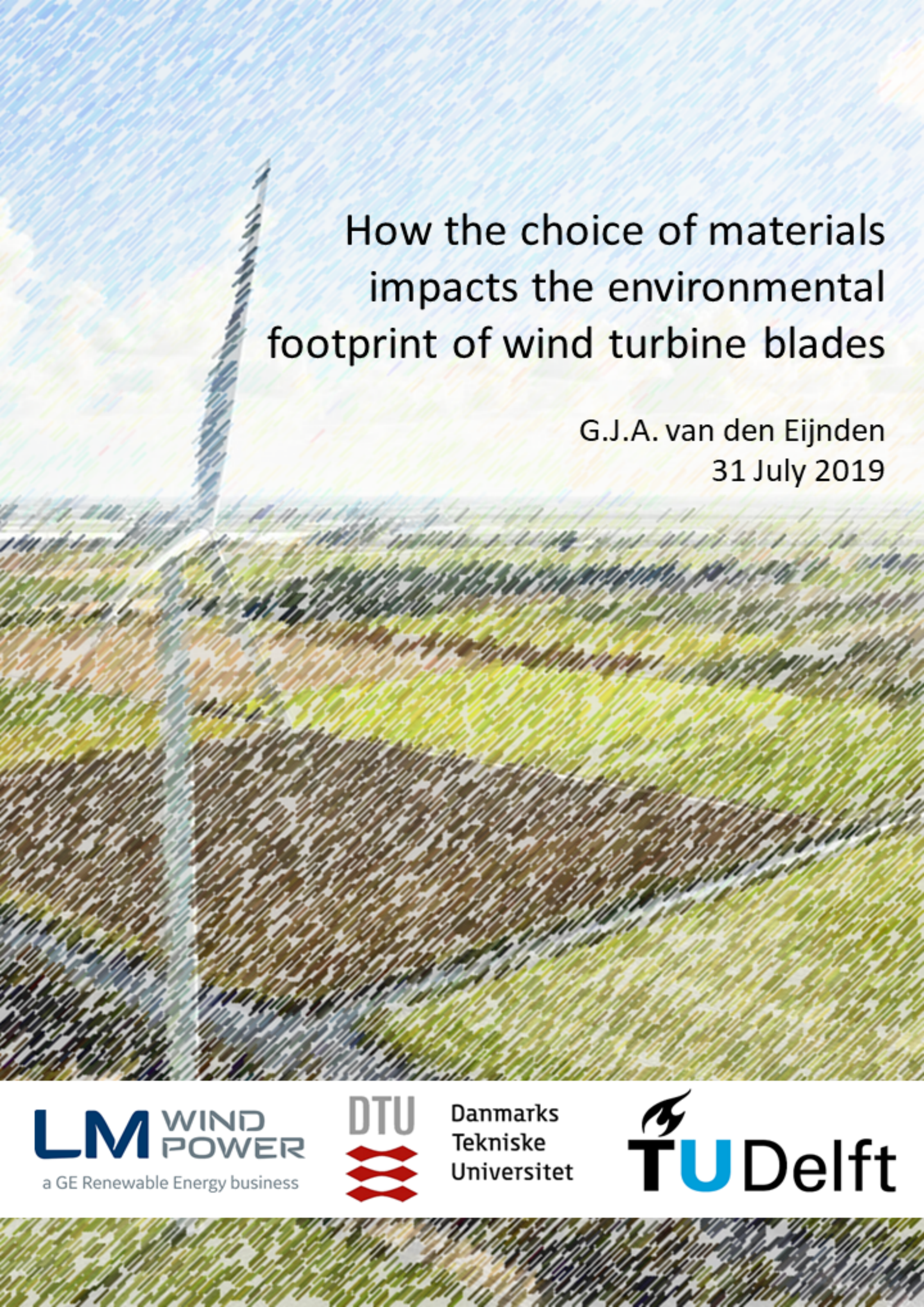

How the choice of materials impacts the environmental footprint of wind turbine blades

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Abstract

In this comparative eco-design study, the environmental impact of LM's 58.7 blade was assessed for multiple material composition and waste management scenarios. Material variations were largely focusses on the resin fraction of the blade. This is since the matrix has the biggest impact of all materials and has a big impact on the available waste management options that are available.

Material and waste management scenarios were largely selected based on a literature review. This knowledge was combined with the knowledge and current direction of LM to determine the investigated scenarios. Life Cycle Assessment (LCA) methodology was applied to calculate the potential emissions and resulting environmental impacts. To calculate the impacts, the Ecoinvent 3.5 database was used in combination with the ReCiPe 2016 Life Cycle Impact Assessment (LCIA) methodology.

Analysis showed that Sub Critical Water (SubCW) hydrolysis likely is the waste management method with the lowest impact for the current used glass fibre - polyester design. However, two design changes can potentially lead to big reductions in total single score impact scores. These two are: designing for reuse of blade sections and interchanging thermoplastic resin for the currently used thermoset polyester resin. Both are beneficial because of the relatively direct reuse/recycling of material.

This research can be extended to more resin types and waste management methods of these resin types. This will shed a broader light on the matter. When waste management methods reuse methods should be prioritized over recycling methods and 'clean' recycling methods (i.e. methods that do not lean on heavily polluting processes) over dirty recycling methods.

Preface

This research is focussed to assist LM Wind Power in the understanding of the effect of material choice in wind turbine blade design on the environmental impact of such blades. This fits well within LM's carbon neutrality program and LM's developing interest to reduce climate impact of its products. It is very much appreciated to have received the opportunity to be part of this development in a meaningful area of work.

I wish to express my gratitude for the guidance I received from my supervisors. First of all, Sybren Jansma for his feedback and ideation during our weekly discussions, providing me with in- and external contacts and helping me find my way in the organisation. Also, Alexis Laurent for his helpfull suggestions of literature and his coaching in proper implementation of LCA methodology. Bo Madsen, Jos Sinke, and Justine Beauson for your help in scoping this research, guidance and feedback on the reporting.

Lastly, I would like to thank my family, friends, team mates, and colleges. My family for their unconditional support throughout the years. This is truly invaluable an will not be forgotten. To my friends and team mates I would like to say thank you for sticking together throughout the hard times and being there to enjoy the good times. Also, many thanks to my colleges for welcoming me within LM and assisting me if possible.

Gérard J.A. van den Eijnden
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Nomenclature

Abriviations

Abbreviation	Meaning
BAPP	2,2-bis[4-(4-aminophenoxy)phenyl]propane
BMI	bis(4,4'-maleimidodiphenyl)-methane
BOM	Bill Of Materials
EoL	End of Life
DMAc	N,N-Dimethylacetamide
DTU	Technical University of Denmark
DUWIND	TU Delft Wind Energy Institute
FE	Freshwater eutrophication
FET	Freshwater ecotoxicity
FPM	Fine particulate matter formation
FRS	Fossil resource scarcity
GFRP	Glass fibre reinforced plastic
GHG	Greenhouse gas
GW, HH	Global warming, Human health
GW, TE	Global warming, Terrestrial ecosystems
GW, FE	Global warming, Freshwater ecosystems
HCT	Human carcinogenic toxicity
HnCT	Human non-carcinogenic toxicity
IR	Ionizing radiation
LCA	Life Cycle Assessment
LCI	Life Cycle Impact
LCIA	Life Cycle Impact assessment
LU	Land use
MET	Marine ecotoxicity
MRS	Mineral resource scarcity
ME	Marine eutrophication
OF, HH	Ozone formation, Human health
OF, TE	Ozone formation, Terrestrial ecosystems
PET	Polyethylene terephthalate
PFA	Paraformaldehyde
PHT	Poly(hexahydrotriazine)
REACH	Registration, Evaluation, Authorisation and Restriction of Chemicals
SCW	Super Crital Water
SOD	Stratospheric ozone depletion

Abbreviation	Meaning
TA	Terrestrial acidification
TGDDM	tetradiglycidyl diaminodiphenylmethane
TET	Terrestrial ecotoxicity
THF	Tetrahydrofuran
TRL	Technology readyness level
UPR	Unsaturated Polyester Resin
VOC	Volatile organic compound
WC, HH	Water consumption, Human health
WC, TE	Water consumption, Terrestrial ecosystem
WC, AE	Water consumption, Aquatic ecosystems

Symbols

Symbol	Description	Unit
δ_{tip}	Tip deflection	m
L	Blade length	m
M	Moment	Nm
E	Youngs modulus	Pa
I	Moment of inertia	m^4
x	Spanwise location along the blade	m
E_{FP}	Youngs modulus in the fibre direction	Pa
V_f	Fibre volume fraction	-
E_{f1}	Youngs modulus of the fibre in the fibre direction	Pa
V_m	Matrix volume fraction	-
E_m	Youngs modulus of the matrix	Pa
E_p	Youngs modulus perpendicular to the fibre direction	Pa
E_{f2}	Youngs modulus of the fibre perpendicular to the fibre direction	Pa
m_{reuse}	Reuse mass fraction	kg/kg
M_{reused}	Mass of the reused part of the blade	kg
M_{Total}	Total blade mass	kg
var	Variation w.r.t the baseline resin composition	-
IS_{AS}	Impact score of the alternative resin composition	
IS_{BL}	Impact score of the baseline resin composition	
IS_{total}	Impact score of the blade	
n	Amount of material entries	-
IS_m	Impact score of material	
IS_w	Impact score of the waste management process	
w_i	Material weight	kg
m	Amount of non-material entries	-
IS_{nm}	Impact score of the non-material process	
q	Quantity	-
m_{blade}	Blade mass	kg
$m_{material}$	Mass of material	kg
c_{blade}	Blade cost	Euro
c_m	Material cost per kilo	Euro
c_e	Extra cost	Euro
$m_{recycle}$	Recycle mass fraction	kg/kg
$m_{recover}$	Recover mass fraction	kg/kg
$m_{landfill}$	Landfill mass fraction	kg/kg
$M_{recycle}$	Mass of recycled portion	kg
$M_{recover}$	Mass of recovered portion	kg
$M_{landfill}$	Mass of landfilled portion	kg

1 Introduction

1.1 Objective

Compared to other forms of energy production, wind energy results in very low CO2 emission [8, 64]. This is especially true during the operating life due to maintenance. However wind energy is not completely emission free. Especially the material extraction of materials used in blade production has an impact on the environment. This is true for the entire wind turbine as well as for the blades specifically. This research focusses on turbine blades build be LM Wind Power.

The impact of the material extraction phase is mainly dependent on materials are used and in what quantities. Originally Unsaturated Polyester Resins (UPR) are used in the blades build by LM Wind Power. The resin is reinforced by glass fibre and locally the bending stiffness is increased by adding balsa wood core material. The choice of materials is, amongst other things, based on price, manufacturability and material properties. However, their impact on the environment was not always part of it in the past. To enable decision makers to include environmental impact of designs in the decision making process extra knowledge is required on the relation between materials and their environmental impact.

To assist gathering this knowledge a life cycle assessment (LCA) was made on different material combination scenarios. This shows these specific scenarios have on the total impact. However, the impact is not only dependent on the choice of material. Different materials allow different waste management methods to be applied.

Waste management can be divided into disposal, recovery of energy, recycling of materials, and (partial) reuse of the product. According to waste legislation of the EU Member States the latter is preferred over the first since this is the most direct way of avoiding impact. To show the difference all four categories of waste management method were covered in this study.

1.2 LCA Methodology

A life cycle assessment is build up out off five building blocks. Goal definition, scoop definition, inventory analysis, impact assessment, and interpretation [24]. It is not a serial, but an iterative process, as shown in Figure 1. First a complete cycle from goal definition until impact analysis is performed. This initial evaluation of the environmental footprint is based on many assumptions. The validity of the results and the sensitivity of result on the assumptions is assessed during the interpretation phase of this initial evaluation.

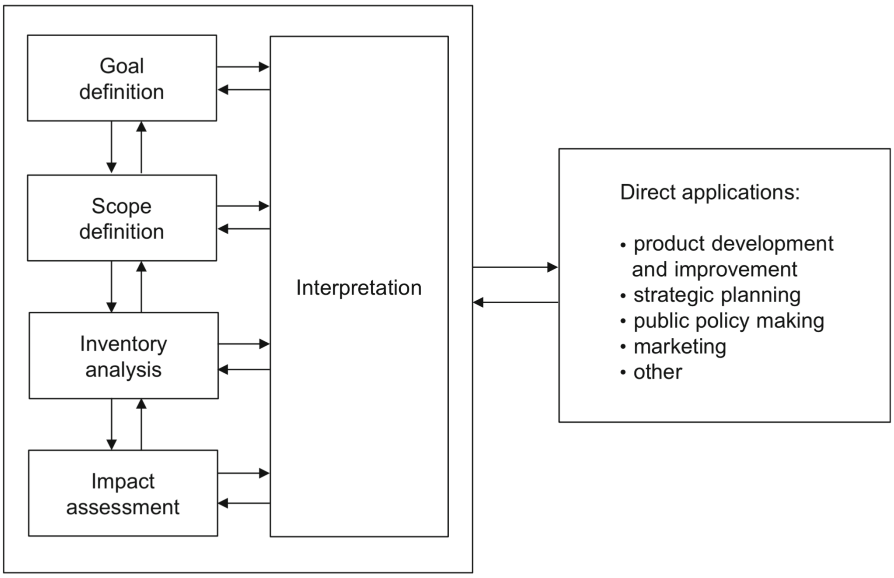

Figure 1: Structure of LCA based on ISO 14040:2006 modified by Hauschild et al., 2018 [30].

1.2.1 Goal definition

This part of the LCA mainly focuses on finding all stakeholders, defining the intended applications of the results, decision making context. This is the basis for the scope definition.

1.2.2 Scope definition

To define the scope first the object of assessment is defined by defining the functional unit and the reference flow. These describe the function of the system and the flow of material used to compare different scenarios. The multifunctionality is assessed and a solution for properly solving this is determined based on the type of system. Based on the decision making context a choice is made between attributional and consequential modelling. Lastly, the system boundaries are determined.

