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Quantitative sustainability assessment of bio-based materials for wind turbine rotor blades

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Quantitative sustainability assessment of bio-based composite materials for wind turbine rotor blades

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Date and Signature

Preface

This thesis is written in partial fulfillment of the requirements for the MSc in Materials Engineering at the University of Padua. It is the result of a 6 months internship at the Quantitative Sustainability Assessment Section of the Department of Management Engineering at the Technical University of Denmark.

I would like to express my sincere gratitude to Morten Birkved and Christen Malte Markussen for accepting my application for this project and for providing ideas, support, and constructive feedback. I would also like to thank all the people of QSA section for the nice, friendly and relaxed working environment. I'd also liko to acknowledge the coffee machine for helping me in the dark Danish winter and at all the Danish climber community to make me forget, in these six months my beloved mountains.

Abstract

Over the recent decades biomaterials have been successfully marketed thanks to the common perception that biomaterials and environmental sustainability *de facto* represent two sides of the same coin. The development of sustainable composite materials, i.e. blades for small-scale wind turbines, has therefore partially been focused on the substitution of conventional fiber materials such as glass and carbon fibers with bio-fibers such as flax fibers. The main unsolved issue is if this material substitution is, from a broad environmental point of view, i.e. taking into account a multitude of environmental impact categories – not only climate change, supporting sustainable development or if the development of sustainable composite materials is more complex and perhaps contra-intuitive leading to negative environmental effects to burden shifting.

In order to assess a wide range of environmental impacts and taking into account positive and negative environmental trade-offs over the entire life-span of composite materials, the Life Cycle Assessment (LCA) methodology can be applied. In this thesis the focus is on the holistic environmental assessment of composite materials,

Based on a case study comparing carbon, glass and flax fiber based composite materials; the applicability of LCA for environmental sustainability assessment of composite materials is demonstrated. In this thesis 4 different types of fibers and fiber mixtures (carbon, glass, flax and a carbon/flax mixed fibers) are compared in terms of environmental sustainability. In order to have comparability between different materials a functional unit of one blade is chosen .All the life cycle steps, from row material production to disposal are included in this study.

Applying one of the most recent life cycle impact assessment methods, i.e. Recipe, it is demonstrated that the environmental sustainability of the flax fiber composite is more or less similar to the conventional composites. This observation may be contra-intuitive (i.e. the common sense would most likely expect the bio-based to be most sustainable), but is mainly due to the fact that the bio-material resin demand is by far exceeding the resin demand of the conventional fibers such as carbon and glass fibers. Furthermore, since the environmental burden of the resin is comparable to the environmental burden of the fibers, the resin demand plays an important role for the overall environmental sustainability . On the other hand, the energy demand and the environmental impacts connected with the production of the carbon and glass fibers revealed to be considerably higher when compared to the impacts resulting from resin production.

Furthermore, some possible end-of-life options for fiber composite material, i.e. Incineration with energy recovery, Co-Processing, Pyrolysis are analyzed in order to provide suggestions on how to the deal with the end-of-life management of a material which can be hardly recycled.

CONTENTS

1. INTRODUCTION

Nowadays composite materials are largely used in many industrial sectors because of their remarkable properties such as lightweight and high mechanical strength. Their use started in the early 1960s and since that time a lot of research has been conducted in order to understand their behavior and improve their properties [Bottoli et al 2011].

In the recent years, the growing awareness rising for the environmental effects of activities in the industrial sector, as well as legislation restrictions, prompted the search for alternative materials to be used in substitution of the currently used inorganic fibre reinforcements with the overall aim to lower their environmental impacts. These reasons motivated the increasing interest, both from industry and academia, towards Biocomposite materials.

Biocomposite materials are materials manufactured with a polymer thermosetting or thermoplastic matrix and reinforces with natural fibers. There are several reasons why biocomposite materials are chosen, but the main reason is connected with the lower density of natural fibers with respect to conventional materials, especially glass fiber, and their good mechanical properties.

Initially Natural Fiber reinforced polymers (NFRP) were used in the automotive and building sectors for non-structural applications. The interest toward this class of material is mainly due to the legislation, which forces the manufacturers to reuse and recycle the vehicle components [Lan Mair 2000]. Afterward the interest has shifted to the use of this material in structural application. There are several studies that demonstrate the possible substitution of conventional material with Biocomposite (Joshi et al 2004) (Duigou et al 2011)

The feasibility of the use of NFRC in a small rotor turbine blade in terms of equivalent mechanical performance compared to conventional material has been demonstrated by the Department of Wind Energy (Bottoli at al 2011). This study also included an assessment of the environmental impact of this material with the MECO methodology, a simplified life cycle-based methodology (Bottoli et al 2011); but the authors concluded that further work was needed in order to assess the environmental impact of this material. Hence there is no demonstration if the use of bio-based composite really helps to reduce the environmental impact of composite materials within this type of application.

Some previous studies assess the environmental impact of Biocomposite, but only few studies refer to wind blade application. In fact, Schmidt and Beyer focused on insulation component made by hemp fibers for vehicles (Schmidt et al 1998), Corbière-Nicollier evaluated the use of China Reed fiber in pallets for transport of goods (Corbière-Nicollier et al 2001); Duigou focused on biocomposite for sandwich panel (Duigou et al 2011). Some of these studies analyze the environmental impact only on an energy usage basis (Schmidt et al 1998), or with a simplified LCA method (Duigou et al 2011). In summary, all the cited studies demonstrate the positive effects of the use of this material for the specific application.

Starting from these premises, the first purpose of this thesis is to analyze the behavior of biocomposite in wind blade application from an environmental point of view. Comparative life cycle assessment has been conducted to evaluate and compare the environmental impacts of conventional and biobased small rotor wind blades realized in a previous project (Bottoli et al 2011).

Secondly, as one of the most critical steps of the life cycle of composites is their end-of life, due to the complexity of the material and its component (especially the matrix), a further analysis has been conducted with regard to this stage. The actual end-of-life management based on incineration with energy recovery has been compared to possible recycling solutions such as Pyrolysis and Co-processing. It should indeed be acknowledged that in the next 20 years an increasing amount of wind blades will be disposed as they will be at the end of their useful life.

2. THEORY AND BACKGROUND

2.1.Blade

The blade analyzed in this thesis, shown in figure 2.1, is specifically designed for a wind turbine car. This car competed in Racing Aeolus, a special race for wind powered car that is organized every year between the Netherlands and Denmark.

The aim of this race is “not only to build the fastest vehicle but also to use the most modern materials and the latest wind technology”; proving a useful test bench for the developing of the wind technology. [http://windturbineracer.dk/].

Fig2.1 The blade and the rotor system

The blade’s aerodynamical and structural design was studied in a previous thesis [Nipper 2009]. From this study a first prototype blade has been realized. This blade was manufactured with CFRP, and used in the first version of the DTU’s car.

The optimization of the CFRP blade was studied in a following thesis project [Bottoli et al. 2011]. The authors additionally designed and realized two other blades: one with pure flax fiber and one hybrid of flax and carbon fiber.

Even though the blade under study is not used and developed for energy production, it represents very well the behavior of bigger blades currently used in energy production, even though in a small scale. The similarity can be explained by the similar materials and design technique, as well as by the structural and mechanical requirements.

Since the blade is a structural moving part, it experiences different kind of loads, and these loads have to be analyzed in order to develop a proper blade. The wind blade experiences two main kinds of loads:

- Steady loads, i.e. aerodynamical loads originating from the wind and centrifugal forces because the blade is moving;
- Unsteady loads, which are due to gravity, non-constant wind and gyroscopic loads.

The total loads acting on the blades were calculated in a previous work [Pignatti 2011]. Every blade must resist at this type of forces in terms of strength and deformation caused. Graphs showing the different forces faced by the blade are shown below:

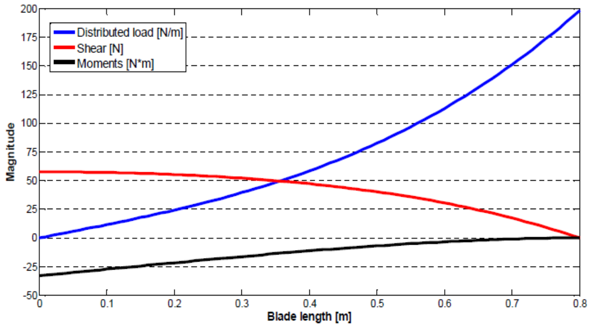


Fig 2.2 **Distributed load (Thrust), shear and moment acting on the blade (Bottoli et al 2011)**

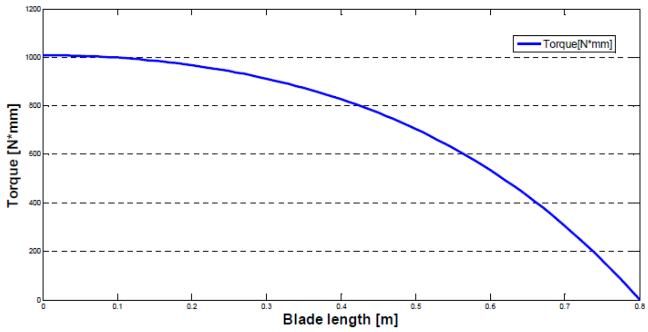


Fig 2.3 **Torque acting on the blade (Bottoli et al. 2011)**

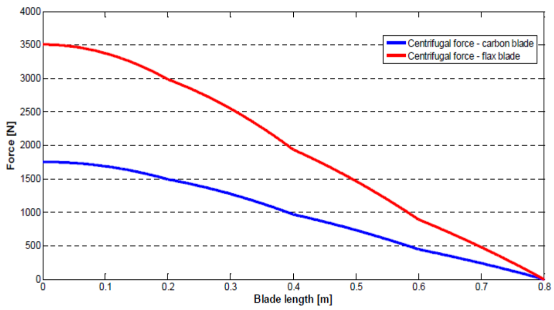


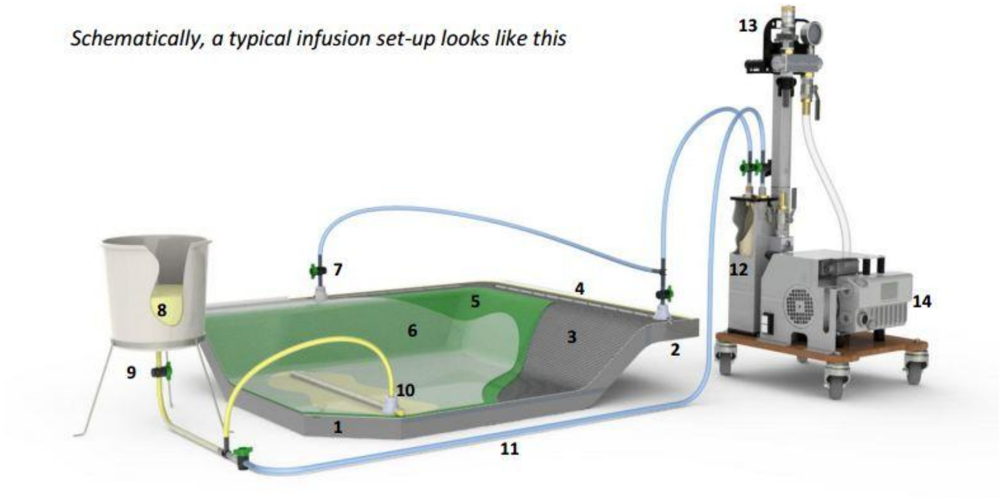
Fig 2.4 **Centrifugal forces for carbon and flax blade (Bottoli et al 2011)**

A change of material affects only the centrifugal forces because they are generated by the weight of the blade, hence by the density of the materials used. But since the blade under study is a small blade, the centrifugal forces are lower than the aerodynamical (created by the resistance against the wind), therefore this effect is not taken into account [Gurit 2010]

The other mechanical loads do not depend on the selected material; it will affect the response on them (i.e. the deformation of the object). To maintain the deformation at a constant level, while changing the material, the thickness and layup of the composite in the blade must be changed accordingly. This explains why the flax blade is heavier than the carbon one.

The production process used to produce the blade is the resin infusion process. In this technique vacuum is applied in order to drive the resin into a laminate. In this process, the dry material is laid in the mould and after the application of vacuum, the resin is introduced. The presence of vacuum allows the resin to flow into the laminate through special tubing system and therefore to impregnate the fibers [Khubchandani 2011].

The resin infusion process is a cost effective method of manufacturing high quality and high strength composite parts that are required in relatively low quantities, i.e. less than a few hundred identical pieces per mould per year, or physically large parts which are difficult, or prohibitively expensive to make by any other method. In figure 2.5 a typical resin infusion system is shown.



Key

1	Mould, leak tight and pre-treated with mould release	7	Vacuum control valve(s). May be just a clamp on the vacuum tube
2	Sealing flange. Typically 75 mm (3”) to 150 mm (6”) wide	8	Resin (normally positioned below the part)
3	Laminate materials. Placed in mould in DRY state	9	Resin control valve. May be just a clamp on the resin feed tube
4	Permeable vacuum line under the bag	10	Resin entry point(s)
5	Disposable materials (typical). Peel ply above the laminate and flow medium above the peel ply	11	Optional vacuum line for pre-evacuation
		12	Resin trap with internal catchpot
6	Vacuum “bag”. May be nylon (disposable) or a reusable film such as silicone rubber	13	Vacuum controls
		14	Vacuum pump

Fig 2.5 Vacuum Infusion Process

2.2.Materials selection

Since different materials have been used, in order to better understand their environmental behavior it is important to know their production process, and their mechanical and technological properties. In the following subchapters a brief description of the different material used is presented.

2.2.1. Flax Fiber

Natural fibers have been considered as reinforcement for a several contemporary composite applications. In addition to being environmental friendly these fibers offer a low density and specific properties comparable to E-glass fiber. Natural fibers have been widely used in the internal panels of automobiles and in applications where stiffness is the chief design driver. These fibers are renewable and have a neutral carbon dioxide cycle [Aktas 2010]. Natural fibers comprise of cellulose, hemicellulose, pectin and lignin.

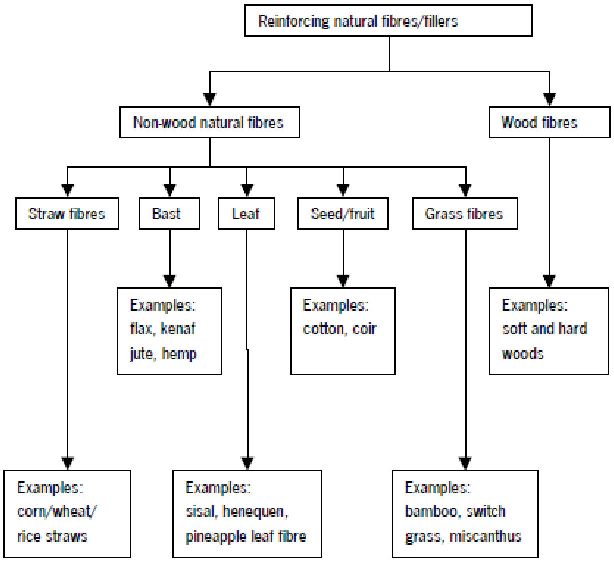


Fig 2.6 The different class of natural fibers

Despite the great variety of natural fiber, only few of them are suitable for the industrial production of "green" composites. Although cotton is indeed one of the most available natural fibers, it has many environmental drawbacks. Its production requires a large amount of fertilizers because the plants tend to exhaust the soil [Madsen 2004] [Pickering 2008]. On the contrary flax, hemp and jute can be harvested with low amount of fertilizers, without pesticides and poor control of the crops [Pickering 2008].

Flax (Linum usitatissimum L.) is probably the oldest textile fibre known to mankind. It has been used since ancient times for the production of linen cloth. The first well documented application is the use of the linen fabric by the Egyptians to wrap their mummies [Bos 2004]. Flax fibre composites are used predominantly in applications where stiffness is the principal design driver. In applications where strength is the main driver flax composites would result in a negative environmental impact, as a larger amount of material would be needed compared to glass fibre, hence resulting in a heavier construction. Rotor blades require a high stiffness, a low density and long fatigue life [Khubchandani 2011].

Flax grows in moderate climates and is presently cultivated among others in large parts of

Western and Eastern Europe, in Canada and the USA. In the traditional flax countries like the Netherlands, Belgium and France, the main focus of flax production lies still on the apparel and home textile market. The main outputs from this production chain are the long fibres for spinning yarn [Müssig 2010]. There are several steps for the production of flax fibre:

- Harvest: the plant are pulled out of the ground in order to retain the longest fibre length and the flower heads is removed;
- Retting: the plant are retted usually directly on the ground, or in warm water;
- Schrouching: the stem parts are removed from the fibre bundles in scotching turbine. The schuced fibres are still relatively coarse and thick and this process introduces defect on the fibre in the form of kink bands over the entire fibre length;
- Hackling: the fibre bundles are then combined together. This process also refines the shape of the fibre in a more or less circular shape. Furthermore, during this process the fibres are strongly bended, and this operation introduces additional defects in the fibre.
- Spinning: as a final step, the fibres are spinned as every fibrous material.

The different production steps are presented in fig 2.7 where input and output for every process are listed.

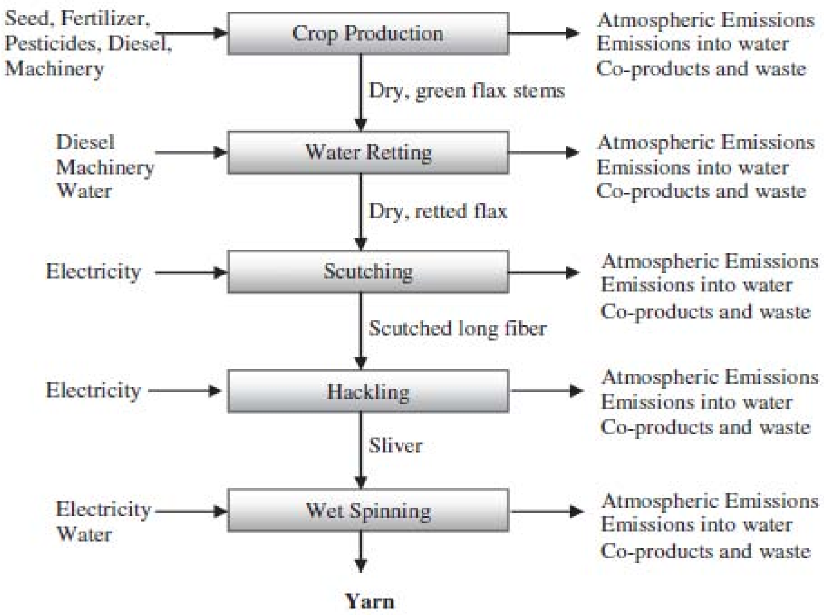


Fig 2.7 **Flax fibre production process. All input and output are listed**

Flax fibre reinforced composites are aimed at the replacement of glass fibre reinforced composites. They are usually used in automobile application (63% of the market), mainly for interior part, even though their use for exterior part is also increasing. The fibres selected for the production of the blade are made by Lineo, a Belgian producer [http://www.lineo.eu]. For blade's realization only unidirectional fibre was used. In the following table mechanical properties, obtained by tensile testing are presented. These values will be used throughout this thesis work.

NFRP UD 0°	
E1	19.93 +/- 0,31 GPa
E2	3,93 +/- 0,10 GPa
σ1	237,84 +/- 4,39 Mpa
Ρ	1,25 g/cm^3
Vf	0,35

Tab 2.1 Mechanical properties of unidirectional 0° NFRP composites.
This value are calculated by (Bottoli et al. 2011) after a series of preliminary tensile testing
[E Tensile modulus, σ Tensile strength, Ρ Density, Vf volume fibre fraction]

The strength of natural fibre composites is their density, although their mechanical properties are not so high. Anyway if they are evaluated in terms of specific mechanical properties (M/ρ) they perform better than the GRFP.
Their mechanical properties are low because the production step introduces defects on the fibre. They will affect strength and stiffness, but also the volume fibre fraction of the final composite, that is really low if compared to the other composites. The main issues connected with natural fibre manufacturing are the following:

- Damaged fibres from mechanical processing designed for softening the fibre to be suitable for textile industry [Huges 2012];
- Twist angle of the fibre in the yarn resulting in off axis loading leading to a low utilization of the theoretical strength/stiffness performance [Rask 2011];
- The non-parallel nature of the fibres means that they have a low packing ability, leading to low fibre volume content, raising the resin uptake and further lowering the mechanical performance in composite applications.

2.2.2. Carbon Fibre

Carbon fibres (CF) are the most efficient fibres regarding mechanical properties especially if evaluated in terms of specific mechanical properties (M/ρ). At the same time they present high prices and high environmental impacts connected with their production. The properties of carbon fibre make them very popular in Aerospace, Military and Sports application.

Carbon fibres are produced from a fibre precursor Polyacrylonitrile (PAN). PAN is a co-polymer made from the monomer of Acrylonitrile that is produced by the Sohio process. PAN fibre are aligned together and then mechanically and chemically tensioned to increase the final properties of the CF. After this initial step the fibre are oxidized at approx 300° C to remove many of the hydrogen bonds. Then the oxidized PAN is carbonized in a furnace with inert atmosphere at around 2000°C, which induces graphitization of the material and a changing in its molecular bond structure.

The total energy demand to produce CF is 704 MJ/kg [Das 2011]. This value is very high principally due to the heat required for carbonization and oxidation processes, as well as for the production of the fibre precursor from fossil fuels.

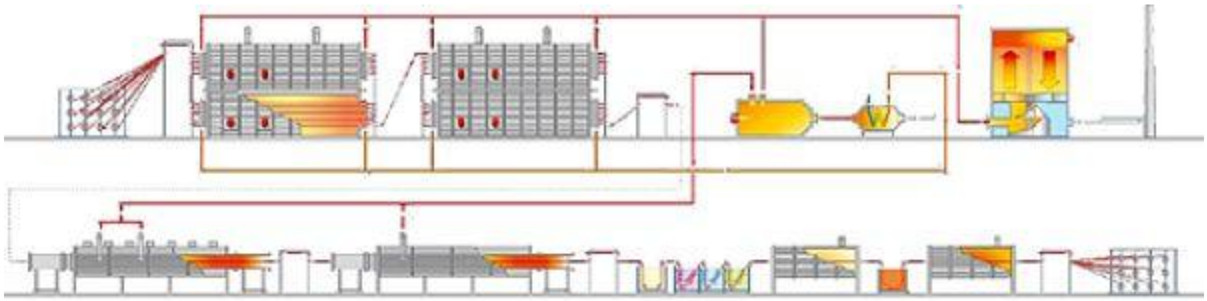


Fig 2.8 **Production process of carbon fibre from PAN precursor fibre.**

The blade was realized with an unidirectional CF reinforcement. Using unidirectional reinforcement allows increasing the properties of the composites tailoring the deposition of the single layers on the specific direction of the stress.

Before the production of the blade some specimens for mechanical testing were made. They were tested in order to obtain the general mechanical properties that will be used as an input in the design of the blade. The properties of the composite are presented in the next table.

CFRP UD 0°	
E1	104,25 +/- 1,45 GPa
E2	46 GPa
σ1	1,979 GPa
P	1,49 g/cm^3
Vf	0,5

Tab 2.2 **Mechanical properties of unidirectional 0° CFRP composite.**
This value are calculated by (Bottoli et al. 2011) after a series of preliminary tensile testing

2.2.3. Glass Fibers

Glass fibers are the most used fibers for reinforcing plastics. They have good mechanical properties and a low price, although they are not so lightweight.

For the production of E-glass fiber (most common used type for reinforcing plastics) the glass raw materials are melted at 1500/1700 °C. Then the molten glass passes through a refining unit and then it is spinned. Subsequently processes as sizing, winding and drying conclude the manufacturing process of the fiber. In figure 2.9 a scheme of a typical glass fiber production process is presented.

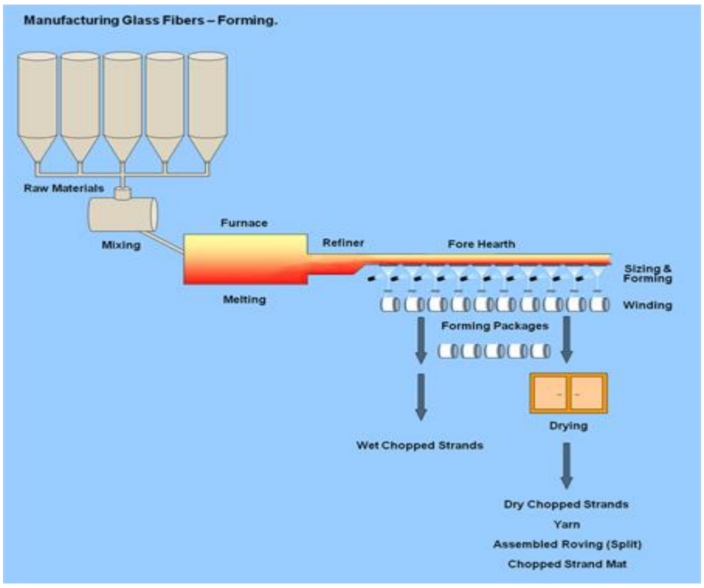


Fig 2.9 **Glass fiber production scheme**

Since this materials wasn't used in the previous project (only flax, carbon and hybrid blade were manufactured) some assumptions about mechanical and process properties were made.

Assuming that the fiber used is E-glass and via Vacuum Infusion Process the volume fraction of the fiber is around 0,52, it is possible to determine the mechanical properties of the composite by micromechanical laminate model [Quaresimin 2009]. The properties of the GFRP are presented in the following table:

GFRP UD 0°	
E1	38 GPa
E2	4,6 GPa
σ1	806 MPa
P	1,88 g/cm^3

Tab 2.3 **Mechanical properties of unidirectional 0° GFRP composite.**
This value are calculated by the author with micromechanical laminate theory.

It is interesting to note that the mechanical properties are higher compared to the NFRP but if evaluated in term of specific stiffness or specific strength (E/ρ; σ/ρ) they result lower respect on the Biocomposite.

The reason why this material scenario was included in the project, refers to the fact that it is the most used material for commercial rotor blades, and thereforeit is the most produced fibrous reinforcement for composites in terms of mass. Additionally NFRP has mechanical properties similar to GRFP, so it is reasonable to compare materials with similar mechanical properties while, in the case of CRPF the mechanical properties are much higher than the NFRP.

2.2.4. Resin

The resin used to produce the blade is a Bio-Based epoxy resin. In order to analyze the environmental performance of this bio-based material also a traditional resin is considered.

Epoxy resin is a high performance matrix for composite materials. It is used also for several applications, from general purpose adhesives to coatings and electronics. This thermosetting resin is bi-components, the epoxy resin itself and a co-reactant, usually called hardener. Combining together these two elements, the polymerization that creates cross link in the polymer structure leading to a thermoset polymer is started.

For composite application it is one of the most performing resins, due to its high mechanical properties, despite its high price. This type of resin is the most used to produce prepregs (high quality pre-composites). The most common and important class of epoxy resins (about 75% of the global epoxy production) is formed from the reaction of epichlorohydrin with bisphenol A. These chemicals are totally fossil based [Rusu 2011].

The production of the blades used a bio-based resin SuperSap 10/100 from Entropy resin. This resin in fact, as opposed to common petroleum based epoxies, contains up to 48% of bio-renewable materials sourced as by-products deriving from waste treatment of industrial process such as wood pulp and bio-fuel production [entropy resin a b 2011]. The presence of these natural components allows a strong reduction of the petrochemical component content in the end product. Thanks to this feature,it is possible to reduce the power and water consumption and the production of waste during the resin production process, thus lowering the emission of greenhouse gasses.

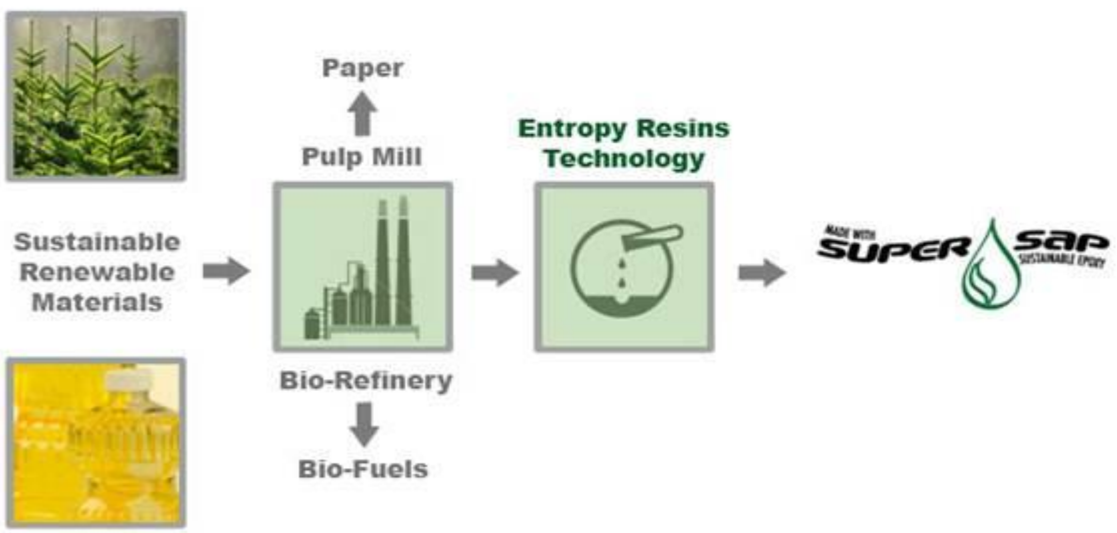


Fig 2.10 **Super-sap biobased epoxy resin (Entropy resin 2011)**

Since no information were available for the composition and the production process of the resin, all the assumption made to develop the product system model of the blade are based on the findings of Rusu [Rusu et al. 2011].

The author identified 3 ways to obtain bio-epoxy from natural products:

- Using bio-based DGEBA (Bisphenol A) from biobased glycerol-derived epichlorydrin;
- Using traditional DGEBA and bio-based curing agent such as cardanol-based novolac;
- Blend epoxidized vegetable oils with bio-epoxy resin in presence of suitable curing agent.

