**Specification**	**Data source**
Production of precursor fibre	Fibre type	PAN fibre	GaBi dataset
Conversion of PAN-fibre to CF	Electrical and thermal energy	Electricity-mix DE Thermal energy DE	GaBi dataset
	Fibre type	HT-fibre	Hohmann[25][56], Das[54], Stiller[59], Griffing[62]
	Mass loss	50% (assumed)	
Weaving of CF fabric	Electrical energy	Electricity-mix DE	GaBi dataset
		0.214 kWh/m^2	Stiller [59]
	Fabric type	Twill 2/2 weaving	Tepex$^{®}$ MDS
	Area weight (dry)	200 g/m^2	
Production of resin polymer	Resin type Polymer form	Polyamide 6 Plastic film	GaBi dataset
Production of organo sheet	Electrical energy	Electricity-mix DE	GaBi dataset
	Type	DBP or CCM	Supplier
	Fibre content	45 vol-%	Tepex$^{®}$ MDS
	Laminate density	1.42 g/cm^3	
	Pressing temperature	280 °C	Supplier, Hohmann[25][56], DSC analysis
	Processing pressure	40-50 bar	
	Process time	8-10 mins	

Previous studies [19][25][43][54][56] have shown that production of carbon fibre and its precursors (polyacrylonitrile fibre) have a significant share (over 65%) of the environmental impact in manufacturing of CFRP products. The PAN fibre is made from crude oil and further processing into carbon fibre which involved energy-intensive processes. In this modelling, dataset from GaBi database, i.e. "Polyacrylonitrile (PAN) fibre, without additives (EU-28)" was deployed for production of PAN fibre. The dataset includes all the prior unit processes based on industrial data within Europe (see Appendix A).

The mass of the PAN fibre required is hugely depending on the conversion processes. In this study, the type of carbon fibre utilised is HT-fibre, which is a standard elastic modulus type with high tenacity. The PAN fibre undergoes stabilisation (oxidation with 23—280 °C), carbonisation (heating with 1000—1700 °C) and surface treatment. The inventory data was taken from Das [54], stating that 72.2 MJ of electricity and 97.7 MJ of thermal energy from natural gas are required to produce 1 kg of CF. The conversion to carbon fibres resulted in approximately 41% to 55% of weight reduction. [19][25][39][59] During the conversion of PAN to carbon fibre, water and electrolyte (normally ammonium chloride) are required for surface treatment and coating of fibres. For this process operation, 2.375 kg of process water and 0.025 kg of electrolyte are needed per kg of CF according to Griffing.[25][62]

Process energy required for manufacturing of carbon fabric through weaving can be taken from Stiller[59], which stated 0.214 kWh/m² of carbon fabric. Given that the area weight of dry fabric is 200 g/m², the energy needed for the fabrication can be calculated as 1.07 kWh/kg CF fabric, which is equivalent to 3.85 MJ/kg fabric. Dataset for polyamide 6 plastic film was taken from the GaBi Database with the data source from Plastics Europe [60].

In order to have a better assumption on the energy consumption for merging PA6 polymer and CF into organo sheets, a differential scanning calorimetry (DSC) analysis was performed. DSC thermal analysis allows the measurement of the difference in the amount of heat required to increase the temperature of a sample and reference as a function of temperature. The results showed that the latent heat of fusion for PA6-CF specimens was 14.4% higher than that of PP-GF specimens. (see Appendix C)

Figure 23 illustrates the product system constructed based on the collected data with GaBi software for virgin PA6-CF organo sheet production. Based on the material data and composite calculation tool [61], 1 kg of PA6-CF composite laminate with 45 vol-% fibre content consists of 0.56 kg of carbon fibre and 0.44 kg of PA6 polymer. The percentage rates stated in the respective unit processes represent their contribution in terms of energy demand within the system.

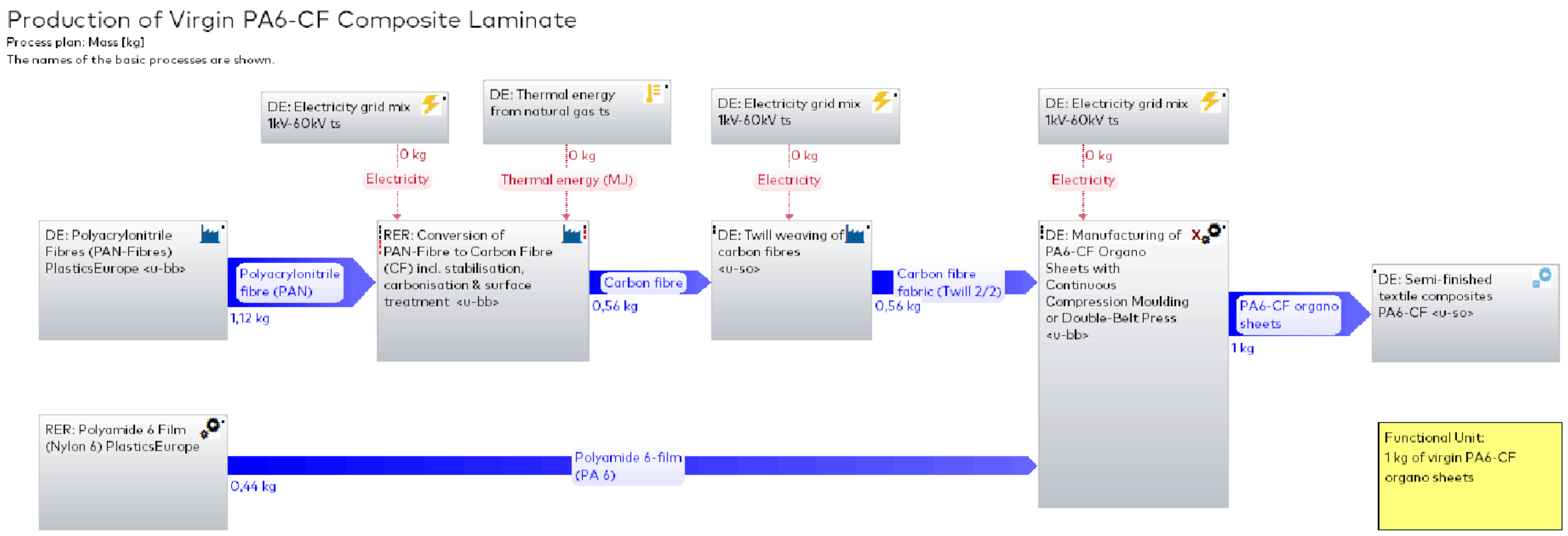

Figure 23: Product system of virgin PA6-CF organo sheets production

6 Life Cycle Impact Assessment (LCIA)

The life cycle impact assessment (LCIA) phase aims to analyse the product system in regard to its potential environmental impacts. The inventory data is inscribed into the product system as elementary flows with the aid of LCA software tools. The GaBi Education Software contains various impact assessment methods such as TRACI, CML 2001, Environmental Footprint 2.0 and ReCiPe 2016 (Hierarchist) Midpoint that allows practitioners to employ based on geographical relevance and selection of ecological impact categories. For this study, the ReCiPe(H) Midpoint method was used. The list of elementary flows from life cycle inventory analysis (LCI) are assigned to the impact categories and transformed into a limited number of environmental impact indicators in accordance to their reference unit equivalent. [10][49]

6.1 Selection of Impact Categories

The impact categories are selected to represent the potential ecological issues that linked to the contemplated product system. This study focuses on the midpoint level of the environmental mechanism (a.k.a. ''problem-oriented approach''), which has a lower uncertainty compared to the end point level, i.e. ''damage-oriented approach''. According to the updated ReCiPe report in 2016, 17 midpoint indicators are included as listed in Table 3 (refer to Chapter 4.3.1) [55]. Based on literature review and results generated through GaBi modelling, four impact categories were selected for this study, namely:

- Climate change
- Acidification, terrestrial
- Water consumption, and
- Fossil resource scarcity.

In addition, process energy and cumulative energy demand were also included in the discussion as the energy consumption are strongly attributed to the ecological impacts and resource uptake from the environment that fed into the technical system.

6.2 LCIA Results for Reverse-Thermoforming

The impact assessment results based on the ReCiPe (H) midpoint are discussed in this chapter. There were 18 midpoint indicators with two additional energy-related indicators, namely process energy and cumulative energy demand (CED) are included. The contributions of these indicators to the potential environmental burdens are displayed with the use of diagrams. The contributions of each process operation towards their respective impact categories were assigned and calculated by the GaBi Software Tools.

The impact assessment results for both remanufactured models of PP-GF and PA6-CF are displayed in **Figure 24** and **Figure 25** respectively. The results showcase a similar trend in both models with regard to their contributions towards the impact categories. This outcome coherent with the implication of Reverse-Thermoforming as the unit operations deployed are identical, only slight alteration in their respective process parameter for both remanufactured models.

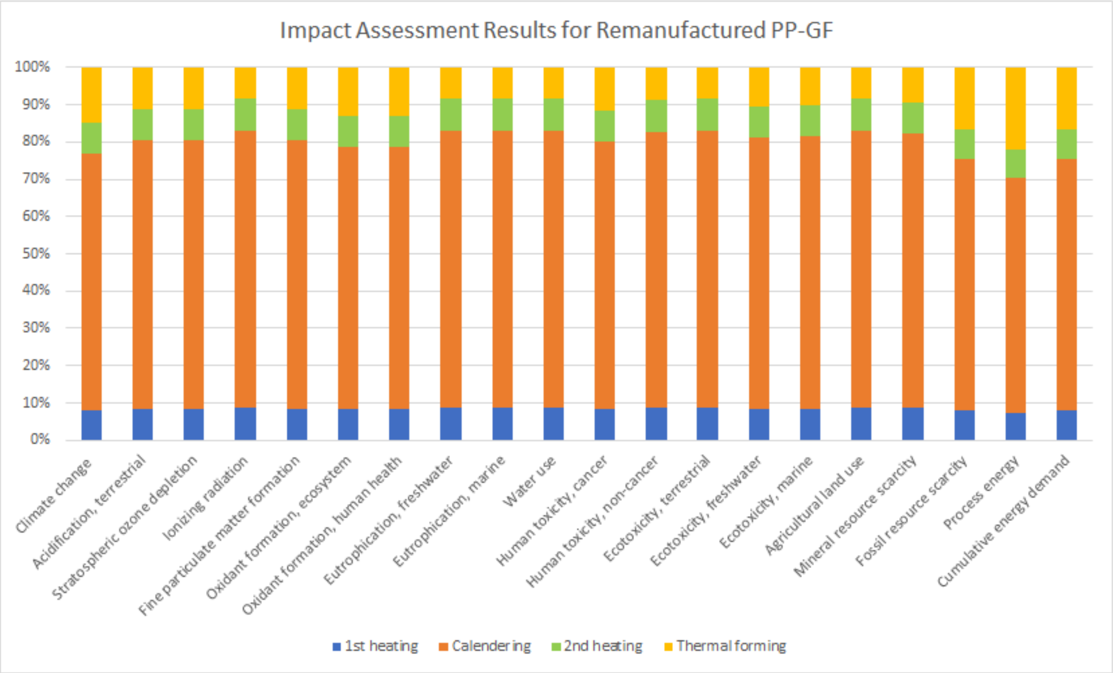

Figure 24: Overall LCIA result for remanufacturing of PP-GF composite

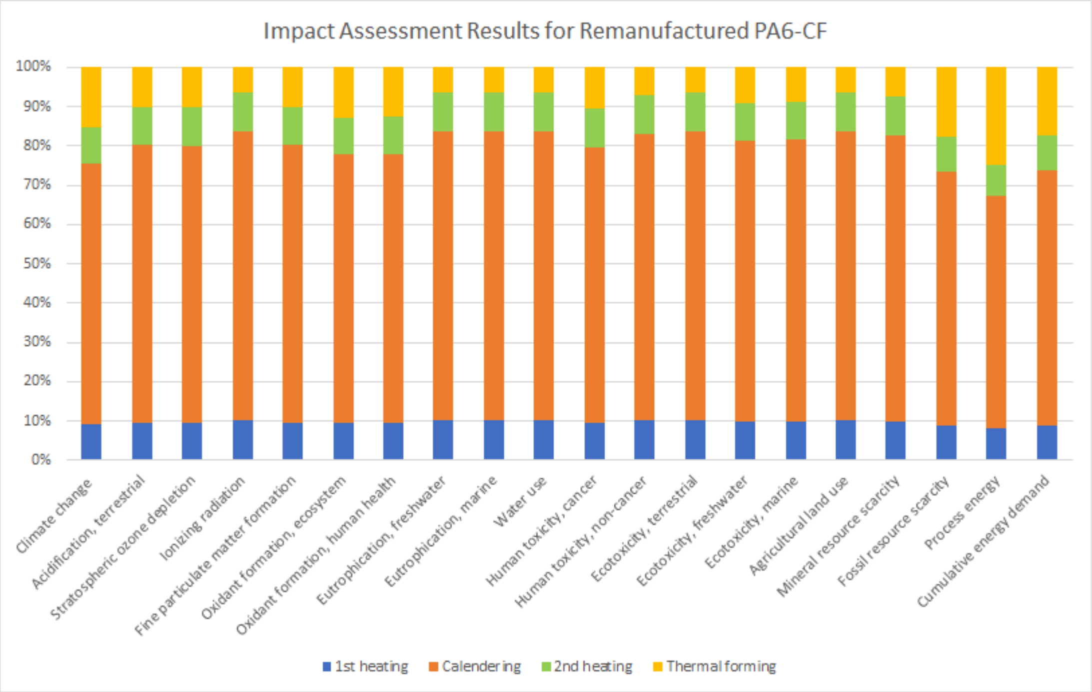

Figure 25: Overall LCIA result for remanufacturing of PA6-CF composite

The blue bar represents the electricity needed for first heating treatment, the orange bar represents the energy consumption for calendering with CDIM system, the green bar represents electricity needed for the second heat treatment and the yellow bar represents the thermal and electrical energy for thermal forming the components. It is evident that the energy consumption for calendering process accounted for the majority of the categories in both models.