1.2.3 Inventory analysis

The main steps of the inventory analysis are the collection of the data, checking the quality of the data and, after constricting the LCI model out of the unit processes, preparing for the sensitivity analysis. This is however only possible after analyzing and listing all processes which take part in the life cycle of the the analyzed system.

1.2.4 Impact assessment

A big part of the impact assessment, including classification and characterization, is automatized in current day LCA software. The choice of LCIA software also determines the impact categories for which results are calculated and the way these results are calculated. Optional steps can be added to the previously described mandatory steps. These optional steps include normalization, weighting and grouping. The two last optional steps introduce subjectivity into the results. It therefor should be considered if these steps add significant benefits to the analysis or not.

1.2.5 Interpretation

During the interpretation phase of the LCA the validity of the LCA model is checked using consistency and completeness checks. Next to this the sensitivity of certain processes is also assessed during this step.

The sensitivity analysis as preformed by varying inputs, within the bounds set by either the database or literature, and assessing their impact on the result.

When the biggest contributors to uncertainty are identified, a second iteration is performed. The goal of the second and following iterations is to revise the goal and scope definition if needed, reduce the uncertainty of the results by increasing the data precision, and identify the new biggest contributor to the uncertainty of the results.

1.3 Structure

The report can be divided in three parts with different focus points. The first part of the report defines the investigated scenarios. This is largely based on a review of existing literature. Next the LCA study is presented. This part follows a classical LCA structure which includes the five steps described in the previous section, but excludes the conclusions, limitations, and recommendations. This is followed by the description of the developed tool which will enable LM to do a quick assessment of the environmental impacts, cost, weight and recyclablility of potential blade designs. Finally there is a concluding chapter which also touches upon limitations and recommendations for future work.

2 Literature review

To gain the necessary knowledge, literature from three research areas was reviewed. These areas are material, LCA, and/or waste management related. This section will evaluate these areas one by one and will elaborate on part of the correlation between these individual fields of study.

2.1 Life Cycle Assessment

Since knowledge on LCA practise and LCA studies on wind turbine (blades) show what areas of research to focus on in the other categories, LCA was taken as a starting point. The steps of an LCA process are shown in Figure 1 and LCA methodology is described in the LCA standard ISO 14040 [24].

LCA results have a high dependency on what database is used. This is since substantial differences could be found between databases for the same material [30]. Next to this, specific data may still be unavailable. This is highly dependent on the database. To give an example, carbon fibre is not included in the Ecoinvent databases up to Ecoinvent 3.5.

There also is a large dependency of LCA results on the used Life Cycle Impact Assessment (LCIA) methodology, as was outlined by a wind turbine case study [41]. This study compares LCA results of seven impact categories calculated using seven different LCIA methods. These seven LCIA method were chosen because they showed to be the best represented methods in literature. The comparison shows that some impact calculations result in comparable numbers for a given impact category for multiple LCIA methods. If the spread between them is relatively small this impact category is seen as more mature and results are therefor assumed to be more certain. This is the case for global warming potential, acidification and ozone layer depletion. For less mature impact categories, e.g. human en ecotoxicity, abiotic depletion and eutrophication, calculated impacts may be several times higher for one LCIA method than for others.

Next to modelling choices, the investigated system is - not surprisingly - a big factor on the results. Existing life cycle assessments of energy systems using kinetic energy of the wind often focus on the whole turbine and do not solely focus on the turbine blades. This is because of the functional units[1] defined during these LCA's, which generally capture the function of the whole turbine instead of the blade. This makes sense if the goal is the compare different turbines based on for

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[1] The functional unit quantitatively defines the function of the investigated system and is used to determine the reference flow during the inventory analysis. [30]

instance emissions per energy output. This choice of functional unit may however not be necessary for a comparative study on turbine blades designed for the same specifications. If the rest of the turbine is able remains unchanged for the different blades and only the blades are varied, the rest of the turbine will not contribute to differences between the scenarios. The rest of the turbine does therefor not have to be modelled [24]. This will significantly simplify the model.

Emissions per kWh go down with the rate power of wind turbines [5,12]. However, the size effect largely fades away when turbine sizes exceed 1 MW some impact categories [5]. Since the average rated power of wind turbines has increased over time, the size effect could be partially caused by advancements in wind turbine engineering (i.e. wind turbines off the same size have become cleaner over time).

Investigating what materials may enable turbines to become bigger is however not part of this research. The sames goes for materials enabling life time extension. However, if materials show promising characteristics, this might be a reason to include these promising materials in the study and see their effect on the Life Cycle Impact (LCI).

The biggest part of the total environmental impact originates from the material extraction phase of the turbine life cycle, with the manufacturing phase as a clear second [10]. The material extraction phase can account for around 70% to 79% of the Greenhouse House Gas (GHG) emissions of the entire wind turbines [10], 5-15% of which is contributed by the rotor. Another study concludes however that the contribution of the rotor to the total GHG-emissions was rated at 40% of the total emissions by [41]. This is a big difference, especially for a mature LCI category as greenhouse potential, and no clear reason was found to clarify these results. It is however illustrative for the big differences in results which are often present between LCA study results.

Only looking at the embodied energy of blades, fibre and resin fractions account for 60.4% and 32.3% percent of the weight and 38.6% and 56.7% of the embodied energy respectively [40]. It is remarkable that the resin contributes substantially more to the embodied energy than the fibre fraction although the weight fraction is substantially lower. The high contribution of the fibre and especially the resin fraction during the material extraction phase motivate the need for recycling. Recycled matrix and fibres may result in avoided production since these materials remain in the technosphere for reuse.

2.2 Waste Management

Waste management can have a big impact on the total environmental impact of the turbine blades. However, before getting into this matter it is important to define what waste management is and what waste management categories there are. Directive 2008/98/EC from the European Parliament defines the following waste hierarchy: prevention, preparing for re-use, recycling, other recovery, and disposal [21]. Where prevention is the most preferred and disposal the least preferred waste management category. This is since prevention is the most direct way possible to reduce the contributions of the material extraction phase and disposal does not benefit the reduce these contributions at all.

Prevention is however not included in the scope of this research. Simple forms of preparing for re-use and multiple recycling techniques are included in the scope of this project. Also energy recovery (incineration) and disposal (landfilling) are include as reference waste management scenarios.

Preparing for reuse scenarios could include life time extension scenarios of entire blades or blades components (e.g. aerodynamic fairing, bulkheads or webs). The reuse scenarios will however need further improvements in the load monitoring and fatigue life predictions. Including these scenarios in this LCA does not say anything about the feasibility from a mechanical point of view, but will only serve as a prediction of the environmental impact using these waste management scenarios.

Recycling scenarios of composite materials used in wind turbine blades can be divided in 3 categories: mechanical, thermal, and chemical recycling. [38]. Thermal and chemical recycling techniques often are combined with a mechanical recycling steps. This is since the chemical and thermal reactors is often to small to fit whole products or components.

Classical mechanical recycling techniques include hammering, grinding, and cutting. These techniques often need considerable amounts of energy to reduce the recyclate down to the desired size. A way to decrease the energy usage is the use of electro-dynamic fragmentation [55].

After reducing the size the composite particles can than be used in thermal or chemical recycling or could be used as material to make new composite products. However, the size of the fibres will be reduced. Products made from the recycled composite will therefor not be suited for heavy loaded structural applications. In case of pallets of thermoplastic resin the products from the mechanical recycling can be processed into granulates used for injection moulding. Flakes of thermoset resin composite can be compacted in a mold and infused with resin. Both methods however are considered down-cycling (i.e. the material properties clearly have been decreased).

The most notable thermal recycling technique, because of its relatively high TRL [56] and ability to reclaim materials [46], is pyrolysis. During the pyrolysis process the matrix is not simply burned. The combination of a high temperature, high pressure and a lack of oxygen causes the resin to split in a gas and liquid fraction.

The gasses are burned in a separate, oxygen-rich reactor and the heat is often reused to power the pyrolysis process. The oils are often claimed as byproducts.

A distinction is made between the different pyrolysis processes: pyrolysis, fluidized bed pyrolysis and microwave assisted pyrolysis. Fluidized bed pyrolysis has the advantage that it allows for the recovery of inserts and allows treatment of painted composites [50]. Microwave assisted pyrolysis reduces the energy need and heating time of the recycling process [39].

A common difficulty of thermolysis processes is removing the matrix while keeping the degradation of fibre properties at a minimum. This difficulty is increased by char residue is left behind on the fibre surface after the thermolysis processes. The residue has a negative effect on the interfacial bonding properties of reclaimed fibres [45]. To remove the char residue, low temperature combustion processes are often used. However, the oxidizing conditions have a negative effect on the fibre strength. The degradation of the fibre properties is not only dependent on the pressure and temperature in the reactor, it largely depends on the fibre type as well. Glass fibre is much more vulnerable to decreasing properties than carbon fibre [50, 52]. With fibre strengths decreasing around 50% [51], the questions remains how suitable this thermal recycling process is for GFRPs.

Current state of the art pyrolysis processes enable one to reclaim the fibrous fraction of the composite, however at the cost of mechanical properties [20, 50].

Another important draw back of pyrolysis is the cost of recycling. Since the pyrolysis process cost more than the synthesis of virgin glass fibre, there is no economic incentive to buy recycled fibres. This is especially the case since the recycled glass fibre also has worse mechanical properties.

The third recycling category, chemical recycling, often uses chemicals to solve the matrix. When the matrix is solved the fibres are removed form the fluid and cleaned to removed the last droplets of the solution containing the matrix. However, it is not always necessary to use chemicals. Solvolysis often uses super critical water ($T > 647.096$ K, $P > 22.064$ MPa [53]) to dissolve the matrix. To bring the temperature and pressure down catalysts and additives can be added. However, these chemicals have an effect on the environment and may influence the fibre quality. Depending on the fibre/matrix-system processes need to be tweaked to optimize the fibre quality and minimize the energy necessary to solve the matrix. Low temperature and pressure solvolysis has comparable effects on fibre quality as solvolysis at higher pressures and temperatures.

To provide an insight in the availability of recycling technologies technology readiness levels of the previously mentioned waste management techniques are described below. The technology readiness levels of the different waste management techniques vary per fibre type [56]. Thermal recycling techniques have a TRL of wide spread of 2-6 for carbon fibre and 3-4 for glass fibre. The TRL of chemical recycling for glass fibre is grouped around a TRL of 2 and the TRL's for carbon fibre is grouped around 3-4. For mechanical recycling the TRL's for caron fibre composites have a TRL of 3 and the glass fibre composites have TRL's groped around 4 or are 8 or 9.

2.3 Material Choice

Material choice influences all parts of the life cycle. However, it especially effects the material extraction phase and the recycling phases. Both fibre and matrix choice strongly influence the embedded emissions of the blades [40]. First looking at the fibres, the difference is clear between the environmental impact per kilo between glass, carbon and bio fibres (e.g. flax).

Bio fibres have significantly lower environmental impact than synthetic fibres. However, a comparison purely on the environmental impact per weight must not be made, fibre properties have to be taken into account. It is clear that bio fibres do not have the same strength as synthetic fibres like glass and carbon fibre [63]. However, hemp and flax fibre do have comparable stiffness and favourable specific stiffness properties. It has been shown however that mechanical properties of bio fibres are dependent on the way they are won (mechanically or manually) [11], the fibre strength may vary with 20%, and the climate in which they were grown [49]. Bio fibres also tent to absorb moisture. This increases the weight and strength, and decreases the stiffness [14].

Resin types effect the environmental impact even more than the fibres [40] and are, because of this, of high importance. In recent years some new resin types have be developed which show an increase in recyclability. Increased recyclability of resins can bring down the emission drastically. BAPP-PHT [66] and Recyclamine [48] are two of these resins and both enable chemical recycling.

BAPP-PHT is a thermoset resin that can be depolymerized by chemical recycling. After the fibres are taken out of the solution, the monomers can be extracted. High fractions of the resin can be reused in other products with the same purposes. This means it van truly be recycled (i.e. not down-cycled). Also the fibres retain their mechanical properties [66].

Elium, produced by Arkema, was also hinted as an interesting resin because of its ability to be infused although it's a thermoplastic. is a thermoplastic resin that can be infused into the fibre layup. It can be recycled in 2 ways: granulates (down-cycling of both the fibres and the matrix) or reactive recycling (mechanical followed by thermal depolymerization).

From this literature review a few things stand out. Wind turbine blades are currently not recycled, but generally landfilled or incinerated. LCA studies show most impact on the greenhouse effect are produced during material extraction. From the individual materials used in glass-fibre composites in blades, resin is the biggest contributor to the GHG-emissions.

Recycling is a solution to lower emissions from the material extraction phase. Recycling techniques for the classically used thermoseting resins are being developed to enable material extraction. However, fibres are generally heavily degraded and, possibly more important for glass fibre reinforced composites, the matrix is for many recycling techniques not recovered. Although still in development, many recycling techniques, including thermolysis and solvolysis, require high amounts of energy, heavily degrade the mechanical properties of the recycled materials and are often more expensive than producing virgin materials. A solution might be found in new resin types and resin components which allow for chemical recycling enabling both fibre and resin recovery.

3 Geometrical Scenario

Since the beginning of electricity producing wind turbines many developments have been made in the blade designs. The progressions made in blade design where brought to life by both companies (e.g. LM Wind Power) and research organizations (e.g. DTU Wind Energy and DUWIND). And although many variations have been evaluated, most commercial wind turbine blades in the multi megawatt range are build with comparable design philosophies.

This design philosophy combines an upwind and a downwind aerodynamic shell with a support structure. This support structure can be a set of webs combined with a main laminate or a wing box. The main laminate can extend further to the leading and trailing edge in case webs are used in the design. Figure 2 shows an exploded view of web supported blade design.