Super-Sap epoxy resin belongs to the third category. It uses bio-based tall oil (pine oil) that is an unintended by-product of the Kraft process during the pulping of wood [Entropy resin 2011 a b]

2.3.Life Cycle Assessment

Life Cycle Assessment is a methodology for analyzing the environmental effects of a product or process throughout all stages of its life. Potential impacts are gauged quantitatively, and the perspective can be holistic, “from cradle to grave”, depending on the assessor’s goal [Ruitme et al. 2009]

LCA is a comprehensive assessment and considers all attributes or aspects of natural environment, human health, and resources [ISO, 2006]. The unique feature of LCA is the focus on products in a life-cycle perspective. The comprehensive scope of LCA is useful in order to avoid problem-shifting, for example, from one phase of the life-cycle to another, from one region to another, or from one environmental problem to another [Finnveden et al 2009].

LCA has been used in the past by large corporation to improve the material efficiencies in production processes or to assist decision making. A worldwide standardization took place with the publication, in 1992, of the first LCA handbook by the Centrum Milieukund Lieden [ILCD 2011].The use of LCA is valid when [Guinee 2002] :

- Analyzing the origins of environmental impactsrelated to a particular product;
- Comparing improvement variants of a given product;
- Choosing between a number of comparable product.

These abilities make LCA one of the key components in the effort to increase sustainable production and consumption, and thereby an important support tool in the decision-making process at both policy and business level [European Commission JRC, 2010].

The methodological framework has been defined by the ISO 14040 and consists in 4 phases as shown below.

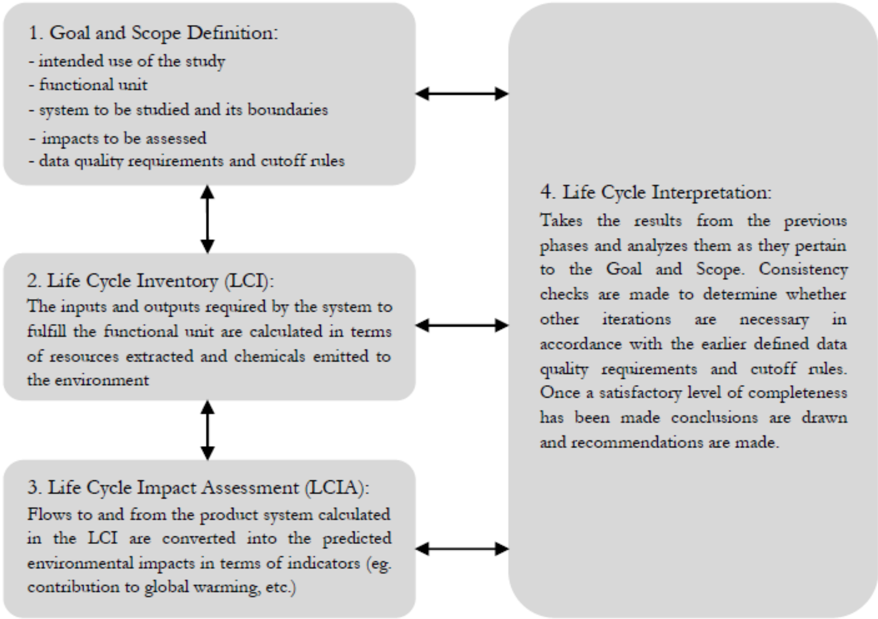


Fig 2.11 **LCA methodology, how it works and a brief description of each step.**

The LCA process is an iterative process: this means that during life cycle inventory phase or during impact assessment stage it could be possible to obtain more information as long as the knowledge about the system under study increases. This information collection can lead to a revision of the goal and scope of the study.

LCA method works with flows of material or energy that come in and out of the system. Therefore, in order to perform a LCA, a functional unit has to be assessed and all the flows of the system are referred to this functional unit.

The results are generally presented as environmental impact related to the functional unit. These impacts can be presented at midpoint level, i.e. in form of Midpoint categories (e.g. Global warming, eutrophication etc.) thus allowing a specific analysis of the environmental performance of the product or process, or at endpoint level, i.e. in the form of Endpoint categories that are the aggregation of the Midpoint categories and represent the total impact on areas of protection (e.g. Human health, environmental damage etc.).

Results presented with Midpoint categories have low uncertainties while with the Endpoint categories it is possible to have a global performance of the product or process but with higher uncertainties.

The LCA modeling in this study has been developed using GaBi 4.4 software , product sustainability software, developed by PE International (2012). GaBi was chosen as the modeling software due to its strong popularity in LCA community.

The EcoInvent 2.0 database (Swiss centre for LCI, 2011) has been used for inventory phase, because it is one of the best standard databases for product modelling. For some processes, that will be described afterwards, not present in the Ecoinvent database, PE professional database has been used.

Life cycle impact assessment has been developed using ReCiPe 2008 method. This method has been chosen as it’s one of the most recent and advanced method for impact assessment and also because this method allows to perform the assessment both at Midpoint and Endpoint level.

A detailed description of this method will be presented in chapter 2.3.5.

In this thesis work the standard approach on LCA, described by ILCD Handbook and ISO 14040, has been followed. Deviation from this standard occurred occasionally, as will be acknowledged when required.

Following the guidelines described on the ILCD Handbook, the goal and scope and product system must be defined. This is the first of the four steps of the LCA methodology , and it is described in the following chapter.

2.3.1. Goal and Scope definition

At the beginning of every LCA the goal and scope of the study need to be defined.

The goal of this study is to compare the environmental impact of natural fiber composites with respect to traditional composites (glass and carbon fiber composites) used in wind blade manufacturing.

In a previous thesis work [Bottoli et al 2011; Nipper 2009], it has been demonstrated that natural composites can substitute the traditional glass composite in terms of mechanical performance. But there are no complete and accurate studies to evaluate if natural fiber composites perform better than the traditional one from an environmental point of view.

The scope definition includes the definition of different elements, as described in the following paragraphs.

2.3.2. Functional unit

The functional unit defines the quantification of identified functions (performance characteristics) of the product. The primary purpose of a functional unit is to provide a reference to which the inputs and outputs are related. This reference is necessary to ensure comparability of LCA results. It is important to determine the reference flow in each product system, in order to fulfil the intended function, i.e. the amount of products needed to fulfil the function. [ISO 14040]

The functional unit of this study is a single blade that fulfils stiffness and design requirements evaluated in the previous work performed by (Bottoli et al 2011). All the flows of the system must be referred to this functional unit.

The primary function of the blade is to convert wind energy into mechanical energy to move the car. The secondary function is to be stiff and strong to resist at the loads created during its movement and to maintain its aerodynamical shape.

2.3.3. System boundaries

LCA models the life-cycle of a product as its product system, which performs one or more defined functions. The essential property of a product system is characterized by its function and cannot be defined solely in terms of the final product. Product systems are subdivided into a set of unit processes. Unit processes are linked to one another by flows of intermediate product and/or waste for treatment, to other product system by product flows, and to the environment by elementary flows [ISO 14040]

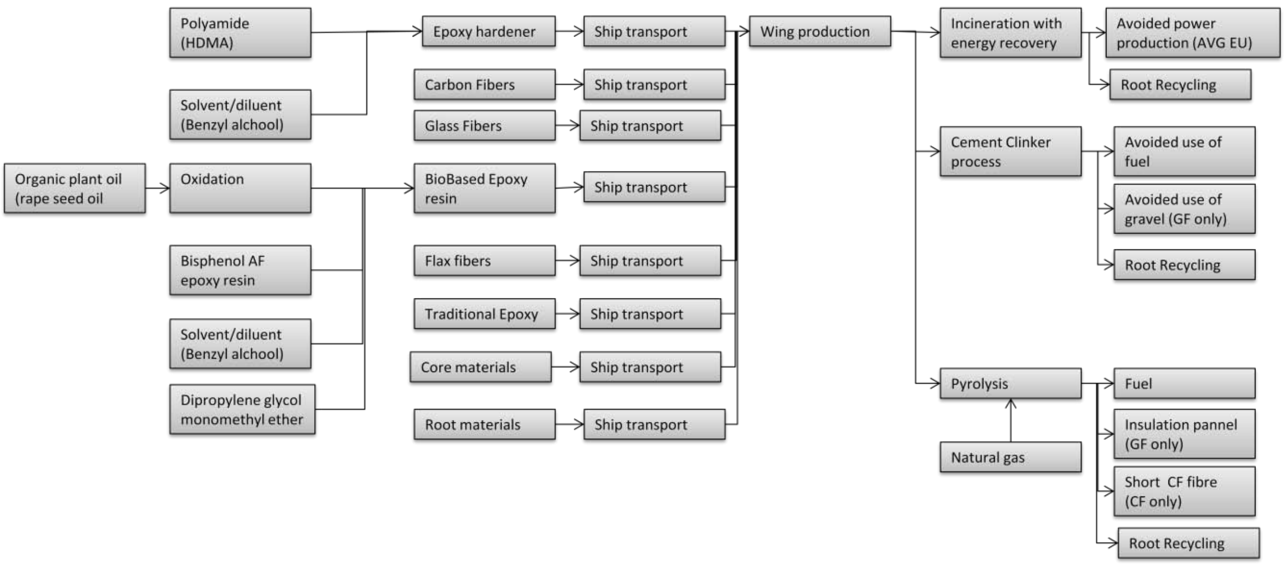


Fig 2.12 **Product system model for the small-scale rotor blade**

It is important to define the system boundaries , all the processes used in the life cycle of the product must be included. The definition of the system boundaries is useful also to solve allocation issues so the system boundaries could be modified to avoid the allocation process (it increases the uncertainties of the results).

The product system in this project is modeled in a “cradle-to-grave” perspective from the extraction of raw materials to the disposal of the blade.

The construction phase is not considered since there is no available data , and also because this phase is the same for all the materials used; so it can be neglected when comparing different material, since this phase doesn’t increase the environment burdens of a specific material. Furthermore the construction phase for a prototype blade is a manual process of layer deposition and the resin is applied via Vacuum infusion process. Hence the environmental burdens of this phase are much lower than other life cycle phases (e.g. extraction of raw material or waste disposal).

In this project the product system is the sum of the different unit processes. It includes all the materials needed for the comparison and also three different end-of-life scenarios. A detailed explanation of the entire product's system will be presented in chapter 3.1.2 and 3.2.3.

2.3.4. Data quality

LCI data quality can be structured by representativeness (composed of technological, geographical and time-related), completeness (regarding impact category coverage in the inventory), precision and methodological appropriateness and consistency [ILCD Handbook, 2010].

According to the ISO 14040 standard we can divide the type of data in primary, collected directly from the product system (usually they are provided by the producer or by direct measurements), and secondary, that are generic data from literature or specific database (e.g. EcoInvent).

To have the real representativeness of the product system only primary data should be used, in order to represent the real situation of the specific product system. But very few LCAs are done in this way because the collection of primary data is highly time consuming, and also some producers don't want to reveal such specific information regarding their products. Using secondary data determines an increase of the uncertainties in the assessment.

In this thesis work the only primary data are the mass of the materials used to produce the carbon, flax, hybrid 50/50 blade. The other data are obtained through assumption or from Ecoinvent or PE databases.

Information regarding the Bio-epoxy composition and the mass of the materials for the glass fiber blade is made by assumption. In the first case using the findings in the study by Rusu et al. [2011] about biobased resin. In the second case assumptions are made using a mechanical comparison that will be presented in a specific section in chapter 3.

On the contrary all the emissions of the specific processes present in the product system model are taken from Ecoinvent database or if not present in the PE database [PE 2011].

2.3.5. LCIA Method ReCiPe

LCIAs the third phase of a LCA; its purpose is to provide additional information to help assess the results from the Inventory Analysis so as to better understand their environmental significance [ISO 14040]. Thus, the LCIA should interpret the inventory results converting them into potential impact on what is referred as the "areas of protection" (Endpoint macro-categories i.e. Human Health, Environmental Damage, Resource Depletion) [De Haes et al 1999; 2002]; or on single environmental categories (midpoint categories e.g. global warming potential, eutrophication ecc) if a detailed view is needed.

An important aspect to remember when choosing between Midpoint and Endpoint is that the first one provides a specific view of a single environmental aspect, meanwhilethe Endpoint level providesa global view on the areas of protection. But to reach this global view more characterization factor are needed, in order to include the entire environmental mechanism,therefore increasing the uncertainties on the results.

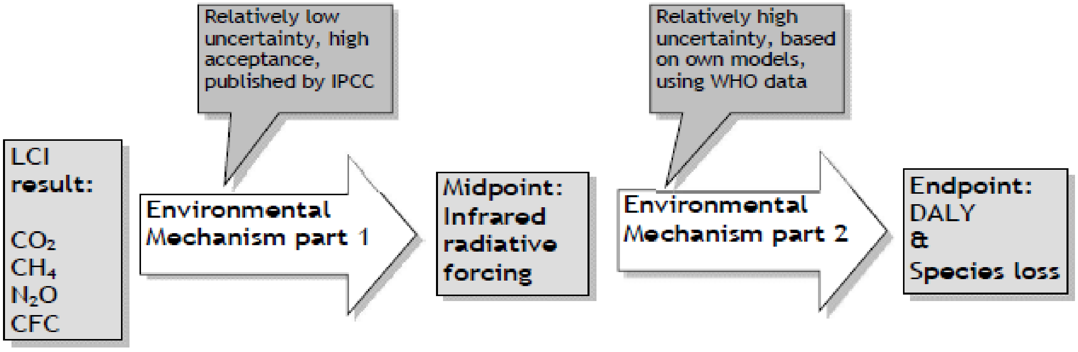


Fig 2.13 **Example of a harmonized midpoint-endpoint model for climate change, linking to human health and eco system damage**

Hence with Midpoint categories there is a focused view with low uncertainties, while with Endpoint categories there is a wide view but with higher uncertainties.

ReCiPe is a method that is harmonized in terms of modeling principles and choices, but which offer results at both the Midpoint and Endpoint level. There are 18 Midpoint impact categories and 3 Endpoint categories with associated sets of characterization factor.

Moreover, similar to other previous method (as EcoIndicator 99), three versions of the characterization factors have been developed, using the cultural perspective theory of Thompson. According to this theory consistent sets of subjective choices on time horizon, assumed manageability etc. can be grouped around three perspectives, identified by the names:

- Individualist
- Hierarchist
- Egalitarian.

In the present hesis the Hierarchist point of view is used, because it represent an “average” point of view and it is the most common view used in decision-making process. In the figure below there is a schematic description of how this method works.

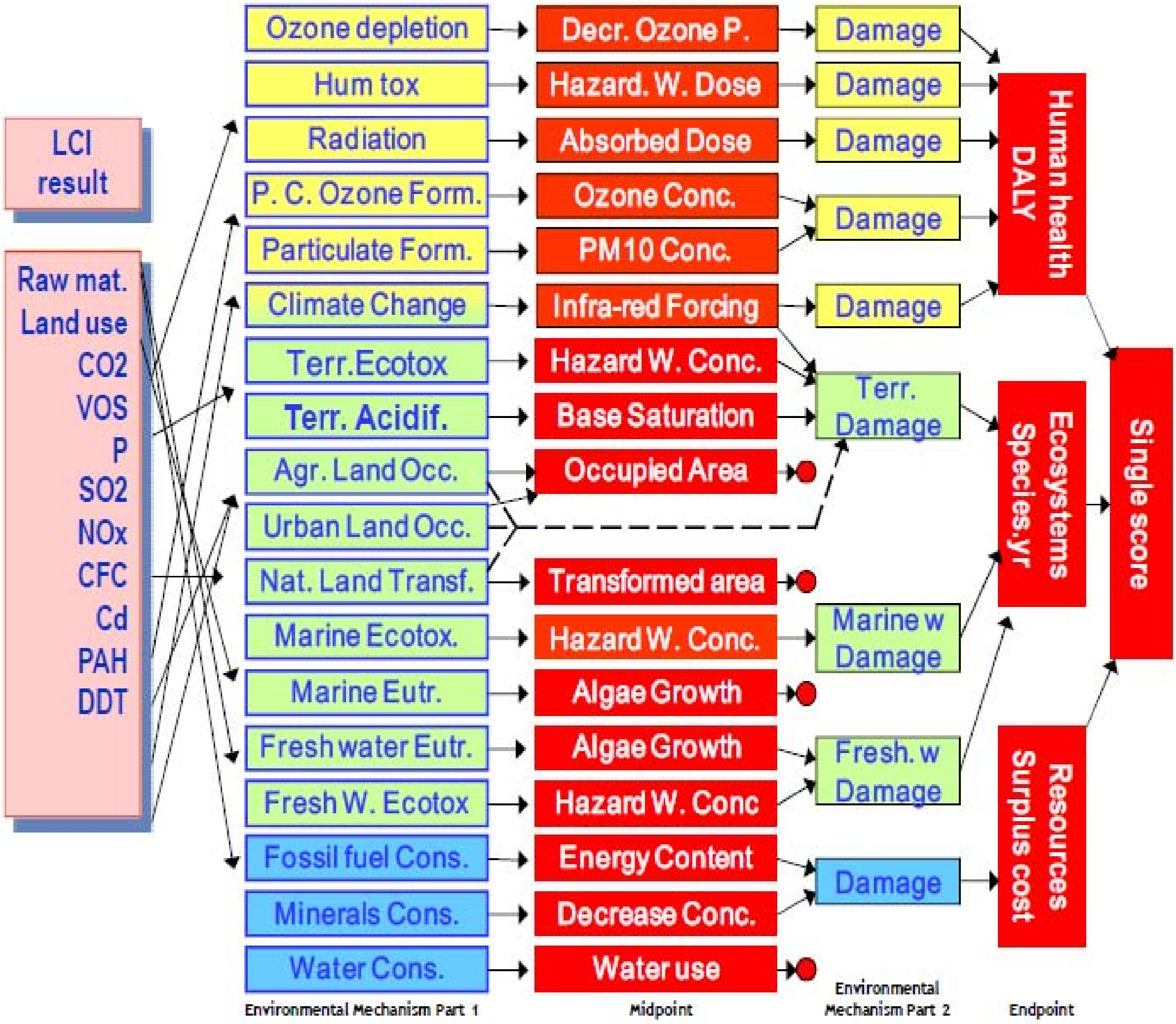


Fig 2.14 **Relation between LCI parameters (left), midpoint indicator (middle) and endpoint (right) in ReCiPe 2008 (ReCiPe 2010)**

2.4.Wind blade End of Life

One of the goals of this thesis work is to analyze the end of life of a wind blade. There are many reasons motivating this deepening.

First of all, if we look t the entire wind turbine, blades are the most critical part in terms of recycling. The reason is that the other parts are composed by materials easy to recycle. For example the tower is mainly made by steel; while blades are mainly made by thermoplastic composites, which are indeed hard materials to recycle [Davidsson 2012]. In the figure below the different materials and typical end of life of an entire wind blade are shown.

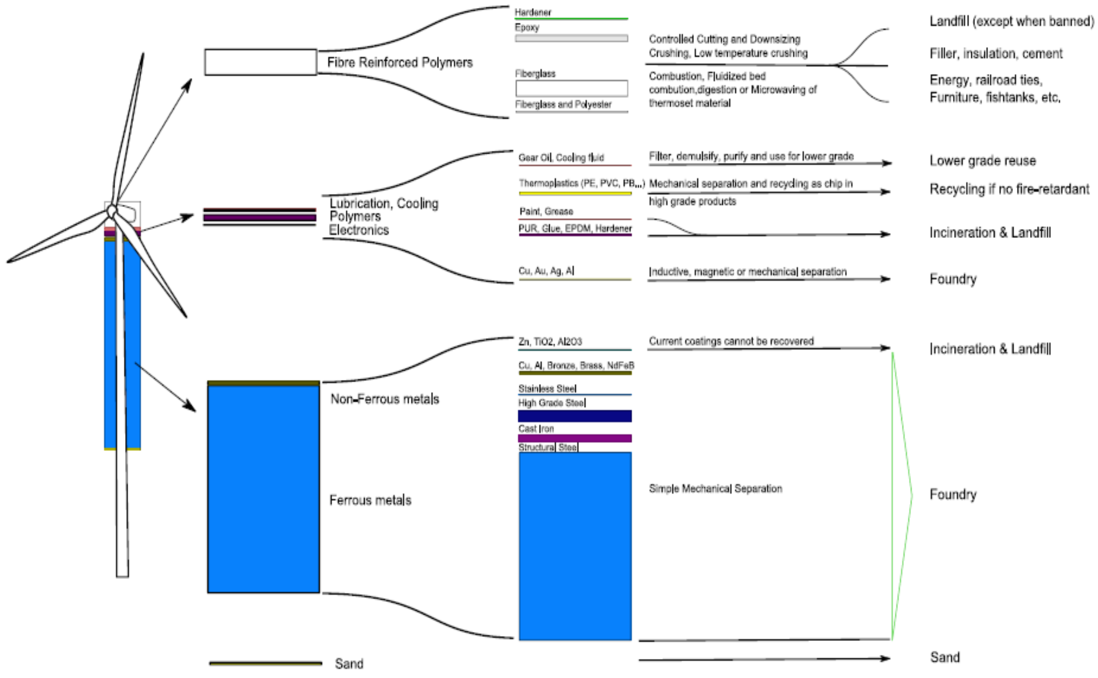


Fig 2.15 **Recycling WTs outlook and technologies available (Cherrington 2011)**

The problems in recycling thermoset composites is connected with the cross linked thermosetting polymers which cannot be remoulded, in contrast to thermoplastics which can easily be re-melted. Some thermosetting polymers such as polyurethane can be relatively easily converted back to their original monomer,. However, the more common thermosetting resins, such as polyester and epoxy cannot be depolymerized to their original constituents.

By their very nature composites are mixtures of different materials: polymer, fibrous reinforcement (glass or carbon fiber) and in many cases fillers (these may be cheap mineral powders added to extend the resin or have some other function, such as fire retardants). There are few standard formulations and for most applications the type and proportion of resin, reinforcement and filler are tailored to the particular end use.

Composites are often manufactured in combination with other materials. For example there may be foam cores to reduce weight and cost or metal inserts to facilitate fastening onto other components. In addition to these specific problems, there are the other problems associated with recycling any material from end-of-life components, such as the need to be able to deal with contamination and the difficulty of collecting, identifying, sorting and separating the scrap material [Pickering 2006].

- The global wind industry is growing fast, from 1980 to 2009 the number of turbines has increased 100 times and the rotor diameter has increased 8 times. As the turbines grow in size and number, so does the amount of material needed for the blades. Professor Henning Albers from the Institut für Umwelt und Biotechnik, Hochschule Bremen, estimates that for each 1 kilowatt (kW) installed, 10 kg of rotor blade material is needed. For a 7.5 megawatt (MW) turbine, that would translate into 75 tons of blade material. In a presentation at Composites Europe in September 2008, Albers predicted that by 2034, around 225 000 tons of rotor blade material are up to be recycled per year worldwide.

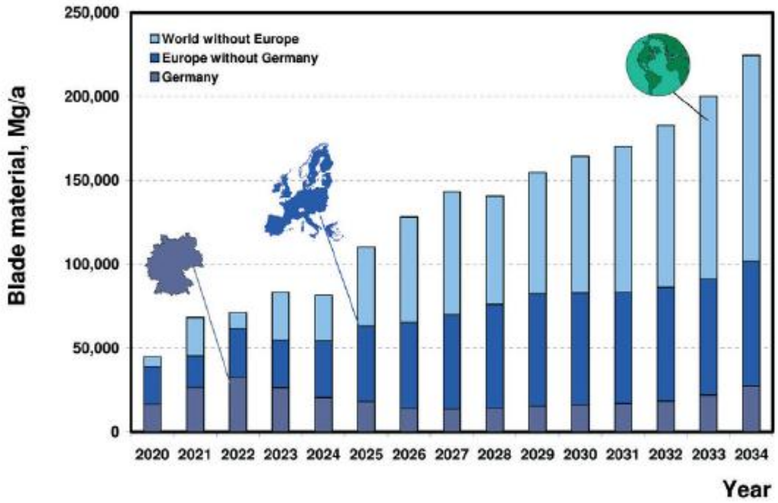


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Fig 2.16 **Expected amount of rotor blade material for re cycling (Larsen 2009)**

Wind turbine blades are predicted to have a lifecycle of around 20-25 years. The question is what to do with them afterwards. In his study on the managementof long-term environmental aspects of wind turbinesDannemand [2007]makes the prediction that from 2040, 380 000 tons of fiber composites will have to be disposed of each year: “Because the wind-turbine industry is relatively young, there is only a limited amount of practical experience on the removalof wind turbines, particularly in respect of offshore wind turbines. It is likely to take more than 20 years before a substantial amount of practical experience regarding the dismantling, separation, recycling, disposal, etc., of wind-power systems is gained.” [Larsen 2009].

The end-of-service life of wind turbines (EOSLWTs) has not been a priority in the past; as a result, little research has been done to address the technological, environmental, and economic issues associated with this phase. A study examining 72 Life Cycle Assessments showed that only 11 of those studies included the decommissioning phase of WTs (Lenzen and Munksgaard, 2002).

Although the small blade assessed in this thesis work is not a commercial rotor wind blade for energy production, it is possible to evaluate the recycling option of such blade and the results can be applied to bigger commercial blade. The difference is that small blade is made only by composite material, while bigger ones are more complex with more material inside. But since the biggest recycling problem is caused by the composite materials, and the share of other materials in the big blade are small compared to the composites, the image given analyzing the end of life of the small blade can represent also the bigger blades.

In this thesis work a preliminary literature review of the possible recycling method for composite materials has been performed. Regarding the different materials analyzed, for NFRP no specific recycling solution has been developed. Only in the paper by (Baley, C et al. 2012)the author propose 3 possible end of life solutions: grinding the composite to produce filler to be used for plastic production, bio-degradation only in case of bio-degradable matrix, and incineration. Since the first is not a proper recycling technique, and in this project a non-biodegradable resin was used, the only possible way to recycle the composite is incineration [Baley 2006]. In the CFRP it would be useful to recover the fibers since they are expansive and highly environmental burdensome. GFRP are also hard to recycle since the fibers are inorganic, so they cannot be incinerated and has to be land filled.

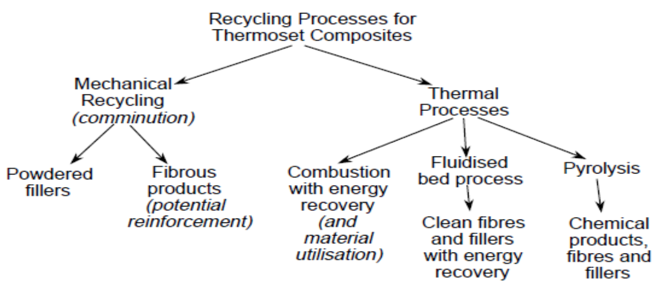


Fig 2.17 Recycling options for composite materials (Pickering 2008)

From this study three possible end-of-life options has been chosen as listed below:

- Incineration with energy recovery: this technology is successfully used in country like Germany and Denmark; composite waste is mixed with 10% MSW (Municipal Solid Waste) to practically dispose waste (Pickering 2006). With this method it is possible to recover only the energy produced by burning the blades.
- Co-processing: burning composites regrind in cement kiln. This practice has taken places in the last years, and allows recovering not only the heat from the incineration of the material but also a recovery of the materials, principally for GRFP, that goes directly in the clinker compound.
- Pyrolysis: this is the most promising method for recycling composites, but it has been tested only in lab-scale prototypes. This technique allows to recover energy from the resin material and to recover fiber with low damage from this process.

Land filling has been excluded from this study because is currently being banned in EU (EU Directive on Landfill of Waste (Directive 99/31/EC). Another possible way to recycle composites is grinding and use the powder produced as a filler. This option also has been excluded due to the poor quality of the recycled, the impossibility to recover energy from the process and for the high energy required for grinding composites. An innovative technology, similar to the Pyrolysis is the Fluidized bed treatment, but for this process there is few literature available. A detailed description of the selected processes is presented in the following paragraphs.

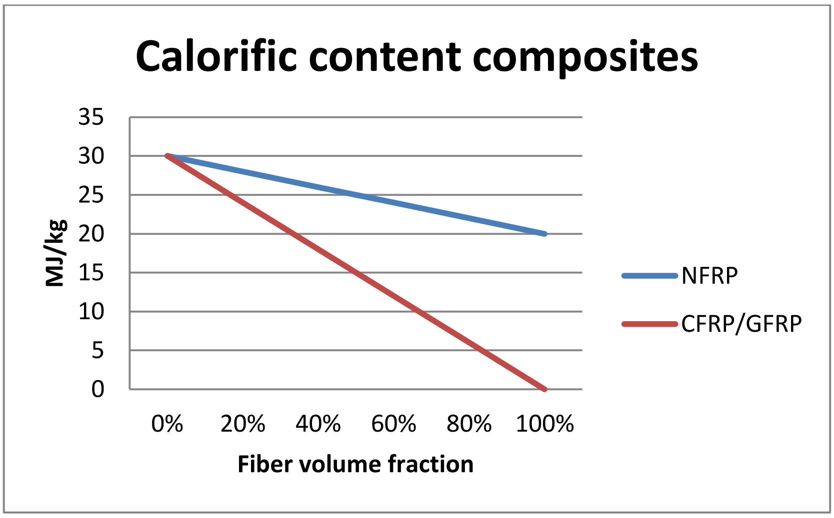
2.4.1. Incineration with energy recovery

This is the traditional and most common route used for the end of life of composite materials. After dismantling and a first cutting process blades are sent to the incinerator where they are grinded again in finer pieces and burned. The heat from incineration is used to create electricity, as well as to feed a district heating system.

However, in case of GFRP 60% of the scrap is left behind as ash after incineration, because glass fibers are incombustible. The same situation happens for CFRP, where in addition there is the risk of short-circuiting of electrical filters for flue gas [Meyer et al 2009]. However, during combustion the fiber reinforcement is completely destroyed and, thus, no fiber recovery is possible. Due to the presence of inorganic loads in composites, this ash may be full of pollutants.It is, depending on the type and post-treatment options, either dumped at a landfill or recycled as a substitute construction material.