As mentioned in Chapter 5.2, the modelling of virgin composite laminate (vCL) was conducted for meaningful comparison with the remanufactured model of the same material constituents. The LCIA results for virgin PP-GF organo sheet production are demonstrated in **Figure 26.**

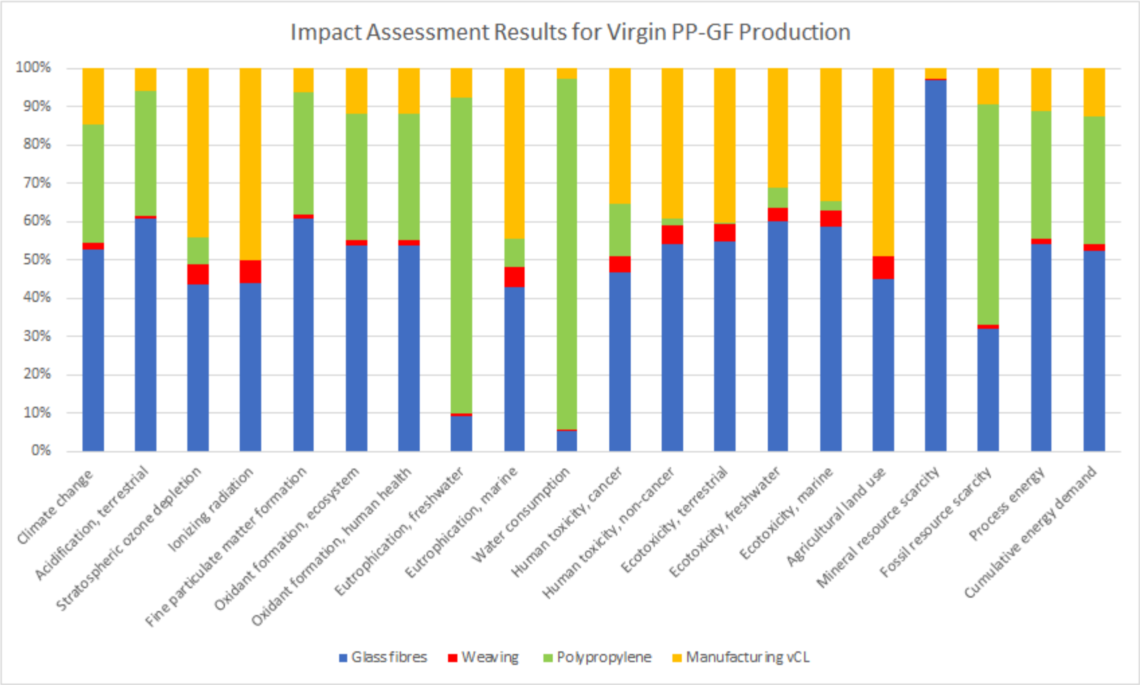

Figure 26: Overall LCIA result for virgin PP-GF production

The manufacturing of glass fibre has contributed over 50% share in terms of potential ecological burdens in 10 impact categories out of the 18. Notably, in categories of freshwater eutrophication and water consumption, the production of polypropylene is the main contributor as it accounted for 82.3% and 91.5% of total share in the two categories.

In **Figure 27**, the impact assessment result for vCL production of PA6-CF organo sheet is presented in accordance to their contributions towards their respective impact categories. Evidently, the manufacturing of PAN fibres and the energy consumption to convert PAN fibres to carbon fibres (electrical and thermal energy) have accounted most of the ecological burdens in overall results.

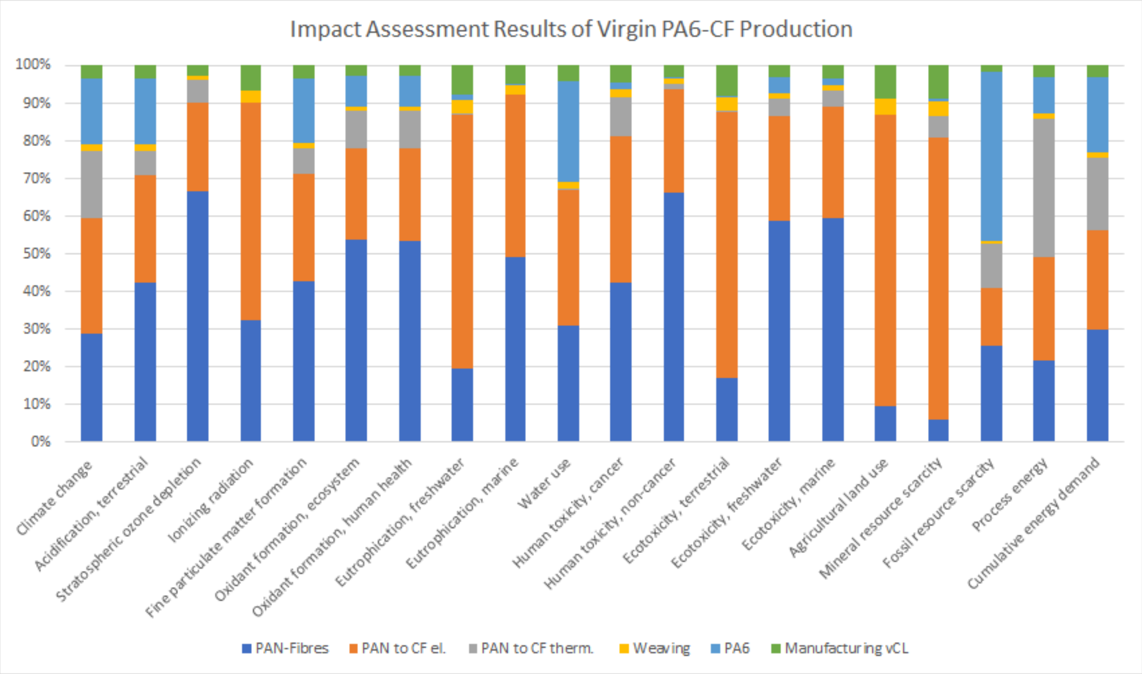

Figure 27: Overall LCIA result for virgin PA6-CF production

The comparison of remanufactured (rCL) and virgin composite laminate (vCL) for PA6-CF is illustrated in **Figure 28**. Note that only heat treatment and calendering for rCL production are involved in this comparison with vCL production as the following heat treatment and thermal forming process are identical and can be simplified. The blue bar in Figure 28 represents the virgin production of PA6-CF (vCL), which is scaled to 100% contributions, whilst the orange bar represents the remanufacturing of PA6-CF (rCL). The results revealed that the remanufactured PA6-CF has in general lower environmental burdens compared to its virgin counterpart.

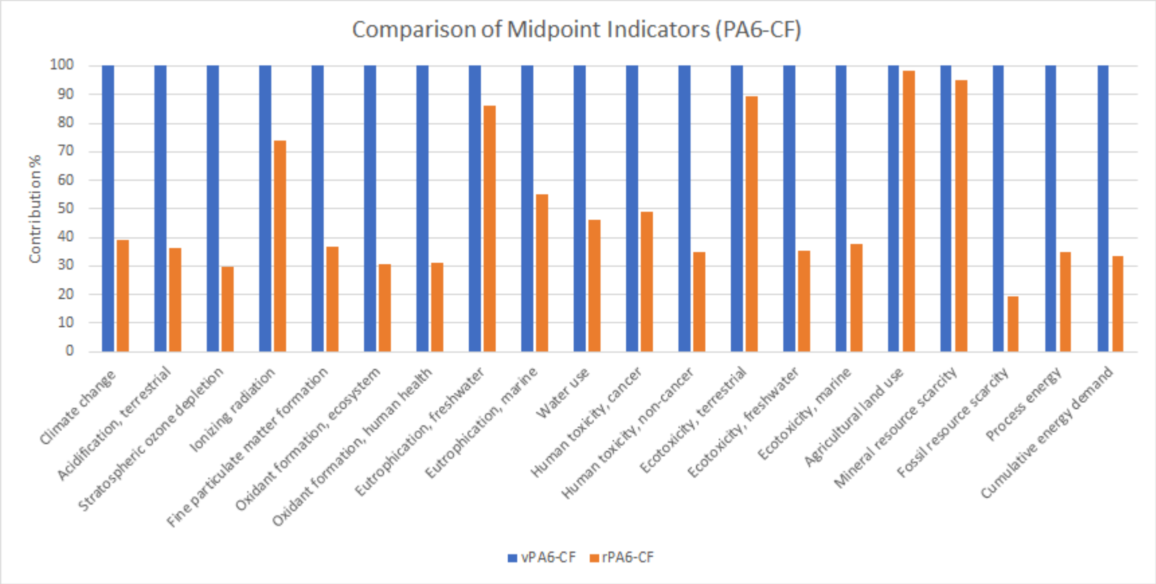

Figure 28: Comparison of LCIA result for virgin and remanufactured PA6-CF at midpoint level

In contrast, the comparison of LCIA results for virgin and remanufactured models of PP-GF has fluctuated across the 18 impact categories and 2 energy-related indicators, as exhibited in **Figure 29.** The green bar stands for contributions of virgin PP-GF production to the impact assessment results, whereas the red bar indicates the contributions of the remanufactured PP-GF model.

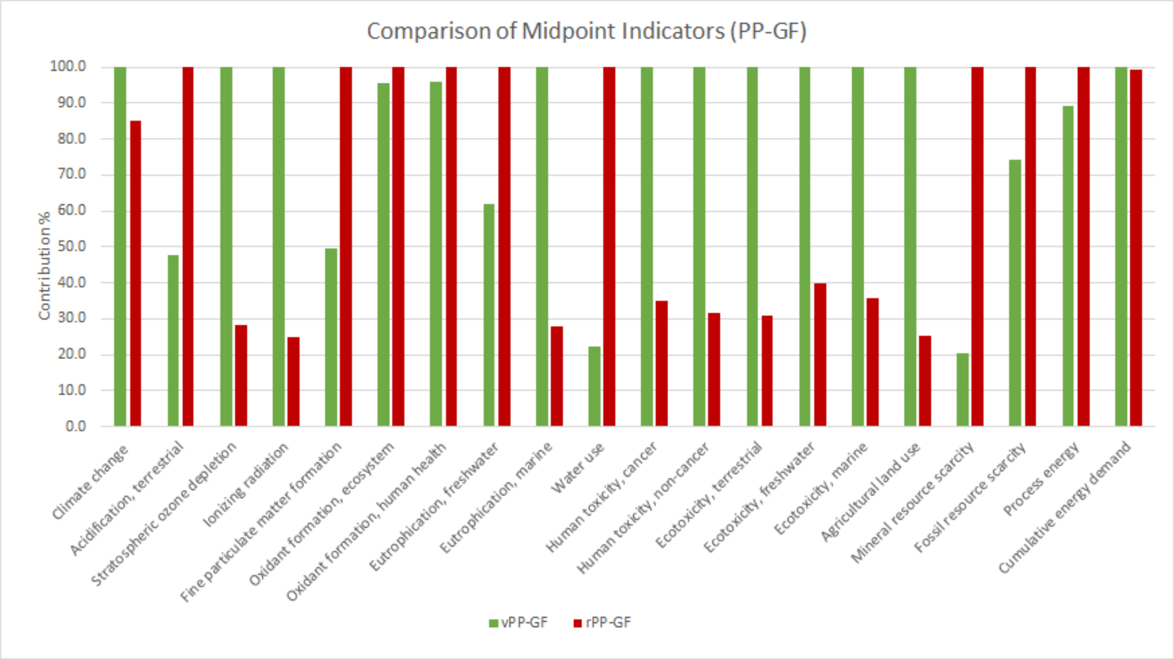

Figure 29: Comparison of LCIA result for virgin and remanufactured PP-GF at midpoint level

A popular explanation for the high potential ecological impacts of remanufactured PP-GF model is the source of electricity. As the Reverse-Thermoforming of composite components is a electrical energy-intensive operation, the dataset related to process energy deployed for the modelling has a massive influence on the LCIA results. The dataset used for electricity in the LCA modelling was "Electricity grid mix-DE", available in GaBi Database. To generate 1 MJ of electricity in Germany, 2.16 MJ of primary energy from non-renewable origin and 0.74 MJ of primary energy from regenerative energy is required. [52][56]

On the other hand, thermal energy is more efficient in production as 1.12 MJ of primary energy in the form of natural gas and coal is able to generate 1 MJ of thermal energy [52]. As the production of glass fibre which accounts for 71% of total weight in PP-GF organo sheet mainly utilised thermal energy during the manufacturing phase, the fabrication of virgin organo sheet has therefore resulted in lower contributions to environmental impacts than the remanufactured counterparts.