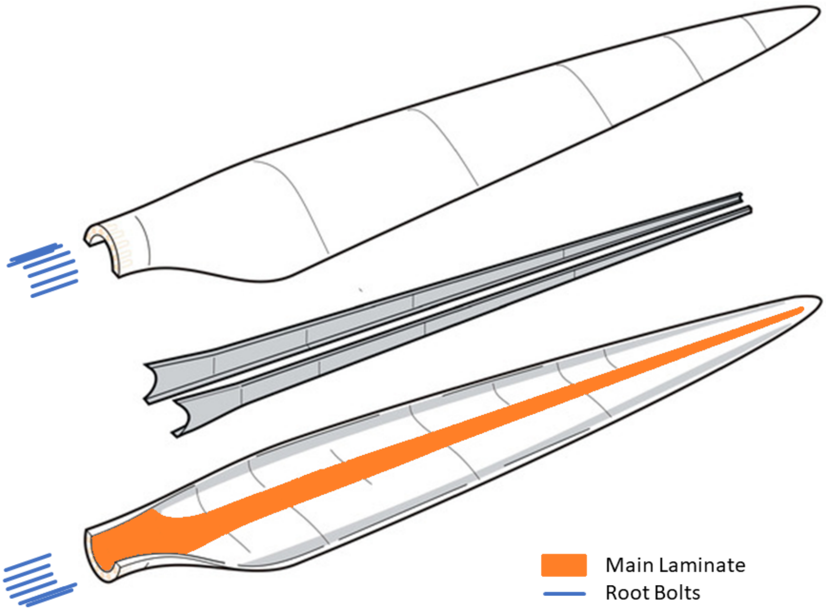

Figure 2: 3D Exploded view of a wind turbine blade based on a figure in [43].

After component production, the shells and webs are assembled and fastened using glue. Depending on the engineering tolerances more or less glue is needed to connect and fill the gaps between the components. A cross sectional view of a web supported blade design is shown in Figure 3.

This design philosophy is also applied to the 58.7 blade from LM Wind Power, which is the blade of assessment for this project. Three 58.7 meter long blades power a 3 MW horizontal axis turbine at an onshore site to provide electrical energy to the grid.

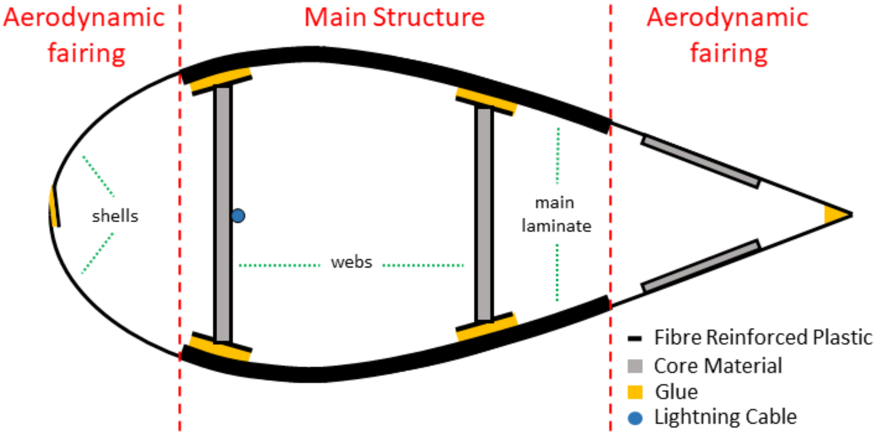

Figure 3: Cross sectional view of a typical multi MW wind turbine blade.

Since material further away from the neutral axis contributes more to the bending stiffness per unit of weight than material close to the neutral axis, the shell is thickest where the blade is thickest along the chord. A result of this is the main laminate. Plies in the main laminate mainly consist of fibres running in the root-tip direction to ensure sufficient bending stiffness.

The webs are positioned in between and glued to the main laminates of the upwind and downwind shell. The upwind and downwind shells are also connected at the leading and trailing edge of the blade using glue.

Some parts of the structure are reinforced with core material to locally increase the bending stiffness of the laminate. Typical areas where core material is added are the webs, the bulkhead and thin parts of the up and downwind shells. Next to this, a lightning cable is added to cope with lightning strikes.

4 Selection of the Material Scenario

To find the effect of materials on the environmental impact of wind turbine blades, blades with different material compositions are compared. Previous studies tell material extraction phase is biggest contributor. However, waste management can reduce the total emissions. This chapter focusses on defining material scenarios.

4.1 Current design

Most wind turbine blades are produced with glass fibre reinforced thermoset composite material. Thermoset resins used in wind turbine blades are generally of an Epoxy or Polyester type. Balsa wood is often used as core material.

LM's 58.7 turbine blade is made from a glass fibre reinforced thermoset composite. The resin is a unsaturated polyester resin, also known as UPR. Locally, balsa wood is used as core material. Polyester resin is relatively cheap compared to epoxy resin, but shrinks considerably during production. Blades made with polyester resin therefore have to be produced with sufficient dimensional tolerances and generally needs large amounts of glue for fastning the shells and webs.

A way to reduce the impact of a product which environmental impact is driven by the material extraction phase can be to reuse of recycle the materials. The usable products from the recycling or reuse preparation process can then be assumed to be avoided materials. Their impact is in this case subtracted from the impact of the initial product. However, this is only likely to happen when clear financial motivation is in place.

However, the non-homogeneous nature of the fibre reinforced composite makes it hard to reclaim separate fibre and resin fractions of the composite. Currently employed composite materials and available recycling techniques do only allow energy recovery and downcycling[2].

4.2 Core Variations

Looking at the contribution of the core, which is about 1% of the total CO2 emissions [9], and the weight fraction of the core, a core variation may not seem the most logical variation from an eco-design point of view. However, a switch from the classically used balsa wood to PET-foam has other benefits and is therefore investigated by LM. To show the environmental impact of this variation in core material, a case study incorporating PET-foam in the blade was assessed in this study.

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[2] Materials can not be reused for the same purpose since the mechanical properties are heavily reduced.

4.2.1 Balsa Wood

Balsa wood is used as core material because of its light weight and great strength and stiffness properties. It is however only produced in a limited amount of places and generally needs to be transported over long distances. Next to this, the properties of the material can largely vary between samples.

4.2.2 PET Foam

PET-foam has more consistent properties than balsa wood. Next to this, it can be produced more locally which reduces dependence on suppliers. An added benefit of using PET-foam in the blade design is that is reduces the weight of the blade. The weight reduction explained in Section 4.5.1. These factors make PET-foam a material of interest for LM Wind Power.

4.3 Resin

4.3.1 Resin Type

Polymeric resins are often used to embed fibres in fibre reinforced composites. A distinction can made between polymers based on there cross-linking characteristics. Cross-linking refers to the way individual strings of polymers are connected to others and there is three cross-linking categories: Thermosets, thermoplastics, and elastomers. Although all three have their benefits, only thermoplastic and theromsetting resins are used in composite design. The main difference between them is that thermoplastic resins do not have crosslinks and thermosetting resins do have cross-links. One of the results of this is that thermoplastics do melt and thermosetting resins do not.

Unsaturated polyester resin (UPR), which is a thermosetting resin, is used by LM Wind Power in their current blades designs. In the life cycle which is currently in place, the resin accounts for a high amount of the total impact. The thermosetting nature of this resin makes it hard to recycle blades on a large scale. UPR is used as the benchmark resin.

An other thermosetting resin which is seen as a better recyclable resin is poly(hexahydrotriazine) (PHT) synthesised from 2,2-bis[4-(4-aminophenoxy) phenyl]propane (BAPP) and paraformaldehyde (PFA), or in short BAPP-PHT. A specific chemical recycling process for BAPP-PHT composites demonstrated a recovery rate of 90% by weight for both monomers (i.e. PFA and BAPP). A nice benefit is that fibres are not be damaged by the recycling process [66].

An advantage of thermoplastic resins is that they can be remoulded. This opens up possible use of new recycling techniques. A problem is however that they are normally not infusible because of there high viscosity. A requirement is that the resin is infusible which rules out most thermoplasts. Arkema's Elium resin however is an infusible thermoplastic resin and is therefore evaluated in the research.

Some resins, like epoxy, need to be baked after infusion to fully set. The added heat allows extra cross-linking of the polymer chains. A nice benefit of the UPR, BAPP-PHT and Elium resins is that they do not require heat induced curing. This means LM's production techniques can remain largely unchanged.

4.3.2 Resin Quantity

Resins can not be simply interchanged. They have a major effect on the mechanics of the composites in which they are used. Their role in especially important when a composite is not loaded in direction of the fibres and fracture toughness. Looking at pure resin systems, both BAPP-PHT and Elium show mechanical properties which are comparable to selected epoxy[3], TGDDM[4] and BMI[5] resin systems [3,66].

Next this, other properties, e.g. the ability of the matrix to bound to the fibre, are key factors in composite design and must be investigate. However, the comparison shows BAPP-PHT and Elium are potential candidates for blade design.

Although blades are designed for may load cases, bending loads due to edge- and flap-wise loads are main drivers of the ply layup design for a blade. These bending loads drive the tip deflection which must be constraint to ensure the tower is not hit by the blade tips. The deflection is proportional to the inverse of the stiffness, as shown in Equation 1. This equation describes the deflection of a slender, originally straight, and slightly tapered beam and is limited to linear elastic and small deflections (δ_{max} is less than one tenth of the span). Although not all of these assumptions are exactly true (i.e. the blade is not perfectly straight) it indicates the role E(x) and I(x) play in beam deflections.

$$\delta_{tip} = \iint_0^L \frac{M(x)}{E(x)I(x)} dx^2 \tag{1}$$

In this equation, δ_{tip} is the tip deformation, L is the length of the beam/blade, x is the distance from the root in the span wise directions, M is the bending moment, E is the Youngs modulus and I is the moment of inertia. Isolating I(x) leads to Equation 2.

---

[3] The selected epoxy resin is a tetradiglycidyl diaminodiphenylmethane/diaminodiophenylsulfone epoxy resin system

[4] TGDDM stands for methylene-bis-(2,6-diethylaniline) and methylene-bis-(2,6-diisopropylaniline) resin system

[5] The selected BMI system is a bis(4,4'-maleimidodiphenyl)-methane resin system toughened by 2,2-bis(4-hydroxy-3-allylphenyl)propane

$$I(x) = \frac{d^2\delta_{tip}}{dx^2}\frac{E(x)}{M(x)} \tag{2}$$

I(x) and E(x) are largely influenced by the structural design of the blade. Equation 2 shows that I can remain the same along the blade if E remains the same along the blade. This is of course when assuming that the moment M(x) and $\delta_{tip_{max}}$ remain the same. E is largely influenced by the fibre fraction and the fibre direction according to the rule of mixtures. The rule of mixtures describes ply properties for a ply with unidirectional fibres and zero porosity. It describes the stiffness along the fibre direction is noted in Equation 3.

$$E_{FD} = V_f E_{f1} + V_m E_m \tag{3}$$

$$\frac{1}{E_P} = V_f \frac{1}{E_{f2}} + V_m \frac{1}{E_m} \tag{4}$$

In these equations, E_{FD} is the ply stiffness in the fibre direction, E_P is the ply stiffness perpendicular to the fibre direction, E_{f1} is the fibre stiffness in the fibre direction, E_{f2} is the fibre stiffness perpendicular to the fibre direction, E_m is the matrix stiffness, V_f is the fibre volume fraction, and V_m is the matrix volume fraction. The stiffness in the fibre direction is largely dominated by the fibre stiffness since it is much higher than the matrix stiffness and the volume fractions are both close to 50% for blade designs. Small variations in the resin stiffness will therefore not influence the ply stiffness to a large extend as long as the fibre volume fraction remains the same. Since fibres are predominately oriented in the span-wise direction, E(x) in Equation 2 is largely driven by E_{FD}.

However for completeness, the ply stiffness perpendicular to the fibre direction is also evaluated. Acknowledging that the fibre and matrix volume fractions are close to 0.5, Equation 4 can be rewritten as Equation 5.

$$E_P = \frac{E_{f2}E_m}{E_f V_m + E_m V_f} \approx \frac{2E_{f2}E_m}{E_{f2} + E_m} \tag{5}$$

Since E_{f2} and E_m are normally much smaller than E_{f1} for Glass Fibre Reinforced Composites (GFRC), E_P is much smaller than E_{FD}. Stiffness in a certain direction is thus largely driven by the plies with fibres in that direction. Since a high amount of unidirectional fibre bundles in the main laminate run in the spanwise direction the blades stiffness is largely dependent on the fibre stiffness and fibre fraction. A slight variation in the matrix stiffness will therefor not effect to balde stiffness to a large extend. The fibre and matrix volumes are therefor assumed to remain the same for all scenarios.

4.4 Fibre

Currently Glass Fibre (GF) is used in the 58.7 blade. GF has great (specific) stiffness and strength properties and is a relatively cheap solution. A logical alternative for GF is carbon fibre. This is another synthetic fibre which is produced in more energy intensive production processes. However, a change from glass to carbon fibre has already been investigated for the 58.7 blade. The life cycle impacts were modelled using a combination of Ecoinvent and ILCD. The results of this research shows a reduction of 2%-11% in all midpoint impact categories (e.g. climate change -5% and particulate matter -8%) except for water resource depletion which has a increased impact of 15% [9].

Also aramid fibre could be considered. Aramid fibres however show, although having high mechanical strength, and high toughness and high damage tolerance, low compressive strength and low adhesion to polymer resins [28]. They are therefore not considered for further analysis.

Biofibres could also be considered. They show, in some cases, compatible or better specific stiffness than GF [63]. These parameters are however very dependent on the way of extraction and growth conditions. This fibre category is because of their moisture absorbence and large variance in the fibre properties not included in further analysis.