The inorganic loads also lead to the emission of hazardous flue gasses in that the small glass fiber spares may cause problems to the flue gas cleaning steps, mainly at the dust filter devices [Larsen 2009].

For NFRP there are fewer problems because the fibers are combustible. The energy content of the composite depends on the amount and type of fiber and matrix, and consequently the energy produced. In the following table the energetic value of the different composites are presented. They are calculated from a study about composite recycling and energy parameters of flax [Pickering 2006] [Komlajeva 2012]. Using NFRP allows having a higher energy content in the composites, making this material attractive for this process.



Tab 2.4 Calorific value of composites in relation with their fiber volume fraction.

2.4.2. Co-processing

In this disposal scenario the resin and the other organic part are burned, as well as in the incineration process. But burning it inside a cement kiln allows also a direct use of the ashes and residues to substitute component of the clinker.

Co-processing composites through the cement kiln route is considered the best recycling option available at the moment [EuCIA 2011]

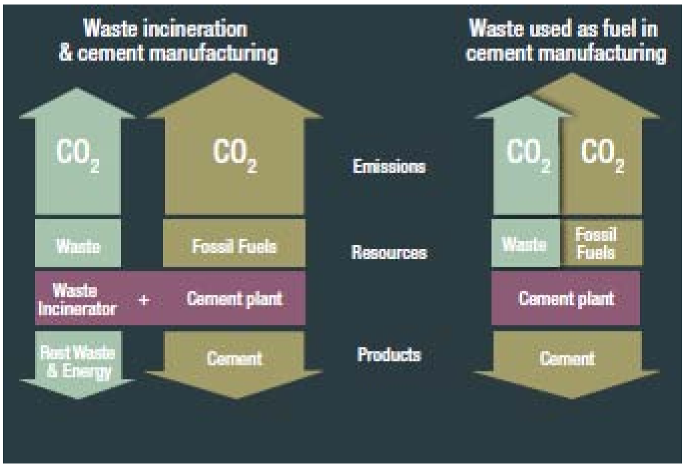


Fig 2.18 **Incineration & cement manufacturing vs Co-processing**

Recycling glass fiber-based composite through co-processing in cement kilns is proving to be highly cost effective. Furthermore it is generating valuable materials, and it is helping to improve the ecological footprint of cement manufacturing. Glass fiber thermoset composite is an ideal raw material for cement manufacturing. The mineral composition of the residual ashes (mainly the GF fiber) is consistent with the optimum ratio between calcium oxide, silica, and aluminum oxide. Additionally, the organic fraction supplies fuel for the reaction heat, right at the spot where it is most needed [EuCIA 2011].

Furthermore, co-processing doesn't increase the emission of the cement kiln and doesn't affect cement quality [CEMBUREAU 2011].

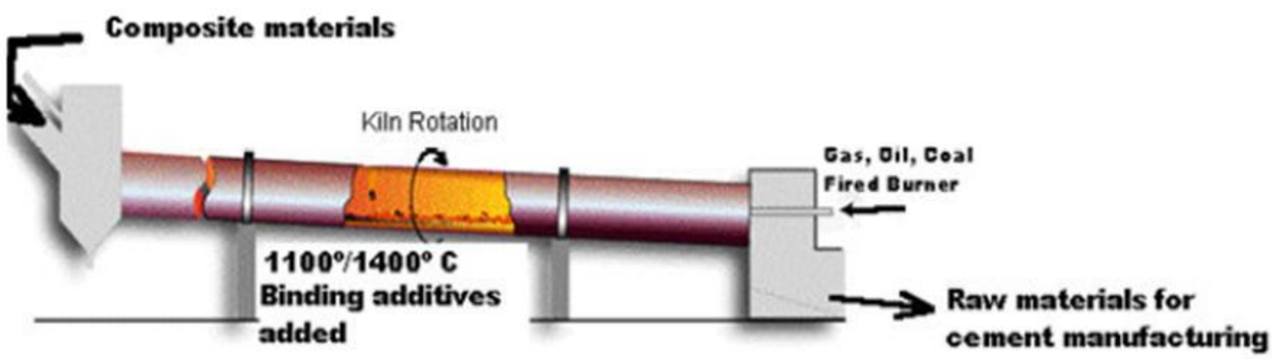


Fig 2.19 **Cement Kiln**

In Germany the first trials of this process started in spring 2008, where GeoCycle launched the project “Sustainable utilisation of rotor blades in the Lägerdorf cement plant”. With the successful conclusion of the operational trial in May 2009, they paved the way to building a new recycling plant. As of February 2010, the first rotor blades was processed in the new plant built by Zajons in Melbeck and utilised in the Lägerdorf cement plant [Schmidl 2010].

For the two other types of composites this routes implies that all the organic materials are burned and only ashes are used as filler in clinker composition. Since there is no information about the effect of this filler in the clinker composition, we can assume a diluted feeding of the composite in the kiln especially for CFRP that has high amount of ashes due to the un-burnable fiber.

Therefore for these types of composites cement kiln route is similar to incineration; it has only the advantage that land filling of ashes is avoided, still no fiber could be recycled.

2.4.3. Pyrolysis

This is the most promising recycling methods, but it has been developed only in lab-scale until now. Pyrolisis consists of heating the composites, after an initial cutting process, in an atmosphere in absence of oxygen, so that the thermoset resin is cracked in smaller organic molecules. This molecules could be used has a fuel, while the fiber could be recovered as the thermal treatment without oxygen doesn’t destroy the fiber and even a degradation of the mechanical properties could appear, depending on the fiber type.

This process makes sense with GFRP and CFRP because they have good thermal resistance; but not for the NFRP because the fiber will be degraded with the resin.

This process has been developed also for other types of hard to recycle materials, e.gcar tyre. In the case of the FRP the blades, after a pre-cutting stage are heated between 450°/500° C in an oven with controlled oxygen. The resin is pyrolysed in synthetic gas, that is used to heat the oven, and a liquid compound, that are the heavier organic molecules. This liquid compound has high calorific value and could be used as a substitute of the crude oil [Cunliffe 2003].

After this process, the fibers are cleaned in another oven with the presence of oxygen, which removes the char present on the fiber’s surface. This char could create problems of adhesion between recycled fiber and resin.

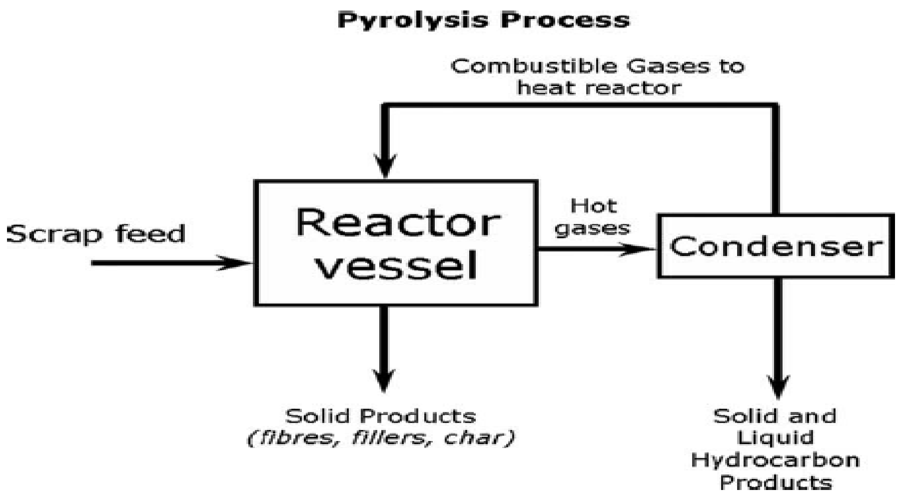


Fig 2.20 **Pyrolysis scheme**

After this process the fibers lose some of their mechanical properties, depending on the fiber's type; additionally the length of the fiber will be lower because of the cutting stage.

In the case of glass fiber there is a high loss of mechanical properties, around 50 %. Hence it is not possible to use them in structural applications, as they are mixed with Polyethylene fibers and heated producing glass fiber panel useful for thermal insulation.

Instead for carbon fiber the loss is lower, around 20%. They can be used as a fibrous reinforcement again to create short fiber composites.

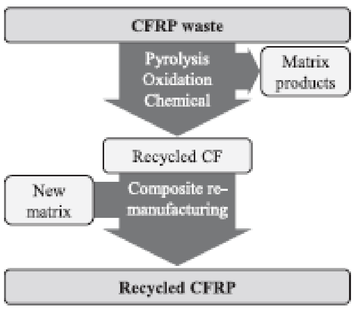


Fig 2.21 **Recycling CFRP with Pyrolysis**

3. METHODOLOGY

3.1. Mechanical Model

The blades experiences different type of forces: aerodynamical and centrifugal whichtry to bend and twist the blade during its rotational movement.

In a previous thesis work [Bottoli et al 2011] a mechanical model of the Carbon, Flax and Hybrid blade was developed with the objective to minimize the twist of the blade.

Other design constraints considered were:

- Tip deflection: the blade is inserted inside a shroud, so the deflection has to be limited to avoid the contact between blade and shroud during rotation. This would cause the damage of the blade.
- Weight: increasing weight increases centrifugal loads but since we are dealing with a small blade this aspect is not so relevant.
- Failure consideration: the tension that undergoes the blade has to be lower than the breaking strength of the material.

Laminate thickness: the moulds represent the outer surface of the blade. Therefore there is a restriction on the total laminate thickness. Moreover in the trailing edge the limit is even tighter because the aerodynamical shape of the blade.

These constraints, the different materials properties and the load that undergoes the blade were analyzed using Finite Element Modeling software (Abaqus) to obtain the optimized lay-up that minimized the twist of the blade. This optimized lay-up was subsequently used to realize the blade.

In the table below the weights of the 3 different blades are listed. The weights were calculated directly from the real blade and the mass of resin and fibers were obtained using the rule of mixture and the fiber weight fraction of the different materials.

Blade Material	Total Mass (g)	Weight fraction	Fiber (g)	Resin (g)
Carbon	246	0,63	155	91
Flax	453,8	0,42	190,6 g	263
Hybrid (50/50)	308	0,50	77 g flax 77 g carbon	154

Tab 3.1 Mass of materials used calculated from the manifactured blade and the micromechanical theory for the amount of fiber and resin.

The glass blade scenario was developed during this thesis to have a comparison with a material largely used in commercial wind turbines.

Because the finite element model wasn't available a different approach was used.

Since the blade is a beam element that has to respect stiffness requirement (minimizing strains) the Ashby's materials indices was used to calculate the mass of the glass blade [Ashby 2010].

This methodology allows, once the constraints have been fixed, to calculate the mass of an object varying the materials.

In this case, the blade was compared to a beam with the objective to have a deflection less than the maximal deflection constrain and minimizing the mass.

In this case the material index (I) is:

$$I = \frac{E^{\frac{1}{2}}}{\rho}$$

Where E is the Tensile Modulus (GPa) and ρ is the density (Kg/m^3). To obtain the mass of the glass blade a comparison with the real blade (flax and carbon) was used. The equation to obtain the mass of the glass blade is:

$$m_g = \left(\frac{E_f}{E_g}\right)^{\frac{1}{2}} \frac{\rho_g}{\rho_f} m_f$$

The steps needed to obtain such an equation are explained in Appendix A.

This calculation was first made with Carbon blade as reference and secondly with Flax blade, and the mean value between them was used. To check the accuracy of this calculation also carbon and flax blade weight were calculated. The results are shown in the table below:

Material	E (GPa)	ρ (g/cm^3)	Mass real (g)	Mass calculated (g)
Glass	38	1,88		495 (f) 500 (c)
Carbon	100	1,5	246	243
Flax	20	1,25	453,8	458

Tab 3.2 Mass of material calculated with Ashby's methodology and comparison with the real weight of the manufactured blade.

As we can see, from the carbon and the flax blade results, although this is a simple model, the results are not so different respect on the real blade mass. In the carbon blade there is an error of 1,2% and in the flax the error is equal to 0,9%.

Therefore it is possible to conclude that the use of this model is valid and it does not involve high errors. The value used during this thesis project is the mean value, namely 497,5 g. Glass fiber composite produced with Vacuum infusion process has a volumetric fraction V_f=0,52, then the mass fraction W_f will be:

$$w_f = \frac{\rho_f V_f}{\rho_c} = 0{,}72$$

Where:

- ρ_f= fiber density (2,6 g/cm^3)
- ρ_c= composite density (1,88 g/cm^3)

With the weight fraction we can calculate the fiber mass

m_f= 358,2 g

And the matrix mass:

m_m=139,3 g

As we can see the mass of a glass fiber blade will be more than the flax one. This is because according to Ashby's method a beam that has to respect flexural stiffness requirement will have mass directly proportional to the ratio $\frac{E^{\frac{1}{2}}}{\rho}$.

The same method has been used to calculate the weight for a hybrid composite blade with different amount of flax fiber. This turns out interesting to see how the environmental score changes varying the share of natural fiber included.In the table below the weight of the blade and the weight of fiber and resin are shown:

Percentage of flax fiber	Blade mass (g)	Carbon fiber mass (g)	Flax fiber mass (g)	Epoxy resin mass (g)
0 %	246,0	155,0	0,0	91,0
10 %	257,1	138,8	15,4	102,8
20 %	269,5	123,5	30,9	115,1
30 %	283,4	108,7	46,6	128,1
40 %	299,0	94,2	62,8	142,0
50 %	316,8	79,8	79,8	157,1
60%	337,2	65,4	98,1	173,8
70%	361,1	50,5	117,9	192,6
80 %	389,4	35,0	140,2	214,2
90 %	424,0	18,4	165,8	239,8
100 %	453,8	0,0	190,6	263,2

Tab 3.3 Mass of a hypotetical hybrid blade with different amount of flax fiber in it. The blade's mass are calculated using Ashby's methodology, for the fiber and resin mass micromechanical theory is used.

All the steps needed to obtain these data are explained in the Appendix B. Even in this case, if we take a look on the 50/50 hybrid, the error respect on the real blade is small, it can be concluded that this blade's mass calculator is valid.

3.2. Product system model

A product system model, capable to include and describe all the life cycle stages of the product was developed. In this model all the process that are inside the system boundaries, defined in the first step of LCA (cap 2.1.3), must be included.

This model was developed using the GaBi 4.4 software [PE 2011]. Most of the process are taken from the Ecoinvent database [Swiss center for LCI 2011], and when not present in that database also the PE professional database [PE 2011] was used.

A schematic description of the product system model and its boundaries is presented in the following graph:

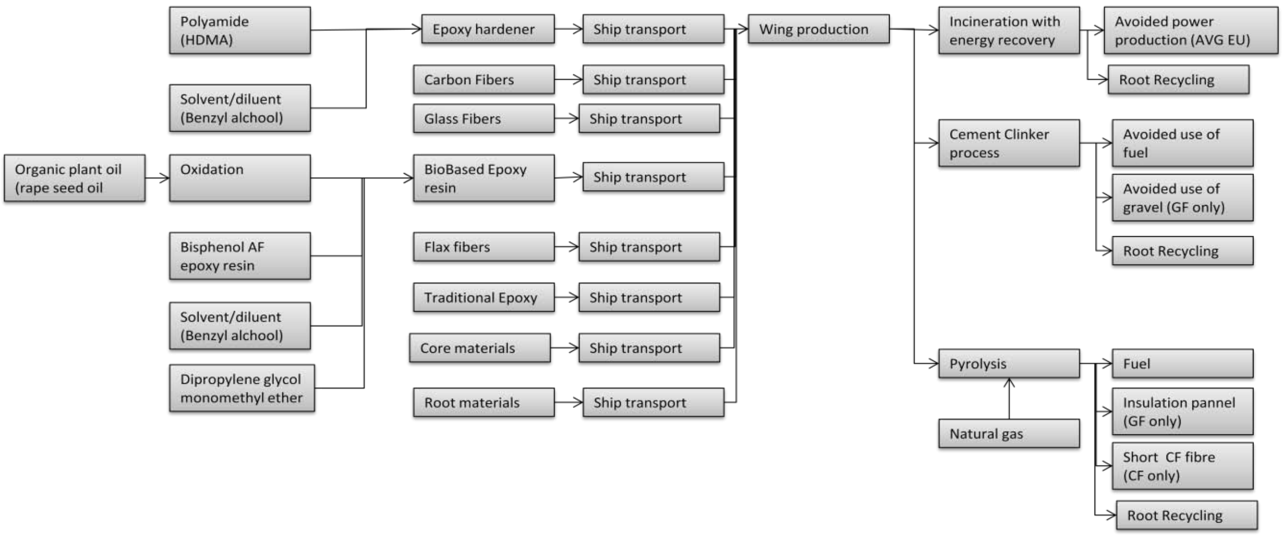


Fig 3.1 Product system model. It includes the materials for each of the four blades scenario and also all the disposal options.

The product system model is developed to describe not only the blade studied in this thesis but also to model a 12m blade for electricity production. The results of the LCA of the 12m blade were not included in this thesis due to the short time for the development of the project. However the project scheme on how to develop the LCA on this 12m blade is presented in appendix E.

The product system model is fully parameterized, facilitating changes in the parameters and therefore allowing different type of analysis and scenarios.

The transport mean for the raw materials is by ship boat. Originally the product system model was developed using transport by airplane; but the results of that scenarios gave too much importance at the transport stage, therefore in order to lower the share of the transport stage transport by boat is used. Transport distances of all materials are estimated with varying uncertainty relating to the specific knowledge on the typical transport means of the materials from materials producer to blade production location and the actual materials origin.

The transport used for the End-Of-Life stage is truck. This is a reasonable assumption, and also the transport distance is calculated from the real distance from Risø campus of the Technical University of Denmark in Roskilde (assumed as the place where the blade are sent to their end of life stage) to the different facilities used for the three end of life options.

The distances used in the model are shown in the table below:

EOL SCENARIOS	KM	NOTE
Incineration	35	From Birkved et al. 2013
Cement Kiln	160	Aarhus (cement clinker plant) Aalborg Portland
Pyrolysis	350	Refiber plant-Risø
Root material	160	Eldan Recycling plant- Risø

Tab 3.4 **Distance assumed for the disposal stage.**

Since most of the information relating to the composition of the Bio-based epoxy resin and hardener is considered confidential information owned by the resin producer [Entropy resin 2011 a,b], assumptions had to be made in order to quantify the composition of both the resin and hardener. All assumptions made with regard to the epoxy composition were based on the findings in the study by Rusu et al.[2011]. It is clear that as the exact data on the composition of the resin are unknown, a further uncertainty is introduced in the assessment. In this thesis project a screening LCA is performed, which typically has a higher uncertainty than a detailed full assessment.

The chosen uncertainty level seems appropriate for a screening level LCA. For a full-blown LCA, more exact data on the resin composition is warranted. we do however consider it less likely that the suppliers/producers of the resins are interested in having their exact product compositions presented to the readers and hence potential competitors in a scientific paper.

Allocation of impacts from the oil used for the production of the bio-based epoxy was based on the assumption that tall oil (pine oil) is an unintended by-product of the “Kraft process" during the pulping of wood. Since the driving product of the pulping process is the pulp, it is possible to assign a 0 allocation factor of impacts to the tall oil. In the presented study a slightly conservative allocation approach was used, allocating 5% of the oil production impacts to tall oil based on the fact that 1000 kg of pulp produces about 20-50 kg of tall oil [Stenius 2000]. The concentrations of the individual epoxy constituents had also to be estimated partly based on [Entropy resin 2011 a,b] and common sense (e.g. that all constituents of a given material had to make up 100 % of the material). There isn’t a specific process for Pine oil, hence a similar process must be found. In this case a similar process was found in the production of rape seed oil.

To describe the remaining materials, aggregated process from the Ecoinvent database [Swiss center for LCI 2011] are used. The only production process not present in the Ecoinvent database is the production of carbon fiber from PAN. For this the aggregated the process from the PE database [PE 2011] is used.

Additional assumption was made to develop the EOL options, because no primary data were available for this phase of the life cycle, and also co-processing and pyrolysis are not yet feasible commercial solution to discard wind blades.

For pyrolysis process the assumption derives from the studies of [Pickering 2006, Cunliffe 2003, Williams]. Since no process were found for pyrolysis the amount of gas needed for heating the component (2,8 MJ/kg of composite) that is an input of the process together with the blade discarded has been calculated. As output the liquid product has the same calorific value and chemical properties of heavy fuel [Cunliffe 2003], so the liquid output from pyrolysis process could avoid the production of heavy fuel oil.

The gaseous output produced are used internally, pyrolysis gas from epoxy resin has an high calorific value since it presents an high methane content [Cunliffe 2003]. In this case it was assumed that the production of this gas avoid the production of part of the gas needed to heat the oven.

For the fibrous product that comes out from this process in the case of the glass fibers there is an insulation panel (short GF fiber+ binder); while for the carbon fiber comes out short carbon fiber. Hence the fibrous part will generate an avoided production of glass fiber mat useful to produce insulation panel for bouildings for the GFRP blade. For the CFRP and the Hybrid the fibrous result will be short carbon fiber.

For pyrolysis of GFRP the production of the binder (a modest amount of PP fiber) to link glass fiber, and the heat needed are not considered because no data were available and also the amount of binder and heat are really low.

Allocation is used for Pyrolysis of CFRP to quantify the avoided production of new carbon fiber. The allocation here is based on physical properties (EC-JRC 2010) specifically mechanical properties. Thus since there is a 20% of loss of mechanical fiber, Pyrolysis could avoid the production of 0,8 kg of new fiber when recycling 1kg of them.

For flax fiber this scenario is not considered since there will be degradation of the resin while the fibrous part creates only char. For NFRP the best and only reasonable EOL scenario is incineration.

4. Results

In this chapter all the results of the LCIA phase are presented. It includes the evaluation of the four main material scenarios, the analysis of the hybrid blade with different fiber ratio in it, a study of different EOL and a comparison between the conventional and bio-based resin. The results are obtained using the ReCiPe methodology and for the normalization and weighting step the Hierarchist perspective is used. Since in GaBi 4.4 the ReCiPe methodology has not been implemented with the right normalization and weighting factors, the results of these steps are calculated using Excel using the normalization and weighting factors present in the ReCiPe report [Goedkoop 2008].

Since the use of this study is intended for internal use in the project only a different approach, of what described in the ILCD handbook is used: results are presented firstly with the single score Ecopoint, in order to have a broader view, then as at Endpoint leveland when needed for specifically analysis as Midpoint.

4.1. Material scenario global view

Here the results of the assessment of 4 different materials for blade production are presented. Fig 4.1 shows the results using the Single Score that is the weighted sum of the 3 Endpoint (Ecosystem damage, Human health and Resource depletion). The weighting factors used, are the normalization factors of the Hierarchist perspective.

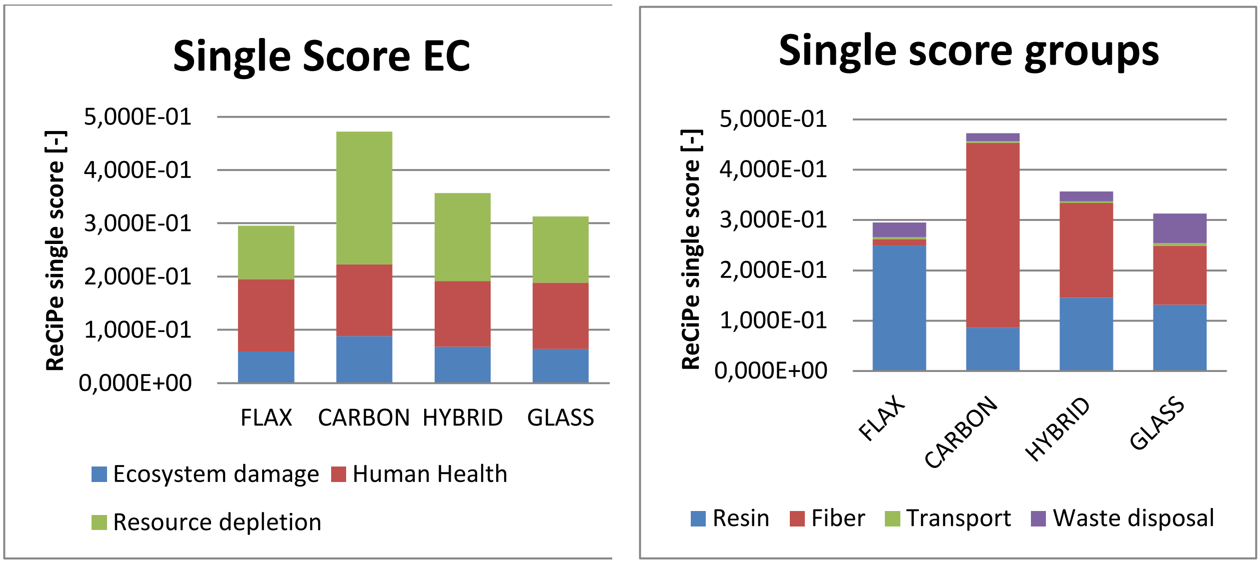


Fig 4.1 **LCIA results of the four material scenario at single score level. In the left graph show the different contribution of the Endpoint categories, after the weighting step, while at the right side the contribution of each life cycle step are presented.**

As we can see the carbon blade has the highest overall impact while the flax blade has the lowest. It is interesting to note that when the material choice changes there is a change also in the definition of the most critic life cycle steps, i.e. for the flax blade the most impacting phase is resin production, meanwhile for the carbon one is fiber production. Transport phase has a really low contribution to the overall impact, as well as waste disposal, except for glass fiber scenario which shows a sensible contribution. Since there are high uncertainties and the differences between the different scenarios are not so high, the best environmental performance can hardly be defined, but strength and weakness can be found for every scenario.

Figure 4.2 presents the results at the Endpoint level. Every midpoint has been characterized and normalized using ReCiPe Hierarchist factors and the midpoint impact categories have been grouped according to the endpoint categories to which they contribute. This type of representation allows to have a clear idea of which part of the ecosphere is contributing the most to the specific midpoint Detailed results at midpoint are presented in appendix C.

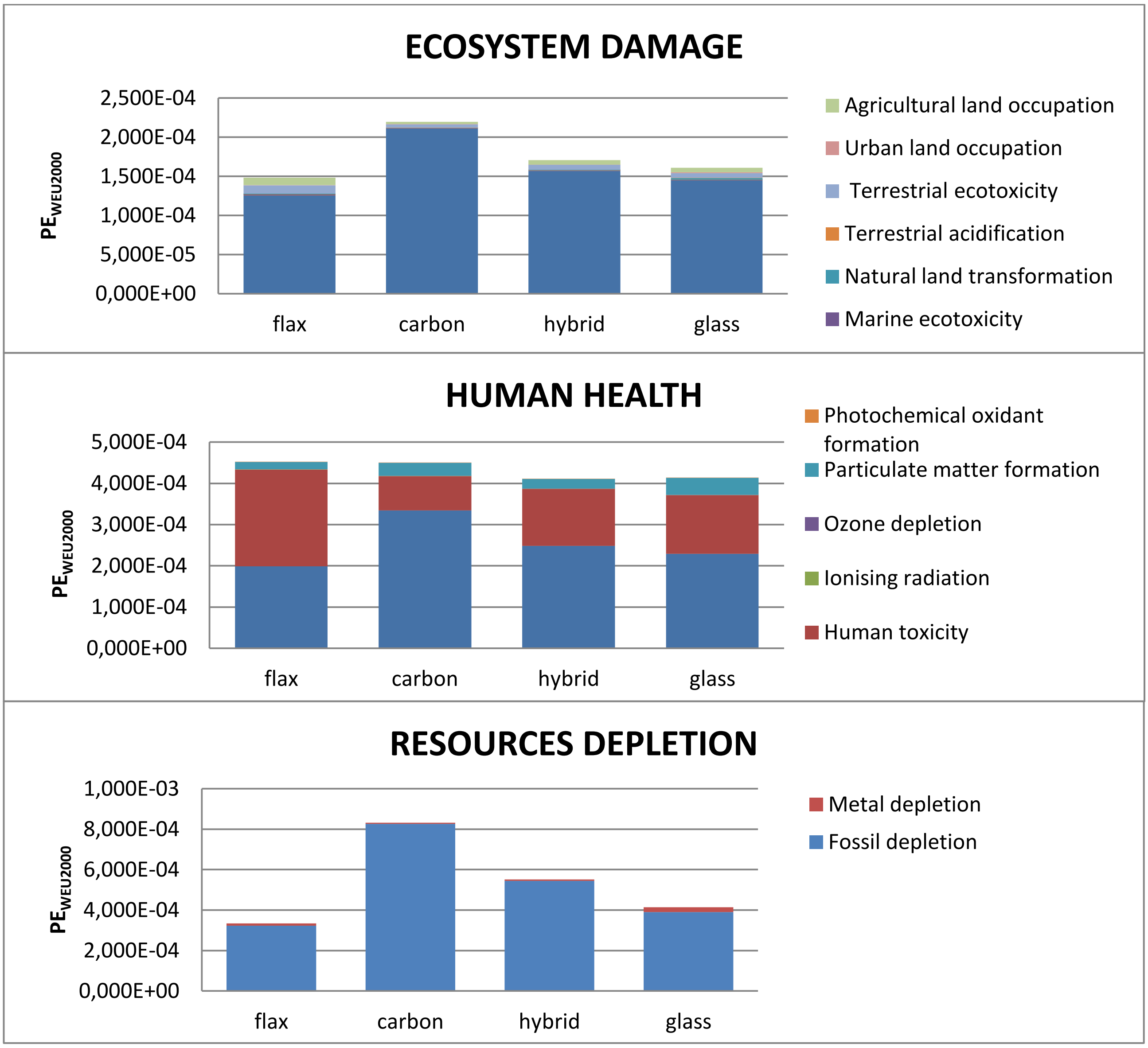


Fig 4.2 LCIA results of the four material scenario at Endpoint level. Every graph shows the contribution of the different impact categories for each endpoint damage categories (Hierarchist perspective).

Flax blade has the best performance in Ecosystem damage and Resources depletion while in Human Health it is the worst option. Carbon blade has high impact in all three Endpoint DG while the hybrid falls in the middle. Glass blade, that represents the conventional material for wind rotor blades contributes equally in the 3 Endpoint categories. Looking at the midpoint categories we can see that the highest contribution for all scenarios are: Fossil depletion (in resources), climate change (in environment and human health) and human toxicity (Human Health). Detailed explanation of these trends are presented in the next chapter.