In order to justify the explanation, parameter modification in terms of electricity input was executed for the modelling of remanufactured PP-GF composite. Datasets "Electricity from wind power-DE" and "Electricity from hydro power-DE" were selected as parameters to replace "Electricity grid mix-DE" for sensitivity analysis. The LCIA results for the selected impact categories are displayed in **Figure 30**.

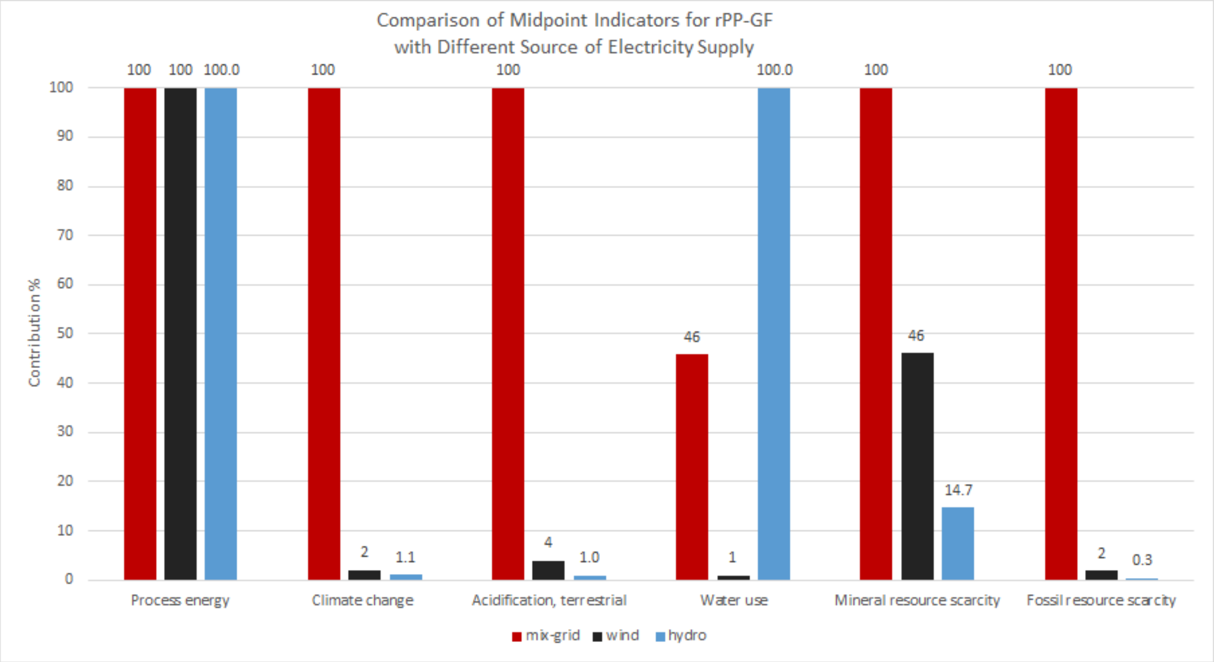

Figure 30: Comparison of LCIA result of rPP-GF based on modified parameters in terms of electricity source

Although the process energy for all the three parameters are the same, the LCIA results demonstrate drastic differences in their contributions towards the midpoint indicators. For impact category Climate Change, the results indicate that electricity from wind power and hydro power only emitted approximately 2% and 1% of greenhouse gas respectively when compared to electricity from mix grid. Similar results are observed in impact categories Terrestrial Acidification, Mineral and Fossil Resource Scarcity. The notable difference appears in category Water Consumption, as the water used for generating electricity from hydro power plant are 64% higher than electricity grid mix and 99% higher than electricity from wind power plant.

7 Interpretation

The interpretation phase aims to analyse the results from all the previous phases and discuss the findings by making linkages to previous studies. By interpreting the data obtained for the selected impact categories, appropriate conclusions and recommendations for future work can be drawn. In this chapter, the results obtained from the modelling of remanufactured and virgin composite laminate are extensively discussed and compared based on their corresponding impact categories.

7.1 Process Energy and Cumulative Energy Demand (CED)

The process energy of a product system represents the direct energy usage during the manufacturing phase of a product. The process energy use is not one of the impact categories included in LCIA methodology but rather an indicator for the magnitude of direct energy consumption during the production phase. The energy in this category is the (total) thermal and electrical energy required for the model remanufacturing at the production site. The process energy, which accounts for production of virgin composite laminate are extracted from the elementary flows of the LCA modelling. Results demonstrated for virgin modelling might not be pinpoint accurate as only the main contributors for process energy in terms of electricity and thermal energy were included.

The cumulative energy demand (CED) of a product is defined as the sum of direct and indirect energy use throughout the entire product life cycle, which includes the energy consumed during the extraction, fabrication and EoL management of the raw and auxiliary materials. CED is also often referred to as primary energy demand (PED) that includes the consumption of both non-renewable resources such as crude oil, coal and natural gas together with renewable energies such as wind and solar energy.[10][25]

Figure 31 presents the process energy use for the virgin and remanufactured models based on calculation and data extracted from GaBi dataset. The CED of the models are demonstrated in **Figure 32**. Both figures suggest that the fabrication of virgin PA6-CF organo sheet has the highest process energy use and CED. These results are mainly contributed by the production of carbon fibre, which includes the production of PAN fibre and the thermal and electrical energy required to convert the PAN fibre to carbon fibre. The qualitative data for process energy and CED can be found in Appendix A.

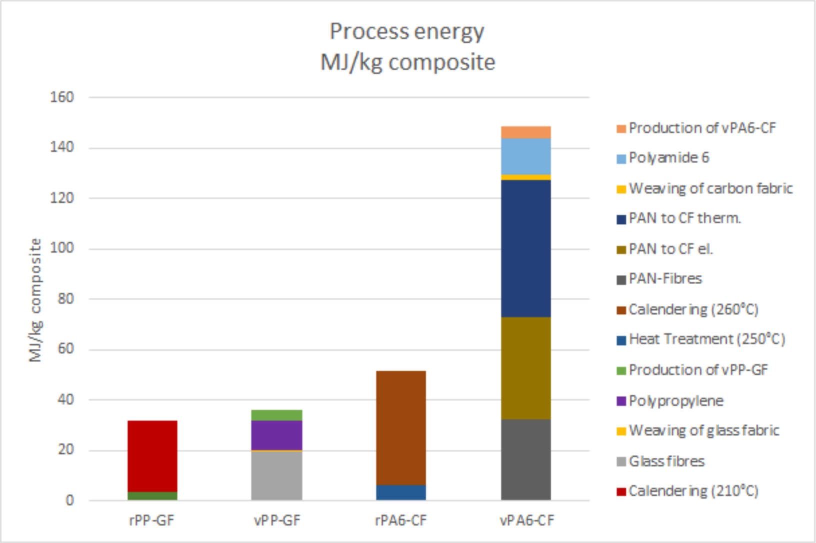

Figure 31: Comparison of process energy for virgin and remanufactured composite laminate

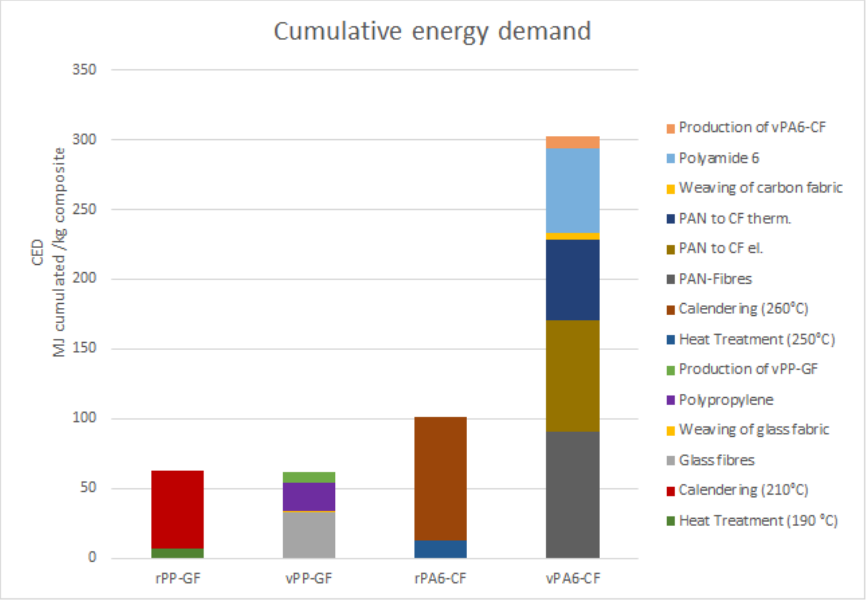

Figure 32: Comparison of cumulative energy demand for virgin and remanufactured composite laminate

7.2 Climate Change

Climate change is generally used to describe the warming of the climate system due to anthropogenic (man-made) activities. The emissions of greenhouse gas (GHG) to the atmosphere is the main contributor to the global warming. The indicator used in this impact category is the increasing rate of global infra-red radiative capacity with unit of watt*year/ m^2. The rising in the temperature of atmosphere and ocean leads to consequences such as rising sea levels and extreme meteorological events. [63] ReCiPe Midpoint use GWP_{100} (Global Warming Potential with 100-years' time frame), developed by the Intergovernmental Panel on Climate Change (IPCC). The reference unit for GWP_{100} are kg CO_2-equivalent. This approach is adopted by the LCIA methodologies as it is comprehensive to the public and normally used in reporting.[64]

Figure 33 illustrates the comparison results for the GWP of the rCL and vCL models for both PP-GF and PA6-CF thermoplastic composites. Production of virgin PA6-CF (20.5 kg of CO_2-eq. per FU) has shown the highest GHG emissions, especially during the production of carbon fibre. The GWP of rPA6-CF is revealed at 8.0 kg CO_2-eq., which is approximately 60% lower than the vPA6-CF. The remanufactured PP-GF has accounted slightly higher GHG emissions compared to its virgin counterparts, with the GWP stating 4.98 kg and 4.24 kg of CO_2-eq. respectively.

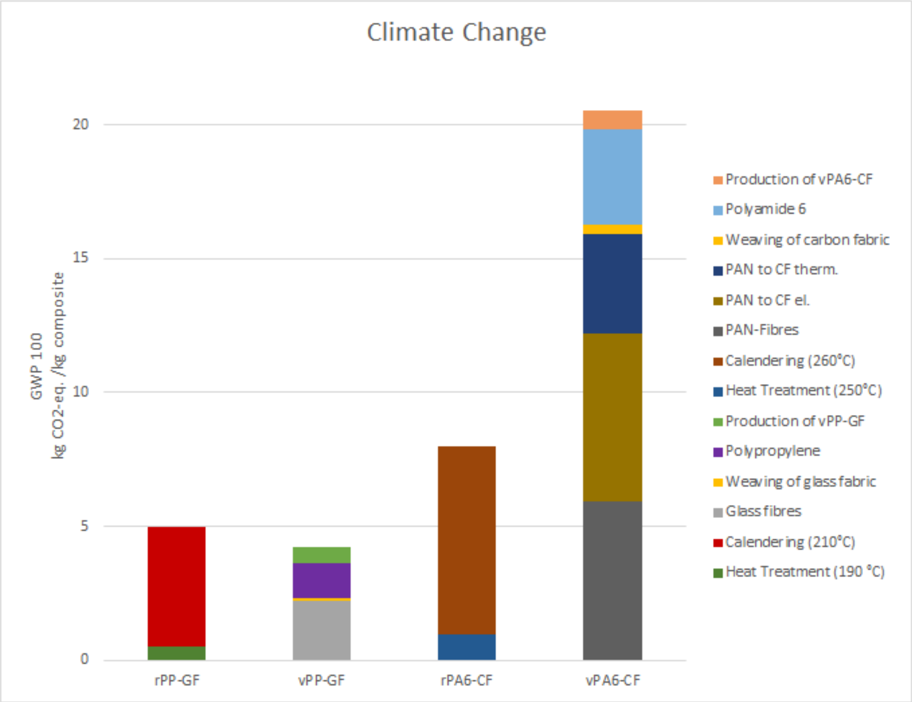

Figure 33: Comparison of global warming potential for virgin and remanufactured composite laminate

7.3 Terrestrial Acidification

Terrestrial acidification is characterised by the chemical changes in natural soils as a result of the deposition of nutrients into more acidic condition. Nitrogen and sulphur inputs are crucial in contributing to acidification as well as the leaching of hydrogen ions, H^+ cations into ecosystem. As a result, the change in soil acidity may cause the plant species to vanish or disappear over time. The acidification potential (AP) allows the conversion of the number of H^+ ions to chemical relative of SO_2 per molecular mass. Thus, the potential for terrestrial acidification is expressed in kg SO_2-eq. in ReCiPe midpoint method. [55][64]

Figure 34 demonstrates the LCIA results for the terrestrial AP in unit of kg SO_2-eq. per kg composite. The results suggested that both remanufactured composite laminates (rPP-GF for 5.3 and rPA6-CF for 8.6 gram SO_2-eq.) have lower burdens on acidification compared to their virgin counterparts. The AP values for virgin PP-GF and PA6-CF are presented as 11.1 and 23.5 gram SO_2-eq. respectively.