4.5 Material Scenarios Definition

Three alternative materials - PET-foam as core material, and BAPP-PHT and Elium as resin - were selected in the previous sections. The material scenarios are defined in Table 1. This section will describe how these materials were integrated in the alternative material designs.

Category	Material	Benchmark	PET core	PHT resin	Elium resin
Fibre	Glass fibre	x	x	x	x
Core	Balsa Wood	x		x	x
	PET		x		
Matrix	UPR	x	x		
	BAPP-PHT			x	
	Elium				x

Table 1: Material scenarios

The material substitution was based on an assumed volumetric equality between the original and substitute material. This holds for both the core and the resin materials. Resin quantity and weight changes are qualitatively described in Table 2. This volumetric assumption is motivated in Subsections 4.5.1 and 4.5.2.

4.5.1 Quantitatively substituting PET Foam for Balsa Wood

Based on an internal audit, PET-foams show sufficient properties for a one-on-one volumetric substitution if the right density is chosen. However, the balsa wood and PET foam are supplied in thicknesses measured in inches and millimetres respectively which makes an one-to-one substitution impossible. The resulting volumetric difference, was calculated based on the core thicknesses of PET and balsa variants of one of LM's blades in the 60 meter range. This showed a slight increase in the volume of the core when changing from balsa wood to PET-foam.

The standard density PET-foam has sufficient mechanical properties to take over the role of the balsa wood in most locations. However, at a limited amount of locations a higher density may be necessary to resist local stress fluctuations. Different foam densities are available to account for this.

To calculate the weight of the PET-foam core, first the weight was calculated assuming the volume remains the same and the PET-foam has a constant density. To account both the volume increase due to unit discrepancies and the locally increased density in the PET-foam, 10% of extra mass was added. By changing the balsa wood core with PET foam the total weight of the blade decreases by 1% percent.

4.5.2 Quantitatively substituting UPR for Elium or BAPP-PHT

The fibre volume remains the same in all scenarios. To keep the same fibre volume fraction in all scenarios, the resin volumes are also kept equal. The resin densities and the corresponding resin and total weight changes are shown in Table 2.

Table 2: Resin Densities and Corresponding Weight Changes

Resin Type	Density (kg m^{-3})	Volume	Blade Weight Change
UPR	1.06E3	V_{UPR}	-
Elium	1.01E3	V_{UPR}	- 1.5%
BAPP-PHT	1.10E3	V_{UPR}	+ 1.2%

5 Selection of Waste Management Scenario

This chapter focusses on the recycling of the fibre reinforced plastic fraction of the blade. This part makes up around 90% of the total weight of the blade. Recycling methods of the other parts of the blade or not varied. Metal and wooden parts are recycled. The rest of the blade is incinerated without energy recovery.

5.1 Landfill

Landfill was modelled as a reference waste management method. This method was used to a large extend until it was prohibited for wind turbine blades in certain countries. When a blade is landfilled it is first reduced in size by cutting and crushing the blade. After this, the blade is transported to the land filling site, excavators put the material into the ground, and it is covered by gravel, plastic, and concrete. Landfilling is a relatively cheap and clean method. It can be seen as a clean method since it produces a low amount of emissions since materials are contained in the product. However, it is far from sustainable since materials are lost and waste piles up indefinitely.

5.2 Mechanical

Mechanical recycling processes developed for GF composites have been developed to high TRL numbers. In current day decommissioning, blades are reduced in size before transport to the waste management plant. This makes transportation much easier and cheaper.

After transportation the composite can be further reduced in size. Thermoset materials can be used as filler materials in other products. This can only be done however in small quantities and will not likely get rid of all blade waste in the future. Thermoplastic materials can however be reduced in size and remoulded into new products. This aligns with the use of the thermoplastic Elium resin and mechanical recycling was therefore selected for the GF/Elium/balsa scenario.

5.3 Thermal

Different thermal waste management methods are available. Some focus just on reducing the amount of weight where others also recover energy or materials. Thermal recycling plants in the proximity of the turbine site are expected to have at least some form of energy recovery installed when the blades are disposed following the time frame mentioned in Section 7.10. Thermal waste management methods without energy recovery are therefore not considered in this study.

5.3.1 Energy Recovery

Incineration is currently used to a large extend for wind turbine waste management. It was therefore selected as an benchmark scenario and used for comparison to other scenarios.

In this scenario, decommissioned blades a first reduced in size by cutting and grinding and transported to the incineration plant. The the material is than incinerated and residue of the burned material is landfilled. Since waste materials are burned, they are (almost completely) converted into emissions. This means the emissions of an incineration process are considerably higher for landfilling where most material is contained inside encapsulated volume of waste. However a benefit is that (almost) no space is required for the disposed material after disposal.

5.3.2 Material Recovery

When GF-composites are recycled thermally, fibre and resin fractions can be recovered in various way depending on the recycling process. A clear down side is however that GF fractions can generally not be reused for the same purposes. This is because GFs are both reduced in size because of the cutting/crushing before transport and because they are damaged when subjected to high temperatures (higher the 200 degrees Celsius). This is not the case for all fibre types. Carbon fibre is for instance better resistant to thermal recycling and will retain more of its mechanical properties. Especially when low amounts of oxygen are available during the thermal recycling process.

However, for the selected material scenarios, which only contain GF as reinforcement fibres, this would mean only resin constituents could potentially be recovered. This can not be considered recycling. Since a focus is on investigating recycling techniques with possibility of reclaiming materials for comparable structural proposes, this category was not included in further analysis.

5.3.3 Cement Kiln Route

Another waste management method, which is currently seen as the most economical way of blade disposal, is considered for analysis. This is the use of blade material in the cement production process. This method is currently available, used, and allows big amount of material to be recycled.

Blades are first downsized and transported to the cement production plant. The composite material is first further reduced in size at the plant. After this the UPR and GF fraction serve two different purposes: the UPR is burned as fuel [7, 22] and GF substitute part of the sand used in cement production [18].

5.4 Chemical

Chemical recycling processes have been developed to reclaim resin and fibre fractions after treating the recyclate. The sub critical water hydrolysis of UPR and hydrolysis of BAPP-PHT are found to be suitable methods of reclaiming materials from the waste material. Both recycling processes approaching closed loop recycling since materials are reclaimed at the end of the process which can be reused in the production of resin of as fibres of reduced size. These chemical recycling techniques were therefore selected for this analysis.

Since the reusable materials do not have to be produced for a new product, but can be reused, extra production of these materials is avoided. They can therefor be modelled as avoided products which reduces the environmental impact of the blades. However, this largely depends on the contributions of the chemicals, used during the recycling process, to the environmental impact.

5.5 Preparation for reuse

According to the waste framework directive there are ways of reducing the impact of product which are more effective than recycling and energy recovery. These include reducing use of material and/or energy resources, reusing products and repairing used products for reuse [21].

To assess the effect of a reuse strategy a separate case study was performed. This scenario uses the same material configuration as the benchmark blade. However at the end of the first life time the blade is transported to a refurbishment facility. Here the blade is split into to be reused and to be disposed sections. The to be reused section are than connected to newly produced structurally critically parts. The blade is than ready for a full lifetime after which the whole blade is incinerated. The reusability of sections is based on their role in the structural design on the blade. This will further be explained in Section 5.5.1.

This is purely hypothetical case study. No design employing a reuse strategy could be made within the resources available to this research. This case study can however give an indication of the potential if a reuse strategy.

5.5.1 Geometrical Scenario

Although the totality of the blade cross section is load bearing, the main structure (i.e. combination of webs and main laminates) takes up most of the loads. The rest of the blade, which is mostly designed for aerodynamic performance and to lead through loads to the main structure, could be referred to as the aerodynamic fairings. Since the aerodynamic fairings have a less critical role in preventing mechanical failure, they might possibly be reused. Figure 4 indicates the positions of the aerodynamic fairing, main structure and possible joint locations.

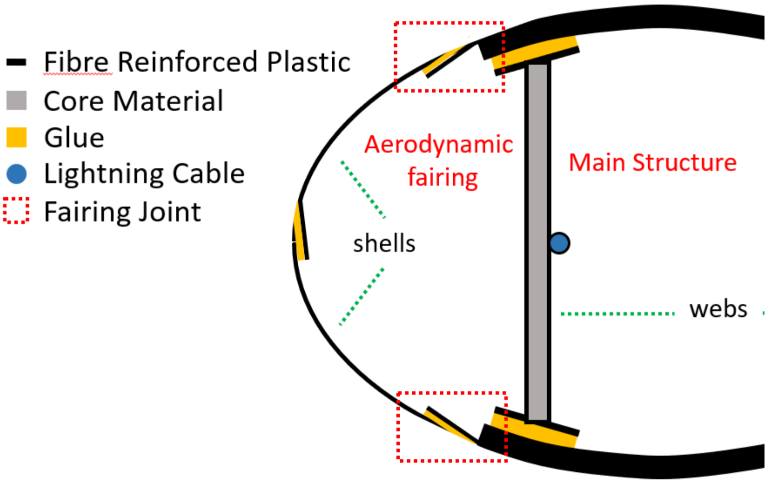

Figure 4: Partial Cross Sectional View of the Reuse Scenario Displaying the Fairing Joints.

In this scenario adhesive is used to join the different blade sections at the refurbishment plant. A possible adhesive joint is indicated in the red dotted box. This is driven by the fact the thermoset matrix (i.e. UPR) is used in the blade. If a themoplastic composite was used, the sections could potentially be joined by welding.

This type of joint would allow easy assembly during remanufacturing, but may also result in a locally unbalanced laminate. This is very dependent on the production tolerances (UPR composites may be subject to considerable shrinkage[6]) and thus the adhesive thickness. Care must be taken to ensure that the unbalance doesn't lead to unwanted internal stresses as a result of the non zero coupling matrix (i.e. B part of the ABD-matrix is non-zero because of unbalance in the laminate).

5.5.2 Model variations

Differences in the life cycle phases are found in all phases of the life time. The biggest changes however are in the amount of material which is used in the blade, the extra adhesive, and the transportation movement of the blade of blade sections.

The increased amount of transport movements is partially compensated by the reduced weight of the transported goods in some transport movements. The

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[6] UPR shrinkage can can reduced by adding small molecule low shrinkage additives (LSA) to the resin. Volume shrinking was significantly reduced by adding succinic acid to UPR. [31] during production [31, 34, 67]

total transportation also only accounts for 5.3% and 8.1% of the FPM and CO2 emissions respectively. A small variation of this - the largest share of the emissions is due to transport from production to turbine site is unchanged - will not have a big impact on the outcome and was therefore not evaluated.

The reuse fraction and the extra adhesive will however have a bigger impact on the end result. The reuse fraction is varied from 0% to 50% and is calculated using Equation 6. In this calculation, M_{reused} is the mass of the reused sections and M_{Total} id the total weight of the blade. It is very unlikely that the reuse fraction exceeds 50% since most mass is part of the main structure. The extra adhesive mass is varied from 0% to 100% of the adhesive in the original blade.

$$m_{reuse} = \frac{M_{reused}}{M_{Total}} \tag{6}$$

5.6 Scenario Selection

This section discusses the selected waste scenarios for different life phases. The production phase and use phase waste management methods are constant for all scenarios. The end of life waste management method is varied between the different scenarios.

5.6.1 Treatment of Production Waste

Consumable waste (e.g. flow mesh, vacuum bag, peel ply) and blade material waste (e.g. glass fibre cut-offs, excess glue, overflowed resin) are produced during blade production. The production waste is incinerated.

5.6.2 Treatment of Maintenance Waste

During the operating life of the blade, 4.5% of total blade mass (4.5% of the GF weight, 4.5% of the GF weight, 4.5% of the GF weight, 4.5% of the GF weight, is used to repair the blade [40]. It is also assumed that 4.5% of total blade mass is removed during the repairs (i.e. the blade mass remains the same). The removed material is incinerated. Wear on tools is assumed to remain the same for all scenarios and is therefore excluded.

5.6.3 Treatment of End of Life Waste

Based on Sections 5.4-5.4, landfill, mechanical recycling of thermoplastics, incineration with energy recovery and chemical recycling were selected. Landfill en incineration are applied to all scenarios and will function as a basis for the comparison between the different material scenarios. As shown in Table 3, the chemical recycling is tailored to the specific resin used in the blade. For some recycling methods the resulting products cause avoided production of resources. These avoided products are shown per input material and per recycling method in Table 22 in Appendix A.

Table 3: Material variation and EoL waste process variations. x: included, SCW: sub critical water hydrolysis, PHT: chemical depolymerization process of BAPP-PHT resin in a mild acidic solution.

Material Scenario	Landfill	Incineration	Cement Kiln	Mechanical	Chemical
Benchmark	x	x	x	-	SCW
PET core	x	x	-	-	-
PHT resin	x	x	-	-	PHT
Elium resin	x	x	-	x	-

6 Goal Definition

In this chapter the goal of the Life Cycle Assessment (LCA) is defined. First the intentions of the project will be stated. This is followed by the assumptions and limitations, the decision context and definition of the target audience. Finally the stakeholders are mentioned.

6.1 Intended Applications

The goal of this project is to find a relation between material choice, blade recyclability and a blade's impact on the environmental. This eco-design knowledge can be used in early stage design phases of future designs.

6.2 Method Assumptions and Impact Limitations

Since only a very limited amount of blade types will be investigated, the results of this study will not be representative for all wind turbine blades. However, many blades are build with the same kind of materials so trends in the data may therefor apply to a subset of wind turbine blades.

Next to this, the expected lifetime of the blade has a big influence on the absolute environmental impact of blades while satisfying the same functional unit. Life time (extension) scenarios of a blade are heavily influenced by the weather conditions endured by the rotor during its operational life. The conditions will vary from site to site and year to year.

6.3 Decision Context

The study may be used for decision making internally in LM and will only result in small-scale changes to the background system (e.g. material suppliers). The decision context is therefore situation A. This refers to ”micro-level decision support” in which micro-level hints to the low impact on the background system.