4.1.1. Flax Blade scenario

In order to better understand the environmental behaviour of each case the analysis of the life cycle step of every materials scenario was studied. The results are presented in fig 4.3

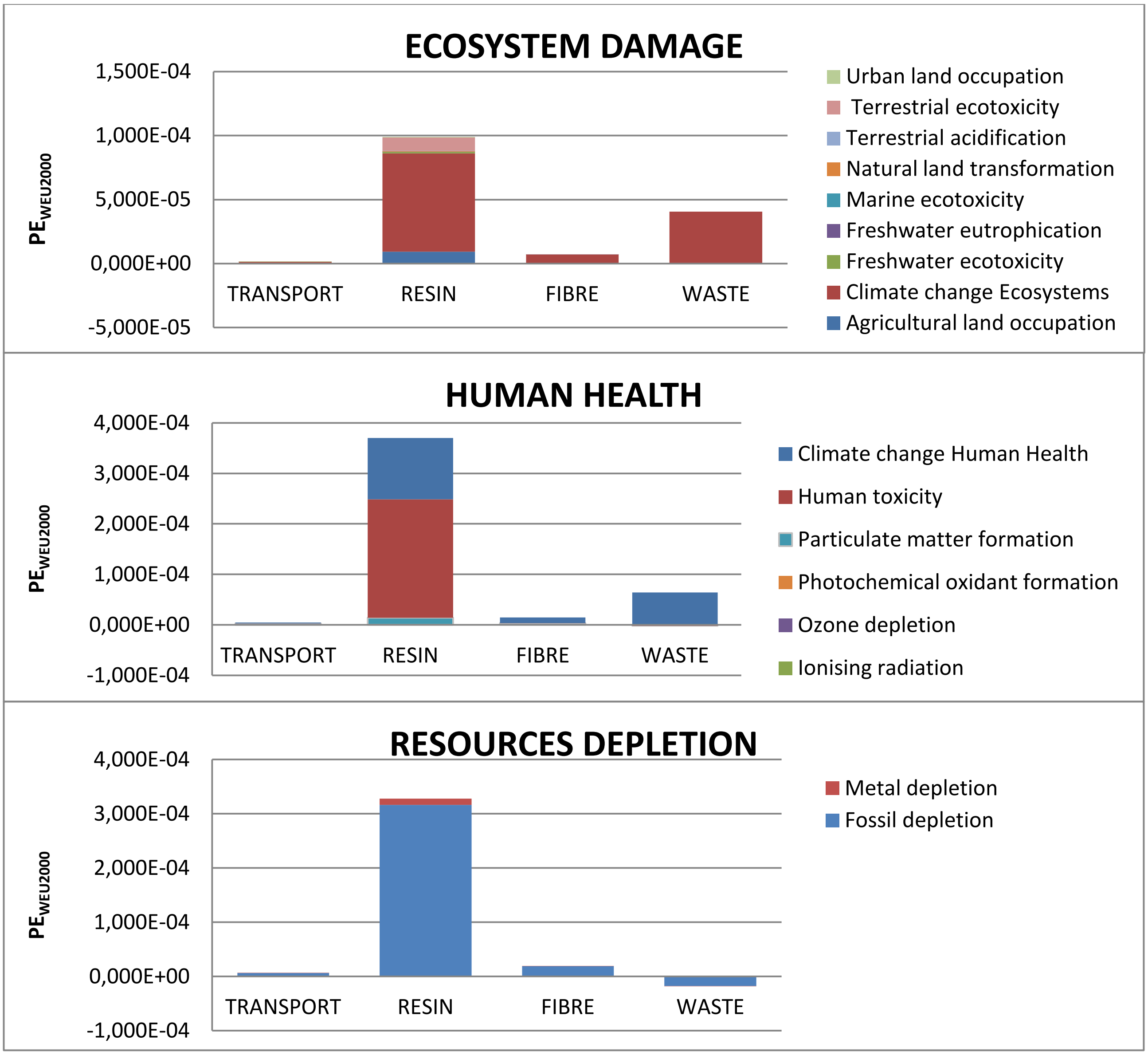


Fig 4.3 LCIA results for the flax blade at Endpoint level. Every graph shows the contribution of the different Midpoint IC for each endpoint damage categories (Hierarchist perspective).

It is clearly understandable that the critical step in the life cycle of the flax blade is resin production. It has the highest contribution in all 3 Endpoint categories, contributing at them with the followingmidpoint IC: fossil depletion, climate change (for ecosystem and for human health), human toxicity.

Regarding the disposal phase there is a positive contribution to the overall impact for Environment damage and Human Health DCs while a negative contribution for Resources depletion DC can be detected as we can recover energy in the incineration process.

4.1.2. Carbon blade scenario

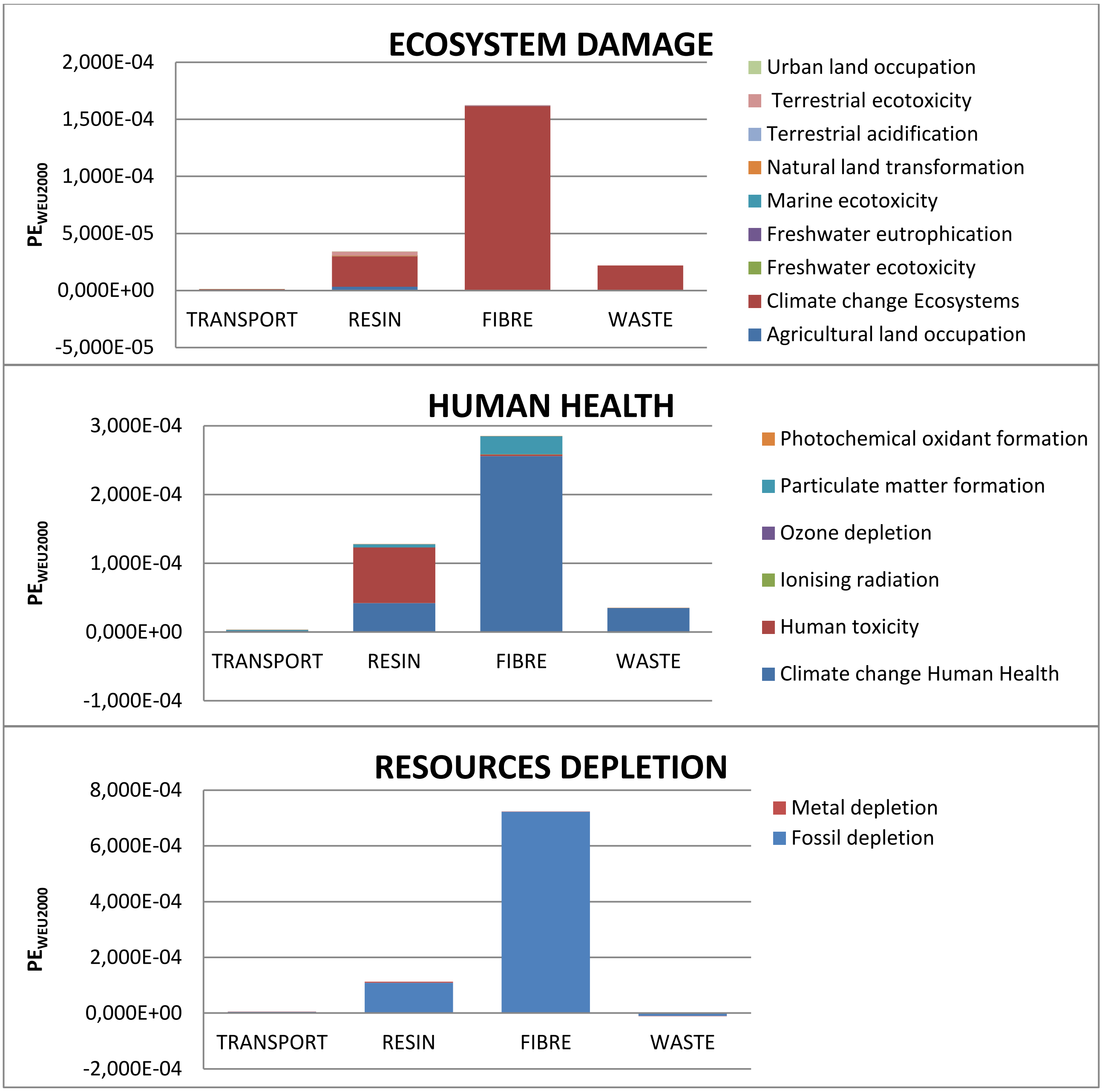


Fig 4.4 LCIA results for the carbon blade at Endpoint level. Every graph shows the contribution of the different impact categories for each endpoint damage categories (Hierarchist perspective).

In this scenario, the critical life cycle step is the production of fiber and it affects all three Endpoint categories. At midpoint level, the highest contribution in terms of impact categories is due to climate change (environmental damage and human health) and fossil depletion (resources). The contribution of resin at the overall environmental impact is lower if compared to the flax scenario. Carbon blade requires less resin for the production process and also the fibers have a really high environmental burden with respect to the natural one.

4.1.3. Hybrid blade scenario

In this case the results show an intermediate behaviour between flax and carbon blade. Fig 4.5 presents the midpoint categories grouped in the three endpoint categories.

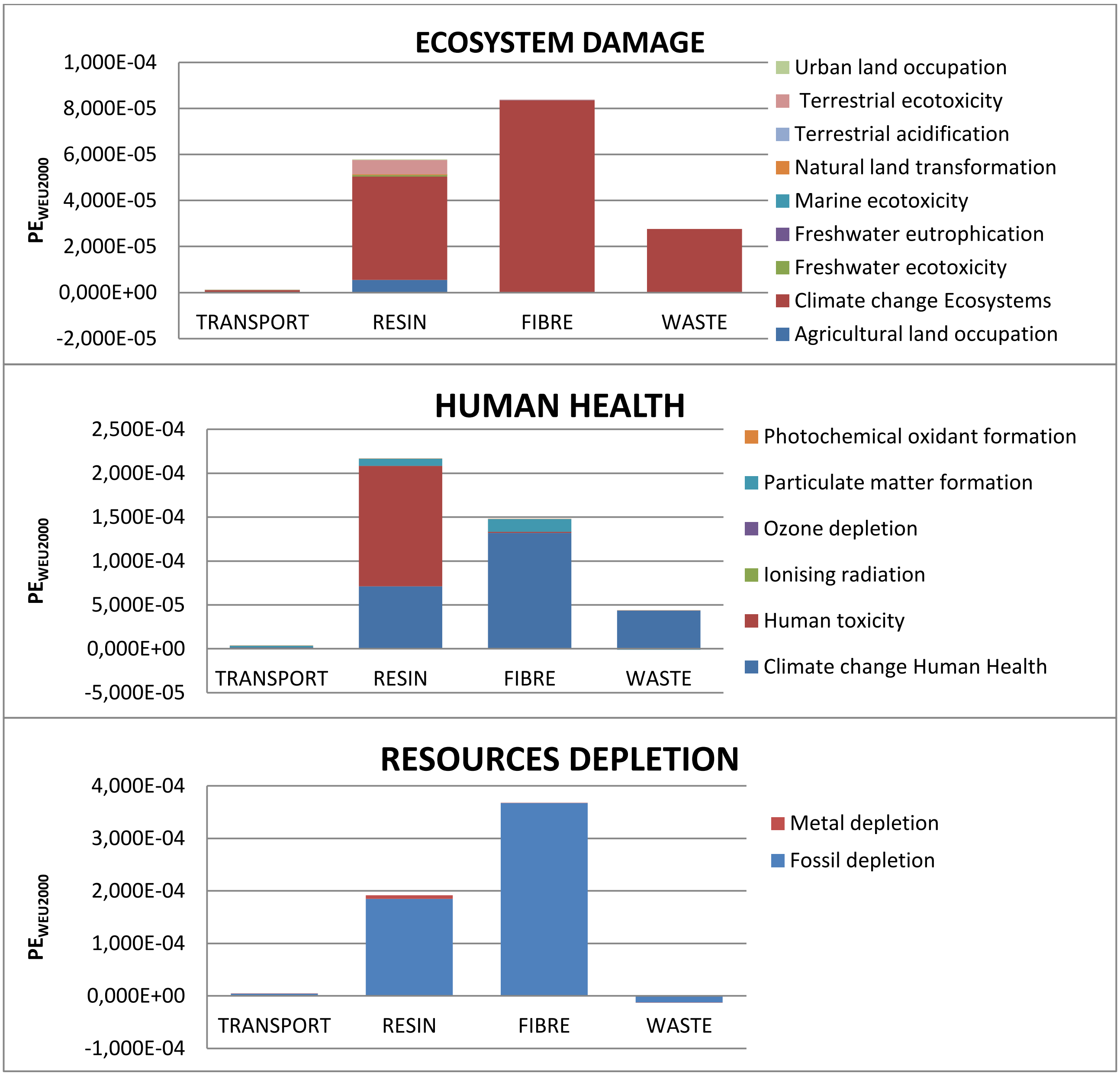


Fig 4.5 LCIA results for the hybrid blade at Endpoint level. Every graph shows the contribution of the different impact categories for each endpoint damage categories (Hierarchist perspective).

The environmental impacts in this case are a combination of the impacts created by the flax blade and the one created by the carbon blade.

4.1.4. Glass blade scenario

Figures 4.6 shows the results of the glass blade scenario at Endpoint level after the normalization step and grouping the midpoint categories at which Endpoint IC they belong.

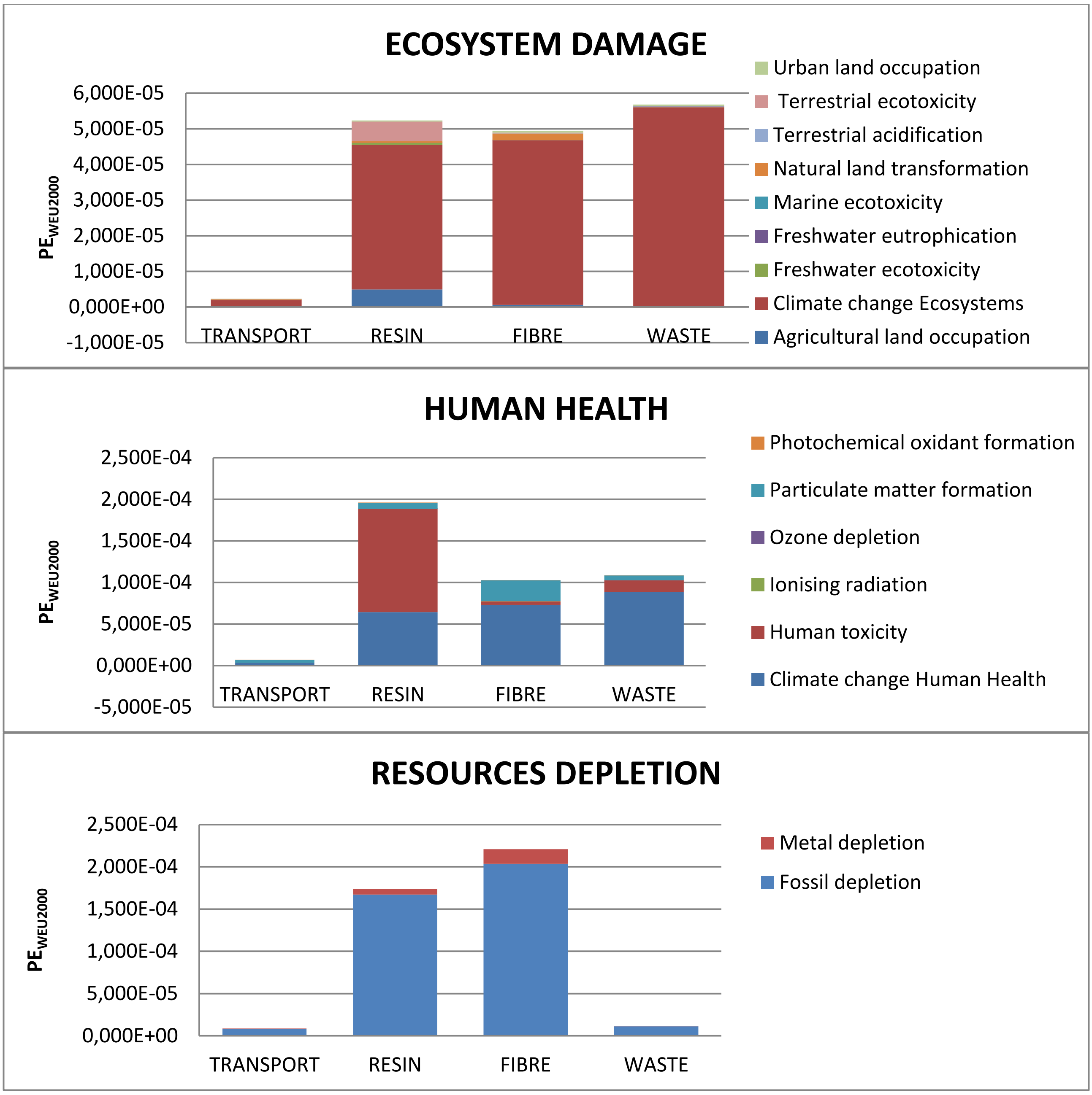


Fig 4.6 LCIA results for the glass blade at Endpoint level. Every graph shows the contribution of the different impact categories for each endpoint damage categories (Hierarchist perspective).

In this case there is not a predominant stage of the life cycle having higher impacts. Resin production, fiber production and waste disposal contribute at the majority of the overall impact of the blade. Resin and fiber production affect all three Endpoints while waste disposal affects only

Ecosystem damage and Human health.

At midpoint level the highest impact category score is due to are climate change (ecosystem, human health) and fossil depletion (resources), similar to the other scenarios. But in the fiber production there is another category having a considerable impact, which is not present in other scenarios, i.e. particulate matter formation.

It is interesting to observe that in this case there is a positive contribution of the waste disposal stage in all 3 Endpoint categories, while in the other scenarios for Resources depletion IC the contribution is negative. This fact will be explained in the next chapter.

4.2. Different amount of flax fiber in hybrid composite

One of the goals of the study was to evaluate in depth the hybrid scenario in order to detect if there is an optimal fiber's ratio from an environmental perspective. In this subchapter the results of this study are presented.

Fig 4.7 shows the results as a single score and it is possible to see how the three endpoint categories contribute at this single score after the weighting step.

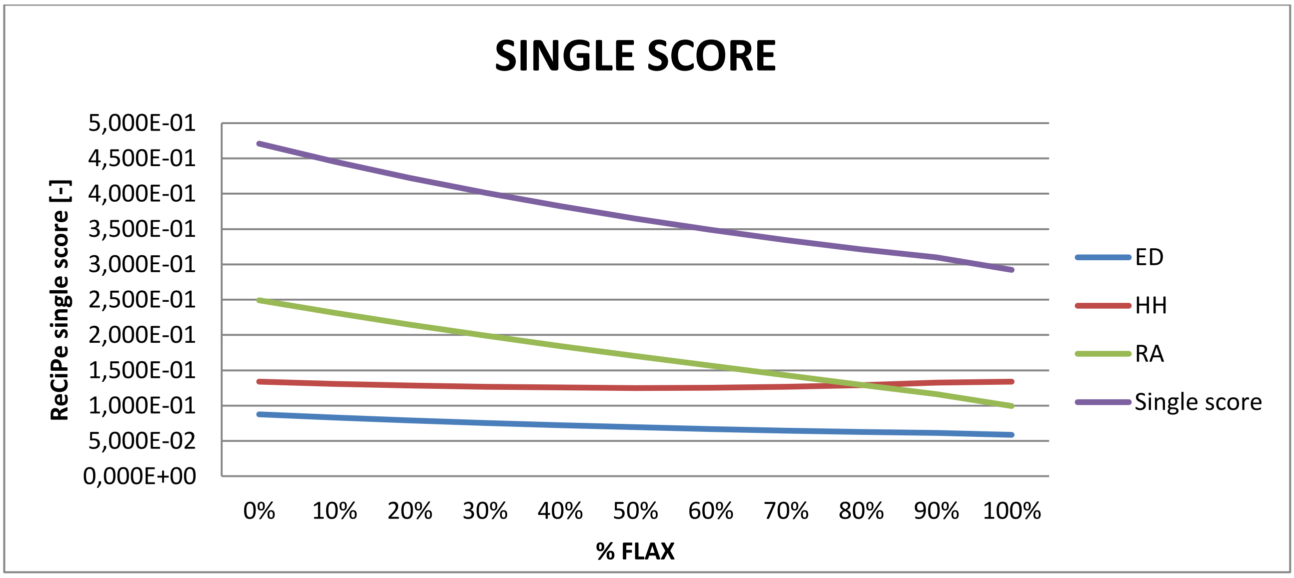


Fig 4.7 LCIA results at single score level for the hybrid blade varying the ratio between conventional and natural fiber . The graph presents the single score result and also the weighted endpoint categories that compose the single score, obtained using the Hierarchist weighting and normalization factors.

There is a non-linear decrease of the single score increasing the amount of flax fiber. If we look at the endpoint DC, i.e. fig 4.8, we can see that the Ecosystem damage shows a low reduction of the impact increasing the amount of flax fiber, mainly caused by the decrease of climate change IC. It is interesting also to observe a growth of Agricultural land occupation due to use of natural material in the blade.

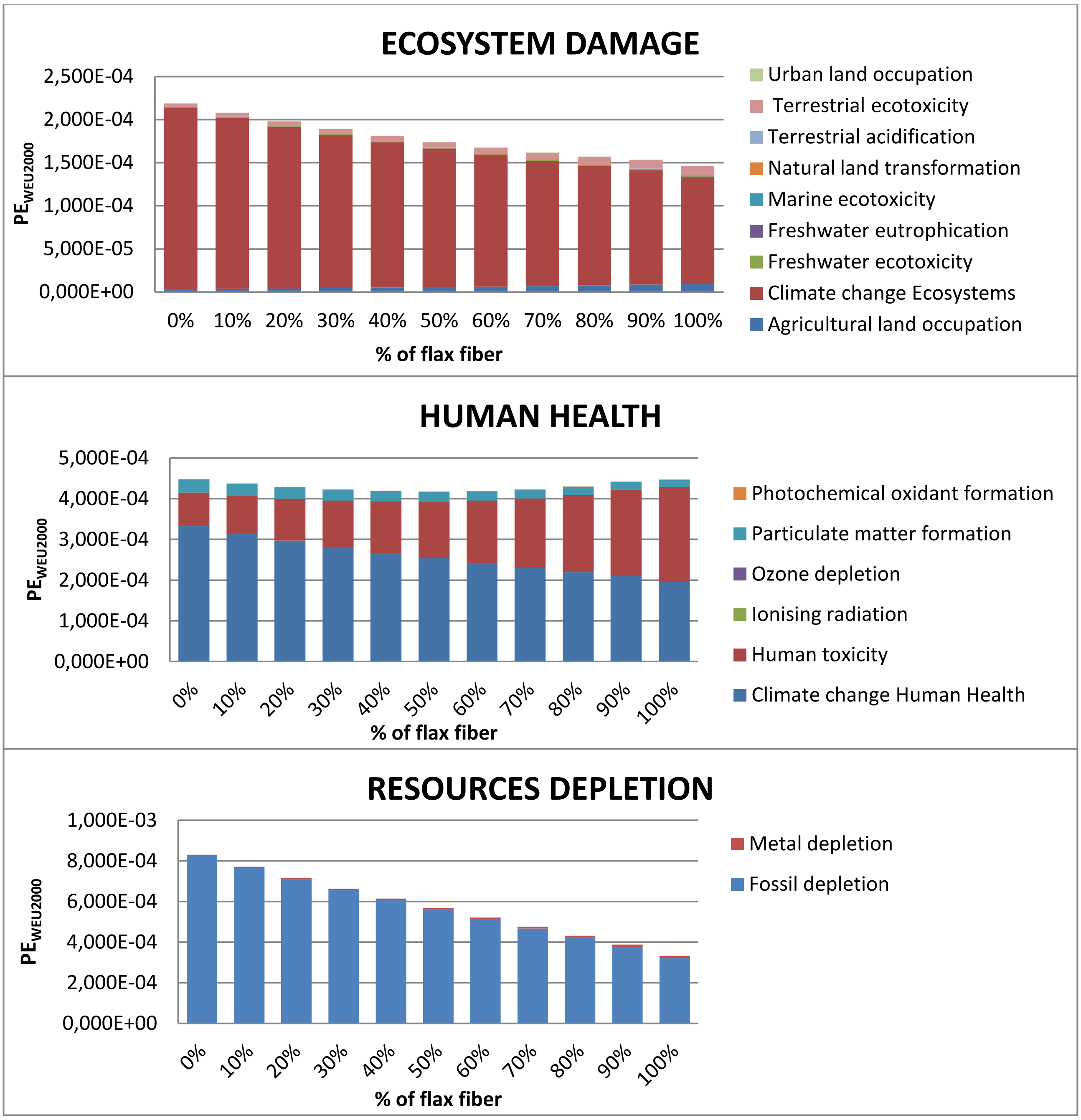


Fig 4.8 LCIA results at Endpoint level for the hybrid blade varying the ratio between conventional and natural fiber. Every graph shows the contribution of the different impact categories for each endpoint damage categories (Hierarchist perspective).

Human Health shows an interesting trend. It maintains more or less constant changing the ratio between carbon and natural fiber; but looking at the midpoint IC it is possible to observe a reduction of climate change IC (due to the decrease of carbon fiber) and an increase in human toxicity IC accordingly to an increase in the flax fiber ratio.

For resources depletion there is a high reduction due by the decrease of fossil based fibers in it.

4.3. End of life options

As explained in chapter 2 there is a strong interest in evaluating the possible end of life options both for wind blade parts and for composite materials since it is difficult to recycle them.

I decided to analyze only carbon and glass blade, because for the flax one fiber's recovery is not possible, hence incineration is the only possible and reasonable solution. Additionally there are no studies that analyze the disposal of bio-based composites. The results show only the contribution of the disposal phase, at single score level not accounting all impact created during the blade's life cycle.

4.3.1. EoL Glass blade

This scenario is interesting because shows the possible way to dispose the current blade used in energy production and also the most used composites in terms of mass production. In the case of commercial wind blades, there are more material used for blade production (e.g. paint, sandwich material, metal parts), but still the image given by this study could represent the trend but does not take into account the complexity created in the disposal stage by the use of several material.

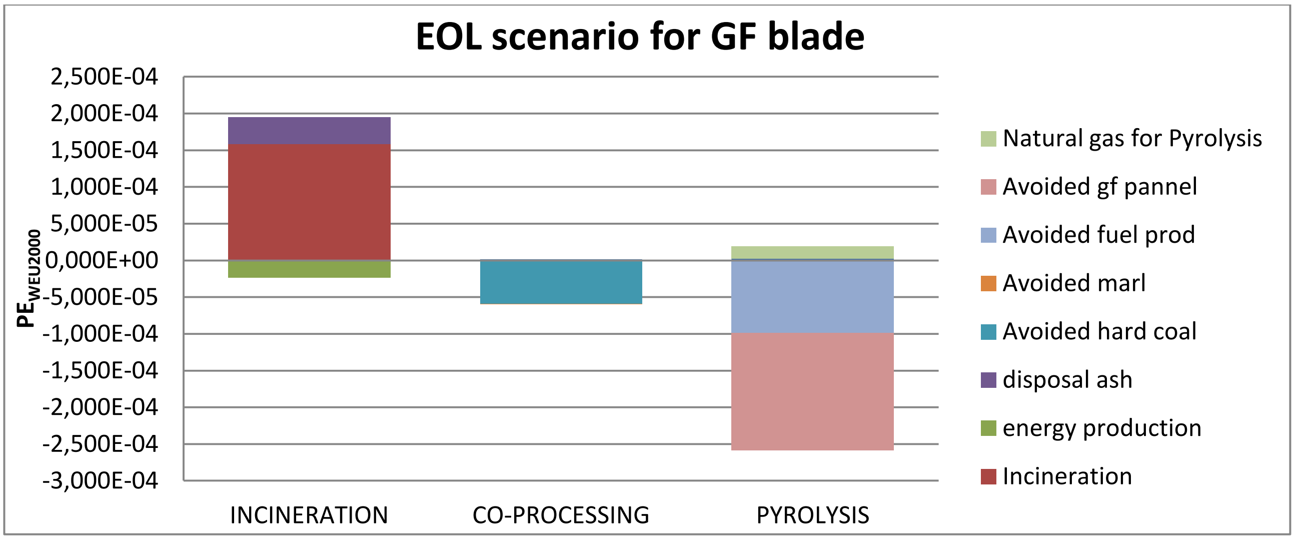


Fig 4.9 **LCIA results for the different disposal scenario for glass fiber blade. The results account only the impact of disposal stage, and are presented at Endpoint level. This graph shows also the contribution of the stage for each disposal scenario.**

The results demonstrate that incineration increases the environmental impact of the blade while co-processing in cement clinker and pyrolysis can reduce the overall impact of the blade. Detailed explanations will be given in the next chapter.

4.3.2. EoL carbon blade

The same End-of-life options are applied at the carbon blade. Unlike the glass scenario in the co-processing route it is not possible to substitute marl, as the fiber doesn't degrade and remains as a filler in the cement. Also for the incineration the ashes contributes to increase the impact because they must be landiflled. For Pyrolysis route carbon fiber could be recovered with a lower loss of mechanical properties (-20%) so they could be used, as short fiber, to reinforce again polymers.