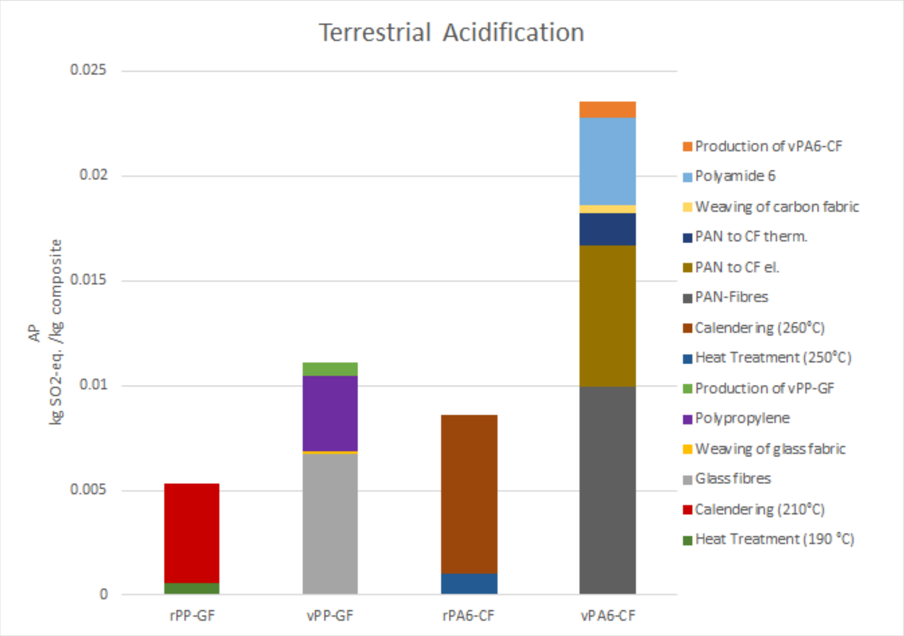

Figure 34: Comparison of acidification potential for virgin and remanufactured composite laminate

7.4 Water Consumption

Water use impacts are acknowledged in two dimensions, namely pollution (degradative use) and consumption (consumptive use). Degradative use is mainly deployed to analyse the pollutant emissions. This study focuses on water resource depletion due to consumption. The reduction of freshwater availability leads to water shortage for living organisms and further causing the extinction of terrestrial and aquatic species. The characterisation factor at midpoint level is cubic meter (m^3) of water consumed per m^3 of water extracted from surface water or groundwater from aquifer. One cubic meter (1 m^3) of water can be calculated as 1000 kg based on the average density of freshwater (1000 kg/m^3). [55][64]

Figure 35 illustrates the LCIA results for water consumption potential (WCP) of the virgin and remanufactured models.

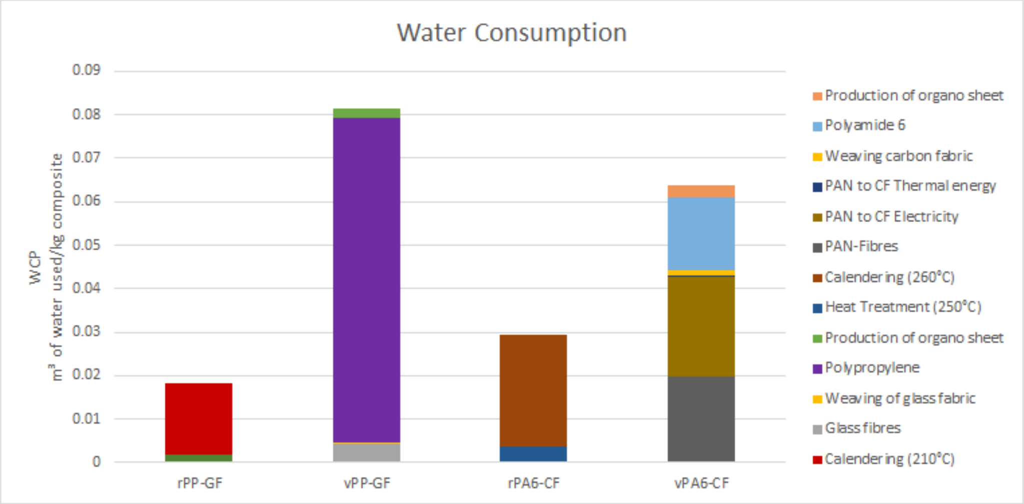

Figure 35: Comparison of water consumption potential for virgin and remanufactured composite laminate

Notably, the water consumption for manufacturing virgin PP-GF composite laminate is the highest among the four models, standing at 0.0816 m^3 of water, which is equivalent to 81.6 kg of water used. Polypropylene film has contributed the majority share (91.5%) of water consumption in virgin PP-GF production. The speculations on high water usage for polypropylene are due to the cleaning phase of mix-grade PP granulate (including PP recyclates) as raw materials and further processed to PP plastic film. The water used in rPP-GF, rPA6-CF and vPA6-CF are displayed as 0.0182 m^3, 0.0293 m^3 and 0.0638 m^3 accordingly. Alternative to the PP polymer, PA6 polymer has shown a lower water consumption. The choice of virgin grade material in the form of PA6 granulate in GaBi database may have led to this outcome.

7.5 Fossil Resource Scarcity

For the impact category fossil resource scarcity, ReCiPe focuses on the depletion of deposits in terms of fossil resources at midpoint level. The characterisation factors for the midpoint indicators are mainly based on the energy content of the fossil fuels. In ReCiPe, the fuel energy content for standard crude oil (42 MJ/kg) is identified as reference, generating values in mass of oil equivalents (kg oil-eq.). [55][64]

Figure 36 presents the impact assessment results for fossil depletion potential (FDP) of the remanufactured and virgin models. The results revealed that virgin PA6-CF has the highest fossil consumption compared to the other three models. The manufacturing of polyamide 6 polymer (5.4 kg oil-eq.) and production of PAN fibres (3.12 kg oil-eq.) have contributed heavily in the fossil depletion potential for virgin PA6-CF organo sheet fabrication (12.1 kg oil-eq.).

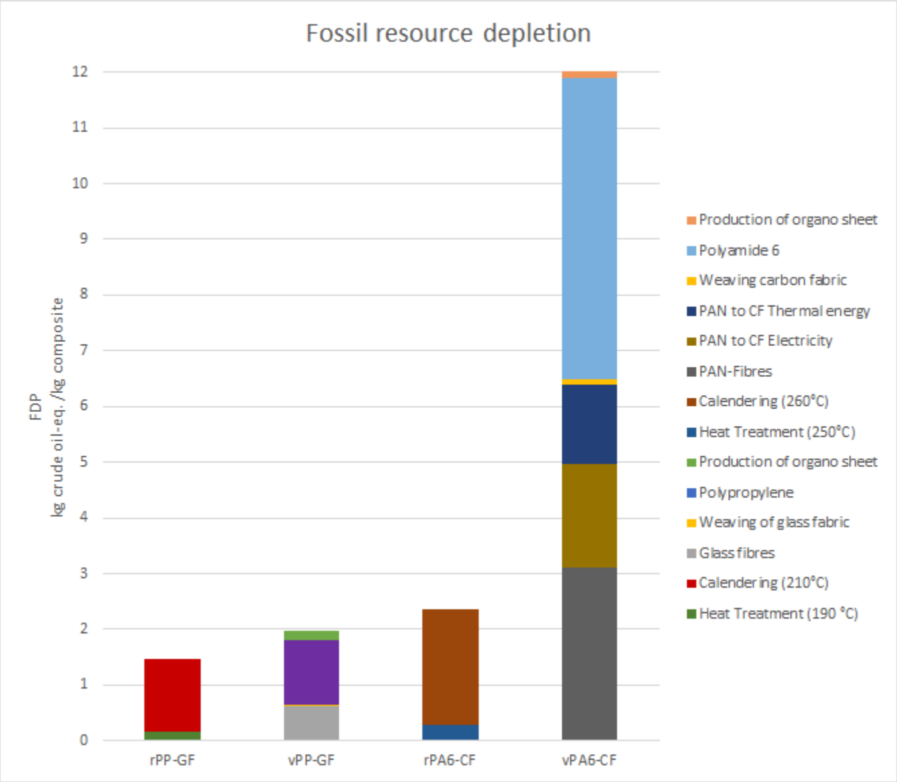

Figure 36: Comparison of fossil depletion potential for virgin and remanufactured composite laminate

8 Conclusion and Recommendations

In this study, remanufacturing technology for continuous fibre reinforced thermoplastic composite, i.e. Reverse-Thermoforming developed by Fraunhofer IWU using Calendering Direct Impregnation (CDIM) System was introduced. A life cycle assessment based on the energy flows required for the remanufacturing process was conducted based on the process parameters. With the aid of LCA Software Tool, the life cycle modelling for remanufactured composite and that of its virgin counterpart was performed. This allows the analysis and comparison of the environmental impacts in the aspects of sustainability and resource efficiency.

The LCA evaluation showed that the environmental burdens and the remanufactured tp-CL with constituents of polyamide 6-carbon fibre (PA6-CF) has lower environmental burdens compared to its virgin counterparts. The global warming potential (GWP) and cumulative energy demand (CED) of rPA6-CF can be reduced by 61% and 66.7% respectively when compared to the virgin production of composite laminate with the same constituents.

For polypropylene-glass fibre (PP-GF) composite laminate, the results indicate both remanufactured and virgin production have similar ecological impacts. Notably, the water consumption of virgin PP-GF production is approximately 4.5 times as high as its remanufactured counterpart. Further analysis demonstrates that the source and supply of electricity is responsible for the majority of the impacts. A simplified sensitivity analysis by substituting the energy source from electricity grid mix to electricity from wind power and hydro power has shown a reduction of GWP of 98% and 98.9%. The integration of renewable energy sources has thus been proven to lower the ecological impact loads, which represent the future focus to improve the environmental performance of the remanufacturing technology.

As the results clearly highlight, the ecological impacts are strongly dependent on the usage and source of electricity. Therefore, the effort on decreasing the electricity and its associated impacts should be prioritised. Energy optimisation during the heating, calendering and thermal forming processes and increasing machine efficiency for equipments involved can further reduce the energy consumption. Upscaling the process capacity from lab scale to industrial mass production can further improve the energy margin per unit as the machine setup time can be reduced.

In order to minimise the emissions of hazardous pollutants, renewable energy sources such as solar, wind and hydro should be integrated for electricity supply. In addition, the use of thermal energy instead of electricity to heat up the heat-assisted tools can also decrease the cumulative energy demand as the process energy conversion rate is higher than electrical energy.

Note that this study is based on various assumptions (as stated in Chapter 5 Life Cycle Inventory (LCI) Analysis) and therefore has its limitations. As this study does not include the transportation, labour work and use phase of the remanufactured composite, the results are not directly comparable with other LCA evaluation for FRP composite production or the End-of-Life management for composite waste.

With the current ISO standards, the guidance offered to practitioners for performing LCA in remanufacturing are not sufficient or rather not clearly defined. An important modelling criteria for remanufactured products is the inclusion or exclusion of the environmental impacts of the original product. The practitioners can decide this system boundary selection at the goal and scope definition stage, which may lead to very different LCA results albeit the same functional unit or reference flow. Thus, an update on LCA standardisation on remanufacturing methodology with Grave-to-Gate and/or Grave-to-Cradle designs is vital in promoting circular economy and innovative waste management strategies by providing explicit guidelines for LCA practitioners.