6.4 Target audience

The results of this study will initially be shared with the committee assessing this master thesis project and LM Wind Power. This report will be shared in the TU Delft repository 5 years after the thesis defence (September 4th 2024). It is also available within LM and possible within General Electric the parent company of LM Wind Power. Employees working in the communications and engineering departments who are involved in sustainability projects may also be part of the audience.

6.5 Commissioner

This research is part of the master thesis conducted by Gerard van den Eijnden as part of a dual degree program at TU Delft and DTU. Gerard worked as a trainee at LM Wind Power during the biggest part of the thesis process, for which he received financial compensation. To LM this study shows how material choices and material substitutions influence the environmental footprint of their turbine blades. This aligns which the carbon neutrality initiative. Supervision was given by Sybren Jansma (LM Wind Power), Bo Madsen (DTU), and Jos Sinke (TU Delft). Alexis Laurent (DTU) and Justine Beauson (DTU) provided information in their fields of research.

- Ir. Sybren Jansma - Process Engineer at LM WindPower (LM Wind power is a subsidiary of General Electric Company)
- Dr. Bo Madsen - Associate professor and head of section at Danmarks Teknisk Universitet (Department of Wind Energy, section of Composite Materials)
- Dr. Jos Sinke - Assistant professor in Aerospace Manufacturing Techniques at Delft University of Technology (department of Aerospace Structures and Materials, Delft Aerospace Materials and Structures Laboratory)
- Dr. Alexis Laurent - Associate professor at Danmarks Teknisk Universitet (Department of Management, section of Quantitative Sustainability Assessment
- Ir. Justine Beauson - Development Engineer at Danmarks Teknisk Universitet (Department of Wind Energy, recycling)

7 Scope Definition

7.1 Deliverables

This non-assertive comparative LCA study, should provide LCI results of different material and recycling scenarios. The LCI categories should at least cover Climate change potential, acidification, resource depletion, human and eco-toxicity and fossil fuel depletion. These impact categories are used to show a graphical comparison between the investigate scenarios. The results are used to show a how the environmental footprint is influenced by the choice in material.

7.2 Functional Unit and Reference Flows

The functional unit allows environmental impacts of different systems to be compared. This is done based on how often/much the different systems satisfy the functional unit. Two energy systems can for instance be compared based on their environmental impact per kWh. The 58.7 blade is described in Section 7.2.1 and the functional unit is defined in Section 7.2.2. This is followed by the definition of the reference flow. This is the amount of blades which are necessary to satisfy the functional unit.

7.2.1 System function

A 58.7 wind turbine blade was designed and is produced by LM Wind Power. It is used to provide torque on the turbine shaft of a wind turbine. It is designed for the generation of 3 MW at an IEC class 3 (low mean wind speed conditions, 7.5 m/s [17]) onshore site. Since a turbine has 3 blades, one blade should produce 1 MW at wind speeds between the rated and cut-out wind speed. The blade is manufactured in Spain and has a design operational life of 20 years. The blade is decommissioned after its production life. Recycling is done with recycling techniques which are currently (2019) expected to be available in 25 years from now (i.e. in 2046).

7.2.2 Functional unit

Based on the function of the 58.7 blade, the functional unit is defined below. The various parts of the functional unit are split up and shown in Table 4.

Transform the kinetic energy of the wind of a IEC wind class 3 site in Denmark into work done on the rotor shaft of a three bladed wind turbine with a, non-changing, rated power of 1 MW for 20 years.

Table 4: Parts of Functional unit

Property	Specification
Function	Do work on the rotor shaft of a wind turbine
Quantity	Rated power of 1 MW (i.e. 1 blade of a 3 MW wind turbine)
Duration	20 years
Location	In Denmark at a IEC wind class 3 site
Means	By transforming kinetic energy of the wind
Time dependency	No changes over time

7.2.3 Reference Flow

Based on the analysis of 350 offshore wind turbines throughout Europe, turbines blades are found to have a chance of 0.01 to fail over the course of 20 years [13]. The reference flow is therefore set at 1.01 blades in order to account for possible catastrophic failure of blades. This is true for all scenarios.

7.3 LCI Modelling Framework

An attributional modelling framework is used since the decision context is situation A. No reasons are found to extend this to a consequential model.

7.4 System boundaries

The high level processes included in the system boundaries are shown in Figure 5. This includes processes in all life phases of the blade. Waste solutions are applied to production, maintenance and EoL waste. The waste solutions can be different for waste from different life phases.

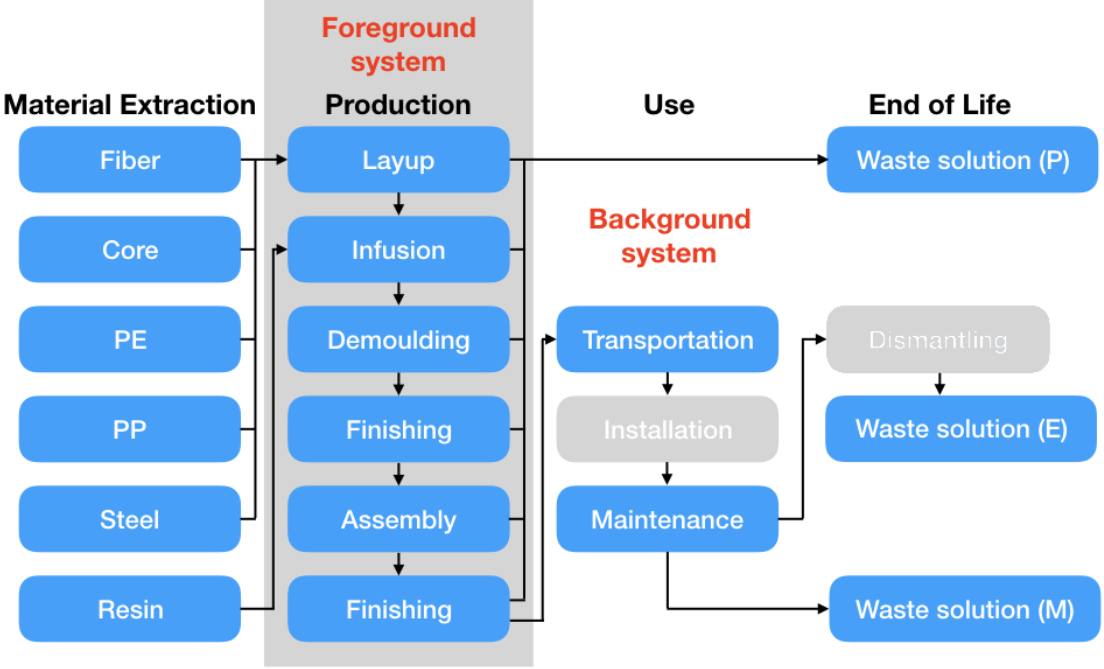

Figure 5: High level processes within the system boundaries

It must be ensured that there is consistency in modeling choices, assumptions and data quality between comparative studies. However, certain parts can be excluded from analysis. These are the parts that are identical for all compared systems [54]. The installation and dismantling of the blades is excluded from this model. The validity of the exclusions is discussed in Section 8.5. Modelling of the material scenarios and waste solutions were discussed in Subsections 8.2 and 8.4.

7.4.1 Recycling Scenarios

From previous LCA studies, it is known that the matrix is the biggest contributor to the environmental impact of wind turbine blades [9, 40]. It is also known that the main impacts originate in the material extraction phase, and that recycling of materials may may reduce the impact of a blade. Next to landfill, incineration and the cement kiln route, waste-solutions which enable matrix recovery were chosen to be investigated.

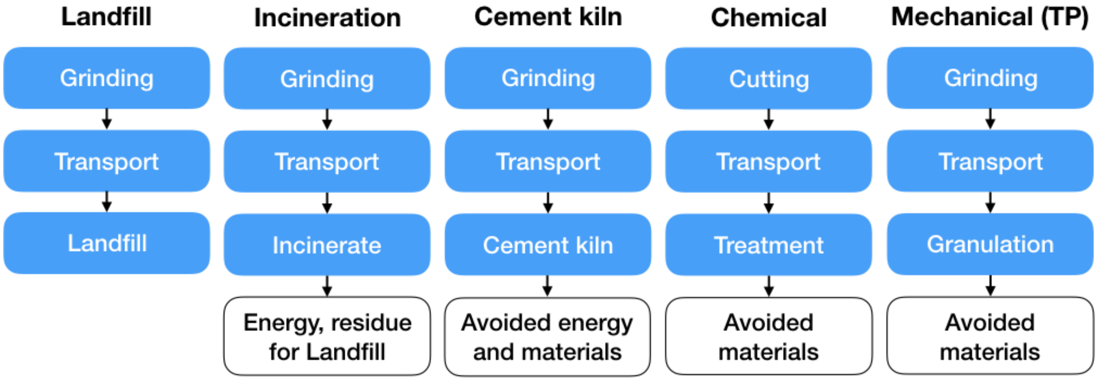

Figure 6: High level processes of the waste solutions

7.5 Representativeness of LCI Data

Used LCI data used to model the production, operation and EoL phases must be representative for Spain, Denmark and Germany respectively. Next to this, especially the energy composition of the grid must have temporal representativeness. Also, all processes must be technically feasible at the time of execution. This is especially important for EoL-solutions which may not be developed yet or may not be used anymore in a few decades from now. The first is a reason why production and maintenance waste are assumed to be incinerated or used in a cement kiln.

7.6 Technological representativeness

Technologies which are currently used by LM are described and measured accurately. Processes in the background system may be modelled in a less representative way.

Unfortunately no information on the current day production waste could be identified. It was therefore assumed that the production waste is incinerated. EoL recycling processes which are still under development (i.e. sub critical water hydrolysis and the chemical recycling of BAPP-PHT) have only been proven on smaller scales. When these processes are further developed and optimized the process in- and outputs may slightly change. The modelling of these processes may therefore not be fully representative for final implemented waste management process.

7.7 Geographical representativeness

The Ecoinvent database covers many inputs for Europe separately from Switzerland and the rest of the world. This increases the geographical representativeness of the analysis.

7.8 Temporal representativeness

Processes and efficiencies change over time. The use of materials during production for instance change over time. This has to do with the learning process of the personnel and possible increases in precision of machinery. Developments in the material usage and waste production are documented by LM and were used in the analysis. It is however acknowledged that technological development may change the learning curve and production processes over time. This possible reduction of the waste will reduced the environmental impact. However, it is not expected to have a large impact on the total environmental impact of the blade since the materials included in the blade have a much larger impact than the production waste.

Legislation changes over time. It is expected that the following decades will result in a large quantity of climate legislation to be pushed. This will have an influence on the energy mix which is discussed below. But also on the allowed forms of waste management, limitations on the use of substances and possible extension of emission taxes or quota systems. Predictions can hardly be made on this. However, a CO2 tax has been discussed by European governments repeatedly and landfilling over wind turbine blades has been prohibited in certain European countries.

The energy grid mix changes over time and is expected to contain a larger share of renewable energy in the future. A future energy scenario was assumed for the recycling process in the years around 2050. This scenario is called ”symphony” and assumes governmental organisations cooperate to shape the future energy market [25].

7.9 Basis for Impact Assessment

Hierarchist (H) ReCiPe 2016 midpoint and endpoint LCIA methods were selected for the impact assessment. This is since the impact mechanisms are understood well for the time frame of 100 years [32]. The ReCiPe midpoint categories are listed below.

- Climate Change;
- Ozone Depletion;
- Terrestrial Acidification;
- Freshwater Eutrophication;
- Marine Eutrophication;
- Human Toxicity;
- Photochemical Oxidant Formation;
- Particulate Matter Formation;

- Terrestrial Ecotoxicity;
- Freshwater Ecotoxicity;
- Marine Ecotoxicity;
- Ionising Radiation;
- Agricultural Land Occupation;
- Urban Land Occupation;
- Natural Land Transformation;
- Water Depletion;
- Mineral Resource Depletion;
- Fossil Fuel Depletion

The midpoint impact scores are used to calculate the endpoint impacts - these are listed below - through the damage pathways shown in Figure 7. The midpoint impact scores are multiplied by the "midpoint to endpoint factors" first and than summed to find the endpoint impacts. The midpoint to endpoint factors can be found on page 25 of the ReCiPe 2016 v1.1 report [32]. The endpoint categories are listed below.

- Damage to Human Health;
- Damage to Ecosystem Quality;
- Damage to Resource Availability

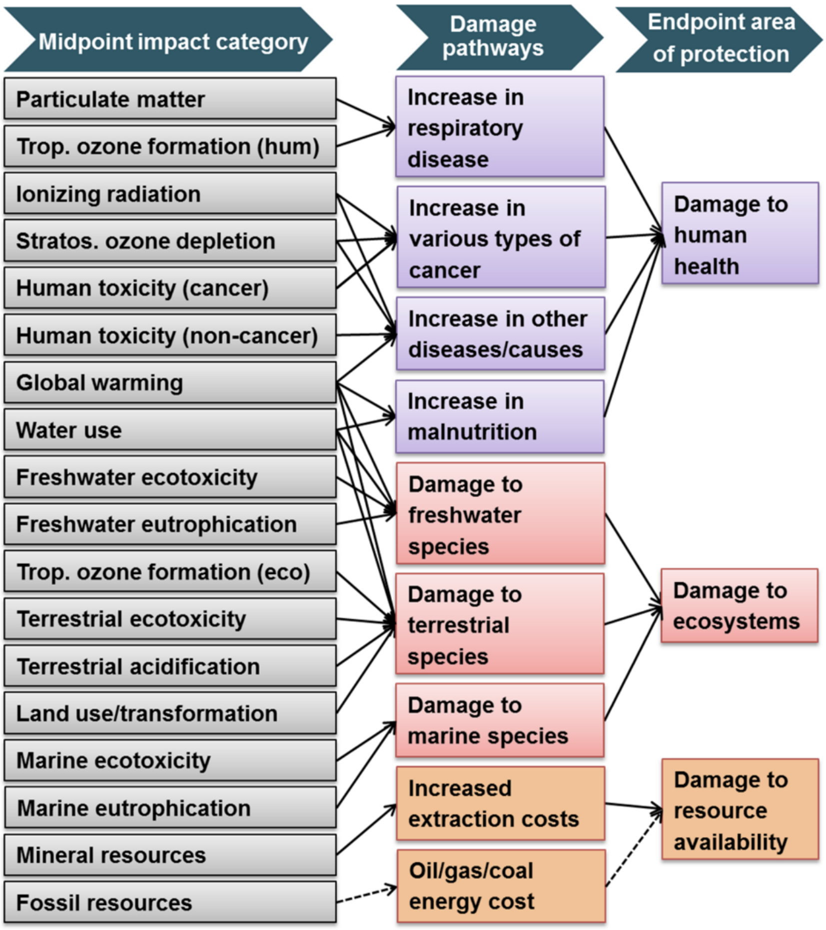

Figure 7: Overview of the impact categories that are covered in the ReCiPe2016 methodology and their relation to the areas of protection. [32]

7.10 Temporal Scope

The 58.7 blade is currently in production in the benchmark material configuration. Other possible scenarios should still be developed before they can enter production. However, to make a fair comparison all blade scenarios are assumed to follow the same time-line with an start of the blade development in 2020. The share time-line is shown in Figure 8. This shows that the use of the products and disposal of manufacturing and maintenance waste start when or shortly after the first blade is in production. The major part of the disposal work however will take place when the blades are decommissioned.