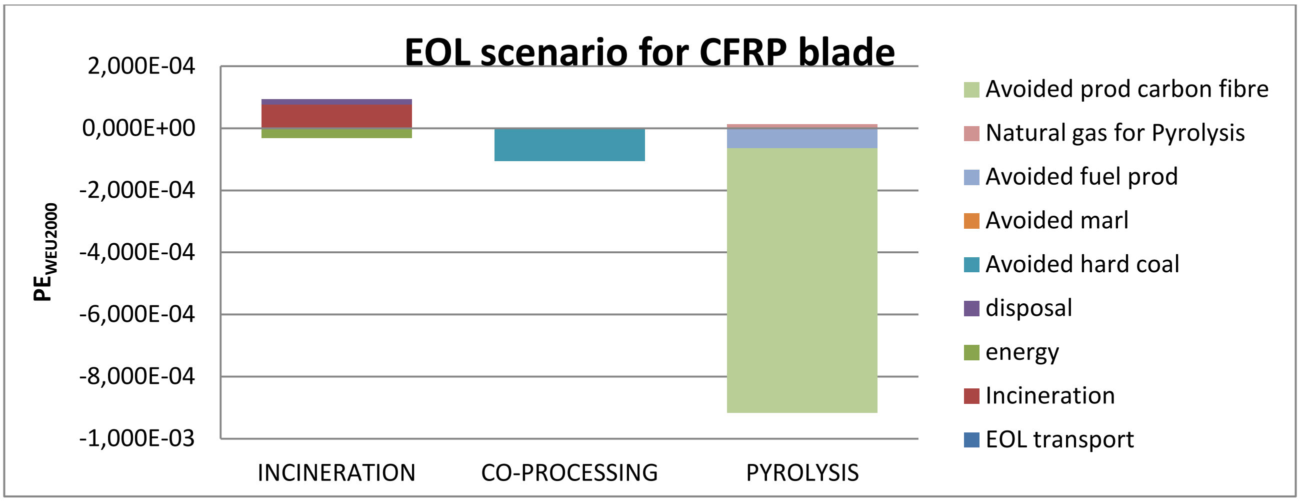


Fig 4.10 LCIA results for the different disposal scenario for glass fiber blade. The results account only the impact of disposal stage, and are presented at Endpoint level. This graph shows also the contribution of the stage for each disposal scenario.

Avoiding the production of carbon fiber can represent an huge improvement in the overall environmental impact of the blade. As described in chapter 2, indeed, carbon fiber production is high energy intensive and all the raw material are petrol-based. In the incineration scenario there is lower energy production but also lower emission with respect tothe glass blade. This is because carbon blade is lighter than the glass one. The same behaviour is found in the co-processing route.

4.4. Resin evaluation

As it is possible to see from the previous results not necessarilybio-based materials performs better than the traditional ones in term of environmental impacts, therefore a study of the resin was done. In this case using the worst scenario in terms of resin used (flax blade) a conventional and the bio-based resin are evaluated. The results are present as a $\Delta IC = IC_{BIOBASED} - IC_{CONVENTIONAL}$. In this case the results are presented at Endpoint level. We can observe a strong reduction of the resources depletion using the bio-based resin, while for the other two Endpoint IC we have a slightly positive increase.

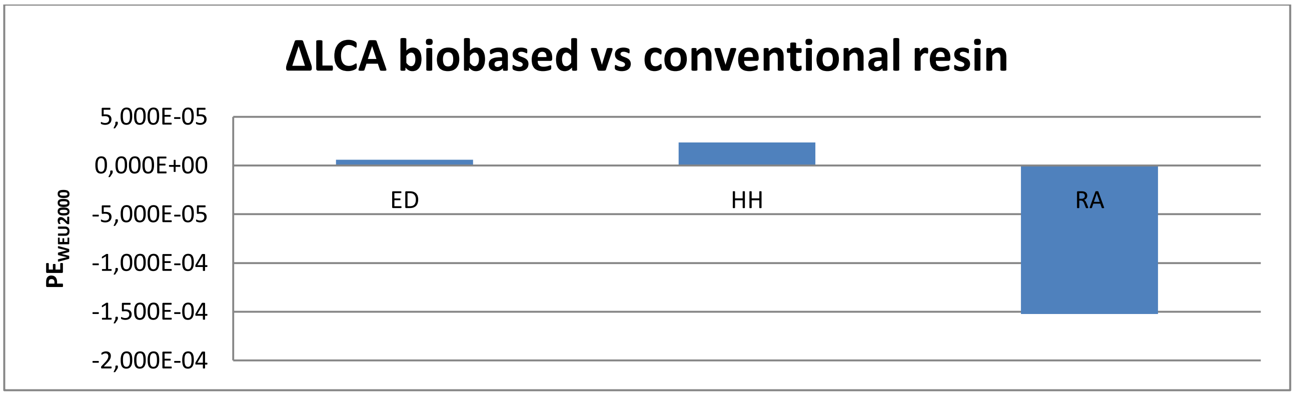


Fig 4.11 ΔLCIA results. The graph show the difference for every Endpoint between the use of biobased resin respect of the conventional one for flax blade scenario.

5. Discussion

This discussion chapter focuses on the results obtained with the model and presented in the previous chapter.

5.1. LCIA of different materials: global view

As we can see from fig 4.1 the best environmental scenario is the flax blade, while the worst is the carbon and hybrid and glass ones are in between.

Carbon blade has the worst performance in the Resources Endpoint DC (i.e. the availability of non renewable resources such as fossil fuels and metals) due mainly to the production process of the fiber. Carbon scenario has the highest impact, at endpoint level, also in Ecosystem damage; while for Human Health DC the four different materials have a similar performance.

For flax blade the most burdensome life cycle stage is resin production, while for carbon and the hybrid blade is the fiber production. In the glass scenario the main contributions are resin and fiber production, but also the waste disposal stage is higher compared to the other materials.

Fig 4.2 shows the results at Endpoint level. For every scenario it is possible to see the different contribution of the midpoint categories to the Endpoint IC which they belong to. Hence, every graph shows the different impact categories (Midpoint) that impact on different areas of protection (Endpoint), i.e. Ecosystem damage, Human health and Resources Depletion.

Looking at the impact on the environment, the main midpoint IC for all the different materials is climate change. For Human Health we have both climate change and human toxicity. It is interesting to note that this last impact category reflects the amount of resin required for the infusion; so we can argue that the most important burden for Human toxicity is achieved by the resin because its productionrequires the use of a lot of harmful chemicals

5.1.1. LCIA results: flax blade

In this subchapter the LCIA results on the flax blade and its life cycle stages are discussed.

As we can see from fig 4.3 the majority of the impacts in this scenario are in the resin production. This is because flax fiber has the lowest volume fraction, so the amount of resin required to produce this blade is much higher with respect to the others (263g for NFRP, while 91g for CFRP and 139g for GFRP). Some impacts are also created by the waste disposal stage, due to emission in the incineration plant. In this case there are positive contribution at the environmental impact for 2 Endpoint categories: Environmental damage, Human health, while the third Impact category has a negative score, i.e. contributes to lower the overall impact of the blade. This negative impact is achieved because electricity is produced incinerating the blade, and this affect mainly this third endpoint IC. Fibers instead present a really low impact, since they are a natural product and the production and manufacturing process is relatively simple and doesn’t involve high amount of chemical substances or energy as for other fibers type. This fact explains also why this blade has the best environmental performance in a global view even if it has high impact on human health.

Looking at the different contribution at the three endpoint DC we can see that the highest Midpoint IC is climate change that affects both environment and human health. Another important contribution is Human toxicity derived entirely from the resin production. This is caused by the large use of chemical in the manufacture of the resin. Additionally this affects also other toxicity IC e.g. terrestrial Ecotoxicity. This fact explains why flax scenario has the higher contribution for Human Health EC.

Another important IC is fossil fuel depletion. As explained before, it comes mainly from the production of the resin (due to the high amount in the composite and because this scenario is using natural fiber that has really low fossil fuel needs). The value of this impact category will be anyway lower respect on the other scenario.

5.1.2. LCIA results: carbon blade

In this scenario the highest impact is caused by the production of fiber. This is clearly understandable looking at the production process of the carbon fiber where a lot of energy is required and the raw material needed to produce it are petrol-based.

The impact of the resin is lower if compared to the flax blade because the volume fraction of CFRP is much higher; hence less resin is required to produce the composite. Also in this case the highest midpoint categories are Climate Change (for environment and human health) and Fossil Depletion. Human Toxicity is lower with respect to flax blade because less resin is used.

Additionally it is interesting to note that the disposal stage has lower impact. Carbon fiber is lighter so there will be lower emission in the incineration step but also a lower energy production. Additionally land filling ashes of carbon fiber increase the overall impact while in the previous scenario all the composite is burned producing much less ashes, but it has a lower magnitude respect on the emission of the incineration.

5.1.3. LCIA results: hybrid blade

Looking at fig 4.5 it is clear that an hybrid blade will have an intermediate performance between the two materials of which it is composed. The flax part helps to reduce impact on Ecosystem and Resource, while the carbon part, which has lower resin uptake, reduces impact on Human Health.

5.1.4. LCIA results: glass blade

This scenario has slightly higher results than the flax one at single score level. But since the uncertainties are high it is not possible to argue that the flax blade performs better, it is only possible to say that they have similar environmental impacts on a single score level.

Looking at the Midpoints impact categories, in this scenario there are 3 main life cycle steps that have the major contribution: resin, fiber, waste. The first two have high contribution in all 3 endpoint categories, while the last has high contribution only in Ecosystem damage and human health DC.

For Resources depletion DC, as opposite to the other scenarios, there is a positive effect on the global impact of the blade. In this case only the matrix part can be burned (around 28% in mass) so energy production is considerably lower than other scenarios and doesn't counterbalance the resources depletion of the emission in incineration process. In the case of the carbon blade this trend is not present, because the mass fraction of the matrix part is higher (37%) so the impact avoided at this Endpoint from electricity production are higher than the impact created by the incineration process.

5.2. Different amount of flax fibers in hybrid blade

Currently there is an increasing interest in the use of natural material in combination with more traditional and performing materials. The mechanical properties of natural fiber materials are not so high although they are good in terms of density and lower environmental impact for their production.

About flax fibers, they don't perform really well in terms of strength. So mixing them with high performance material (i.e. carbon) could create a hybrid composite material that combines the positive effect of the natural fiber with the high strength properties of carbon fiber.

his is the case of the hybrid blade scenario. The blade was designed to have the same amount (in weight) of carbon and flax fiber.

In this thesis work after assessing the 50/50 hybrid another research question arose: "How is the environmental performance of the hybrid blade changing the ratio between the two fibers?"

A mechanical model was set up to find the weight of the material needed to fulfill the design requirements and it is presented in chapter 3.1. Then, with these data 11 different scenarios (one of every 10% of more flax fiber in mass) has been analyzed in the product system model.

The results are shown in fig 4.7. In the first graph the results are presented as a single score using the Hierarchical perspective and weighting factor.

As it can be seen the correlation between the different fiber's ratio and the single score environmental performance is not linear. Increasing the amount of flax fiber imply a general decrease of the single score, i.e. a better global environmental performance. This is caused mainly by the strong decrease in the Resources Depletion Endpoint IC that is, even after the weighting step, the highest endpoint impact category, since this Endpoint is controlled by the production of the carbon fibers. The other two Endpoint DCs don't show big changes.

Looking at the different midpoint impact categories (fig 4.8), they are grouped after the characterization and normalization step, using the Hierarchist perspective in 3 main Endpoint categories that will compose the single score after weighting step.

In the first graph, that includes all the impact on the ecosystem, there is a general increase in the environmental performance increasing the amount of flax fiber. This is mainly caused by the decrease in Climate Change IC (this IC after the normalization step contributes both in the environmental damage and human health) due to the use of a natural fiber.

Climate change is the most relevant IC and it is mainly correlated with the production of carbon fiber. Climate change IC is related with the production of greenhouse gases (GHG) hence the production process of carbon fiber that requires high temperatures for the carbonization will have a high effect on this IC. But the trend is not linear (as the decrease in mass of the carbon fiber) because some other parts of the life cycle affect this IC (e.g. the resin, transport, ecc). Another, less important, trend can be seen in the natural land transformation IC. This IC shows an increase in the score according to an increase of the amount of flax fiber, because increasing the use of a natural fiber will require more land for growing this plant.

On Human Health endpoint IC it is possible to observe a different trend. The hybrid composite shows a minimum around the 50% of flax fiber in the composite. Increasing the amount of natural fiber implies a decrease in climate change, as explained before. But this increased amount of flax fiber will require a higher amount of resin to produce the blade (since the volume fraction of NFRP is lower that the CFRP), that affects the human toxicity IC because is mainly related to the resin production.

Looking at the third Endpoint IC, resources depletion, we can see a clear image: there is a strong decrease of the impact as long as the flax fiber is increasing. As shown in the graph this is caused by the strong decrease in Fossil depletion IC because we are replacing a fossil based fiber with a natural one.

5.3. End of life scenario

As discussed in chapter 2.4 the end of life of wind blade is currently a challenge due to the recycling regulation and the difficulty in recycling of thermoset materials.

In this thesis 3 different End-of-Life scenarios are evaluated. For every material's type there are different outputs from the recycling process and different environmental impacts. The flax scenario was not included because it is not possible to recover the fiber, so the best and only reasonable way to recycle it is incineration with energy recovery.

5.3.1. End of life scenario glass blade

The glass blade scenario was firstly analysed as it is the most relevant for the current wind industry since the majority of the actual wind blades are made by GFRP. Additionally, GFRP composites have major problem respect on the others because the fiber aren't organic so if incinerated they won't burn.

In fig 4.9 the results are expressed showing the different contribution of the life cycle stages for the single score. It is possible to observe that incineration is the only one that has no positive effect on an environmental perspective. This is because the incineration of GFRP doesn't produces a lot of energy. Only about 38% of the material is burnable, the rest is glass fiber that is fireproof; hence the emission of incinerating a GFRP blade are higher respect on the energy output if compared to other scenario where both fiber and resin are burnable.

In the co-processing route process the blade is used as a fuel and instead of landfill the unburned part (mainly glass fiber) they are used in substitution of the marl. The environmental assessment shows that the main contribution is done by the avoided use of fossil fuel while the avoided extraction of marl gives a minor contribution.

In the case of the pyrolysis process, the GFRP blade gives as output fuel from the organic part and an insulation panel from the reinforcement; while the gaseous product are used internally and contributes to lower the amount of natural gas needed to heat the pyrolysis oven.

This results show a huge potential decrease in the environmental impact of the blade. Using pyrolysis is it possible to reduce the total impact of 42% and using the co-processing in the cement clinker the impact can be lowered up to 24%. However these results are not precise, the positive effect are overstimed, due to the uncertainties and to the several assumptions used to create the pyrolysis process

5.3.2. End of life scenario carbon blade

It is interesting to evaluate this scenario because since carbon fiber are expensive, and highly environmental burdensome there is the willing to find a way to recycle them.

Looking at fig 4.10 it is possible to observe that incineration route, even in this case, contributes to increase the overall impact of the blade. But the environmental burden of this recycling option is lower compared to the incineration of glass fiber for two main reasons:

- Blade mass is considerably lower than the glass blade. This implies that there are lower emissions in the incineration step since less material is burned.
- The resin's mass fraction (37%) is higher than the glass blade fraction (28%), so the avoided impact from the electricity output will be higher than the impact created by the incineration, especially for Resources Depletion Endpoint IC.

Co-processing the blade in this case contributes to lower the overall emission of the blade. But even in this case no fiber recycling is possible. Additionally there will be the problem of the residues ashes of carbon fiber, since no information was found about its compatibility in the clinker compound (not accounted in this study).

With the pyrolysis process, in this case, is possible to recover fiber with a lower loss of mechanical properties. It allows using them again to reinforce polymers. The picture given by this scenario shows clearly the huge positive effect in decreasing the impact of the blade by recycling the fiber, since the highest emission for carbon blade are done by the fiber production.

5.4.Different resin

In order to evaluate also if the biobased resin performs better in terms of environmental sustainability than the traditional one a comparison between the two is also made. A common scenario is chosen, in order to have the same reference. Furthermore, in order to analyze the most critic case regarding the use of resin, the selected blade is the flax one.

As you can see there is a high decrease in the resources consumption. This is clearly the scope of a Bio-based resin where part of the chemical derived from fossil resources are substituted by chemicals derived by natural materials (in this case pine oil). This fact gives a decrease in the Resources Depletion IC of -31% if referred to the contribution of the single resin and -14% considering the entire flax blade.

But at the same time there is an increase in the other two damage categories. For Human Health the increase is +6,8% on the total impact of the resin and +3,3% on the flax blade. The Environmental IC shows an increase of +6,4% on the total impact of the resin and +2% on the total blade.

In the following table the change from conventional to biobased resin has been analyzed for every impact category. Considering these results, it is possible to justify the results shown in tab 5.1.

For Ecosystem Damage EC the 2 main negative contributions are agricultural land occupation IC and terrestrial Ecotoxicity IC. They are mainly due by the need of agricultural land for the production of pine oil. The principal positive effect is in climate change IC as the use of a bio-based resin decreases the use of fossil and consequently the is a decrease in the generation of GHG gases.

For Human Health EC there is a high increase of the Human Toxicity IC caused by the increase of chemical treatment occurred to prepare the resin. But this increase is compensatedby the decrease in Particulate Matter Formation IC. As expected for Resource Depletion EC the improvement is totally obtained by the less consumption of fossil fuels, which is the main goal for a Bio-based product.

Endpoint IC	Impact Category	% Impact on Resin	% Impact on total blade
Environmental Damage	- Agricultural land occupation	9,6%	3,0%
	- Climate change Ecosystems	-8,1%	-2,5%
	- Freshwater ecotoxicity	0,4%	0,1%
	- Freshwater eutrophication	0,0%	0,0%
	- Marine ecotoxicity	0,0%	0,0%
	- Natural land transformation	0,5%	0,1%
	- Terrestrial acidification	-0,2%	-0,1%
	- Terrestrial ecotoxicity	3,9%	1,2%
	- Urban land occupation	0,3%	0,1%
Human Health	- Climate change Human Health	-3,4%	-1,7%
	- Human toxicity	23,5%	11,4%
	- Ionising radiation	0,0%	0,0%
	- Ozone depletion	0,0%	0,0%
	- Particulate matter formation	-13,2%	-6,5%
	- Photochemical oxidant formation	0,0%	0,0%
Resources Depletion	- Metal depletion	1,2%	0,5%
	- Fossil depletion	-32,9%	-14,6%

Tab 5.1 Variation of the midpoint categories using biobased resin instead of conventional one. In the third column the difference is calculated on the total impact of the resin, while in the forth on the total impact of the blade.

6. CONCLUSION

This chapter focuses on the strong and weak points of this thesis project. Furthermore, when possible, the best solution in terms of environmental sustainability of the various topics studied is presented.

The uncertainties in the results are quite high, due to the many assumptions made to develop the model. Furthermore, the differences in some scenarios are not so high, hence it is not possible to define the best environmental solution, but it is possible to find trends on environmental behaviour of the materials studied.

6.1.Materials

As explained in chapter 5 the differences at single score level are not so high to identify which material performs better on an overall view. This is especially because in order to have a single value that expresses all the impact created by the product more uncertainties are added. But it is possible to identify that for every material there is a different behaviour, i.e. different critic life cycle step or different impact on the damage category.

Flax scenario demonstrates high impact at the human health caused by the larger amount of resin needed in this scenario. While it has low contributes at resource and environmental damage. It can be concluded that despite this is a natural material, it doesn't perform, for now, better than the conventional material, i.e. GFRP. This could be contra intuitive, but taking a wider perspective, as provided by the use of LCA methodology, and not focusing only on the resource depletion (where natural composite clearly performs better) we can identify a sort of problem shifting from resources depletion to human health. So, according to the presented results there is no sense to substitute GRFP with NFRP in this type of applications. But if the study and knowledge about natural fibers will increase in the future finding solutions that increase fiber's volume fraction in the composite, there will be a strong advantage in the use of NFRP. Furthermore, decreasing the amount of resin imply that also the mechanical properties (evaluated with micromechanical model) will increase doubling the advantage in the use of this material.

Carbon scenario has instead high impact at the Ecosystem and at Resources level, by the carbon fiber production phase. But the properties of this material are so high that there is no sense for the substitution of this composite with a biobased one. Especially thanks to its high mechanical properties carbon composites has the lowest weight, this fact could help to lower emission in other different products, for example in the transport or use phase.

The hybrid scenario shows a good compromise. CFRP helps to improve the mechanical properties of the product (making it lighter), while NFRP helps to reduce the overall environmental impact of the product. There is also another interesting issue: in the case of product where high flexural stiffness is required, the hybrid composite could be designed with a sandwich structure. Using NFRP as the core part (because their low density), while CFRP in the external part creates a composite with high flexural stiffness. This could also help to prevent buckling in shell structures.

Regarding the resin this study demonstrates a better environmental performance for the bio-based resin. But due the numerous assumptions a full LCA study would be needed to confirm this result. In order to obtain inventory data enabling a full LCA, exact data of epoxy production and composition hereof as well full inventory data sets on the vegetable oil feedstock would be needed. This would however imply that the epoxy producer would have to reveal confidential information.

6.2.Models

The models used in this study seem to be appropriate. The mechanical model used shows small errors although it could be used only to investigate product's mass changing the material used. It doesn't give any information about the mechanical design (for example information about layer orientation, failure criteria, etc.), thus it could be used in an early stage of the design of a product to investigate which material to use.

Furthermore Ashby's methodology could show in which case natural materials perform better than the glass composite, exploiting their lower density.

In this project the blade was assumed to act as a beam. Ashby's material index, for beam in flexion, is $I=E^{0,5}/\rho$. Hence in this case NFRP will weight 9% less than the GFRP (value obtained dividing the material's index of the two material). If we consider instead another mechanical behaviour, like a panel in bending, Ashby's index is $I= E^{0,33}/\rho$. Hence in this case the natural composite will be 24% lighter than the GFRP, which means lower environmental impact. A demonstration of this reduction is shown in the article of Corbièrre-Nicollier [Corbièrre-Nicollier et al 2001].

This observation could address where to focus in future studies about natural material in rotor blades application: a partial substitution in the shell of big commercial blade. Part of this study has already been started in this thesis project but, due to lack of time the results are not presented in this report. However a description of the project scheme is presented in Appendix E.

6.3.End of life options

The results of this study show that there will be a strong decrease on the environmental impact moving from incineration to co-processing or pyrolysis. However, the image given is too optimistic, because of the several assumptions made to create the model due to a lack of information and data from existing recycling plant For example the Eol options don't consider the cutting process, that could be high energy intensive. Additionally since we are dealing with material with low density it would be interesting to refine the model evaluating the transport phase for disposal stage not in terms of mass but in volume. Furthermore since there is no information about the Pyrolysis process, the model for this EoL option assess only the theoretical energy required for the process and the output given. No information were found about emission, efficiency for this option, hence the results gives an unrealistic view.

For GFRP the best solution seems to be pyrolysis. But including an economical evaluation and taking into account the uncertainties of the results the difference between co-processing and pyrolysis wouldn't not be so high. Additionally recycling glass fiber is not as interesting as recycling carbon fiber. Especially because glass fibers are heavily degraded by the process, they lose their sizing and 50% of mechanical properties. So, in fact this process could be defined as "downcycling". Hence co-processing GFRP could be more attractive than Pyrolysis.

In the case of CFRP there is a strong interest to recycle the fiber, thanks to their high price and high impact for the production. Hence pyrolysis in this case emerged as the best option, considering also that no information about the behaviour of CF as a filler in cement are available (it could lower the mechanical properties). The problem for pyrolysis would be instead that the amount of CFRP disposed is really low to the needs of a commercial recycling center.

For NFRP as explained in the discussion chapter the best recycling option at the moment would be incineration with energy recover so that also the fiber could be used to produce energy. Further work on the recycling of NFRP could be done studying the use of biodegradable resin so all the composite could be composted [Baley 2012].

7. Paper for 34th Risø Interational Symposium on Material Science

As an output of this project a scientific paper has been prepared. It will be presented at the 34th international symposium on material science which will be held in September 2013 at Risø campus in Roskilde. In this conference some of the results of the present study will be presented, especially about the hybrid blade scenario. The results are evauated using airplane as raw material transport,. It interesting to note how the results changes switching the transport from a “low emission” transport mean (ship) to a “intensive emission” as airplane. This could explain one of the weakest point of LCA, i.e. the variability of the results while hanging the parameter in the model especially in the case of low difference between the scenarios assessed. The paper is attached in the following pages.

SELECTION OF ENVIRONMENTAL SUSTAINABLE FIBER MATERIALS FOR WIND TURBINE BLADES - A CONTRA INTUITIVE PROCESS?

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ABSTRACT

Over the recent decades biomaterials have been marketed successfully supported by the common perception that biomaterials and environmental sustainability de facto represents two sides of the same coin. The development of sustainable composite materials such as blades for small-scale wind turbines have thus partially been focused on the substitution of conventional fiber materials with bio-fibers. The major question is if this material substitution actually, is environmental sustainable. In order to assess a wide pallet of environmental impacts and taking into account positive and negative environmental trade-offs over the entire life-span of composite materials, life cycle assessment (LCA) can be applied. In the case study 4 different types of fibers and fiber mixtures (carbon, glass, flax and a carbon/flax mixed fibers) are compared in terms of environmental sustainability and cost. Applying one of the most recent life cycle impact assessment methods, it is demonstrated that the environmental sustainability of the mixed fibers based composite material is better than that of the flax fibers. This observation may be contra-intuitive, but is mainly caused by the fact that the bio-material resin demand is by far exceeding the resin demand of the conventional fibers such as carbon and glass fibers, and since the environmental burden of the resin is comparable to that of the fibers, resin demand is in terms of environmental sustainability important. On the other hand is the energy demand and associated environmental impacts in relation to the production of the carbon and glass fibers, considerable compared to the impacts resulting from resin production. The ideal fiber solution, in terms of environmental sustainability, is *hence* the fiber composition having the lowest resin demand and lowest overall energy demand. The optimum environmental solution hence turns out to be a 70:30 flax:carbon mix, thereby minimizing the use of carbon fibers and resin. On top of the environmental sustainability assessment a cost assessment of the four fiber solution was carried out. The results of the economical assessment which turns out to

not complement the environmental sustainability, pin-point that glass fibers are the most effective fiber material.

INTRODUCTION

The purpose of the present case study is to perform a screening LCA facilitating benchmarking of 4 different wind turbine blade types, with the aim of illuminating the environmental sustainability performance of bio-composites such as flax based composites and bio-based resin relative to conventional composites such as carbon and glass fibre epoxy based composites.

The dominating industrial and scientific focus on bio-based composite materials (Mussig 2010) (Pickering 2008) (Mohanty, Misra, Lawrence 2005) are mainly concerned with the technical performance of the materials, but the sustainability of these new materials needs to be addressed as well. The study at hand addresses the environmental issues by presenting the results of a quantitative comparative sustainability assessment of four prototype small-scale wind turbine blades differing only in type and amount of fibre reinforcement material, i.e. conventional and bio-based and/or in the type of resin, a conventional epoxy resin and a bio-based epoxy resin. All blades were designed for being used in a wind turbine car concept (Gaunaa Øye Mikkelsen 2009).

Quite a number of LCAs on wind power technology have been published over the last two decades. LCAs of wind power technologies found in the existing literature most often focuses on the comparison of the environmental burdens of different life cycle stages of a wind turbines and/or comparison of complete turbines of various sizes (Davidsson, Höök, Wall 2012). Many of these studies highlight the fact that blades are one of the most environmental burdensome parts of a wind turbine. Still LCAs on wind blades are rare.

A few publications involving comparative LCAs of various windmill blade types or bio-based composites for wind blades have been identified. One of the most recent publications addressing LCA of materials for windmill blades focuses on the application of nano-carbon for reinforcement of wind-mill blades (Mergula, Lowrie, Khana, Bakshi). A further “grey” literature publication focuses on the application of bamboo for windmill blades (Xu, Qin, Zhang 2009). These two publications are as far as we know the only publications assessing the environmental performance of wind turbine blades applying LCA.

As conventional reinforcement, a typical carbon fibre fabric was selected, and as bio-based reinforcement, a commercial flax fibre fabric was selected. Both fibre fabrics were reinforced with a bio-based epoxy resin with “typical” mechanical properties, but sourced from bio-waste. In a previous study, a full technical documentation was done of the mechanical properties of the three materials combinations: carbon/epoxy, flax/epoxy and hybrid carbon/flax/epoxy composites (Bottoli, Pignatti 2011). From this, finite element models were constructed to dimension the small-scale wind turbine blades. Manufacturing was done using vacuum infusion to ensure high quality and reproducibility corresponding to industrial standards.

Initially a comparative LCA was carried out (Markussen, Birkved, Madsen) and based on this assessment it was concluded that further analysis and inclusion of glass fibre reinforcement (currently the most used reinforcement for wind blade) was needed in order to evaluate the environmental trade-offs between carbon and flax fibre reinforcement in the hybrid blade. To assess these scenarios a mechanical modelling approach was applied.

METHODS

The product system model was set-up in GaBi 4.4 (PE 2011a), and built based on readily available commercial unit processes from either the GaBi professional database (PE 2011b) or the Ecoinvent database (Swiss center for LCI 2011). The parameterised model is illustrated in Fig. 1. The product system model covers all relevant life cycle stages of the blade's life cycle from extraction of raw materials, such as crude oil for the epoxy resin, to fuels for waste disposal (here incineration with energy recovery) of the blades. The experimental input for the model are the material quantities consumed during manufacture of the blade prototypes.