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A Appendix: GaBi Modelling

A.1 GaBi datasets used in LCA Modelling

Dataset	**Process description in GaBi Database**
Electricity-mix	Electricity grid mix 1kV-60kV; AC, technology mix; consumption mix, to consumer; 1kV - 60kV DE GUID: a1388758-0402-40c4-976b-6a805c8e46e0
Thermal energy	Thermal energy from natural gas; technology mix regarding firing and flue gas cleaning; production mix, at heat plant; 100% efficiency DE GUID: 009f27a6-f336-4200-81c0-28e4fa5638a4
Glass fibres	Glass fibres; from mineral components; production mix, at plant; Borosilicate glass / E-glass DE GUID: ee3777281-8d03-4dbe-90bf-fa51f61556a2
PP film	Polypropylene film (PP); PlasticsEurope; technology mix; production mix, at producer; extended PP RER GUID: e914192c-3c72-4005-b4a6-f916fbf3c2b2
PAN fibres	Polyacrylonitrile fibres (PAN); from acrylonitrile and methacrylate; polymerisation, dissolving, spinning; single route, at plant; PAN without additives, 53 g/mol EU-28 GUID: db00901a-338f-11dd-bd11-0800200c9a66
PA6 granulate	Polyamide 6 Granulate (PA6); technology mix; consumption mix, at producer; Nylon 6 granulate from Caprolactam DE GUID: 5a61a7d5-c17e-47ce-9f64-77fa762fe68e
Plastic film	Plastic Film (PE, PP, PVC); PlasticsEurope; technology mix; production mix; at producer; PE, PP, PVC GLO GUID: 7094f46a-2202-44e5-a1cc-8e939be9ff6b

Ammonia (31.8%)	Ammonia mix (NH_3); Haber-Bosch process, from natural gas; production mix, at plant; 0.7714 kg/m^3, 17.03 g/mol EU-28 GUID: 7963a3c7-823f-47a7-a761-cd04a4fecc40
Hydrogen chloride (68.2%)	Hydrogen chloride; technology mix; production mix for PVC production, at plant RER GUID: c71f9b0f-be89-4be7-a00c-086230324492
Compressed air	Compressed air 7 bar (medium power consumption); 7 bar, medium efficiency; consumption mix, at plant; medium electricity consumption GLO GUID: 591678ea-db78-427a-8b62-f0c2a329c5bb
Process water (cooling water)	Process water; ion exchange, from groundwater; single route, at plant; 1000 kg/m3, 18 g/mol; EU-28 GUID: db009015-338f-11dd-bd11-0800200c9a66
Electricity from hydro power	Electricity from hydro power; AC, technology mix of run-off river, storage and pump storage; production mix, at power plant; 1kV - 60kV DE GUID: 86a54b74-fc71-41fa-8bb0-4722e8c61357
Electricity from wind power	Electricity from wind power; AC, technology mix of onshore and offshore; production mix; at plant; 1kV - 60kV DE GUID: f932f79b-6251-4a77-bf04-5ce9bfea759f

A.2 Modelling of remanufactured organo sheet with GaBi

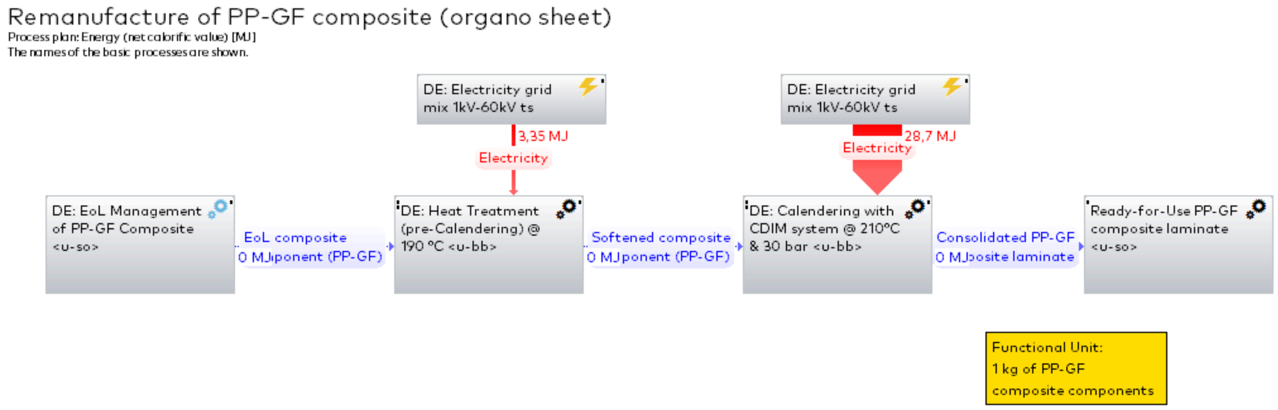


Figure 37: Remanufactured PP-GF organo sheet (rPP-GF)

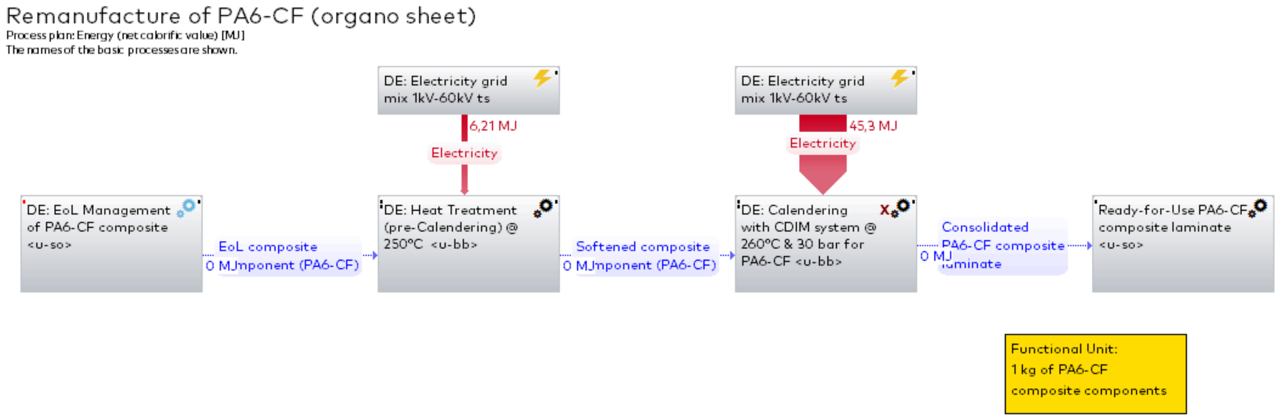


Figure 38: Remanufactured PA6-CF organo sheet (rPA6-CF)

A.3 Qualitative results of ReCiPe midpoint

Table 11: List of impact category with abbreviation and reference unit equivalent

Impact Category	**Abbreviation**	**Reference unit eq.**
Climate change	GWP	kg CO_2 to air
Acidification, terrestrial	TAP	kg SO_2 to air
Stratospheric ozone depletion	ODP	kg CFC-11 to air
Ionizing radiation	IRP	kBq Co-60 to air
Fine particulate matter formation	PMFP	kg PM 2.5 to air
Oxidant formation, ecosystem	EOFP	kg NO_x to air
Oxidant formation, human health	HOFP	kg NO_x to air
Eutrophication, freshwater	FEP	kg P to water
Eutrophication, marine	MEP	kg N to water
Water use	WCP	m^3 water
Human toxicity, cancer	HTPc	kg 1,4-DCB to urban air
Human toxicity, non-cancer	HTPnc	kg 1,4-DCB to urban air
Ecotoxicity, terrestrial	TETP	kg 1,4-DCB to soil
Ecotoxicity, freshwater	FETP	kg 1,4-DCB to water
Ecotoxicity, marine	METP	kg 1,4-DCB to marine water
Agricultural land use	ALOP	m^2 yr
Mineral resource scarcity	SOP	kg Cu
Fossil resource scarcity	FDP	kg crude oil
Process energy	Q	MJ used
Cumulative energy demand	CED	MJ of primary energy cumulated

Table 12: Quantitative LCIA results for PP-GF remanufactured model

Impact Category	**1. Heating (190 °C)**	**Calendering (210 °C)**	**2.Heating (190 °C)**	**Thermal forming**	**Total**
GWP	0.522	4.46	0.522	0.968	6.472
TAP	5.58E-04	4.77E-03	5.58E-04	7.33E-04	6.62E-03
ODP	2.54E-07	2.17E-06	2.54E-07	3.39E-07	3.02E-06
IRP	1.02E-02	8.73E-02	1.02E-02	9.85E-03	1.18E-01
PMFP	1.70E-04	1.46E-03	1.70E-04	2.26E-04	2.03E-03
EOFP	5.67E-04	4.85E-03	5.67E-04	8.99E-04	6.88E-03
HOFP	5.64E-04	4.83E-03	5.64E-04	8.93E-04	6.85E-03
FEP	2.19E-06	1.88E-05	2.19E-06	2.12E-06	2.53E-05
MEP	1.61E-05	1.37E-04	1.61E-05	1.56E-05	1.85E-04
WCP	1.91E-03	1.63E-02	1.91E-03	1.85E-03	2.20E-02
HTPc	1.65E-04	1.41E-03	1.65E-04	2.26E-04	1.97E-03
HTPnc	1.04E-02	8.89E-02	1.04E-02	1.07E-02	1.20E-01
TETP	1.76E-01	1.51E+00	1.76E-01	1.71E-01	2.03E+00
FETP	3.49E-05	2.98E-04	3.49E-05	4.26E-05	4.10E-04
METP	1.17E-04	1.00E-03	1.17E-04	1.39E-04	1.37E-03
ALOP	3.94E-02	3.37E-01	3.94E-02	3.81E-02	4.54E-01
SOP	9.43E-04	8.06E-03	9.43E-04	1.02E-03	1.10E-02
FDP	0.153	1.31	0.153	0.327	1.943
Q	3.35	28.7	3.35	10.11	45.51
CED	6.56	56.1	6.56	13.71	82.90

Table 13: Quantitative LCIA result for PA6-CF remanufactured model

Impact Category	**1. Heating (250 °C)**	**Calendering (260 °C)**	**2.Heating (250 °C)**	**Thermal forming**	**Total**
GWP	0.966	7.04	0.966	1.614	10.586
TAP	1.03E-03	7.54E-03	1.03E-03	1.06E-03	1.07E-02
ODP	4.71E-07	3.43E-06	4.71E-07	4.97E-07	4.87E-06
IRP	1.89E-02	1.38E-01	1.89E-02	1.16E-02	1.87E-01
PMFP	3.17E-04	2.31E-03	3.17E-04	3.29E-04	3.27E-03
EOFP	1.05E-03	7.65E-03	1.05E-03	1.42E-03	1.12E-02
HOFP	1.05E-03	7.62E-03	1.05E-03	1.41E-03	1.11E-02
FEP	4.06E-06	2.96E-05	4.06E-06	2.53E-06	4.02E-05
MEP	2.98E-05	2.17E-04	2.98E-05	1.86E-05	2.95E-04
WCP	3.54E-03	2.58E-02	3.54E-03	2.21E-03	3.51E-02
HTPc	3.05E-04	2.22E-03	3.05E-04	3.36E-04	3.17E-03
HTPnc	1.93E-02	1.40E-01	1.93E-02	1.33E-02	1.92E-01
TETP	3.27E-01	2.38E+00	3.27E-01	2.04E-01	3.24E+00
FETP	6.46E-05	4.71E-04	6.46E-05	5.91E-05	6.59E-04
METP	2.17E-04	1.58E-03	2.17E-04	1.91E-04	2.20E-03
ALOP	7.31E-02	5.33E-01	7.31E-02	4.51E-02	7.24E-01
SOP	1.75E-03	1.27E-02	1.75E-03	1.31E-03	1.75E-02
FDP	0.284	2.07	0.284	0.568	3.206
Q	6.21	45.3	6.21	18.92	76.64
CED	12.2	88.6	12.2	23.67	136.67

Table 14: Quantitative LCIA results for virgin PP-GF organo sheet production model

Impact Category	**Glass fibre (GF)**	**Weaving**	**Polypropylene (PP)**	**Merging of GF and PP**	**Total**
GWP	2.230	0.074	1.320	0.616	4.240
TAP	6.76E-03	7.87E-05	3.63E-03	6.59E-04	1.11E-02
ODP	2.97E-07	3.58E-08	4.78E-08	3.00E-07	6.81E-07
IRP	1.06E-02	1.44E-03	0.00E+00	1.21E-02	2.41E-02
PMFP	2.01E-03	2.41E-05	1.06E-03	2.02E-04	3.30E-03
EOFP	3.05E-03	7.99E-05	1.86E-03	6.69E-04	5.66E-03
HOFP	3.02E-03	7.95E-05	1.86E-03	6.66E-04	5.63E-03
FEP	3.09E-06	3.09E-07	2.79E-05	2.59E-06	3.39E-05
MEP	1.84E-05	2.26E-06	3.21E-06	1.90E-05	4.29E-05
WCP	4.35E-03	2.69E-04	7.47E-02	2.25E-03	8.16E-02
HTPc	2.57E-04	2.32E-05	7.47E-05	1.94E-04	5.49E-04
HTPnc	1.70E-02	1.47E-03	5.40E-04	1.23E-02	3.13E-02
TETP	2.84E-01	2.49E-02	1.81E-03	2.08E-01	5.19E-01
FETP	7.97E-05	4.91E-06	7.00E-06	4.12E-05	1.33E-04
METP	2.34E-04	1.65E-05	9.89E-06	1.38E-04	3.98E-04
ALOP	4.27E-02	5.56E-03	0.00E+00	4.66E-02	9.49E-02
SOP	4.28E-02	1.33E-04	5.47E-05	1.11E-03	4.41E-02
FDP	0.632	0.022	1.140	0.181	1.975
Q	19.488	0.473	11.960	3.960	35.881
CED	32.654	0.924	20.846	7.740	62.164