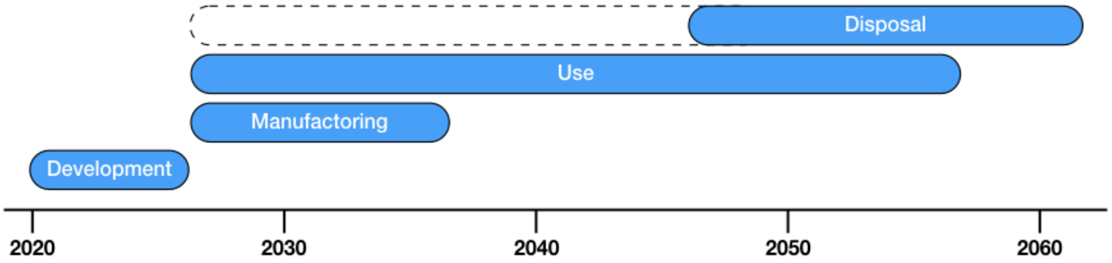

Figure 8: Temporal scope of blade scenarios

It is hard to predict what the waste context is in 25 years from now. It is highly influenced by legislation on both waste management and energy compositions. This was discussed in Section 7.6.

8 Inventory Analysis

The chapter describes the processes which are part of the blade lifecycle. 58.7 blade from LM Wind Power is analyzed in different material configurations and for different waste solutions. The different material and waste solutions are described in Sections 4 and 8.4. The high level processes inside the system boundaries were shown in Figure 5.

A subdivision is made between the foreground system, every thing that happens within LM Wind Power, and the background system which includes all other processes.

8.1 Identification of Foreground Processes

This section focuses on identifying and describing all high level processes which fall within the foreground system. The different foreground processes are described in Subsections 8.1.2-8.1.5. However, first the reference flow is defined in Subsection 8.1.1.

The production techniques used to produce the blades remain the same (vacuum assisted resin transfer molding, without post-curing) for different material configurations. The cycle time and use of consumables may vary slightly depending on the resins viscosity and polymerization time however. For the BAPP-PHT resin no information of the viscosity was found. Elium is known to have a low viscosity but a very short window (20-30 minutes) in which it can be used for infusion [3]. Extra flow media and or injection points may be needed to ensure proper infusion. This is at this however hard to predict at this moment in time and will not have a very big impact on the total impacts of the blade.

The foreground currently only contain processes in the production phase. The processes in the material extraction, use and disposal phases are therefore part of the background system. The modelling of these life phases is described sections 8.2-8.4.

8.1.1 Reference Flow

The reference flow is 1.005 blades of the 58.7P type. The reference flow was set at 1.005 blades since 1% of installed blades need replacement during their lifetime [13]. The time of failure was not communicated, so the time of failure was initially set at 50% of the design lifetime. The reference flow is therefore 1.005 instead of 1.01 since this would assume the blade breaks at the beginning of its lifetime. It must be acknowledged that this study is based on off-shore wind turbines from a non-disclosed manufacturer. It is impossible to predict if there is a significant difference between the failure rates of the turbines investigated in the paper by Carroll and this research.

8.1.2 Layup

The laminate is manually build up in the mould. This process is done layer by layer. The core material and other inserts also are placed in the mould during this process. Lastly, the vacuum bag and infusion materials are installed. The quantities of all materials used during the layup process including the consumables are described in the Bill Of Materials (BOM). The quantities described in the BOM are precise and known since this blade has been in production for some time.

On top of the material usage described in the BOM, material waste is produced. Weights of fibre glass cut-offs, resin overflow and adhesive waste are documented. The gathered data, was cleared of rows with missing data and trends were analysed over time. The average waste weights were used in the analysis. For waste streams which are measured, the measured waste quantities are used instead of the waste estimations from the BOM.

8.1.3 Vacuum assisted resin transfer molding

First all air is removed from the layup. When all possible air leaks are closed and all air is removed, the resin is mixed. The resin is forced in by the pressure difference after opening the valves.

Depending on the type of resin, additional curing steps might be necessary. This is however not the case for polyester resin. The same is true for the BAPP-PHT resins. However, although Elium does not necessarily require post-curing because of its high polymerization rate, if maximum mechanical properties are required post-curing at 80°C for 4 hours is required [3]. For this research however this post-curing is excluded from the model.

8.1.4 Demoulding and finishing

After the resin has set, the component can be demoulded. The component must now be prepared for assembly. This often contains cutting and grinding steps and surfaces must be prepared for adhesive bonding during the assembly steps.

8.1.5 Assembly

The up-wind shell, down-wind shell and webs are lifted into place and bonded with adhesive. The excess adhesive is either removed or contained by ”glue catchers” during the bonding process. Glue catchers are used to prevent excess adhesive to move away from the bondline. The excess adhesive is one of the measured waste products and this measured amount is used in the waste modelling.

8.2 Modeling of the Material Extraction Phase

Environmental impacts of many material extraction processes are included in the Ecoinvent 3.5 database. This includes glass fibre and unsaturated polyester resin. However, far from all material are included in the Ecoinvent database. PET-foam, BAPP-PHT and Elium are not included. The latter two have a big impact on the final result and not having this data in the database potentially results in high uncertainty. The sensitivity analysis is discussed in Section 10.3.

8.2.1 Unsaturated Polyester Resin (UPR)

Polyester resin is currently used to produce the 58.7 blade. This thermoset resin is relatively cheap, does not require thermal curing after infusion and has sufficient mechanical properties.

Polyester is produced using dibasic organic acids and polymeric alcohols as constituents. Maleic Anhydride is generally used as the organic acid. The material extraction process of polyester resin is modelled in the Ecoinvent 3.5 database. Further information on this resin can be found in the Ecoinvent database.

However, the viscosity of UPR is generally too high for easy infusion. Styrene is added to the UPR to increase the infusability and plays a role in cross linking. The weight fraction can be varied to achieve the desired viscosity. Styrene is a Volatile Organic Compound (VOC) which is emitted into the air during production. The total emission of styrene was estimated to be 38 kg per blade.

8.2.2 Elium

Elium is a thermoplastic resin developed by Arkema Inc.. Other than thermosets, thermoplastics have the ability to be melted after polymerization. This enables welding, press forming and remoulding. These techniques can be used during production and for manufacturing or recycling purposes.

Depending on the temperature, Elium is infusible during the first 80%-85% of the polymerization time. This is possible because of its low viscosity (100 mPa s, at 298.15 K [3]). The fact that this resin is infusible, allows Elium to be used in the same production process as the current polyester composites.

The mechanical properties of glass fibre reinforced Elium are, according to the producer Arkema Inc., comparable to glass fibre reinforced polyester [4].

Table 5: Material properties of Elium RT-300 resin reinforced with Chomarat 600T PW fabric, $V_f = 0.53$. [4]

Material Property	Magnitude	Unit
Tensile Strength	557	MPa
Tensile Stiffness	27	GPa
Compressive Strength	347	MPa
Compressive Stiffness	28	GPa
Resin Density	1.01	g cm^{-3}

The composition of (co-)polymers and activator is shown in Table 6. A range of ratios defined by Arkema this brings a certain amount of uncertainty. Next to this, the exact copolymer is not defined. It is however known what acrylic monomers Arkema produces. This knowledge is used to define a combination of composition scenarios. These composition scenarios are used to determine the variation of the impact of Elium Resin. These Scenarios are discussed in more detail in Subsection 10.3.2.

Table 6: Composition of the Elium Resin

Role	Name	Amount	Data Cource
Polymer	Methyl methacrylate	49.26%-83.74%	Material Safety Data [1]
Copolymer	Acrylic copolymers	9.85%-49.26%	Material Safety Data [1]
Activator	Luperox	1.5%	Technical Data Sheet [3]

The amount of added Luperox can vary from 1.5% to 3.0%. The amount of Luperox added to the resin determines the polymerisation time. For a 3.0% weight fraction of Luperox, Elium has an injection time between 35 and 25 minutes in ambient temperatures of 15 and 25 degrees Celsius respectively [3]. 1.5% of Luperox ensures the slowest polymerization and longest polymers. A Luperox weight fraction of 0.015 was selected since a longer polymerization time will allow the infusion operator to manipulate the infusion process in a more controlled way and possible use less injection points. The infusion time of 30 minutes will still result in a short cycle time.

The effect of various resin compositions was tested in Section 10.3. The resin composition defined as the 'baseline' scenario is however the composition which was used throughout the rest of the calculations. This resin compositions is presented in Table 7.

Table 7: Baseline Elium composition

Monomers	Baseline
Methyl Methacrylate	0,7
Methyl Acrylate	0,1
Acrilic acid	0,1
Butyl Acrylate	0,1

8.2.3 BAPP-PHT

BAPP-PHT is considered because of it mechanical properties which are in line common commercial high-performance epoxy and BMI resins [66] combined with it recyclability.

Since BAPP-PHT is not included in Ecoinvent it had to be modelled based on process descriptions from literature. BAPP-PHT is synthesized using 8 molles of BAPP per 16.8 molles of Paraformaldehyde [66]. However BAPP and Paraformaldehyde aer not included in the database either. The latter is the polymerization product of formaldehyde. This polymerization takes place under warm (373.15 K) and low pressure conditions [47]. Formaldehyde is included in the Ecoinvent database. 2,2-Bis[4-(4-Aminophenoxy)Phenyl]Propane or in short 'BAPP' was prepared from bisphenol-A and p-chloronitrobenzene in the presence of potassium carbonate and DMAc (N,N-Dimethylacetamide) then reduced by Pd/C-H2 and finally recrystallized from ethanol before use [23].

The quantities used to synthesize the BAPP-PHT resin are shown in Tables 8-9. Bisphenol A is included in the REACH list of the European Chemicals Agency. This list contains substances that are restricted from use in certain products. As can be seen in the 'restriction on "Bisphenal A"'-document, enclosed in Appendix F, this restriction is not on the use of Bisphenal A in resins. However, attention must be paid to the development of this list to be aware of the status of substances like Bisphenal A. Since this may prohibit their use.

Table 8: Mass fractions of chemicals to synthesize BAPP-PHT [66]

Chemical	Amount (mmol)	Molar mass (g/mol)	Mass Fraction
PFA	16.8	30.03	0.13
BAPP	8.0	410.52	0.87

Table 9: Mass fractions of chemicals to synthesize BAPP [66]

Chemical	Amount (mmol)	Molar mass (g/mol)	Mass Fraction
p-chloronitrobenzene	2,0	157,55	0,58
Bisphenol A	1,0	228,29	0,42

8.2.4 PET-foam

PET foam can be produced using a reactive extrusion process [6,15]. Next to (recycled) PET, pyromellitic dianhydride (PMDA) is used in PET-foam production. If PMDA is used in concentrations above 0.3 wt% the product becomes chemical, thermal and hydrodynamic instability [6]. This causes a crosslinking reactions and gel formation. Because of this, PMDA concentration are lower than 0.3 % by weight. Since the weight fraction of PMDA in PET-foam is so low and the potential amount of PET in the blade is small as well, the PMDA fraction was excluded from analysis.

8.3 Use Phase

After production the blades are transported to the site and installed. The blade is transported from the production facility in Spain to the site in Jutland. This is done by 32 ton truck over a distance of approximately 2400 km. 10% is added to the blade mass during transport to account for the rig containing the blade. The impact of installing the blades onto the turbine is assumed to be constant between the different scenarios and is therefore not modelled. This is justified since this is a comparative study and it will not benefit certain scenarios over others. The impact of a single hoist is also very small compared to the impact of for instance the transportation of the blade to the turbine site. During the operational life maintenance is performed on the blade. It is assumed that 4.5% of the composite mass is used for repair work [40].

8.4 Modeling of Waste management processes

This section focusses on the modelling of the waste management processes. First the production and maintenance waste management is discussed before elaborating on the common ground of all EoL waste management options. Later in this section, the specific waste management options are discussed.

During the EoL waste treatment metallic inserts like the lightning cable are recovered and recycled. Core materials are always separated from the rest of the laminate in case of the balsa wood core but this is not in case of the PET core.

This is since the balsa core can be reused in board production although it is slightly contaminated with resin. This is unfortunately not the case for the PET core and this will be landfilled or incinerated with the rest of the blade.