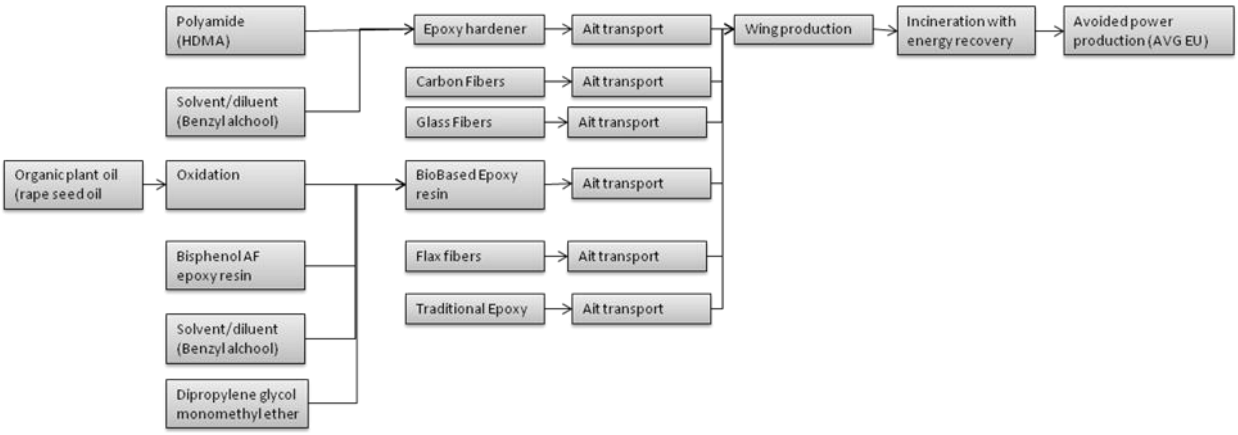


Fig. 7-1: product system model

Due to lack of experimental data a sequence of assumptions had to be made in order to quantify the composition of both the resin and hardener. Further explanation of these assumptions and the allocations needed to develop the product system model are presented in (Marcussen et al.). All estimation work relating to model construction and model parameterisation is by the authors considered to reflect the actual conditions as well as possible and hence are the uncertainties relating to the estimation work and assumptions as low as possible. It is important to keep in mind that the uncertainties relating to the estimation work are approximately equally large for all blade type scenarios and hence are the overall ratios between the impact potentials of the blade types therefore considered to have a considerable lower uncertainty than the absolute impact potentials (i.e. many of the uncertainties being the same for all blade types, will equal out by the comparison).

In a comparative LCA the same functional unit is used. In this case study all the blades have to meet the same stiffness requirements. For the first three scenarios (carbon, flax and hybrid 50/50) a full mechanical analysis of the blades was performed (Bottoli, Pignatti 2011); however for the glass and the hybrid blades with mixing ratios different than 50:50 there wasn't any mechanical analysis.

To obtain the same stiffness of the blades the Ashby's methodology has been (Ashby 2011). This material selection methodology, allows varying the material of an object maintaining the design requirements. In this case, the blade was compared to a beam in order to have a deflection less than the maximal deflection constrain and minimizing the mass. These design requirements are the same as those used to perform the mechanical analysis of the other blades the resulting masses serves as inputs for the product system model.

In this case the Ashby's material index is: $$I = \frac{E^{\frac{1}{2}}}{\rho} \qquad (1)$$

Hence to obtain the mass of a glass fibre blade with the same flexural stiffness of the other blades the following equation was used.

$$m_g = \left(\frac{E_r}{E_g}\right)^{\frac{1}{2}} \frac{\rho_g}{\rho_r} m_r \quad (2)$$

where E (GPa) is the elastic modulus of the material, ρ (g/cm3) is the density and m (g) is the mass of the blade. The subscript $_r$ is referred to the reference material, while g is referred to the glass composite blade. The calculation has been performed with both carbon and flax blades as reference material. The results are presented in table 1. In order to evaluate the accuracy of the applied mechanical model, the 50:50 carbon:flax blade scenario is evaluated to avoid that that large errors are introduced due to the applied mechanical performance assessment approach.

Table 1: Mechanical performance evaluation results of the "pure" materials (materials only applying one fibre type).

Material	E (GPa)	ρ (g/cm^3)	Mass real (g)	Mass calculated (g)
Glass	38	1,88		495 (f) 500 (c)
Carbon	100	1,5	246	243
Flax	20	1,25	454	458

The results obtained for the flax and the carbon blade indicates that no large error is introduced using this simple mechanical performance assessment approach. To obtain the mass of the glass fiber needed on the inside of the composite, the law of mixture was been used, assuming a fibre volume fraction (Vf) of 0,5

The same approach was applied to calculate the weight for the hybrid composite blades with different of flax fiber contents.

Table 2: weight of the hybrid blades and of the fiber and resin demands

% of flax fiber	Blade mass (g)	Carbon fiber mass (g)	Flax fiber mass (g)	Epoxy mass (g)
0 %	246	*155*	*0*	*91*
10 %	257	139	15	103
20 %	270	124	31	115
30 %	283	109	47	128
40 %	299	94	63	142
50 %	316	*80*	*80*	*157*
60%	337	65	98	174
70%	361	51	118	193
80 %	389	35	140	214
90 %	424	18	166	240
100 %	453	0,0	191	263

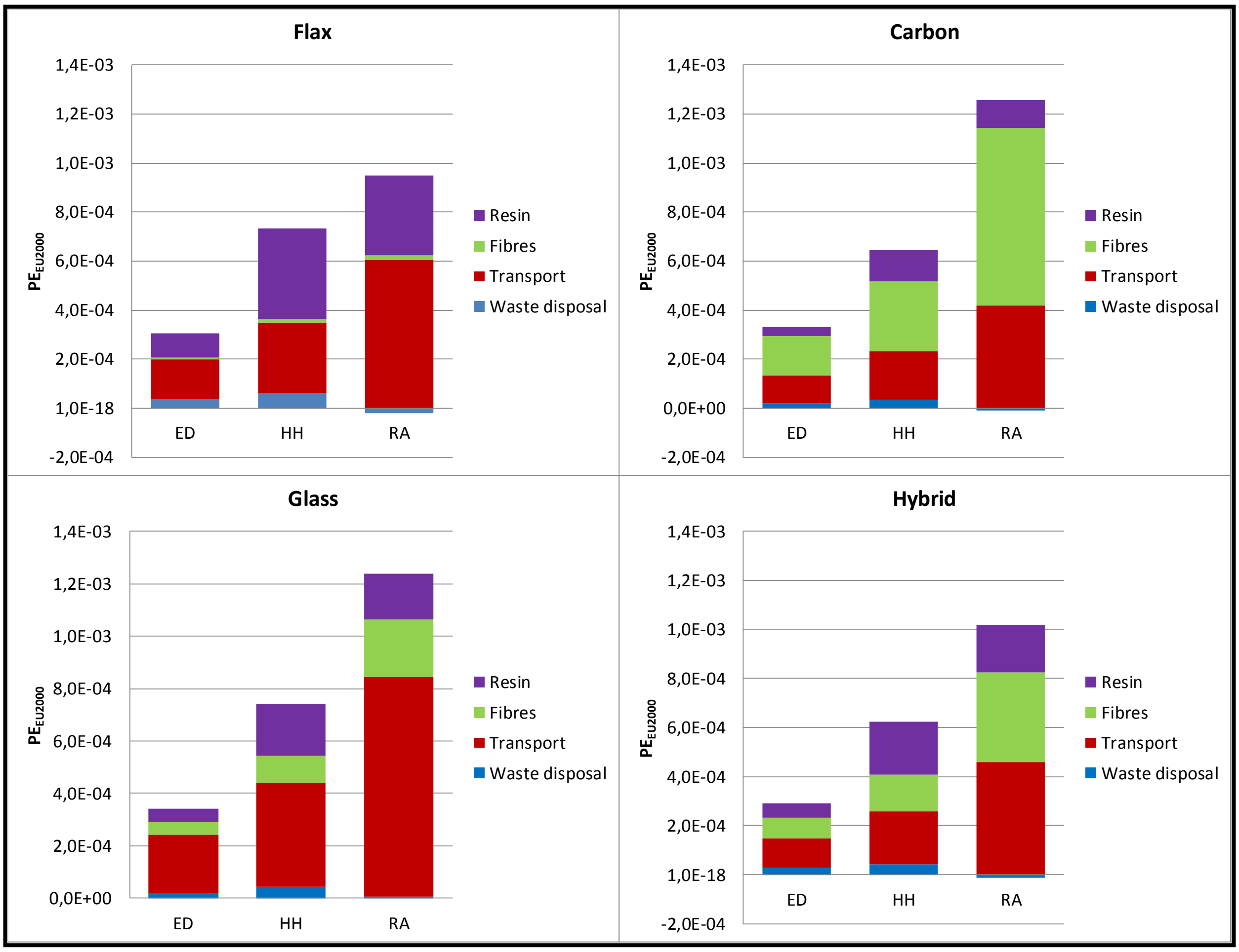
For the assessment of the environmental impacts induced by the different blade designs the ReCiPe Life Cycle Impacts Assessment (LCIA) methodology was applied (Goedkop et al., 2013). ReCiPe is within the LCA community considered one of the most recent and complete LCIA methodologies

(Marcussen et al.). In this case study the Hierarchical assessment perspective is used, since it is the assessment perspective representing an "average political orientation".

This ReCiPe methodology allows for assessment both on midpoint and endpoint level. In this study the results are presented at endpoint level or as aggregated endpoints in the form of single score combining all the endpoint categories.

RESULTS

The product system model assessment results are presented in Fig. 2.



7.2?: Impact assessment results at endpoint level for all blade types obtained applying the ReCiPe impact assessment methodology on each blade alternative, applying the Hierarchist result assessment perspective, presented according to product system activity ED = Ecosystem damage, HH = Human Health damage, RA=Resource depletion damage.

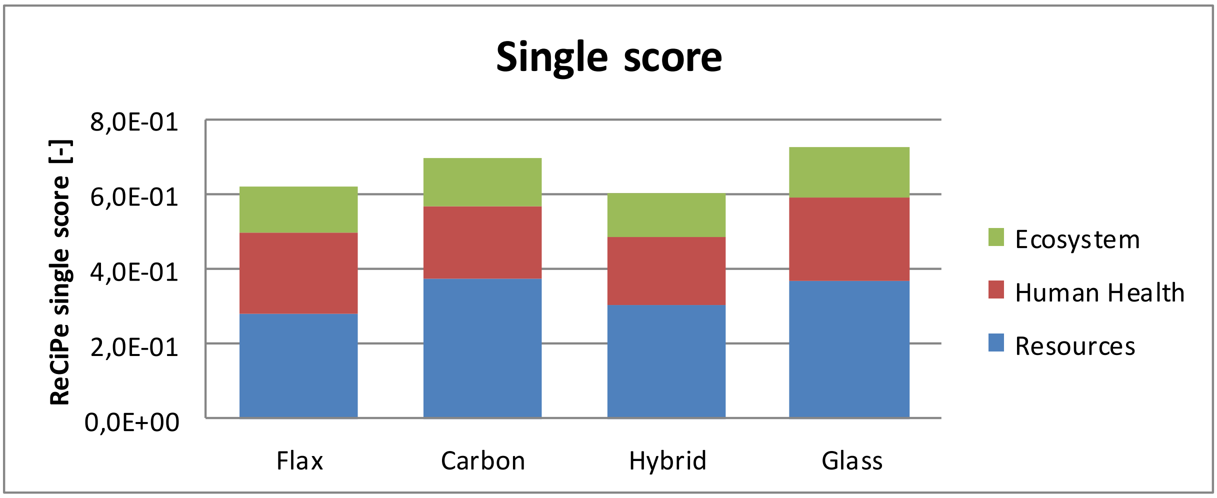


Fig. 3: Impact assessment results on endpoint level for all blade types obtained applying the ReCiPe impact assessment methodology on each blade alternative, applying the Hierarchist result assessment perspective.

In order to illustrate the differences between bio-based blades and glass fibre blade, in terms of their contributions to the specific endpoint or single score, the results are also presented in Δ-LCA result form. According to the Δ-LCA result interpretation approach, only the differences in impacts are highlighted, by calculating the differences in contributions to impact categories as:

$$\Delta IP_i = IP(flax/hybrid)_i - IP(glass)_i$$

Where: ΔIP_i *is the difference to the specific endpoint impact category*

IP is the endpoint impact category of the specific blade scenario.

The results of the Δ-LCA between bio-based and glass fibre are presented in Fig. 4. For further in-depth information about the Δ-LCA and the carbon and flax blade please see (Marcussen et al.).

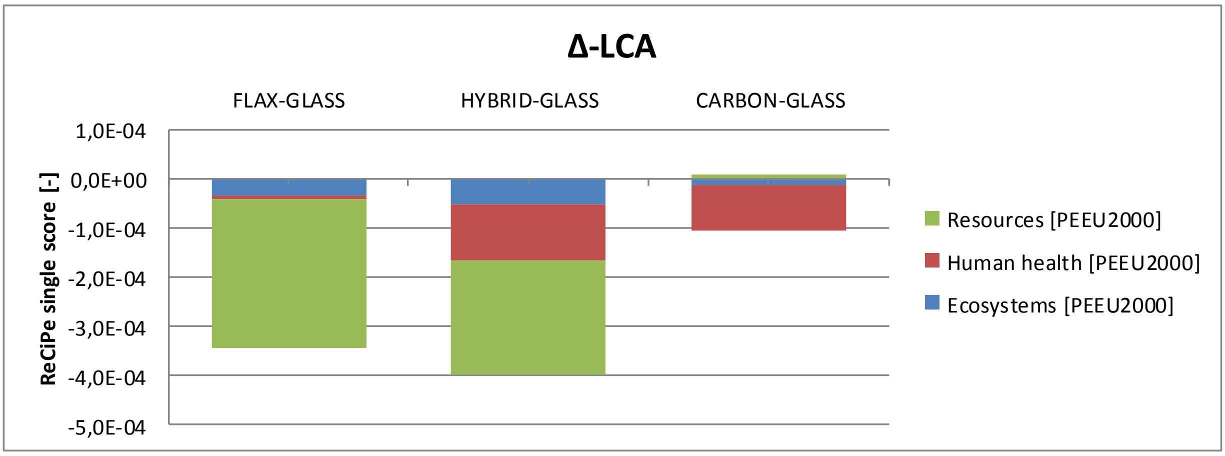


Fig. 4: Impact assessment result difference on endpoint level for all blade types obtained applying the ReCiPe methodology on each blade alternative, applying the Hierarchist result assessment perspective.

The environmental performance of the hybrid blade varies according to the amount of flax fibre applied. The results on the hybrid blade assessment are presented in Fig. 5.

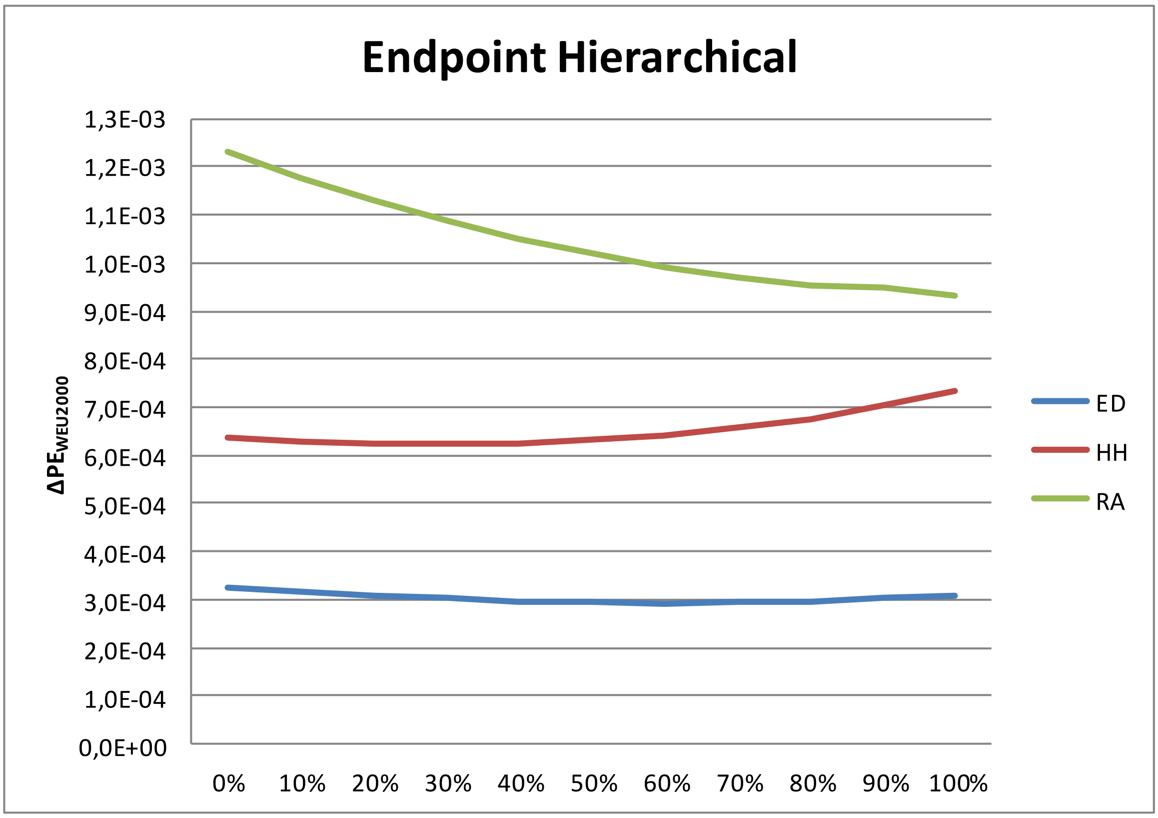


Fig. 5: Impact assessment result for the hybrid blade applying different flax contents on midpoint level obtained applying the ReCiPe impact assessment methodology on each blade alternative, applying the Hierarchist result assessment perspective.

The impacts from different fibre ratios of the hybrid blade are presented in Fig. 5.

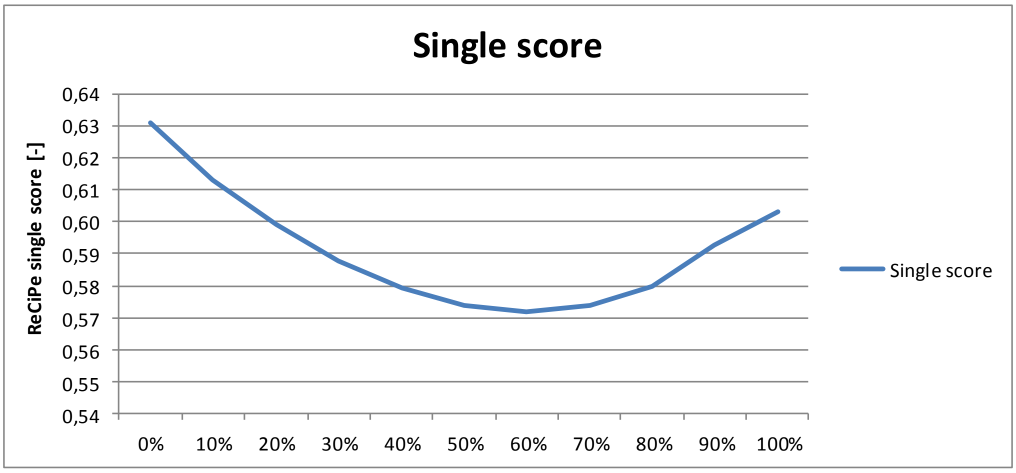


Fig. 6: Impact assessment result for the hybrid blade applying different flax contents on single score level obtained applying the ReCiPe impact assessment methodology on each blade alternative, applying the Hierarchist result assessment perspective.

In Fig. 7 the prices/costs of the hybrid blades are presented applying different fiber ratios. The material prices originates from (Bottoli, Pignatti) and are related to the prototype scale. Although the prices don't represent the true price in an industrial massive scale production setting, the prices are considered representative on a relative scale.

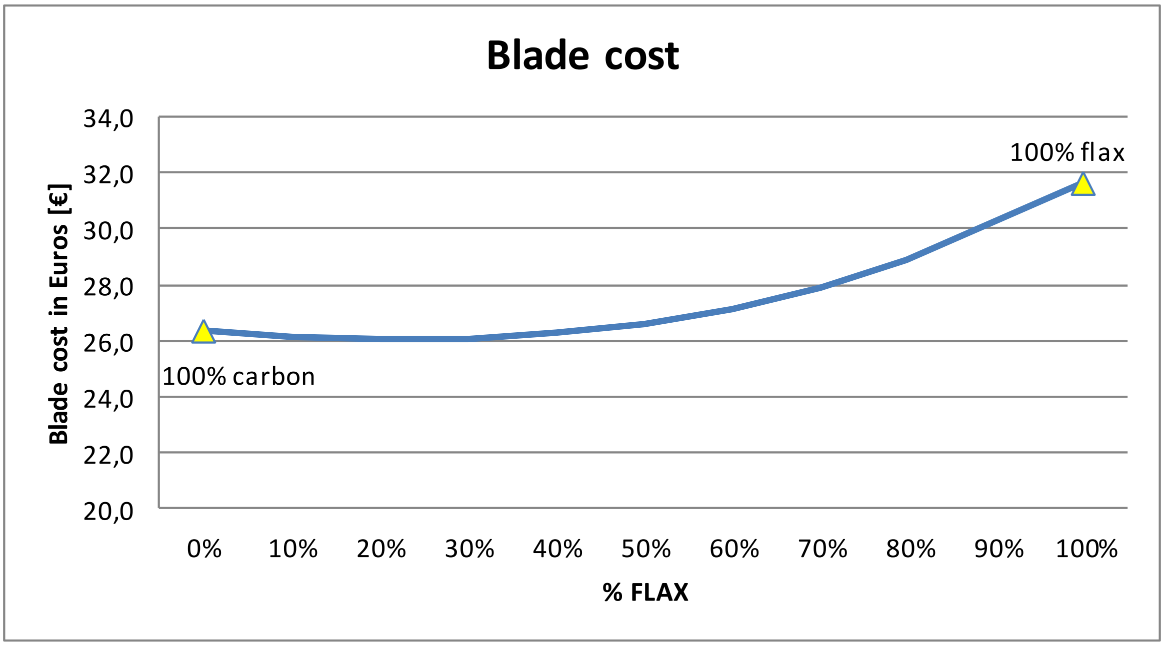


Fig. 7: Hybrid blade cost in US. $ as function of the ratio of flax applied.

In the last graph Fig. 8 the result of the Δ-LCA comparing a flax blade made with bio-based resin and one with conventional epoxy resin.

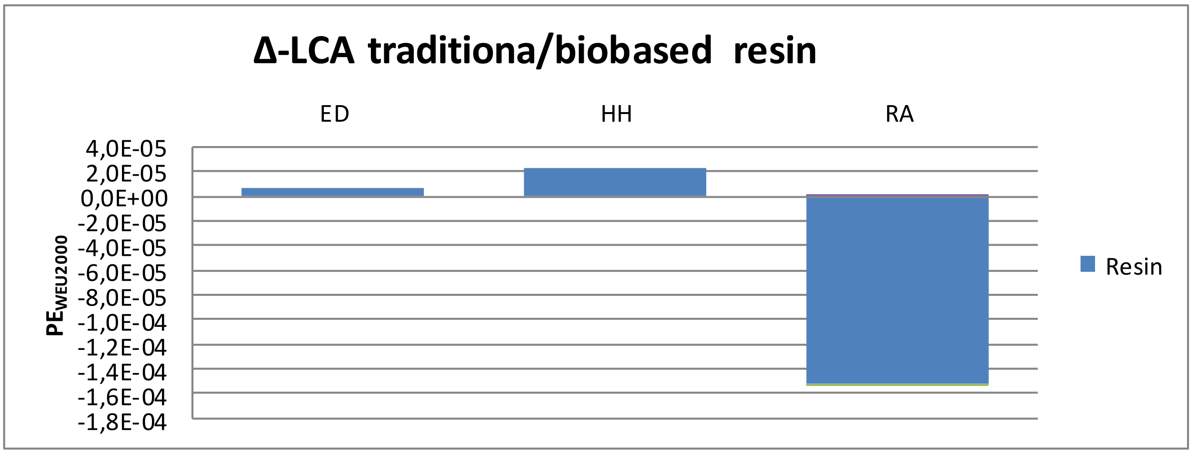


Fig. 8: Impact assessment result on both endpoint level comparing the impact from a flax blade applying conventional resins and a bio-resin.

DISCUSSION

A general view on the LCA result on the 4 different materials as presented in Fig. 1-3 clearly indicate that the hybrid blade has the best environmental performance. This observation is in accordance with the fact that the hybrid blade combines the low non-renewable resource depletion related with the flax fibre, the high specific stiffness of this blade type and the low resin uptake of the carbon fibre.

On the other hand, the glass fibre has the worst environmental performance (see Fig. 1-3). This is because the production process of the glass fibre in general is more environmentally burdensome than the flax fibre and comparable burdensome to the carbon fibre. Additionally the fibre itself has poor specific stiffness, necessitating a higher mass in order to obtain the same flexural stiffness as the other alternative. The high mass of the glass fibre blade types further increases the environmental burdens of the transport phase. For a detailed analysis of the carbon, flax, hybrid 50-50 scenario please see (Marcussen et al.).

Focusing on the Δ-LCA (Fig. 4) results it is observed that all the other materials perform better than the glass blade. Compared to the flax blade, the glass fibre blade has higher a contribution to Resource Depletion. This is caused by the production process and the transport processes (flax fibre are assumed produced in Europe while carbon and glass fibres are produced in China).

In Fig. 4 the hybrid/glass blade comparison reflects the same issues, however in addition there is a higher contribution to Human Health damage for the glass fibre mainly caused by the difference in mass between the two blade types, which causes increases in the emissions related the transport stages. This pattern is also observed for the carbon/glass blade comparison.

The carbon/glass blade comparison reveals no big differences in terms of Resource Depletion; because both of the fibre production forms require considerable amounts of energy.

The single score results on the Hybrid blade with covering different flax:carbon rations indicates there is a minimum for the single score as presented in Fig. 6. The optimal solution is a ratio of 70% of flax fibre and 30% of carbon fibre.

As presented in Fig. 5 increasing the amount of flax fibre lead to a decreases in the Resource Depletion, on the other hand; since flax fibre has a low volume fraction, the more flax fibres require more resin. Increasing the amount of resin implies that Human Health damage increases since Human toxicity is mainly related to the production and use of the epoxy resin.

As is observed from Fig. 7, is there a minimum cost of the hybrid composites. This minimum cost solutions seems to have the same flexural performance as the other alternatives and is app. 20% flax 80% carbon. The price of flax fibre is high, because there is only a small demand for this product. Carbon fibre on the other hand has over the last decade shown a remarkable decrease in the price mainly caused by the high demand for this product.

As presented in Fig. 8 does application of a bio-based resin reduce the overall environmental burden of a blade. Flax blades however has the highest resin uptake among all the blade alternatives compared in this case study.

CONCLUSIONS

In the study at hand it has been demonstrated that the optimum material in terms of environmental sustainability performance, is a hybrid solution with consisting of 30% carbon 70% flax. This ratio is however not the cheapest hybrid alternative.

At the same time, it has been demonstrated, that in terms of cost is the optimum solution a 20% flax 80% carbon hybrid solutions.

Despite the fact that the optimum solutions in terms of environmental performance and cost are different the data uncertainty related to the assessment does not allow for judgement of whether the two optima are different or not.

The use of a bio-based epoxy resin has shown an increase in the environmental performance. This is an interesting observation for this type of material types, since despite being of "bio" origin" this material types still has a considerable environmental burden.

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APPENDIX A: Mass calculator for equal flexural stiffness

Since in the previous steps of the project of the small-scale wind turbine blade only the flax, carbon, hybrid blades were designed and realized, some additional work was done for creating an additional scenario of a GFRP blade.

This additional scenario is really interesting because glass fiber is the common and most used material for wind blades, while carbon fiber has some limited applications usually in bigger blades as a local reinforcement in the most stressed part of the wind blade (i.e. web spar or trailing edge).

Instead of going through the traditional design step as for the other blades, such as micro/macro-mechanical modeling, Finite Element Modeling etc, a simplified method was chosen. This method of materials selection was developed by Ashby. It allows to determine the mass of a component changing the material used (i.e. changing the material's stiffness or strength) having identified its specific function and keeping constant shape of the component.

The use of this simplified method is possible because only the mass of the blade is needed as an input for the product system model. No information about the inner structure of the composite is needed (e.g. the layer orientation or fabric's type used).

Ashby's method identifies 3 main groups of component with their typical function:

- Tie in tension;
- Panel in bending;
- Beam in flexion.

For every function a different materials index must be used. In our case, the blade is assumed to behave as a beam in flexion.

The flexural stiffness of an object is defined as:

Flexural stiffness: $S = \frac{C_2 EI}{L^3}$

Where: C2= constant (depends on loads distribution)

E=elastic modulus of the composite

I= inertia moment depends on section shape

L=length of the blade

If referred to a general beam with square section: $S = \frac{C_2 E I_{sq} \phi_B^e}{L^3}$

Where: I_{sq}=inertia moment of a squarded shaped beam

ϕ_B^e= elastic bending shape factor

In order to compare the same component with different material; it must have same deformation under the same load. In other words, the flexural stiffness must be equal.

$S_{glass}=S_{flax}=S_{carbon}=S_{hibrid}$

$$S = \frac{C_2 E I_{sq} \phi_B^e}{L^3} = \frac{C_2 E A^2 \phi_B^e}{12L^3}$$

The mass could be expressed as the volume of the component multiplied by its density.

$$m = LA\rho \rightarrow A = \frac{m}{L\rho}$$

Substituting this expression in the flexural stiffness

$$S = \frac{C_2 E \phi_B^e}{12L^3} * \frac{m^2}{L^2\rho^2} \rightarrow m^2 = \frac{12SL^5}{C_2}\frac{\rho^2}{\phi_B^e E}$$

$$m = \left(\frac{12S}{C_2}\right)^{\frac{1}{2}} L^{\frac{5}{2}} \frac{\rho}{(\phi_B^e E)^{\frac{1}{2}}}$$

$$S^{\frac{1}{2}} = \frac{m}{L^{\frac{5}{2}}}\left(\frac{C_2}{12}\right)^{\frac{1}{2}} \frac{(\phi_B^e E)^{\frac{1}{2}}}{\rho}$$

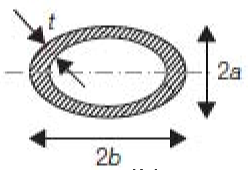
We want the same flexural stiffness: $S_g = S_f$

$$\frac{m_f}{L^{\frac{5}{2}}}\left(\frac{C_2}{12}\right)^{\frac{1}{2}} \frac{(\phi_{Bf}^e E_f)^{\frac{1}{2}}}{\rho_f} = \frac{m_g}{L^{\frac{5}{2}}}\left(\frac{C_2}{12}\right)^{\frac{1}{2}} \frac{\left(\phi_{Bg}^e E_g\right)^{\frac{1}{2}}}{\rho_g}$$

$$m_g = \left(\frac{\phi_{Bf}^e E_f}{\phi_{Bg}^e E_g}\right)^{\frac{1}{2}} \frac{\rho_g}{\rho_f} m_f$$

ϕ_B^e Is the elastic bending shape factor. Assuming that the blade is a hollow cylinder (is permitted because this blade has a simple shape):

$$\phi_B^e = \frac{3a\left(1+3\frac{b}{a}\right)}{\pi t\left(1+\frac{b}{a}\right)^2} \text{ (a,b=; t<<a,b)} \rightarrow \frac{\phi_{Bf}^e}{\phi_{Bg}^e} \sim 1$$



Hence the mass of the glass blade, if compared to the flax one, will be:

$$m_g = \left(\frac{E_f}{E_g}\right)^{\frac{1}{2}} \frac{\rho_g}{\rho_f} m_f$$

In order to verify if this method gives acceptable results, not only the GFRP scenario was calculated but also the flax and the carbon one and they were compared to the weight of the real component:

Material	E (GPa)	ρ (g/cm^3)	Mass real (g)	Mass calculated (g)
Carbon	100	1,5	246	243 (f)
Flax	20	1,25	453,8	458 (c)
Glass	38	1,88		495(f) 500 (c)

Tab A.1 Comparison between real mass of the blade and the mass calculated with Ashby's methodology. Properties of the material used are also presented.