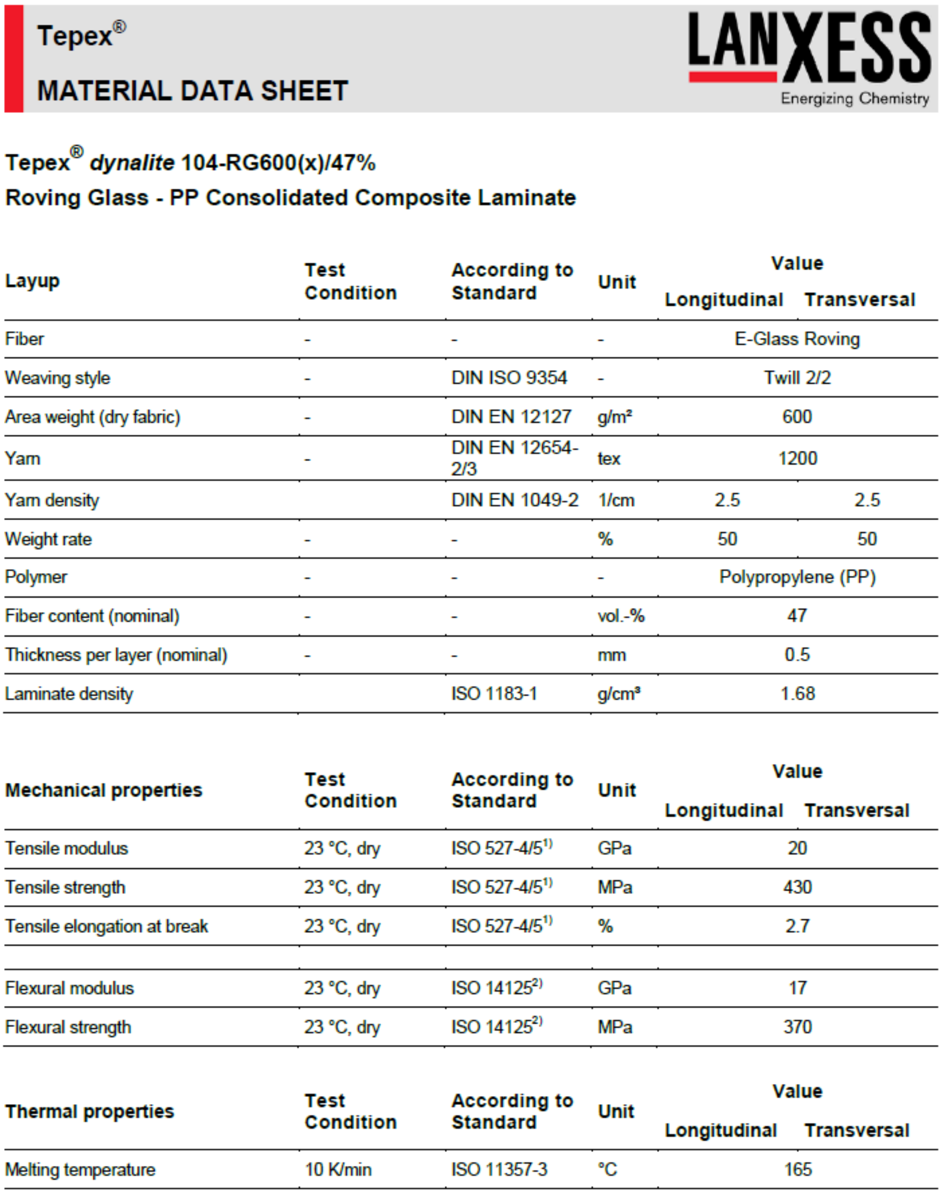
Table 15: Quantitative LCIA results for virgin PA6-CF organo sheet production model

Impact Category	**PAN fibre**	**PAN to CF el.**	**PAN to CF therm.**	**Weaving**	**Polyamide6 (PA6)**	**Merging CF and PA6**	**Total**
GWP	5.920	6.290	3.700	0.335	3.560	0.727	20.532
TAP	9.97E-03	6.73E-03	1.55E-03	3.59E-04	4.18E-03	7.78E-04	2.36E-02
ODP	8.72E-06	3.07E-06	7.50E-07	1.64E-07	3.08E-09	3.45E-07	1.31E-05
IRP	6.89E-02	1.23E-01	1.70E-04	6.57E-03	0.00E+00	1.42E-02	2.13E-01
PMFP	3.05E-03	2.06E-03	4.85E-04	1.10E-04	1.22E-03	2.38E-04	7.16E-03
EOFP	1.52E-02	6.83E-03	2.81E-03	3.65E-04	2.26E-03	7.90E-04	2.83E-02
HOFP	1.49E-02	6.80E-03	2.78E-03	3.63E-04	2.23E-03	7.86E-04	2.79E-02
FEP	7.65E-06	2.64E-05	9.68E-08	1.41E-06	5.28E-07	3.06E-06	3.91E-05
MEP	2.20E-04	1.94E-04	1.04E-06	1.03E-05	1.26E-06	2.24E-05	4.49E-04
WCP	1.98E-02	2.30E-02	1.02E-04	1.23E-03	1.70E-02	2.66E-03	6.38E-02
HTPc	2.18E-03	1.99E-03	5.35E-04	1.06E-04	9.22E-05	2.29E-04	5.13E-03
HTPnc	3.01E-01	1.25E-01	5.32E-03	6.69E-03	1.21E-03	1.45E-02	4.54E-01
TETP	5.19E-01	2.13E+00	1.09E-02	1.13E-01	5.34E-03	2.46E-01	3.02E+00
FETP	8.96E-04	4.21E-04	7.12E-05	2.24E-05	6.25E-05	4.86E-05	1.52E-03

Impact Category	**PAN fibre**	**PAN to CF el.**	**PAN to CF therm.**	**Weaving**	**Polyamide6 (PA6)**	**Merging CF and PA6**	**Total**
METP	2.83E-03	1.41E-03	2.04E-04	7.54E-05	8.11E-05	1.63E-04	4.76E-03
ALOP	5.88E-02	4.76E-01	8.27E-04	2.54E-02	0.00E+00	5.50E-02	6.16E-01
SOP	9.13E-04	1.14E-02	8.70E-04	6.06E-04	1.05E-04	1.31E-03	1.52E-02
FDP	3.120	1.850	1.420	0.099	5.400	0.214	12.103
Q	32.500	40.400	54.700	2.160	14.100	4.670	148.530
CED	91.000	79.100	58.700	4.220	60.600	9.140	302.760

B Appendix: Technical Data Sheet

B.1 Consolidated Composite Laminate



Tepex®

MATERIAL DATA SHEET

LANXESS
Energizing Chemistry

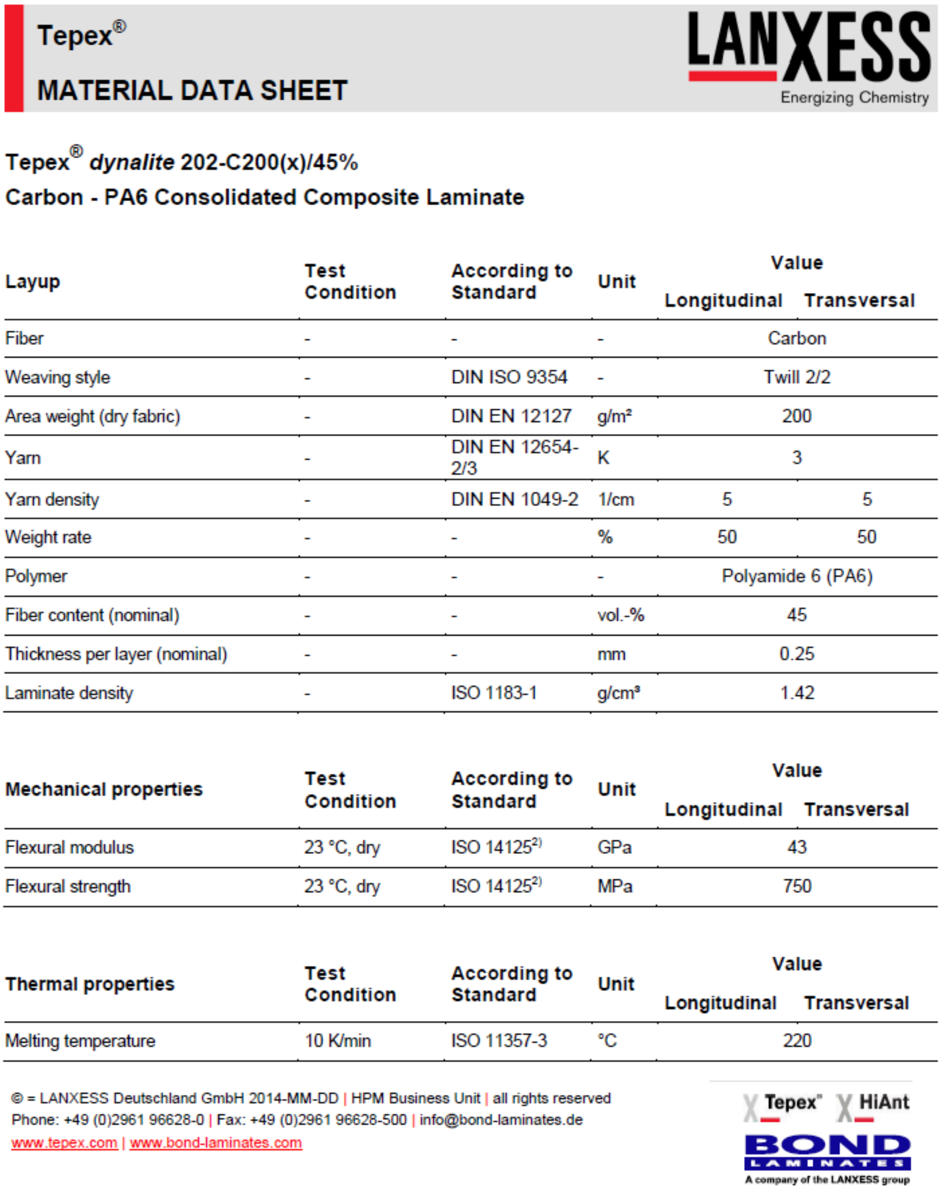
Tepex® *dynalite* 104-RG600(x)/47%
Roving Glass - PP Consolidated Composite Laminate

Layup	**Test Condition**	**According to Standard**	**Unit**	**Value**	
				Longitudinal	**Transversal**
Fiber	-	-	-	E-Glass Roving	
Weaving style	-	DIN ISO 9354	-	Twill 2/2	
Area weight (dry fabric)	-	DIN EN 12127	g/m²	600	
Yarn	-	DIN EN 12654-2/3	tex	1200	
Yarn density		DIN EN 1049-2	1/cm	2.5	2.5
Weight rate	-	-	%	50	50
Polymer	-	-	-	Polypropylene (PP)	
Fiber content (nominal)	-	-	vol.-%	47	
Thickness per layer (nominal)	-	-	mm	0.5	
Laminate density		ISO 1183-1	g/cm³	1.68	

Mechanical properties	**Test Condition**	**According to Standard**	**Unit**	**Value**	
				Longitudinal	**Transversal**
Tensile modulus	23 °C, dry	ISO 527-4/5[1)]	GPa	20	
Tensile strength	23 °C, dry	ISO 527-4/5[1)]	MPa	430	
Tensile elongation at break	23 °C, dry	ISO 527-4/5[1)]	%	2.7	
Flexural modulus	23 °C, dry	ISO 14125[2)]	GPa	17	
Flexural strength	23 °C, dry	ISO 14125[2)]	MPa	370	

Thermal properties	**Test Condition**	**According to Standard**	**Unit**	**Value**	
				Longitudinal	**Transversal**
Melting temperature	10 K/min	ISO 11357-3	°C	165	

Figure 39: Tepex® PP-GF composite laminate



Tepex®

MATERIAL DATA SHEET

LANXESS
Energizing Chemistry

Tepex® *dynalite* 202-C200(x)/45%
Carbon - PA6 Consolidated Composite Laminate

Layup	Test Condition	According to Standard	Unit	Value	
				Longitudinal	Transversal
Fiber	-	-	-	Carbon	
Weaving style	-	DIN ISO 9354	-	Twill 2/2	
Area weight (dry fabric)	-	DIN EN 12127	g/m²	200	
Yarn	-	DIN EN 12654-2/3	K	3	
Yarn density	-	DIN EN 1049-2	1/cm	5	5
Weight rate	-	-	%	50	50
Polymer	-	-	-	Polyamide 6 (PA6)	
Fiber content (nominal)	-	-	vol.-%	45	
Thickness per layer (nominal)	-	-	mm	0.25	
Laminate density	-	ISO 1183-1	g/cm³	1.42	

Mechanical properties	Test Condition	According to Standard	Unit	Value	
				Longitudinal	Transversal
Flexural modulus	23 °C, dry	ISO 14125[2]	GPa	43	
Flexural strength	23 °C, dry	ISO 14125[2]	MPa	750	