8.4.1 Production and Maintenance Waste

The waste which is produced during the production and maintenance stages are handled in a different way than the EoL waste. The production and maintenance waste is managed using currently available methods. The separated waste streams are recycled or incinerated as described in Table 10.

Table 10: Production and Maintenance Waste Handeling

Waste stream	Waste management method
Aluminum	Aluminium, treatment of aluminium scrap
Steel	Recycled as Steel, low-alloyed
Paper and cardboard	Recycled as Paper, woodcontaining
Elium	Recycled as Nylon6
Balsa	Recycled as Residual Wood
PET-Foam	Incinerated as PET
Rest	Incinerated

8.4.2 End of Life Waste

The selected scenarios all have in common that they require downsizing before transportation to the recycling plant.

Lightning cable and the core are separated from the rest of the blade. These are individually recycled. The lightning cable is recycled as low alloyed steel. De core is also disposed of separately. The core is recycled as residual wood in case a balsa wood core is used. This is possible since the balsa wood does not absorb large quantities of resin and the fact that residual wood can be used for shipboard production which allows for a level of impurities higher than the resin absorption. This is unfortunately not the case for the PET foam care. Contamination of the foam by the resin doesn't allow the foam to be recycled. It is therefore incinerated.

8.4.3 Landfill

The blade is de-installed, mechanically reduced in size to ease transportation and transported to the landfill site. It is than assumed to be inserted in a sanitary landfill.

8.4.4 Incineration (benchmark)

After de-installing the blade and mechanically reducing its size, the blade is transported to the incineration plant. The different portions of the blade are assumed to have different contributions to the incineration process. The two biggest fractions are highlighted. GF is assumed to be incinerated as glass and the resin fractions are assumed to be incinerated as plastic. However, the different types of resin have different combustion heats and emission patterns. These were modified from the basic plastic incineration process accordingly.

During incineration Energy is recovered. The energy recovery is calculated using the energy recovery efficiency of 40.6% of a combined heat and power recovery incineration plant [59]. 30.7% is recovered as electrical energy and 9.9% as heat for district heating. The combustion heats of the main components are shown in Table 11.

Table 11: Combustion heat of main blade constituents

Material	LHV (MJ/kg)	source
PET	23,22	[62]
UPR	25,80	[62]
Elium	24,5	[35]
PHT	34,7	[35]

The heating values of Elium and BAPP-PHT are unknown and were therfore estimated using Equation 7 [35]. HHV is in this equation the higher heat value in MJ/kg, w_C, w_H, w_O, and w_N are the weight percentages of carbon, hydrogen, oxygen and nitrogen respectively. This formula was validated with 1478 data points of fuel data and has a mean absolute percentage error of 7.73%.

$$HHV = 0,3532 * w_C + 1,1065 * w_H - 0,1009 * w_O + 0,07472 * w_N \tag{7}$$

8.4.5 Cement kiln

The cement kiln route is generally seen as an economical way of recycling. Also, a high amount of material needed in cement production and this is therefore a possible way of handing a substantial amount of waste.

Matrix is burned as fuel and its combustion energy (the LHV of UPR is shown in Table 11 is fully substitutes heavy fuel used in the cement kiln process. Glass is used partially as filler material and partially takes over the role of clay in the mixture.

Table 12: Energy requirement for mechanical recycling of Composites

Material	Energy Required (MJ/kg)	source
UPR (course)	0,1008	[58]
PHT (course)	0,1008	[58]
Elium (fine)	0,29	[58]

8.4.6 Mechanical Grinding

Mechanical recycling steps are almost always taking to reduce the size and increase the transportability of the blades. Since this reduces the size of the composite to large chunks the required energy is lower than for complete mechanical recycling. After this the chunks of composite are transported to the recycling treatment plant.

For the scenario using Elium the composite is grinded down even further and granulated to produce a product which can substitute glass fibre reinforced Nylon 6 for injection moulding. Nylon 6 is a short fibre reinforced plastic which is very suitable for injection moulding.

8.4.7 Chemical - Sub Critical Water

A subcritical water hydrolysis process is described by [44]. Polyester resin is solved in a aquatic NaOH solution at a temperature of T = 230°C = 503.15 K and at a pressure of P = 2.4 MPa. The polyester resin depolymerizes at these relatively mild conditions. Propylene glycol (0,09 kg per kg of recyclate) and clean short fibres can be reclaimed after this process.

8.4.8 Chemical - BAPP-PHT

BAPP-PHT is depolymerized in a 1 M HCl/THF solution at room temperature and 88.6% to 94.7% of the BAPP is recovered [66]. The reclaimed BAPP and PFA can be used again to polymerize BAPP-PHT for the same purposes. This process can therefore be considered to be true recycling. The glass fibre fraction is assumed to be damaged by the acidic solution and is recycled as glass. This recycling process has been demonstrated on laboratory scale, but not on larger scale yet.

8.5 Exclusions

Certain parts of the system were excluded from analysis. This was done to make the modelling manageable or simply because contributions of an operations are equal between all scenarios. When parts of the systems are exactly the same between the compared systems they do not change the comparison between the systems and should be removed from the model according to the ILCD handbook [16].

8.5.1 Installation and Dismantling

The blade weights of the different material scenarios are comparable. The installation and dismantling operations are therefore assumed to be the same and are therefore excluded in the model.

8.5.2 Contributions of engineering and administrative processes

The contributions of engineering, sales and administrative works, and contributions of the buildings excluded from the model. This is mainly for practical reasons and in line with literature.

8.6 Accounting for Geographical Location and Time

The 58.7 blade is produced in the LM production facility in Castellón, Spain. After this the blade is transported to Denmark and installed on site. After its use phase the blade is disposed of in Denmark. The geographical positions were taken into account while modelling by selecting processes for the appropriate location (e.g. Electricity, medium voltage ES— market for — APOS, U). This same was done for the time. Developments in material production processes were not accounted for. However, various energy scenarios are included in the Ecoinvent database, on top of this two energy scenarios for 2050 were add. These are the ”Jazz”, a more consumer driven or individualistic development, and ”Symphony”, a more voter-driven or collective development approach [25].

8.7 Data Collection

Data from the foreground system was supplied by LM Wind Power. This includes data on the bill of materials, energy consumption, waste production and specific parameters of the investigated blade. This data is known with relatively high accuracy.

Data on the background system was mostly found in literature or the Ecoinvent database. Ecoinvent contains data on the material extraction and disposal phases as well as data on transportation and energy usage. Some materials are however not included in the database and they needed to be modelled according to references in literature.

Care was taken to used multi-annual or generic data. An example for this is the production waste. The quantities were largely based on the BOM and made more accurate for GF and resin wastage based on waste measurements for a high quantity of blades.

8.7.1 Data Sources

To model the life cycle of the 58.7 blade data was gathered at different sources. Information sources cover both internal (i.e. data from LM) as external information. Internal data mostly covers the foreground system. The external information moslty covers the background system. To provide an overview they are shown in Table 13.

8.7.2 Negotiating Confidentiality with Transparency

Certain data from the foreground system was shared by LM for the analysis, but can not be shared in this report because of their confidentiality. This includes the density of certain materials, data on waste production, resin/adhesive compositions, and certain product names. The method of the data handling can however be described. This will be done in this subsection.

Waste Data

Data on waste production was supplied be the factory in Spain. Data rows with missing data were excluded and trends were investigated. Possible increase or decrease of the waste per blade indicates the maturity of the process. To find the waste of the average blade, the multi annual average waste values was used in further analysis.

Bill of Materials (BOM)

The Bill of Materials (BOM) was investigated to determine the used materials and there quantities. For this the nett quantities were used. The material names were translated to materials included in the Ecoinvent database were possible. When this was not possible, materials were modelled using other materials which were described in the Ecoinvent database. Elium and BAPP-PHT are examples of materials that are not covered in the Ecoinvent database and need to be modelled based on raw materials included in Ecoinvent and additional information from literature. The modelling of the processes which are not included in Ecoinvent and needed to be modelled based on other materials are described in Sections 8.2 and 8.4.

8.7.3 Resolving System Multifunctionality

During the production and maintenance phases waste streams are produced. These waste streams are outputs of the system which are not included in the reference flow. If they can not be recycled in a closed loop system, these 'alternative output streams' can potentially be used for different products. The alternative output streams make the system a multifunctional system. Subdividing the system is the preferred solution for multifunctionality according the LCA-standard [24]. This is however not possible for the blade production process. The second preferred solution is system expansion.

Some alternative waste streams can be reused in other production processes and will result in the avoidance of production of these materials. Some of these alternative waste streams can substitute the same substance, other materials are more likely to replace other materials. The first is applicable to products which can be truly recycled like PET bottles. However, for mechanically recycled Elium this would not be reasonable. Recycled glass fibre reinforce Elium would more likely replace GF reinforced thermoplastic resins which are used for injection moulding (e.g. GF reinforced Nylon-6).

Table 13: Information Sources per Life-Phase used for LCA Modeling

Life Phase	Data point	Source document	Source	Accessibility
MA	Material extraction	Ecoinvent 3.5 database	Ecoinvent	Commercially Available
MA	PET-foam Production Process	Literature	[6]	Public
MA	BAPP-PHT Constituents	Literature	[23, 47, 66]	Public
MA	BAPP-PHT properties	Literature	[66]	Public
MA	Elium Constituents	Product information	[1, 2]	Public
MA	Elium Properties	Product information	[3, 4]	Public
Prod.	Production location	Intranet	LM Wind Power	Public
Prod.	Material masses	Bill of Materials	LM Wind Power	Not public
Prod.	Production energy	BoBa report and database	LM Wind Power	Not public
Prod.	Styrene emissions	BoBa report and database	LM Wind Power	Not public
Prod.	Energy impacts	Ecoinvent 3.5 database	Ecoinvent	Commercially Available
Prod.	Production waste masses	Waste Measurements	LM Wind Power	Not public
Use	Transport impacts	Ecoinvent 3.5 database	Ecoinvent	Commercially Available
Use	Transport route	BoBa report and database	LM Wind Power	
Use	Replacement rate	Literature	[13]	Public
Use	Maintenance materials usage	Literature	[40]	Public
EoL	Grinding energy	Literature	[57, 58, 65]	Public
EoL	Heat of combustion	Literature	[62]	Public
EoL	Energy recovery incineration	Literature	[59]	Public
EoL	Cement kiln	Literature	[33]	Public
EoL	Sub Critical Water	Literature	[44]	Public
EoL	BAPP-PHT recycling	Literature	[66]	Public
EoL	Future Energy Scenarios	Literature	[25]	Public

9 Impact Assessment

9.1 Meaning of Impact Results

Impact results show the predicted impact of a product. It is explicitly noted that this is only an estimation of the real impacts. The difference between prediction and estimation is caused by both aleatoric and epimistic uncertainties.

Connected to this is the significance of results. For LCA studies the Monte Carlo Analysis can be used to determine the significance of results. A Monte Carlo Analysis was however not included in the licence allocated to this project. Alternative scenarios were therefore used to approximate the bounds of the uncertainty. Sensitivity and uncertainty will be assessed in Sections 10.2 and 10.3.

9.2 Characterised Results at Mid- and Endpoint Indicator Levels

The characterised results show the summed impact per impact category from every process in the described system. To accomplish this various emissions are first converted into a quantity of a reference substance (e.g. CO_2 equivalents) and than summed to find the characterised impact (e.g. global warming potential).

Emissions theoretically can, but do not necessarily contribute to all impact categories. However, emissions can also contribute to only one impact category. An example is CO_2. CO_2 does only contribute to global warming potential, but does not to other impact categories. Different substances generally have, next to this, different contributions to impact categories. For example, CO_2 and methane both only contribute to global warming potential, but for the same emitted weight methane has a 34 times stronger effect on the greenhouse effect than CO_2 according to the hierarchist ReCiPe 2016 midpoint analysis

Characterisation factors translate emissions to impacts and depending on the goal and scope of a project different characterisation schemes may be more appropriate. Characterisation factors are namely dependent on the evaluated timeframe (i.e. emmitted elements with long halftimes have a more predominant effect in the Egalitarian/long term perspective, elements with short halftimes have a more predominate effect in the Individualist/short term perspective). The ReCiPe's Hierarchist LCIA methods balance between short and long term timeframes and is often used in scientific models. It calculates the impact of emissions over 100 years. The ReCiPe Hierarchist methodology is used throughout this project. Long term emmissions are included.

Characterized midpoint indicator results per scenario (i.e. material and recycling scenarios) are found in the Appendix **??**. The same results, however normalized w.r.t. the impact of the benchmark-incineration scenario, are shown in

Appendix B. In the analysis of the results special attention was paid to the global warming potential (GWP) and the fine particulate matter formation (FPMF). These two categories have the biggest impact on the environmental damage, as described in Subsection 9.2.2.

9.2.1 Midpoint Indicators

Non-normalized midpoint indicator results show the characterised summation of emission impacts. Based on the midpoint indicators, comparisons can be made within a single impact category at a time (i.e. the global warming potential of one scenario can be compared with the global warming potential of other scenarios). However, an impact score from one impact category can not be related to impact scores from other impact categories.

This makes it hard to compare scenarios based on the total impact. It would only be possible to make assertive comparisons, based on the total impact, if the scores in all impact categories show a significant difference in favour of one scenario against all others. However, midpoint indicator scores are very well suited to make comparisons based on one indicator category. Although one might say that an LCA in this case loses its advantage over a singe impact analysis.

Midpoint indicator results are shown in Appendix B. The volume of data and figures is large and only a selection of the results will be shown in this section. The selection is based on the endpoint total impact scores as shown in Section 9.2.2.[7] The scenarios with the lowest total impacts are selected adn shown in Figures 9 and 10. All values are normalized to the midpoint indicator scores of the incinerated GF/UPR/balsa blade.

Global warming potential lower for GF/polyester/balsa scenario when recycled using the sub critical hydrolysis recycling process and for the incinerated GF/PHT/balsa blade.