Although several assumptions were made to develop this method, this gives good results. In general the error is less than 1,2% in the worst case scenario. Hence we can conclude that this method is valid for evaluating the mass of a simple component changing the material used.

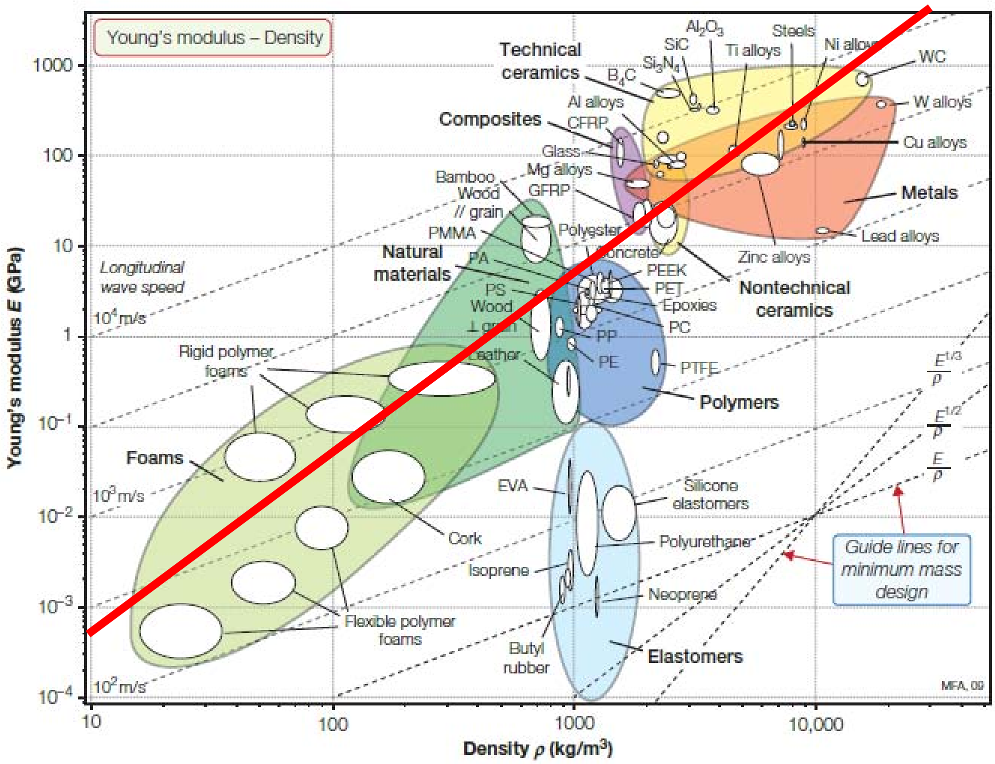


Fig A.1 Ashby's chart. A different way for material selection. Every material has coordinates that represent their properties (in this case Elastic modulus and density. Choosed a reference material the material that performs better will be in the upper part of the line parallel to the references line for the material index.

APPENDIX B: Hybrid Mass Calculator

One goal of this thesis work was to analyze the environmental behavior of the hybrid blade changing the ratio between natural fiber and carbon fiber. A similar approach to the glass blade scenario was used because only the hybrid 50/50 was studied and realized before. As stated in appendix A we are only interested in the fiber and resin mass (i.e. blade mass) since is the only input required for the product system model. Hence using a method that calculates the component mass assuring same flexural stiffness is valid. We need to find only the composite density and elastic modulus at the changing of the ratio between the fibers. The ratio between the two fibers could be defined as X:

Mass flax fiber=X* Mass carbon fiber → $m_f = xm_c$

The mass of the flax part in the composite (m_{fc}) will be the flax fiber mass plus the mass of the resin required for the infusion of the natural fiber:

$m_{fc} = \frac{m_f}{W_f}$ (W_f= fibre weight fraction in a natural composite (0,42)

For the carbon part of the composite:

$m_{cc} = \frac{m_c}{W_c} = \frac{m_f}{xW_c}$ (W_c= fibre weight fraction in a carbon composite (0,63)

We can define a weight fraction between the two different composites (resin + fiber) inside the blade. Weight fraction of flax composite part:

$$W_{fc} = \frac{m_{fc}}{m_{tot}} = \frac{xW_c}{W_f + xW_c}$$

Weight fraction of carbon composite part:

$$W_{cc} = \frac{m_{cc}}{m_{tot}} = \frac{W_f}{W_f + xW_c}$$

We can define the composite volume as:

$$V = \frac{m_{fc}}{\rho_{fc}} + \frac{m_{cc}}{\rho_{cc}}$$

(ρ_{fc}=density of flax composite 1,25 g/cm^3; ρ_{cc}=density of carbon composite 1,5 g/cm^3)

Hence the composite density will be:

$$\rho = \frac{m_{tot}}{V_{tot}} = \frac{(W_f + xW_c)\rho_{fc}\rho_{cc}}{xW_c\rho_{cc} + W_f\rho_{fc}}$$

For evaluating the elastic modulus we use the laws of mixture; it is the traditional way in the micromechanical modeling to calculate the longitudinal elastic modulus of a composite. In order to use the law of mixture we must define the volume fraction of the two parts that make up the composite.

$$\text{Volume fraction flax composite} = V_f = \frac{V_{fc}}{V_{tot}} = \frac{m_{fc}\,\rho_{tot}}{\rho_{fc}\,m_{tot}} = W_{fc}\frac{\rho_{tot}}{\rho_{fc}}$$

$$\text{Volume fraction carbon composite} = V_c = \frac{V_{cc}}{V_{tot}} = \frac{m_{cc}\,\rho_{tot}}{\rho_{cc}\,m_{tot}} = W_{cc}\frac{\rho_{tot}}{\rho_{cc}}$$

Thus the elastic modulus using the laws of mixture will be:

$$E = E_{fc}V_{fc} + E_{cc}V_{cc}$$

(E_{fc}=elastic modulus of flax composite (20 GPa) E_{cc}= elastic modulus of carbon composite (104 GPa)

$$E = \frac{xE_{fc}W_c\rho_{cc}\rho_{fc}}{xW_c\rho_{cc} + W_f\rho_{fc}} + \frac{E_{cc}W_f\rho_{fc}\rho_{cc}}{xW_c\rho_{cc} + W_f\rho_{cc}}$$

Once defined elastic modulus and density we could add this in the mass for equal stiffness calculator presented in appendix A. The results given by this calculation are presented in the following graph:

X fiber ratio	Mass tot	W_{fc}	W_{cc}	Mass flax composite	Mass carbon composite	Mass flax fiber	Mass carbon fiber	Mass resin
0	246,0	0,00	1,00	0,0	246,0	0,0	155,0	91,0
0,1	257,1	0,14	0,86	36,7	220,4	15,4	138,8	102,8
0,2	269,5	0,27	0,73	73,5	196,0	30,9	123,5	115,1
0,3	283,4	0,39	0,61	110,9	172,5	46,6	108,7	128,1
0,4	299,0	0,50	0,50	149,5	149,5	62,8	94,2	142,0
0,5	316,8	0,60	0,40	190,1	126,7	79,8	79,8	157,1
0,6	337,2	0,69	0,31	233,5	103,8	98,1	65,4	173,8
0,7	361,1	0,78	0,22	280,8	80,2	117,9	50,5	192,6
0,8	389,4	0,86	0,14	333,8	55,6	140,2	35,0	214,2
0,9	424,0	0,93	0,07	394,7	29,2	165,8	18,4	239,8
1	467,5	1,00	0,00	467,5	0,0	196,3	0,0	271,1

Tab B.1 **Mass for the hybrid composites changing the natural fiber ratio. The ratio that allows a comparison with the real manifactured blade are highlited in red.**

We can evaluate the accuracy of this model comparing the results given by this calculator respect of the real blade (i.e. x=0; 0.5; 1). The error is 3% for the 100% flax blade and 2,5% for the 50/50 hybrid blade. The error is small although this is a simplified method, thus using this method to calculate the input for the product system model is considered valid.

APPENDIX C: data & assumptions

1. LCI Data

a. Material scenario

FLAX FIBER SCENARIO				
Category	**Flow**	**Amount**	**Unit**	**Source/Explanation**
Fibers	Flax fiber	0,21	kg	Real blade +10% of waste (Bottoli)
	Carbon fiber	0	kg	Real blade +10% of waste (Bottoli)
	Glass Fiber	0	kg	Calculated with Asbhy + 10% waste
Resin	Bio-epoxy	0,193	kg	From Bottoli +10% of waste
	Traditional	0	kg	See biobased epoxy
	Hardener	0,0965	kg	From Bottoli +10% of waste
Transport	Flax fiber	1540	Km	From Belgium (Lineo factory)
	Carbon fiber	7190	Km	From China (Birkved 2013)
	Glass Fiber	7190	Km	Assumed China
	Bio-epoxy	9030	Km	Entropy resin USA
	Traditional	9030	Km	Assumed USA
	Hardener	9030	Km	Entropy resin USA
Incineration	Incineration	0,454	Kg	All the blade
	Electricity production	0,747	MJ	Only the burneable part are considered
	Ashes	0	Kg	Glass and carbon fiber
	Distance use→Incineration	35	Km	From Birkved
	Incinerator →Landfill	100	Km	Assumed
Co-Processing	Avoided coal extraction	0	Kg	Calculated using calorific value (alloc)
	Avoided marl extraction	0	Kg	Assumed (Mass of glass fiber)
	Distance use→Cement kiln	160	Km	Assumed (Roskilde-Aalborg Portland factory)
Pyrolysis	Natural gas	0	Kg	From Cunliffe & Pickering, subtracted the gas production from the process
	Avoided fuel production	0	Kg	Calculated from Cunliffe & Pickering
	Avoided production Glass mat	0	Kg	Assumed equal to GF mass
	Avoided production Carbon fiber	0	Kg	Calculated with allocation base on mechanical properties (-20%)
	Distance use→ Pyrolysis	350	Km	Assumed (Roskilde-ReFiber plant)
CARBON FIBER SCENARIO				
Category	**Flow**	**Amount**	**Unit**	**Source/Explanation**
Fibers	Flax fiber	0	kg	Real blade +10% of waste (Bottoli)
	Carbon fiber	0,171	kg	Real blade +10% of waste (Bottoli)
	Glass Fiber	0	kg	Calculated with Asbhy + 10% waste
Resin	Bio-epoxy	0,0667	kg	From Bottoli +10% of waste
	Traditional	0	kg	See biobased epoxy
	Hardener	0,0334	kg	From Bottoli +10% of waste
Transport	Flax fiber	1540	Km	From Belgium (Lineo factory)
	Carbon fiber	7190	Km	From China (Birkved 2013)
	Glass Fiber	7190	Km	Assumed China
	Bio-epoxy	9030	Km	Entropy resin USA
	Traditional	9030	Km	Assumed USA

	Hardener	9030	Km	Entropy resin USA
Incineration	Incineration	0,246	Kg	All the blade
	Electricity production	0,15	MJ	Only the burneable part are considered
	Ashes	0,155	Kg	Glass and carbon fiber
	Distance use→Incineration	35	Km	From Birkved
	Incinerator →Landfill	100	Km	Assumed
Co-Processing	Avoided coal extraction	0	Kg	Calculated using calorific value (alloc)
	Avoided marl extraction	0	Kg	Assumed (Mass of glass fiber)
	Distance use→Cement kiln	160	Km	Assumed (Roskilde-Aalborg Portland factory)
Pyrolysis	Natural gas	0	Kg	From Cunliffe & Pickering, subtracted the gas production from the process
	Avoided fuel production	0	Kg	Calculated from Cunliffe & Pickering
	Avoided production Glass mat	0	Kg	Assumed equal to GF mass
	Avoided production Carbon fiber	0	Kg	Calculated with allocation base on mechanical properties (-20%)
	Distance use→ Pyrolysis	350	Km	Assumed (Roskilde-ReFiber plant)
HYBRID SCENARIO				
Category	**Flow**	**Amount**	**Unit**	**Source/Explanation**
Fibers	Flax fiber	0,083	kg	Real blade +10% of waste (Bottoli)
	Carbon fiber	0,083	kg	Real blade +10% of waste (Bottoli)
	Glass Fiber	0	kg	Calculated with Asbhy + 10% waste
Resin	Bio-epoxy	0,113	kg	From Bottoli +10% of waste
	Traditional	0	kg	See biobased epoxy
	Hardener	0,0565	kg	From Bottoli +10% of waste
Transport	Flax fiber	1540	Km	From Belgium (Lineo factory)
	Carbon fiber	7190	Km	From China (Birkved 2013)
	Glass Fiber	7190	Km	Assumed China
	Bio-epoxy	9030	Km	Entropy resin USA
	Traditional	9030	Km	Assumed USA
	Hardener	9030	Km	Entropy resin USA
Incineration	Incineration	0,308	Kg	All the blade
	Electricity production	0,38	MJ	Only the burneable part are considered
	Ashes	0,077	Kg	Glass and carbon fiber
	Distance use→Incineration	35	Km	From Birkved
	Incinerator →Landfill	100	Km	Assumed
Co-Processing	Avoided coal extraction	0	Kg	Calculated using calorific value (alloc)
	Avoided marl extraction	0	Kg	Assumed (Mass of glass fiber)
	Distance use→Cement kiln	160	Km	Assumed (Roskilde-Aalborg Portland factory)
Pyrolysis	Natural gas	0	Kg	From Cunliffe & Pickering, subtracted the gas production from the process
	Avoided fuel production	0	Kg	Calculated from Cunliffe & Pickering
	Avoided production Glass mat	0	Kg	Assumed equal to GF mass
	Avoided production Carbon fiber	0	Kg	Calculated with allocation base on mechanical properties (-20%)
	Distance use→ Pyrolysis	350	Km	Assumed (Roskilde-ReFiber plant)
GLASS FIBER SCENARIO				
Category	**Flow**	**Amount**	**Unit**	**Source/Explanation**
Fibers	Flax fiber	0	kg	Real blade +10% of waste (Bottoli)
	Carbon fiber	0	kg	Real blade +10% of waste (Bottoli)
	Glass Fiber	0394	kg	Calculated with Asbhy + 10% waste

Resin	Bio-epoxy	0,102	kg	From Bottoli +10% of waste
	Traditional	0	kg	See biobased epoxy
	Hardener	0,0511	kg	From Bottoli +10% of waste
Transport	Flax fiber	1540	Km	From Belgium (Lineo factory)
	Carbon fiber	7190	Km	From China (Birkved 2013)
	Glass Fiber	7190	Km	Assumed China
	Bio-epoxy	9030	Km	Entropy resin USA
	Traditional	9030	Km	Assumed USA
	Hardener	9030	Km	Entropy resin USA
Incineration	Incineration	0,497	Kg	All the blade
	Electricity production	0,229	MJ	Only the burneable part are considered
	Ashes	0,358	Kg	Glass and carbon fiber
	Distance use→Incineration	35	Km	From Birkved
	Incinerator →Landfill	100	Km	Assumed
Co-Processing	Avoided coal extraction	0	Kg	Calculated using calorific value (alloc)
	Avoided marl extraction	0	Kg	Assumed (Mass of glass fiber)
	Distance use→Cement kiln	160	Km	Assumed (Roskilde-Aalborg Portland factory)
Pyrolysis	Natural gas	0	Kg	From Cunliffe & Pickering, subtracted the gas production from the process
	Avoided fuel production	0	Kg	Calculated from Cunliffe & Pickering
	Avoided production Glass mat	0	Kg	Assumed equal to GF mass
	Avoided production Carbon fiber	0	Kg	Calculated with allocation base on mechanical properties (-20%)
	Distance use→ Pyrolysis	350	Km	Assumed (Roskilde-ReFiber plant)

b. EoL Glass blade

INCINERATION				
Category	**Flow**	**Amount**	**Unit**	**Source/Explanation**
Fibers	Flax fiber	0	kg	Real blade +10% of waste (Bottoli)
	Carbon fiber	0	kg	Real blade +10% of waste (Bottoli)
	Glass Fiber	0394	kg	Calculated with Asbhy + 10% waste
Resin	Bio-epoxy	0,102	kg	From Bottoli +10% of waste
	Traditional	0	kg	See biobased epoxy
	Hardener	0,0511	kg	From Bottoli +10% of waste
Transport	Flax fiber	1540	Km	From Belgium (Lineo factory)
	Carbon fiber	7190	Km	From China (Birkved 2013)
	Glass Fiber	7190	Km	Assumed China
	Bio-epoxy	9030	Km	Entropy resin USA
	Traditional	9030	Km	Assumed USA
	Hardener	9030	Km	Entropy resin USA
Incineration	Incineration	0,497	Kg	All the blade
	Electricity production	0,229	MJ	Only the burneable part are considered
	Ashes	0,358	Kg	Glass and carbon fiber
	Distance use→Incineration	35	Km	From Birkved
	Incinerator →Landfill	100	Km	Assumed
Co-Processing	Avoided coal extraction	0	Kg	Calculated using calorific value (alloc)
	Avoided marl extraction	0	Kg	Assumed (Mass of glass fiber)

	Distance use→Cement kiln	160	Km	Assumed (Roskilde-Aalborg Portland factory)
Pyrolysis	Natural gas	0	Kg	From Cunliffe & Pickering, subtracted the gas production from the process
	Avoided fuel production	0	Kg	Calculated from Cunliffe & Pickering
	Avoided production Glass mat	0	Kg	Assumed equal to GF mass
	Avoided production Carbon fiber	0	Kg	Calculated with allocation base on mechanical properties (-20%)
	Distance use→ Pyrolysis	350	Km	Assumed (Roskilde-ReFiber plant)
CO-PROCESSING				
Category	**Flow**	**Amount**	**Unit**	**Source/Explanation**
Fibers	Flax fiber	0	kg	Real blade +10% of waste (Bottoli)
	Carbon fiber	0	kg	Real blade +10% of waste (Bottoli)
	Glass Fiber	0394	kg	Calculated with Asbhy + 10% waste
Resin	Bio-epoxy	0,102	kg	From Bottoli +10% of waste
	Traditional	0	kg	See biobased epoxy
	Hardener	0,0511	kg	From Bottoli +10% of waste
Transport	Flax fiber	1540	Km	From Belgium (Lineo factory)
	Carbon fiber	7190	Km	From China (Birkved 2013)
	Glass Fiber	7190	Km	Assumed China
	Bio-epoxy	9030	Km	Entropy resin USA
	Traditional	9030	Km	Assumed USA
	Hardener	9030	Km	Entropy resin USA
Incineration	Incineration	0	Kg	All the blade
	Electricity production	0	MJ	Only the burneable part are considered
	Ashes	0	Kg	Glass and carbon fiber
	Distance use→Incineration	35	Km	From Birkved
	Incinerator →Landfill	100	Km	Assumed
Co-Processing	Avoided coal extraction	-2,13	MJ	Calculated using calorific value (alloc)
	Avoided marl extraction	-0,358	Kg	Assumed (Mass of glass fiber)
	Distance use→Cement kiln	160	Km	Assumed (Roskilde-Aalborg Portland factory)
Pyrolysis	Natural gas	0	Kg	From Cunliffe & Pickering, subtracted the gas production from the process
	Avoided fuel production	0	Kg	Calculated from Cunliffe & Pickering
	Avoided production Glass mat	0	Kg	Assumed equal to GF mass
	Avoided production Carbon fiber	0	Kg	Calculated with allocation base on mechanical properties (-20%)
	Distance use→ Pyrolysis	350	Km	Assumed (Roskilde-ReFiber plant)
PYROLYSIS				
Category	**Flow**	**Amount**	**Unit**	**Source/Explanation**
Fibers	Flax fiber	0	kg	Real blade +10% of waste (Bottoli)
	Carbon fiber	0	kg	Real blade +10% of waste (Bottoli)
	Glass Fiber	0394	kg	Calculated with Asbhy + 10% waste
Resin	Bio-epoxy	0,102	kg	From Bottoli +10% of waste
	Traditional	0	kg	See biobased epoxy
	Hardener	0,0511	kg	From Bottoli +10% of waste
Transport	Flax fiber	1540	Km	From Belgium (Lineo factory)
	Carbon fiber	7190	Km	From China (Birkved 2013)
	Glass Fiber	7190	Km	Assumed China
	Bio-epoxy	9030	Km	Entropy resin USA
	Traditional	9030	Km	Assumed USA
	Hardener	9030	Km	Entropy resin USA

Incineration	Incineration	0	Kg	All the blade
	Electricity production	0	MJ	Only the burneable part are considered
	Ashes	0	Kg	Glass and carbon fiber
	Distance use→Incineration	35	Km	From Birkved
	Incinerator →Landfill	100	Km	Assumed
Co-Processing	Avoided coal extraction	0	Kg	Calculated using calorific value (alloc)
	Avoided marl extraction	0	Kg	Assumed (Mass of glass fiber)
	Distance use→Cement kiln	160	Km	Assumed (Roskilde-Aalborg Portland factory)
Pyrolysis	Natural gas	1,2	MJ	From Cunliffe & Pickering, subtracted the gas production from the process
	Avoided fuel production	0,129	Kg	Calculated from Cunliffe & Pickering
	Avoided production Glass mat	0,358	Kg	Assumed equal to GF mass
	Avoided production Carbon fiber	0	Kg	Calculated with allocation base on mechanical properties (-20%)
	Distance use→ Pyrolysis	350	Km	Assumed (Roskilde-ReFiber plant)

c. EoL Carbon Blade

INCINERATION				
Category	**Flow**	**Amount**	**Unit**	**Source/Explanation**
Fibers	Flax fiber	0	kg	Real blade +10% of waste (Bottoli)
	Carbon fiber	0,171	kg	Real blade +10% of waste (Bottoli)
	Glass Fiber	0	kg	Calculated with Asbhy + 10% waste
Resin	Bio-epoxy	0,0667	kg	From Bottoli +10% of waste
	Traditional	0	kg	See biobased epoxy
	Hardener	0,0334	kg	From Bottoli +10% of waste
Transport	Flax fiber	1540	Km	From Belgium (Lineo factory)
	Carbon fiber	7190	Km	From China (Birkved 2013)
	Glass Fiber	7190	Km	Assumed China
	Bio-epoxy	9030	Km	Entropy resin USA
	Traditional	9030	Km	Assumed USA
	Hardener	9030	Km	Entropy resin USA
Incineration	Incineration	0,246	Kg	All the blade
	Electricity production	0,15	MJ	Only the burnable part are considered
	Ashes	0,155	Kg	Glass and carbon fiber
	Distance use→Incineration	35	Km	From Birkved
	Incinerator →Landfill	100	Km	Assumed
Co-Processing	Avoided coal extraction	0	Kg	Calculated using calorific value (alloc)
	Avoided marl extraction	0	Kg	Assumed (Mass of glass fiber)
	Distance use→Cement kiln	160	Km	Assumed (Roskilde-Aalborg Portland factory)
Pyrolysis	Natural gas	0	Kg	From Cunliffe & Pickering, subtracted the gas production from the process
	Avoided fuel production	0	Kg	Calculated from Cunliffe & Pickering
	Avoided production Glass mat	0	Kg	Assumed equal to GF mass
	Avoided production Carbon fiber	0	Kg	Calculated with allocation base on mechanical properties (-20%)
	Distance use→ Pyrolysis	350	Km	Assumed (Roskilde-ReFiber plant)
CO-PROCESSING				

Category	Flow	Amount	Unit	Source/Explanation
Fibers	Flax fiber	0	kg	Real blade +10% of waste (Bottoli)
	Carbon fiber	0	kg	Real blade +10% of waste (Bottoli)
	Glass Fiber	0394	kg	Calculated with Asbhy + 10% waste
Resin	Bio-epoxy	0,102	kg	From Bottoli +10% of waste
	Traditional	0	kg	See biobased epoxy
	Hardener	0,0511	kg	From Bottoli +10% of waste
Transport	Flax fiber	1540	Km	From Belgium (Lineo factory)
	Carbon fiber	7190	Km	From China (Birkved 2013)
	Glass Fiber	7190	Km	Assumed China
	Bio-epoxy	9030	Km	Entropy resin USA
	Traditional	9030	Km	Assumed USA
	Hardener	9030	Km	Entropy resin USA
Incineration	Incineration	0	Kg	All the blade
	Electricity production	0	MJ	Only the burneable part are considered
	Ashes	0	Kg	Glass and carbon fiber
	Distance use→Incineration	35	Km	From Birkved
	Incinerator →Landfill	100	Km	Assumed
Co-Processing	Avoided coal extraction	-1,39	MJ	Calculated using calorific value (alloc)
	Avoided marl extraction	0	Kg	Assumed (Mass of glass fiber)
	Distance use→Cement kiln	160	Km	Assumed (Roskilde-Aalborg Portland factory)
Pyrolysis	Natural gas	0	Kg	From Cunliffe & Pickering, subtracted the gas production from the process
	Avoided fuel production	0	Kg	Calculated from Cunliffe & Pickering
	Avoided production Glass mat	0	Kg	Assumed equal to GF mass
	Avoided production Carbon fiber	0	Kg	Calculated with allocation base on mechanical properties (-20%)
	Distance use→ Pyrolysis	350	Km	Assumed (Roskilde-ReFiber plant)
PYROLYSIS				
Category	**Flow**	**Amount**	**Unit**	**Source/Explanation**
Fibers	Flax fiber	0	kg	Real blade +10% of waste (Bottoli)
	Carbon fiber	0	kg	Real blade +10% of waste (Bottoli)
	Glass Fiber	0394	kg	Calculated with Asbhy + 10% waste
Resin	Bio-epoxy	0,102	kg	From Bottoli +10% of waste
	Traditional	0	kg	See biobased epoxy
	Hardener	0,0511	kg	From Bottoli +10% of waste
Transport	Flax fiber	1540	Km	From Belgium (Lineo factory)
	Carbon fiber	7190	Km	From China (Birkved 2013)
	Glass Fiber	7190	Km	Assumed China
	Bio-epoxy	9030	Km	Entropy resin USA
	Traditional	9030	Km	Assumed USA
	Hardener	9030	Km	Entropy resin USA
Incineration	Incineration	0	Kg	All the blade
	Electricity production	0	MJ	Only the burneable part are considered
	Ashes	0	Kg	Glass and carbon fiber
	Distance use→Incineration	35	Km	From Birkved
	Incinerator →Landfill	100	Km	Assumed
Co-Processing	Avoided coal extraction	0	Kg	Calculated using calorific value (alloc)
	Avoided marl extraction	0	Kg	Assumed (Mass of glass fiber)
	Distance use→Cement kiln	160	Km	Assumed (Roskilde-Aalborg Portland factory)

Pyrolysis	Natural gas	0,561	MJ	From Cunliffe & Pickering, subtracted the gas production from the process
	Avoided fuel production	-0,0842	Kg	Calculated from Cunliffe & Pickering
	Avoided production Glass mat	0	Kg	Assumed equal to GF mass
	Avoided production Carbon fiber	0,124	Kg	Calculated with allocation base on mechanical properties (-20%)
	Distance use→ Pyrolysis	350	Km	Assumed (Roskilde-ReFiber plant)

d. Different resin

BIOBASED RESIN FLAX BLADE				
Category	**Flow**	**Amount**	**Unit**	**Source/Explanation**
Fibers	Flax fiber	0,21	kg	Real blade +10% of waste (Bottoli)
	Carbon fiber	0	kg	Real blade +10% of waste (Bottoli)
	Glass Fiber	0	kg	Calculated with Asbhy + 10% waste
Resin	Bio-epoxy	0,193	kg	From Bottoli +10% of waste
	Traditional	0	kg	See biobased epoxy
	Hardener	0,0965	kg	From Bottoli +10% of waste
Transport	Flax fiber	1540	Km	From Belgium (Lineo factory)
	Carbon fiber	7190	Km	From China (Birkved 2013)
	Glass Fiber	7190	Km	Assumed China
	Bio-epoxy	9030	Km	Entropy resin USA
	Traditional	9030	Km	Assumed USA
	Hardener	9030	Km	Entropy resin USA
Incineration	Incineration	0,454	Kg	All the blade
	Electricity production	0,747	MJ	Only the burneable part are considered
	Ashes	0	Kg	Glass and carbon fiber
	Distance use→Incineration	35	Km	From Birkved
	Incinerator →Landfill	100	Km	Assumed
Co-Processing	Avoided coal extraction	0	Kg	Calculated using calorific value (alloc)
	Avoided marl extraction	0	Kg	Assumed (Mass of glass fiber)
	Distance use→Cement kiln	160	Km	Assumed (Roskilde-Aalborg Portland factory)
Pyrolysis	Natural gas	0	Kg	From Cunliffe & Pickering, subtracted the gas production from the process
	Avoided fuel production	0	Kg	Calculated from Cunliffe & Pickering
	Avoided production Glass mat	0	Kg	Assumed equal to GF mass
	Avoided production Carbon fiber	0	Kg	Calculated with allocation base on mechanical properties (-20%)
	Distance use→ Pyrolysis	350	Km	Assumed (Roskilde-ReFiber plant)
CONVENTIONAL RESIN FLAX BLADE				
Category	**Flow**	**Amount**	**Unit**	**Source/Explanation**
Fibers	Flax fiber	0,21	kg	Real blade +10% of waste (Bottoli)
	Carbon fiber	0	kg	Real blade +10% of waste (Bottoli)
	Glass Fiber	0	kg	Calculated with Asbhy + 10% waste
Resin	Bio-epoxy	0	kg	From Bottoli +10% of waste
	Traditional	0,193	kg	See biobased epoxy
	Hardener	0,0965	kg	From Bottoli +10% of waste