Thermal properties	Test Condition	According to Standard	Unit	Value	
				Longitudinal	Transversal
Melting temperature	10 K/min	ISO 11357-3	°C	220	

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www.tepex.com | www.bond-laminates.com

Tepex® HiAnt
BOND LAMINATES
A company of the LANXESS group

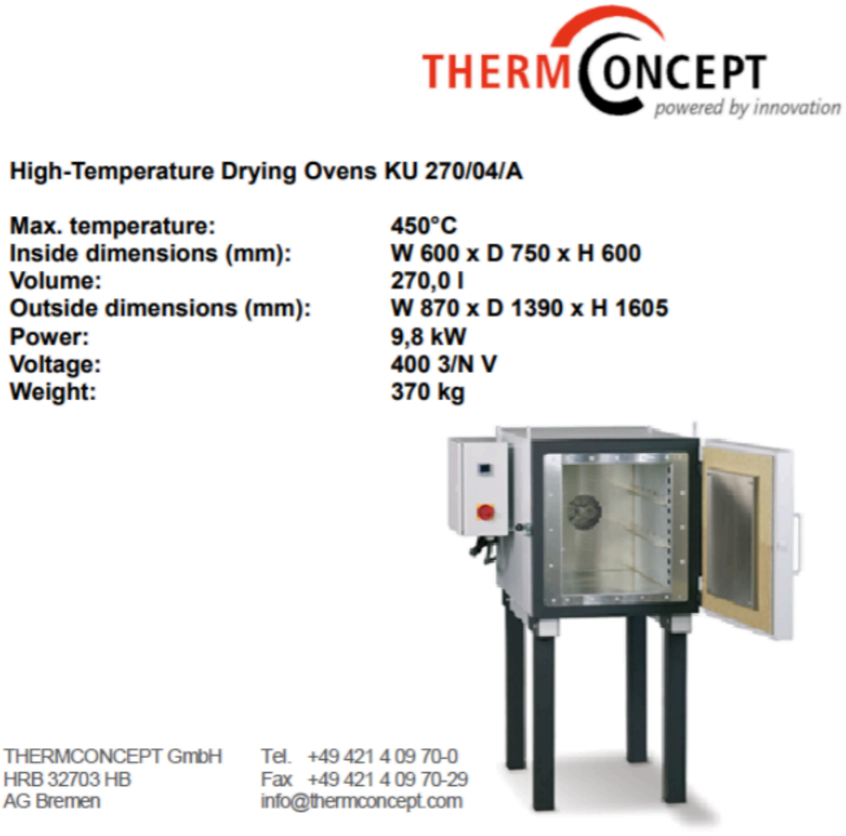
Figure 40: Tepex® PA6-CF composite laminate

]

B.2 Machinery and Equipments

```
W          50.00Hz      05/06/12  09:09
05/06/12  09:09:17
            ①             ②             ③
Wh     0145017 m     0144943 m     0144124 m
VARh   0081976 m     0084378 m     0083003 m
       0000000       0000000       0000000
VADh   0004200 m     0003824 m     0004265 m
VAh    0166639 m     0167767 m     0166377 m
W...  PF...
```

Figure 41: Qualistar+® electricity meter (model C.A 8335)



High-Temperature Drying Ovens KU 270/04/A

Max. temperature:	**450°C**
Inside dimensions (mm):	**W 600 x D 750 x H 600**
Volume:	**270,0 l**
Outside dimensions (mm):	**W 870 x D 1390 x H 1605**
Power:	**9,8 kW**
Voltage:	**400 3/N V**
Weight:	**370 kg**

THERMCONCEPT GmbH
HRB 32703 HB
AG Bremen

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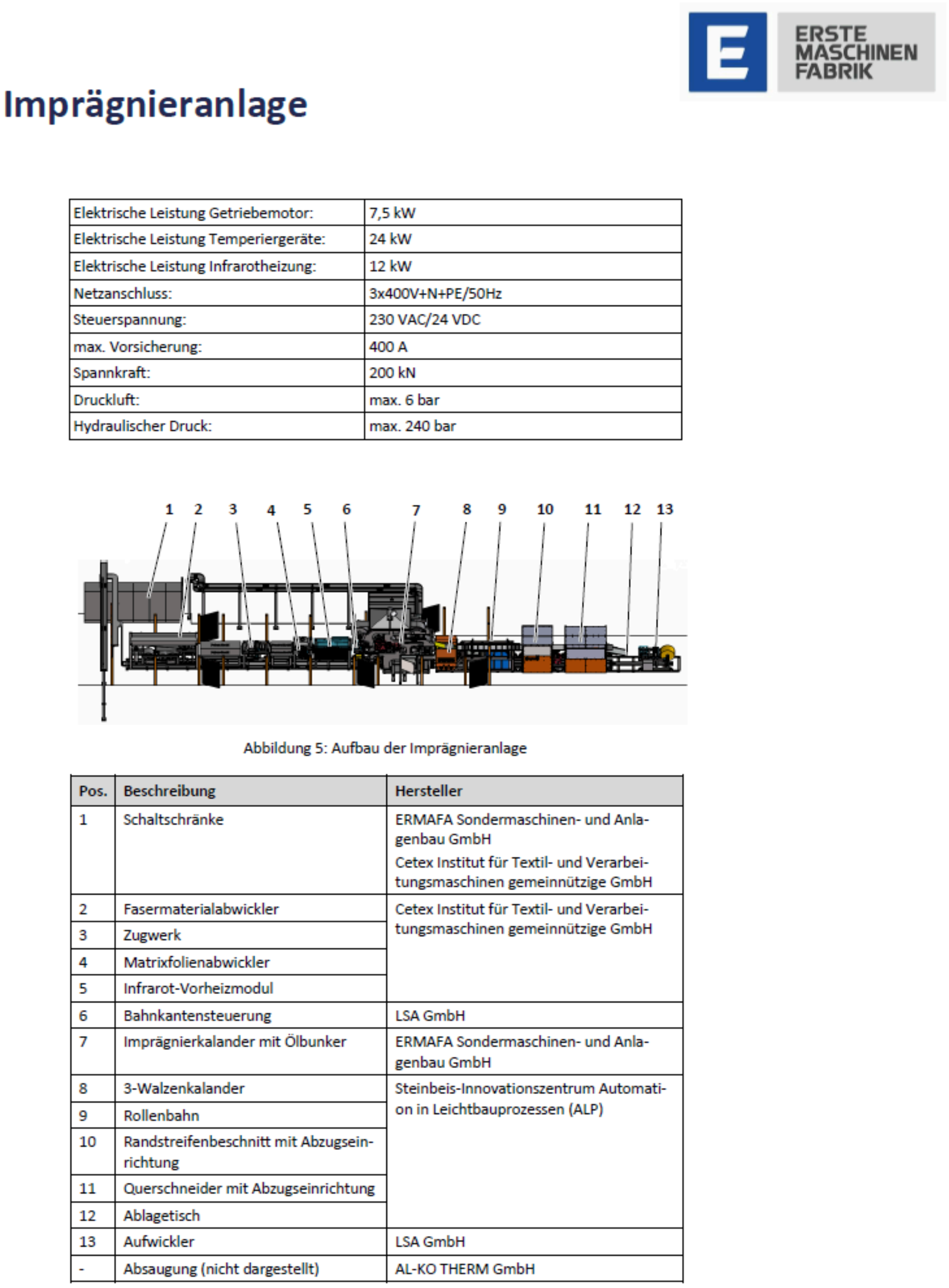
Fax +49 421 4 09 70-29
info@thermconcept.com

Figure 42: THERMCONCEPT oven (model KU 270/04/A)



Imprägnieranlage

Elektrische Leistung Getriebemotor:	7,5 kW
Elektrische Leistung Temperiergeräte:	24 kW
Elektrische Leistung Infrarotheizung:	12 kW
Netzanschluss:	3x400V+N+PE/50Hz
Steuerspannung:	230 VAC/24 VDC
max. Vorsicherung:	400 A
Spannkraft:	200 kN
Druckluft:	max. 6 bar
Hydraulischer Druck:	max. 240 bar

Abbildung 5: Aufbau der Imprägnieranlage

Pos.	Beschreibung	Hersteller
1	Schaltschränke	ERMAFA Sondermaschinen- und Anlagenbau GmbH Cetex Institut für Textil- und Verarbeitungsmaschinen gemeinnützige GmbH
2	Fasermaterialabwickler	Cetex Institut für Textil- und Verarbeitungsmaschinen gemeinnützige GmbH
3	Zugwerk	
4	Matrixfolienabwickler	
5	Infrarot-Vorheizmodul	
6	Bahnkantensteuerung	LSA GmbH
7	Imprägnierkalander mit Ölbunker	ERMAFA Sondermaschinen- und Anlagenbau GmbH
8	3-Walzenkalander	Steinbeis-Innovationszentrum Automation in Leichtbauprozessen (ALP)
9	Rollenbahn	
10	Randstreifenbeschnitt mit Abzugseinrichtung	
11	Querschneider mit Abzugseinrichtung	
12	Ablagetisch	
13	Aufwickler	LSA GmbH
-	Absaugung (nicht dargestellt)	AL-KO THERM GmbH

Figure 43: Calender-Direct Impregnation Machinery (CDIM) system

RÖCHER
MASCHINENBAU

Technische Daten

Hydraulische Ständerpresse RSP 160.42SZ
Presskraft : 160 bis 1600 kN
Stößelhub : ca. 1000 mm
Einbauhöhe des Werkzeuges : max. 1200 mm
Werkzeugtisch für kundenseitige Werkzeuge : 900 mm x 1000 mm
Schließgeschwindigkeit : ca. 30 mm/s
Rücklaufgeschwindigkeit : ca. 220 mm/s
Betriebsspannung : 3~AC 400V 50Hz
Betriebsdruck : 300 bar

Figure 44: Röcher hydraulic press with heat-assisted forming tools

C Appendix: Experimental Data

C.1 Differential Scanning Calorimetry (DSC)

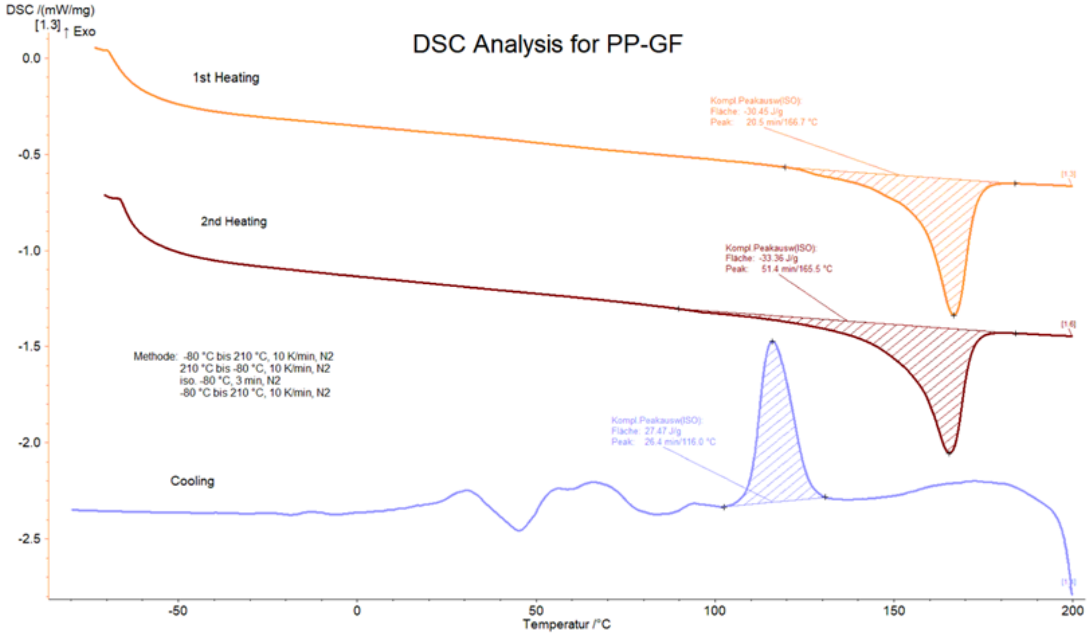


Figure 45: DSC analysis for PP-GF composite

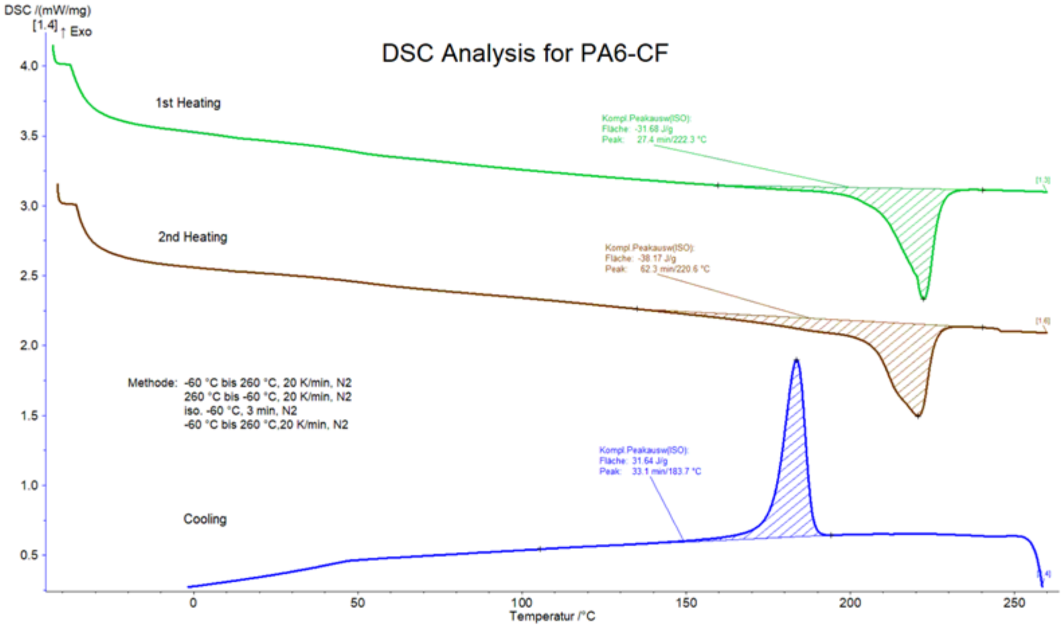


Figure 46: DSC analysis for PA6-CF composite

C.2 Calendering with CDIM system

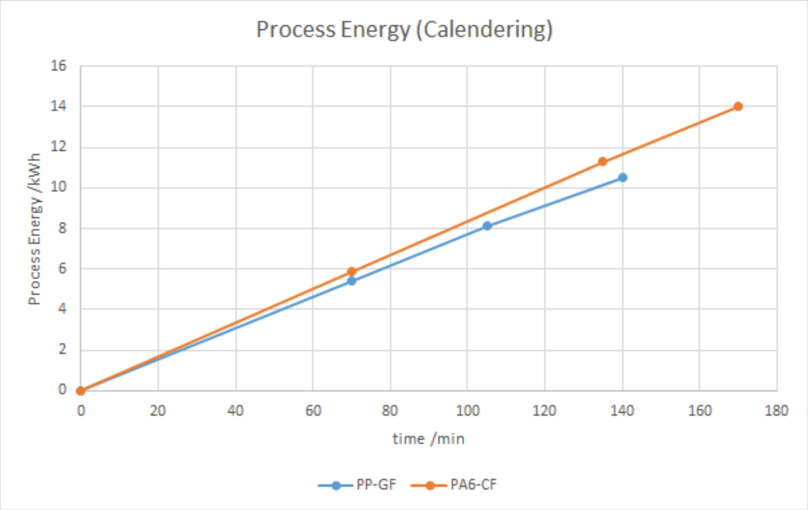


Figure 47: Process energy for Calendering

Simulated diagram based on the heating rate of CDIM system and energy data recorded with Qualistar electricity meter

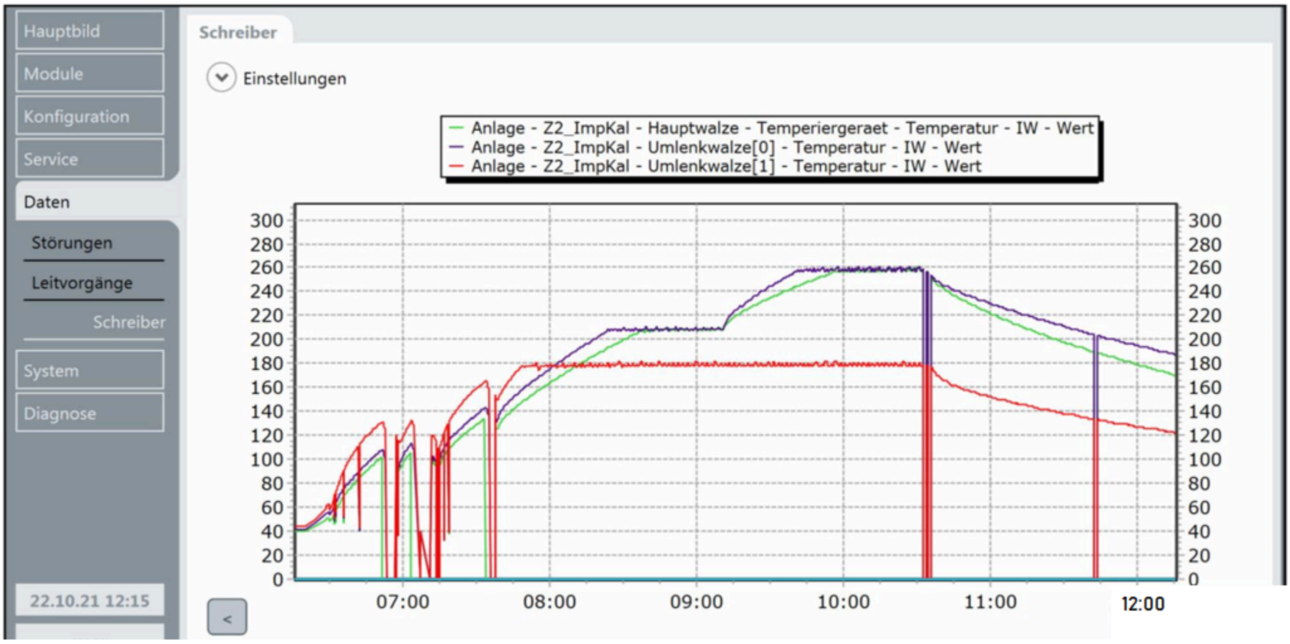


Figure 48: Temperature profile of CDIM system during calendering process

C.3 Remanufactured Composite Laminate

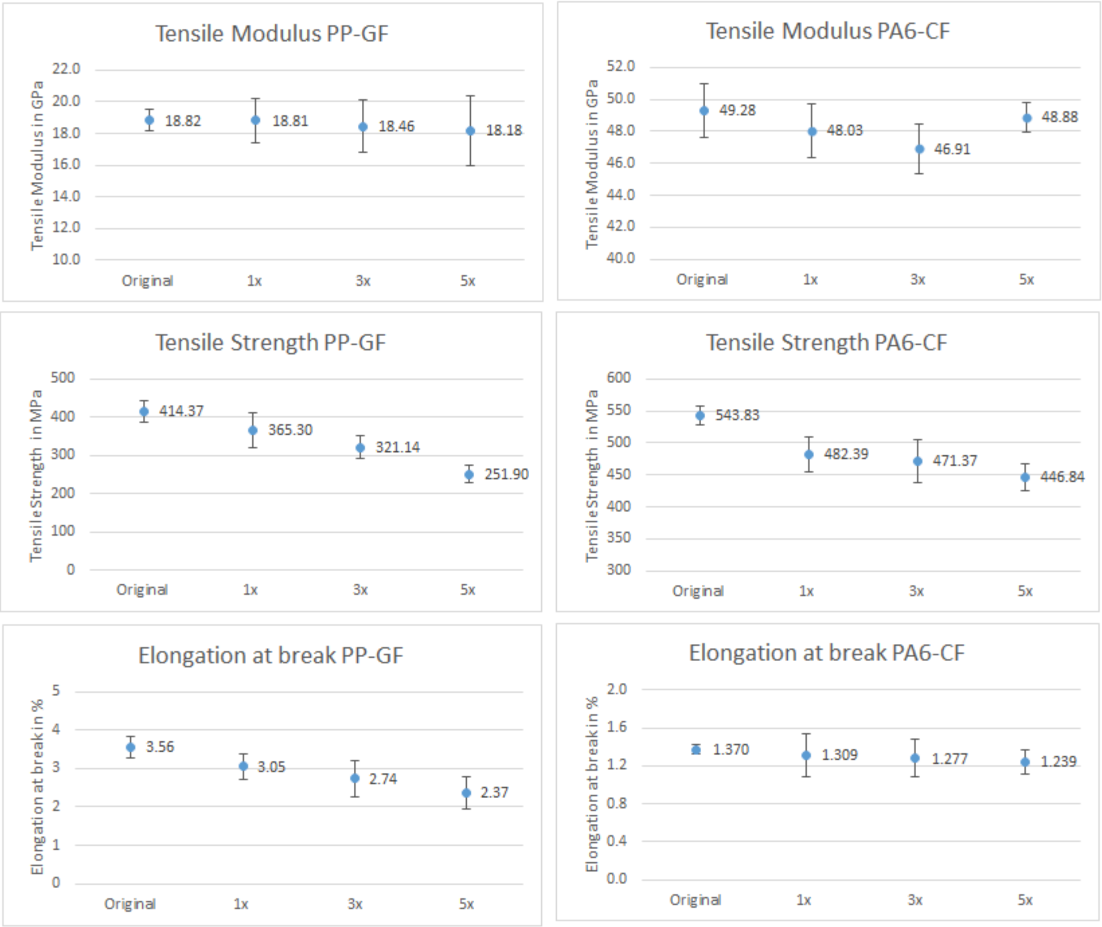


Figure 49: Mechanical properties of rCL (PP-GF and PA6-CF)

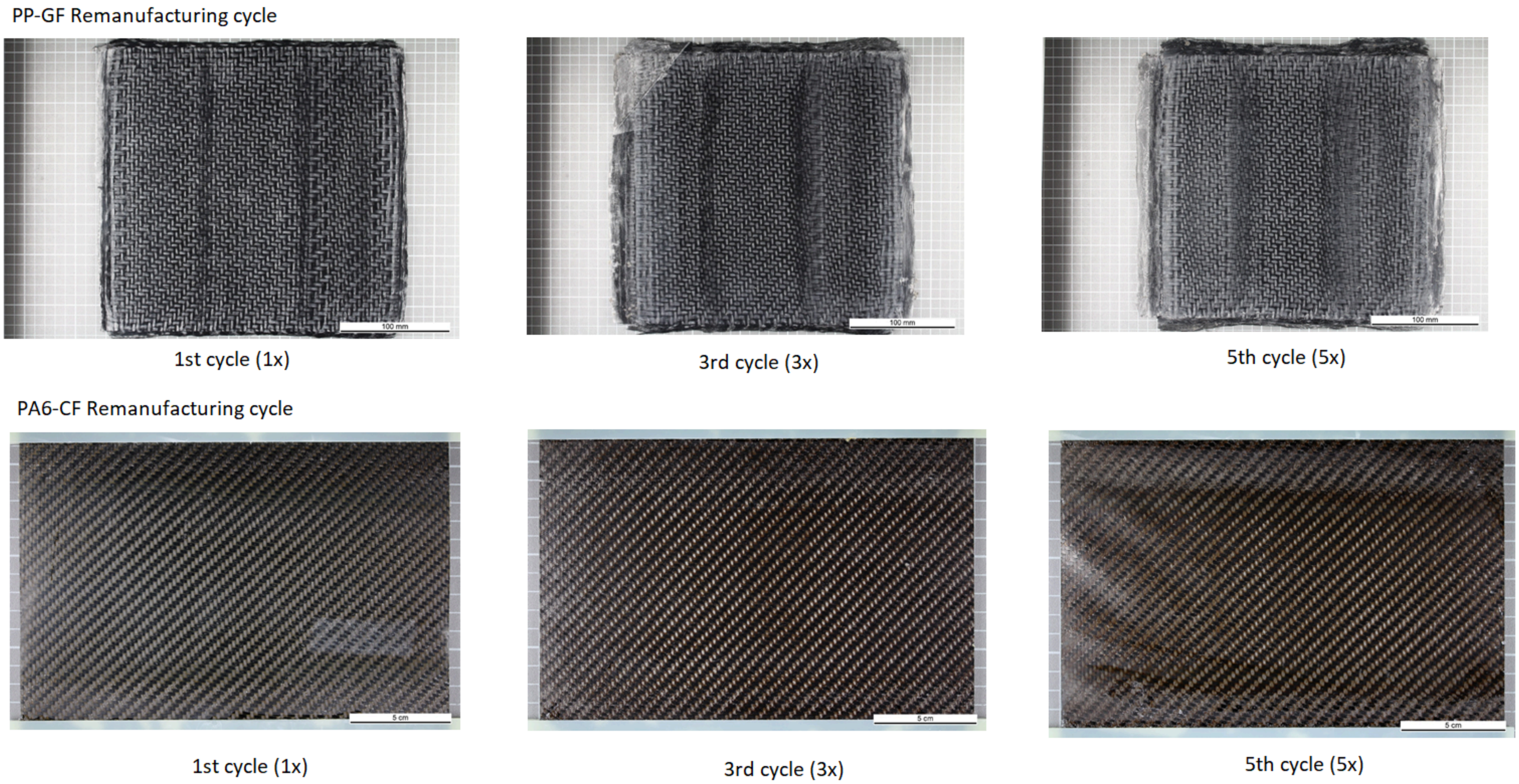


Figure 50: Physical appearance of remanufactured composite laminates