Transport	Flax fiber	1540	Km	From Belgium (Lineo factory)
	Carbon fiber	7190	Km	From China (Birkved 2013)
	Glass Fiber	7190	Km	Assumed China
	Bio-epoxy	9030	Km	Entropy resin USA
	Traditional	9030	Km	Assumed USA
	Hardener	9030	Km	Entropy resin USA
Incineration	Incineration	0,454	Kg	All the blade
	Electricity production	0,747	MJ	Only the burneable part are considered
	Ashes	0	Kg	Glass and carbon fiber
	Distance use→Incineration	35	Km	From Birkved
	Incinerator →Landfill	100	Km	Assumed
Co-Processing	Avoided coal extraction	0	Kg	Calculated using calorific value (alloc)
	Avoided marl extraction	0	Kg	Assumed (Mass of glass fiber)
	Distance use→Cement kiln	160	Km	Assumed (Roskilde-Aalborg Portland factory)
Pyrolysis	Natural gas	0	Kg	From Cunliffe & Pickering, subtracted the gas production from the process
	Avoided fuel production	0	Kg	Calculated from Cunliffe & Pickering
	Avoided production Glass mat	0	Kg	Assumed equal to GF mass
	Avoided production Carbon fiber	0	Kg	Calculated with allocation base on mechanical properties (-20%)
	Distance use→ Pyrolysis	350	Km	Assumed (Roskilde-ReFiber plant)

2. ASSUMPTIONS USED TO BUILT THE MODEL

	Flow name	Process in Gabi	Justification	Implications
Fiber raw materials	Flax fiber	FR: flax long fibre PE	Best representative process	Minimal
	Carbon fiber	DE: Carbon fibre (CF from PAN) PE	Best representative process	Minimal
	Glass fiber	RER: Glass fibre, at plant	Best representative process	Minimal
Core	Core material	RER: polyurethane, rigid foam, at plant	Available process	Minimal if core is made by PUR. Wrong if it is made by balsa wood (not available in Ecoinvent)
Hardener	HDMA	Hexamethylenediamine (HDMA; via Adipic acid) PE	Best representative process	Minimal
	Benzyl alcohol	RER: benzyl alchol at plant	Best representative process	Minimal
	Hardener Mixer	Custom process	Assumes only mixing of the components (1:10) no energy counted	Lower the impact of hardner production (marginal effect)
Bio Epoxy (vegetable oil)	Pine tall oil	Organic Rape seed oil (custom premade)	No process found for pine oil	Best compromise
	Oil mill	CH: oil mill	Best representative process	Minimal
	Sewage treatment	CH: treatment, sewage, from residence to wastewater	Best representative process	Minimal

		treatment, class 2		
	Bentonite	DE: bentonite at processing	Best representative process	Minimal
	Rape seed	CH: rapeseed organic, at regional storehouse	Best representative process	Minimal
	Heat	RER: heat, natural gas, at industrial furnace >100kw	Best representative process	Assumed same consumption for US production
	Hexane	RER: hexane, at plant	Best representative process	Minimal
	Phosphoric acid	RER: phosphoric acid industrial grade 85% in h20 at plant	Best representative process	Minimal
	Transport	RER: transport freight rail	Best representative process	Minimal
	Transport	RER: transport, lorry>16t fleet average	Best representative process	Minimal
	Transport	RER: transport lorry 3.5 16t fleet average	Best representative process	Minimal
	Electricity	UCTE: electricity, medium voltage, production UCTE, at grid	Best representative process	Minimal
Epoxidized oil	Chemical Plant	RER: chemical plant organics	Best representative process	Minimal
	Transport	CH: transport, freight, rail	Best representative process	Minimal
	Transport	RER: transport lorry>16t fleet average	Best representative process	Minimal
	Electricity	DK:electricity, medium voltage, production DK, at grid	Best representative process	Could underestimate impact if US production
Epoxy resin traditional	Epoxy resin	DE: epoxy resin mix (EP) PE	Best representative process	Minimal
	Benzyl alcohol	RER: benzyl alcohol at plant	Best representative process	Minimal
Transport raw materials	Transport	OCE: transport, transoceanic freight ship	Available process in Ecoinvent	Lower emission transport mean
Wing production	Wing production	Custom process	No accounting for emission consumption and use of production materials	Underestimate the construction stage, not influent for comparative LCA (similar for all scenario)
Eol Incineration	Truck to incinerator	GLO: Truck PE	Available process	Minimal
	Truck to landfill	GLO: Truck PE	Available process	Minimal
	Fuel Truck	EU-15:Diesel ELCD/PE-GaBi	Best representative process	Minimal
	Incineration	RER: Polyamide (PA) 6.6 ELCD/PE GaBi	Available process	Different calorific value from nylon. This value has been corrected manually with the corrected calorific value
	Avoided electricity	RER: power grid mix PE	Available process	Minimal (could overestimate the positive effect of incineration if

				consider in Denmark)
	Landfill ashes	CH: disposal average incineration residue 0% water, to residual material landfill	Best representative process	Minimal
Co-processing	Truck to cement clinker	GLO: truck PE	Available process	Minimal
	Fuel	EU-15: Diesel ELCD/PE GaBi	Available process	Minimal
	Avoided fuel	RER: hard coal coke, at plant	Available process	Quantity allocated via physical properties (i.e calorific value))
	Avoided marl	CH: calcareous marl, at plant	Available process	Minimal (valid only for GF scenario)
Pyrolysis	Truck to Pyrolysis centre	GLO: truck PE	Available process	Minimal
	Fuel	EU-15: Diesel ELCD/PE GaBi	Available process	Minimal
	Gas for the process	RER: natural gas, burned in industrial furnace	Available process	Value to be decreased to the gas produced inside the process that have same calorific value (Pickering)
	Glass fiber	CH: glass wool mat, at plant	Best representative process	Not counted: PE wire bonding agent (minimal) heat for bonding (minimal)
	Liquid products	RER:heavy fuel oil, at regional storage	Best representative process	From Cunliffe
	Carbon fiber	DE:Carbon fibre (CF from PAN) PE	Best representative process	Allocation using mechanical properties (-20% recycled fiber)

APPENDIX D: SCALING UP

The blade studied in this thesis project is a small scale turbine blade. It will be interesting to investigate if the results given by this blade could represent also bigger commercial rotor blades for electricity production.

To do that a project scheme for this study has been developed, but due to the lack of time results could not be provided in this thesis work.

Additionally, as discussed in chapter 6, in order to make better use of natural composites is to use them in parts that have similar mechanical behavior to a panel in bending. Looking at a big blade structure we can see that is composed by two main part: a central structure, usually called spar caps that act against the bending moment, and the shell that plays the primary function is to provide the aerodynamical shape of the blade.(Gurit 2011).

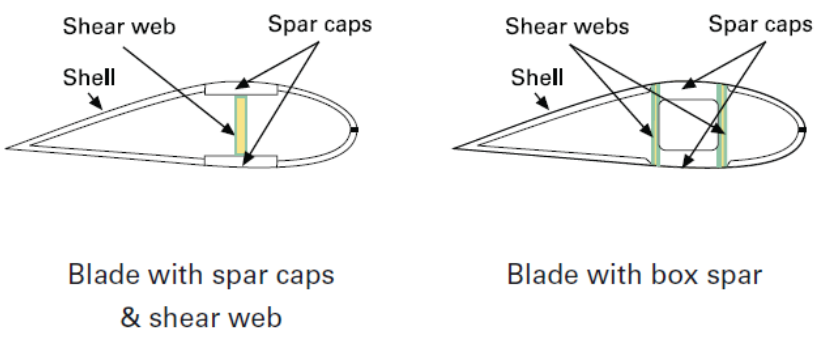


Fig D.1 **Section of the two most common blade design.**

Hence, following Asbhy's methodology, spar caps will act as a beam while shell will act as a panel in bending. Both of them are made by composite material, additionally shell are made by sandwich material, that is composed by an internal layer of lightweight (usually low density material, foam or honeycomb structure) material surrounded by two layers of composites. Hence it will be interesting to study a possible substitution of part of shell with natural composites in place of glass composite. Then once obtained the weight of the blade with some part substituted,an LCA could be performed, to see if there is a better environmental performance. Logically as explained in cap 6 natural composite in the case of the shell could be up to 24% lighter than the glass one allowing a better environmental performance (less weight less impact) and also lightening the blade (allowing less stress on the blade due to its weight).

The product system was modeled in GaBi also to analyze this scenario, letting him manage also core material (for sandwich part) and the root part of the blade that is made generally by metal.

D. 1 Mechanical model

In order to evaluate if the blade with material substitution fulfill the mechanical design requirement it is necessary to perform a finite element analysis. This is a highly time consuming process; but a specific software was developed by Risø research center to facilitate this work.

The BMT tool comprises of an excel spreadsheet with various components. The output of the tool is a 3D finite element model of a wind turbine blade. The BMT is extremely easy to use, where the modules such as geometry, layup, groups etc. can be changed quickly. The tool helps in making optimization studies very easy to perform. The scritpt created as output by BMT, are then used in Patran as the pre-processor stage and then ABAQUS or MARC as the post processor to evaluate the mechanical responses of the blade at the design loads. BMT tool was used to obtain the structure of the blade. The BMT tool comprises of the following modules:

- Material
- Layup
- Geometry
- Mesh
- Groups

It is possible to change each one of the modules to perform an optimization of the standard blade implemented in BMT. In this case, it is only required to change the material modules. This module in the BMT tool contains all the materials used to build the blade, and all the mechanical properties for each of these materials. The default materials were glass fiber composites having a volume fraction close to 60%.

Material Script

Material Script

Material Variables	
Solver	Marc

Material Data

Mesh No.	ID	Material 1	Material 2	Material 3	Material 4	Material 5	Material 6	Material 7	Material 8	Material 9	Material 10	Material 1
Include/Exclude (FE)		Include	Include	Include	Include	Include	Include	Include	Include	Exclude	Exclude	Exclude
Name	-	Root	Core	UD1600	Tr900	Tr900a	Bi600	Bi600s	Glue340			
Type	-	Isotropic	Isotropic	3d Orthotropic	3d Orthotropic	3d Orthotropic	3d Orthotropic	3d Orthotropic	Isotropic			
Elastic Modulus 11	2	1,00E+11	4,85E+07	4,34E+10	1,63E+10	1,63E+10	1,63E+10	1,63E+10	3,00E+09			
Elastic Modulus 22	3			1,45E+10	1,63E+10	1,63E+10	1,63E+10	1,63E+10				
Elastic Modulus 33	4			1,45E+10	1,45E+10	1,45E+10	1,45E+10	1,45E+10				
Poisson Ratio 12	5	0,30	0,40	0,27	0,44	0,44	0,44	0,44	0,38			
Poisson Ratio 23	6			0,30	0,30	0,30	0,30	0,30				
Poisson Ratio 31	7			0,09	0,30	0,30	0,30	0,30				
Shear Modulus 12	8			3,83E+09	1,02E+10	1,02E+10	1,02E+10	1,02E+10				
Shear Modulus 23	9			3,83E+09	1,02E+10	1,02E+10	1,02E+10	1,02E+10				
Shear Modulus 31	10			3,83E+09	1,02E+10	1,02E+10	1,02E+10	1,02E+10				
Density	16	3,00E+03	8,00E+01	1,99E+03	1,93E+03	1,93E+03	1,93E+03	1,93E+03	1,18E+03			
Thermal Expan. Coeff 11	24											
Thermal Expan. Coeff 22	25											
Thermal Expan. Coeff 33	26											
Structural Damping Coe	30											
Reference Temperature	1											
Conductivity	17											
Specific Heat, Cp	23											
Kommentar	-											

Fig D.2 **Material module in BMT**

Flax fiber fabrics must be defined in this module. Properties of flax fabrics would need to be inputted into this module. It must be said that the material for the root and core should not be altered when trying to input flax composites.

The second step look at the Layup model, import the material from the material module and then substituting in the layup model the part that are wanted to change.

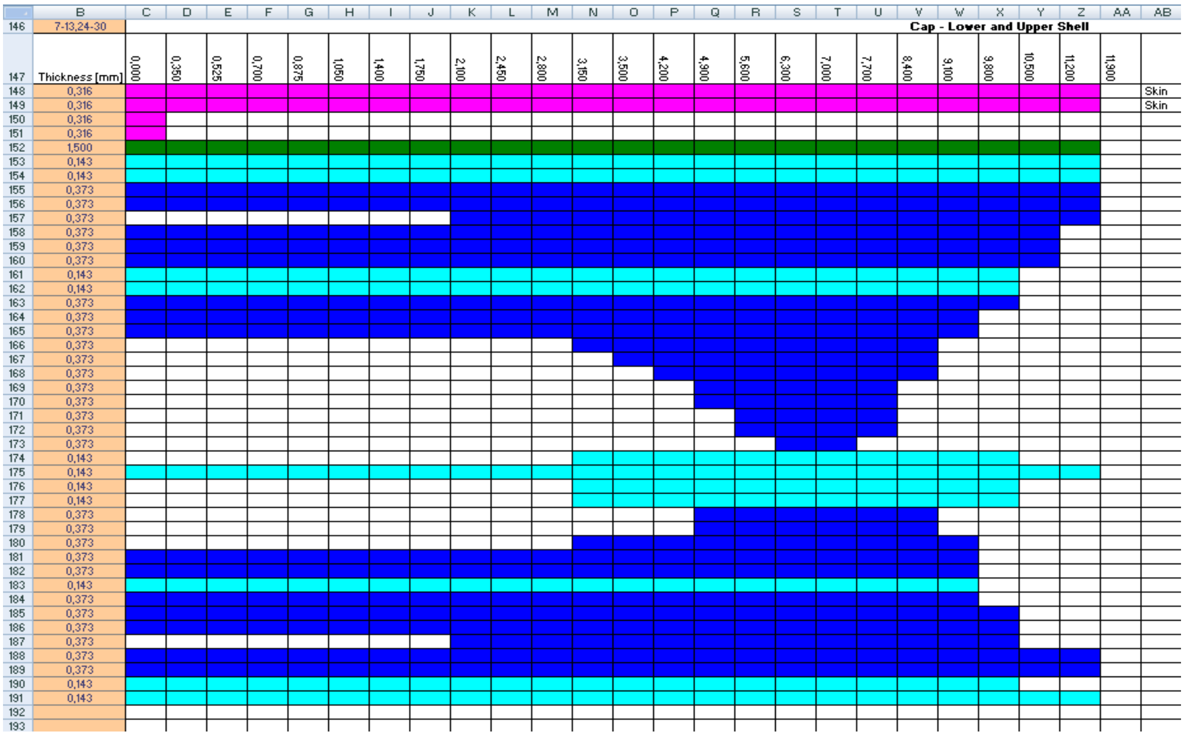


Fig D.3 **Layup module in BMT**

Finally a script for each module must be created with the following order:

- Material
- Layup
- Geometry
- Mesh
- Group

Once the above scripts are created in the module in the following order, the next step can be commenced which is the preprocessing stage, using Patran. Patran works combining together the scripts and creating the blade structure that after this step could be inputted in the Finite Element Analysis software.

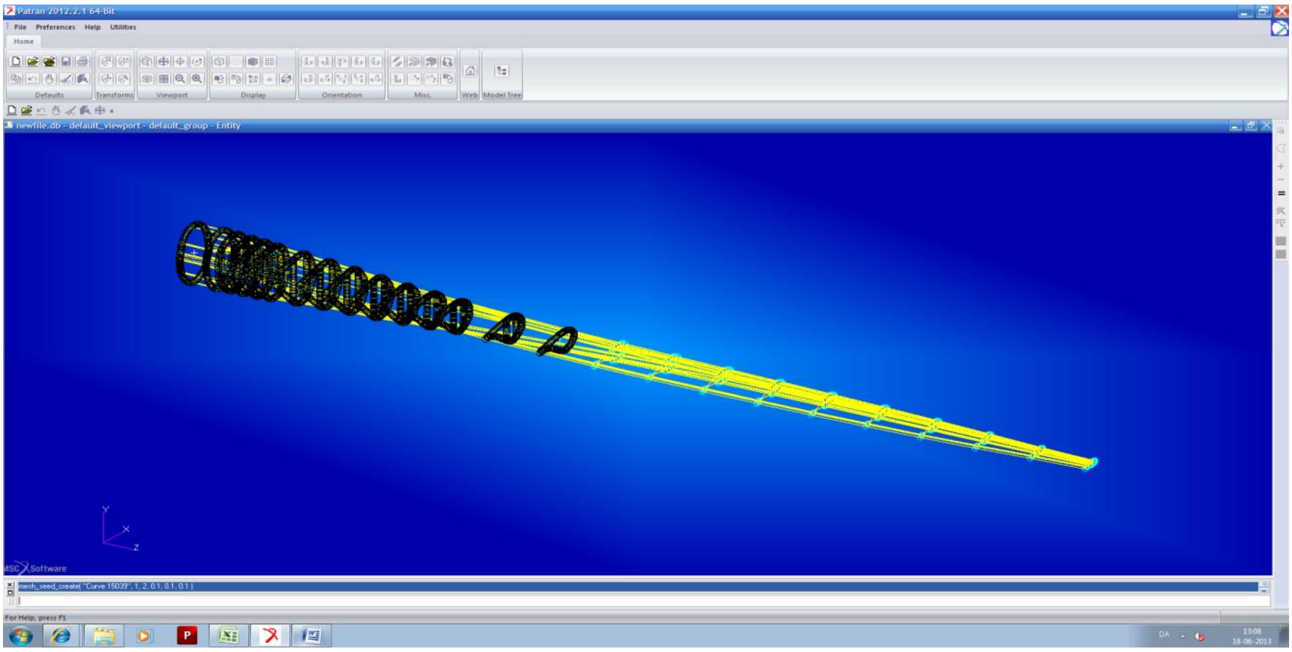


Fig D.4 **Combining the script created in BMT using Partan**

Then this model is inputted in Abaqus where are added also the loads and where it is possible to evaluate deformations and strength and failure criteria. At this point a stiffness criteria should be defined in order to see if the blade created fulfill design requirements. At this step also it is possible to extract the mass of the material inside the blade. This information then will be used as input in the product system model.

D.2. Which part to substitute?

In BMT tools blade’s section is divided and numbered in several part. Fig2 present the numbering system

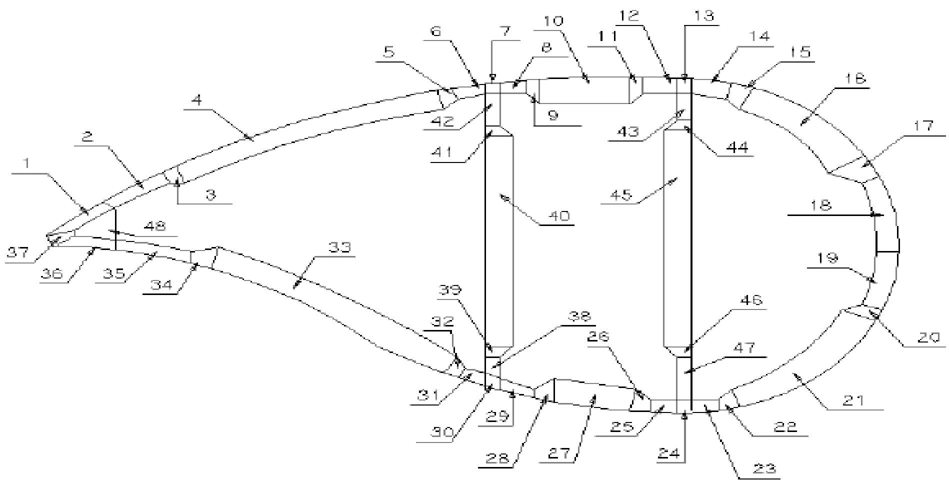


Fig D.5 **Numbering on the different part of the blade’s section in BMT**

In a previous work [Khubchandani 2011] the standard scenario is compared to a scenario where all the part are substituted by flax composite. But this work doesn’t show good results, the deformation in the pure flax blade were too high. Thus 7 scenarios were created:

- Standard reference scenario: no material substitution
- Webspar substitution (from nr38 to 47)
- Front shell substitution (from nr14 to 23)
- Trailing edge upper side substitution (from nr3 to 5)
- Training edge lower side substitution (from nr 32 to 34)
- Outer shell substitution (14/23, 3/5, 32,34)
- Outer shell + webspar

It is important to note that in any scenario the spar cap is substituted. This because as explained before spar caps is the load carrying part so in a conservative approach this part don’t have to be changed.

RIASSUNTO ESTESO IN ITALIANO

I materiali compositi sono largamente utilizzati in svariati settori industriali grazie alle loro straordinarie proprietà meccaniche combinate a una bassa densità. Il loro uso è iniziato dagli anni ’60 e da allora molta ricerca è stata compiuta per capirne il comportamento e migliorarne le caratteristiche.

Negli ultimi anni, il crescente interesse verso gli effetti ambientali delle attività industriali, assieme a restrizioni legislative ha spinto verso la ricerca di materiali alternativi ai rinforzi fibrosi inorganici con lo scopo di abbassare l’impatto ambientale di tali materiali. Queste motivazioni hanno spinto industrie e università a investire e studiare su i materiali compositi a base naturale (NFRP).

Inizialmente i NFRP erano usati nel settore automobilistico ed edilizio per applicazioni non strutturali, soprattutto come barriera termica/isolante. Successivamente l’interesse si è spostato verso applicazioni strutturali. Diversi studi hanno dimostrato la fattibilità nell’uso di NFRP come possibili sostituzioni di compositi tradizionali (Joshi et al 2004) (Duigou et al 2011).

La possibilità dell’uso di compositi a base naturale in una micro-pala eolica è stata dimostrata dal Wind Energy department alla DTU (Bottoli et al 2011). Questo studio ha incluso una valutazione di sostenibilità iniziale tramite la metodologia MECO. Gli autori però hanno concluso che ulteriori studi erano necessari per valutare l’effettiva sostenibilità dei NFRP. Quindi, non c’è l’effettiva dimostrazione che, per il settore eolico, i materiali a base naturale aiutino ad abbassare l’impatto ambientale della produzione di tali pale eoliche.

In questa ricerca si è analizzata la sostenibilità ambientale di un composito a base naturale con fibre di lino rispetto a compositi tradizionali in applicazioni eoliche. Specificatamente DTU ha sviluppato tre micro-pale eoliche da 80 cm con materiali diversi. Tali pale dovevano rispettare gli stessi requisiti di rigidezza e resistenza meccaniche e sono state montate su una macchina a propulsione eolica sviluppata per Aeolius, una gara per macchine a vento, che ogni anno si disputa in Olanda a cui partecipano le migliori università del mondo.

Punto forte i tale manifestazione è che, sebbene le macchine a vento abbiano delle pale molto piccole, esse rappresentano in piccola scala il comportamento di grandi pale, per cui tecnologie, materiali e processi produttivi sono del tutto similari a quelli per la produzione di grandi pale per la produzione di energia.

Un'altra parte di studio di tale progetto si è sviluppata sulle possibili modalità di riciclo dei materiali compositi analizzando le possibili tecnologie per il riciclo di tali materiali e andando a valutarne il loro impatto rispetto a tutto il ciclo di vita del prodotto.

Selezione dei materiali

Le fibre utilizzate in tale progetto sono due tipi di fibre convenzionali: fibra di vetro e fibra di carbonio che funzionano da riferimento rispetto al composito a base naturale da analizzare. La pala in fibra di carbonio è stata progettata e realizzata in un precedente studio (Bottoli et al 2011) mentre lo scenario con la fibra di vetro è stato sviluppato tramite assunzioni ottenute tramite il modello di Ashby.

La fibra naturale selezionata per questo progetto è la fibra di lino. Tale fibra è stata selezionata perché può essere cresciuta con un basso impiego di pesticidi e fertilizzanti poiché non tende ad esaurire il suolo, contrariamente alla più comune fibra naturale quale il cotone.

Le fibre di lino posseggono buone proprietà meccaniche e una bassa densità che la rendono una fibra ideale per il rinforzo di materiali polimerici.

Il processo produttivo però, derivato dall'industria tessile, tende ad abbassarne le proprietà meccaniche, soprattutto le resistenza meccanica. Inoltre tende ad innalzare l'assorbimento di resina necessaria per la produzione del composito. Tali problematiche sono dovute a tre motivi principali:

- Le fibre vengono danneggiate perché il processo produttivo è studiato per ammorbidire le fibre rendendole ideali per l'industria tessile.
- L'angolo di filatura delle fibre comporta il carico delle fibre fuori asse principale comportando una minore utilizzazione delle proprietà meccaniche teoriche.
- Inoltre l'angolo di filatura e siccome le fibre sono di origine naturale e quindi corte comporta un elevato assorbimento di resina comportando un conseguente abbassamento delle proprietà meccaniche del composito.

Valutazione del ciclo di vita

Per poter analizzare la performance ambientale di un prodotto o servizio è necessario analizzarlo lungo tutto il suo ciclo di vita, valutando gli impatti creati "dalla culla alla tomba".

La valutazione del ciclo di vita (LCA) è una metodologia che permette la quantificazione degli impatti ambientali creati da un prodotto/servizio lungo tutto il suo ciclo di vita, partendo dalla quantificazione di input e output lungo il ciclo di vita del prodotto.

Tale metodologia, standardizzata dalla norma ISO 14000 e 14040, si compone di quattro fasi iterative tra loro:

- Definizione di obbiettivo e campo di applicazione.
- Inventario del ciclo di vita (LCI) dove tutti le emissioni e gli input dei vari step del ciclo di

vita del prodotto vengono analizzati.
- Valutazione degli impatti (LCIA) i vari flussi calcolati dall'LCI vengono ora convertiti tramite metodologie standard in impatti ambientali. A seconda del metodo selezionato diversi tipi di impatto possono essere analizzati.
- Interpretazione: lo studio LCA si conclude sempre con la fase di interpretazione dei dati dove vengono presentati punti deboli del ciclo di vita unitamente a soluzioni e consigli su quale fase intervenire per abbassare l'impatto ambientale del prodotto/servizio studiato.

Modalità di riciclo

Da un iniziale ricerca sulla letteratura sono stati selezionati tre diversi tipi di riciclo per materiali compositi. Tali modalità sono state analizzate tramite metodologia LCA per analizzare qual'era la soluzione migliore per il fine vita della pala eolica studiata nel progetto. La motivazione dello studio del fine vita delle pale eoliche è dovuta a due principali cause:

- Il settore eolico è in fase di crescita esponenziale. Non vi sono ancora esempi pratici sulle modalità di smaltimento di tali impianti perché pochi di loro hanno raggiunto il fine della vita utile.
- I materiali compositi sono materiali difficili da riciclare a causa dell'eterogeneità dei materiali che li compongono e soprattutto dell'utilizzo di polimeri termoindurenti che non sono riciclabili.

Le tecnologie di riciclo selezionate sono tre:

- Incenerimento con recupero energetico. Questa è una modalità comune ed è stata presa come riferimento per valutare altre metodologie più innovative permettono di abbassare l'impatto ambientale del ciclo di vita del prodotto.
- Co-processing: tale metodologia prevede l'utilizzo dei materiali compositi come sostituzione di parte del combustibile utilizzato nella produzione di materiale cementizio. Tale metodologia, del tutto similare all'incenerimento, ha il punto forte che limita i processi di combustione da due ad uno solo contribuendo ad abbassare le emissioni globali del processo.
- Pirolisi: tale metodologia non è ancora utilizzata nella realtà industriale è stata sviluppata solo a livello di laboratorio. Essa prevede unitamente al recupero energetico della matrice il recupero della fibre che nei precedenti processi andava persa. Tali fibre possono essere utilizzate nuovamente nella produzione di altri manufatti.

Risultati

Lo scenario in fibra di carbonio è quello che presenta impatti più elevati interamente riconducibili alla fase di produzione della fibra ad alta intensità energetica. La pala in NFRP ha un comportamento globale simile a quello della fibra di vetro. Le uniche differenze sono che per il NFRP visto la grossa quantità di resina utilizzata per l'infusione della pala si hanno alti impatti sulla salute umana dovuti al processo produttivo della resina epossidica. A livello di consumo di risorse tale composito si comporta molto bene, visto che le fibre naturali richiedono molte meno risorse non rinnovabili per la loro produzione.

Analizzando il fine vita del prodotto. Si hanno comportamenti diversi a seconda del materiale utilizzato.

Per NFRP la soluzione migliore rimane ancora l'incenerimento col recupero di energia. Anche se la ricerca si sta focalizzando nella produzione di matrici biodegradabili che potrebbe rendere tale materiale interamente compostabile.

Per GFRP la soluzione migliore risulta il co-processing. Questo per due principali motivi: le fibre possono essere inglobate nella miscela cementizia senza nessun problema visto che posseggono gli stessi componenti chimici utilizzati nella produzione del cemento. Inoltre sebbene la Pirolisi possa recuperare tali fibre essa tende a danneggiare troppo le fibre (l'apretto viene rimosso dal trattamento termico) comportando l'utilizzo di tali fibre in applicazioni non strutturali come pannelli isolanti per l'impiego in edilizia.

Per CFRP la soluzione migliore risulta la pirolisi. Questo è dovuto soprattutto al fatto che le produzione di tali fibre è molto costosa ed ad alta intensità energetica. Poiché le fibre riciclate hanno solo un lieve abbassamento delle proprietà meccaniche ed esse possono essere utilizzate di nuovo in applicazioni strutturali, è di enorme interesse, non solo ambientale il riciclo di tali fibre.