Low variation between the scores in the Global warming, Stratospheric ozone depletion, Ionizing radiation, Ozone formation (Human health and Terrestrial ecosystems), Fine particulate matter formation, and Terrestrial acidification relative to the other impact categories. Big differences are present between the ionizing radiation results from the different scenarios.

9.2.2 Endpoint Indicators

Endpoint indicators quantify a systems impact on the environment and are calculated based on the characterised midpoint indicator scores. The midpoint indicator

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[7] For abbreviations of the impact categories please refer to the Nomenclature.

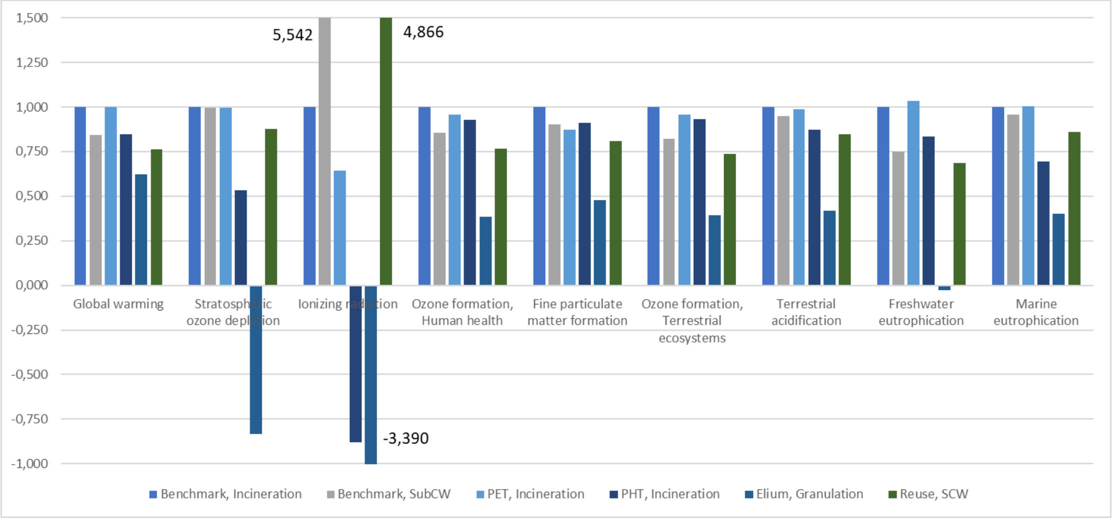

Figure 9: Midpoint indicator scores for a selection of scenarios.

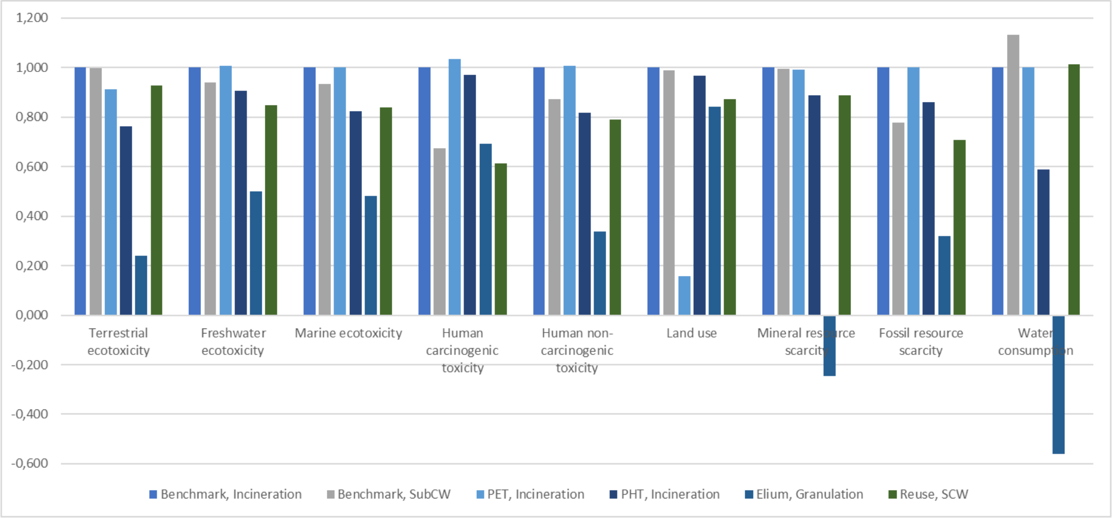

Figure 10: Midpoint indicator scores for a selection of scenarios.

scores are translated to endpoint impact scores making use of the damage pathways. A weighting set can be chosen to compute the single score impact. Although weighting step add a layer of subjectivity to the results [29], it is, together with normalization, becoming they are becoming essential parts of LCA practice [36, 60]. Table 14 shows the normalization en weighting sets for the ReCiPe H endpoint analysis. In the computation of the results weighting set 'A' was used.

Table 14: Normalisation and Weighting Factors used in the ReCiPe H Endpoint Methodology

Damage Category	Normalisation	Weighting (A)	Weighting (H)
Human Health	42.1	400	300
Ecosystem	1396	400	400
Resources	0.000037	200	300

Endpoint indicators were used to identify the most impactful midpoints categories. The percentages of endpoint indicator contributions to the total impact are shown in Table 23 in Appendix **??**. A compact representation is shown in Table 15.[8]. These values are the average contributions of all scenarios.

Table 15: Contribution Percentages per ReCiPe H Endpoint Impact Category Normalized w.r.t. the total contribution per material-EoL scenario.

Impact category	Minimum	Maximum
GW, HH	36,1%	42,2%
GW, TE	3,6%	4,2%
FPM	36,6%	43,8%
HCT	3,9%	7,2%
HnCT	3,9%	5,9%

Table 15 show that, on average, the biggest environmental impacts (>4%) are caused by emissions of greenhouse gasses, fine particulate matter, and emission toxic to the human population. The tables in Appendix **??** confirm that this is not only on average true, but actually the case for all scenarios.

It must be noted that life cycle toxic emissions in Ecoinvent are mostly correlated to energy [26,27]. Non-energy related toxic releases however are generally less well covered in the Ecoinvent database. This includes limitations and lack of data characterising toxic emissions in the disposal stage [29]. Human toxicity impact

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[8] For abbreviations of the impact categories please refer to the Nomenclature.

scores may therefore be underestimated. The contributions of the human toxicity are nevertheless much smaller than those of the global warming potential and the fine particulate matter formation. Focus will therefore be on these two indicators and on the total impact. The endpoint impact scores are shown in Figure 11. The results are normalized w.r.t. the impact scores of the incinerated GF/UPR/balsa blade.

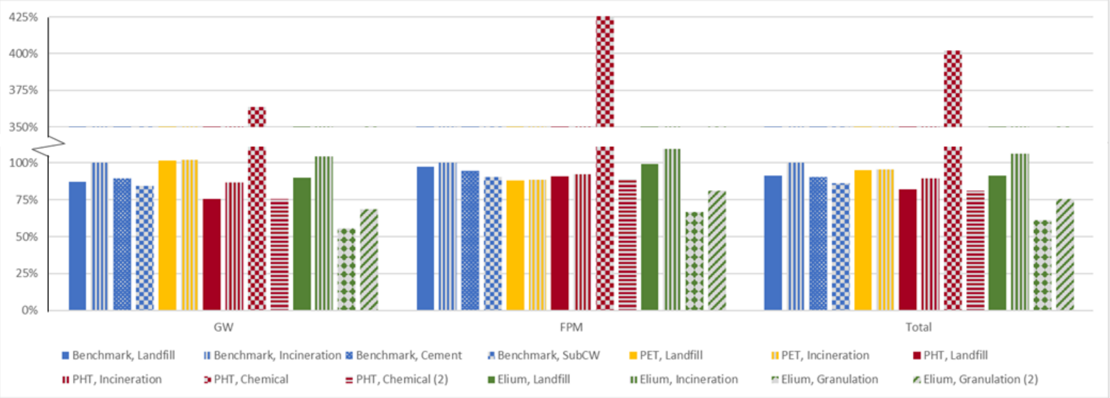


Figure 11: Global Warming (GW), Particulate Matter Formation (PMF), and total impact scores for the assessed material and waste management scenarios normalized with respect to (w.r.t.) the incinerated benchmark blade.

The endpoint indicators show that the global warming potential of the benchmark blade is highest for the incineration waste scenario. The landfill scenario is no likely to be available in the future, but looks promising when the emissions are assessed. This is because the emissions are low during this recycling process since substances are largely contained inside the product. The biggest contributions are from transport, mechanical steps taken to reduce the size and embed to composite waste, and the cement used in the landfilling process. Contributions of other scenarios will not be dicussed in this section, but in Section 9.3. This holds for landfilling in general and will not further be discussed. The landfilling scenario only serves as a reference to the other solutions.

The cement kiln and Sub Critical Water (SCW) processes have lower contributions to GW and produce less Fine Particulate Matter (FPM). Sub critical water hydrolysis looks the most promising based on these results. This is likely since both resin constituents and glass are regained at the end of this process.

Greenhouse gas emissions of both PET scenarios are comparable with the incinerated GF/UPR/balsa blade scenario. The FPM and total impact scores are however lower. This is likely due to the substitution of PET foam for balsa in the material extraction phase since the FPM score is already lower for the landfill scenario.

FPM scores are lower than the reference value for all PHT scenarios. The global potential shows a different pattern however. The chemical recycling has an extremely high global warming potential compared to all other scenarios. This is likely to be due to the used of chemical during the recycling process.

The Elium resin scenarios show comparable GW results to the UPR scenarios for the landfill and incineration waste processes. The granulation process bares much lower nett GHG-emissions. The contribution of the FPM is however much higher for this scenario. Also the landfill and incineration scenarios have comparable or slightly higher contributions than the reference scenario.

The processes and substances that contribute most to the variation in the results were identified and are discussed in Section 9.3.

9.3 Contribution Analysis

The processes and substances that contribute most to the variation in the impact scores were identified using the network analyses tool in Simapro and are discussed in this section. All contributions are based on characterised results.

But before going into specific scenarios, the contribution to the greenhouse gas and fine particulate matter emissions were analysed. The results for the UPR, GF and balsa fraction are shown in Table 16. It is seen that the contributions of the UPR and GF fractions to the material extraction phase are comparable to the values found in the BoBa study as mentioned in Section **??**. Next to this the material extraction phase accounts for around two thirds of the total green house gas emissions. The relatively big impact of the material extraction phase can be explained due to the low energy and material input during the production and use phase compared to the amount of material that goes into the blade.

Table 16: GF/UPR/balsa Incineration Scenario: Endpoint contributions of the UPR and GF fractions to the Material Extraction (Mat. Ext.) and Life Cycle impacts.

Substance / Phase	GW, Mat. Ext.	FPM, Mat. Ext.	GW, Life Cycle	FPM, Life Cycle
UPR	50%	31%	30%	24%
GF	30%	48%	26%	37%
Balsa	2%	18%	1%	14%
Material Extraction	-	-	62%	78%
Disposal	-	-	14%	7%

9.3.1 Benchmark, Incineration

The greenhouse gas emissions for the incineration process are high compared to the greenhouse gas emissions of the landfill scenario. This is largely due to the incineration of the resin and glass fibre. The incineration process accounts for 10% of the total greenhouse gas emissions. The FPMF of the incineration process is 7% of that of the total life cycle.

9.3.2 Benchmark, Sub Critical Water Hydrolysis

The sub critical water hydrolysis process results in a CO_2 and FPM reduction w.r.t. all other GF/UPR/balsa scenarios. 12% reduction of FPM and 13% reduction of GHG due to reclaiming resin constituents. The total recycling process reduces the GH and FPM emission with 3% and 19% respectively.

9.3.3 BAPP-PHT, Material Extraction

The emissions associated with the material extraction of BAPP-PHT are much lower than those of polyester. The greenhouse gas emissions are about 40% lower and the emitted fine particulate matter is reduced by about 30%.

9.3.4 BAPP-PHT, Chemical Recycling

The large increase in the greenhouse gas emissions is the result from the use of TetraHydroFuran (THF) during the recycling process. THF is a organic compound used to increase the wettability of the composite during the solving process. If the THF is used during one cycle with a 4:1 weight ratio w.r.t the recyclate, the THF accounts for in 83% of the greenhouse gas emissions. Although the results look very conclusive, a big amount of uncertainty is present. The impact scores largely depend on the efficiency of the process. Section 10.3.1 will reflect on this.

9.3.5 Elium, Material Extraction

The Elium resin has a slightly higher impact than the Polyester. Next to this, the exact resin composition of Elium is unknown. This results in a spread of possible scores rather than a single value. The uncertainty is discussed and quantified in Section 10.3.2. The baseline composition of the elium Elium results in an increase of 20% and 19% in GW and FPM w.r.t. to polyester resin.

9.3.6 Elium Resin, Incineration

The slightly higher impact of the incinerated GF/Elium/Blade is linked to the increase of the impacts of the material extraction phase.

9.3.7 Elium, Granulation

The granulation scenario of the Elium Resin has the lowest scores in the GW and FPM categories. This is explained by the contributions of the avoided production. These contributions are listed in Table 17.

Table 17: Contribution of GF/Elium Composite to Impact Categories.

Recyclate	Avoided Product	GW	FPM
Elium	Nylon-6	-54%	-24%
Continuous GF	Short GF	-26%	-31%

10 Interpretation

10.1 Completeness and Consistency

10.1.1 Completeness - Inventory items

Checks were made to ensure that material streams were accounted for. An example of one of these checks was on the total blade weight. The BOM weight entered in Simapro was summed to find the total weight. This was corresponding to the known blade weight.

10.1.2 Completeness - Impact categories

To check the validity of the model outcomes were compared with data from literature. Figure 12 and 13 show the water usages and CO2 footprints of assessments on wind turbine blades [40]. Emission free disposal was assumed in the assessment. This data was compared with the four material composition scenarios with landfill at disposal.

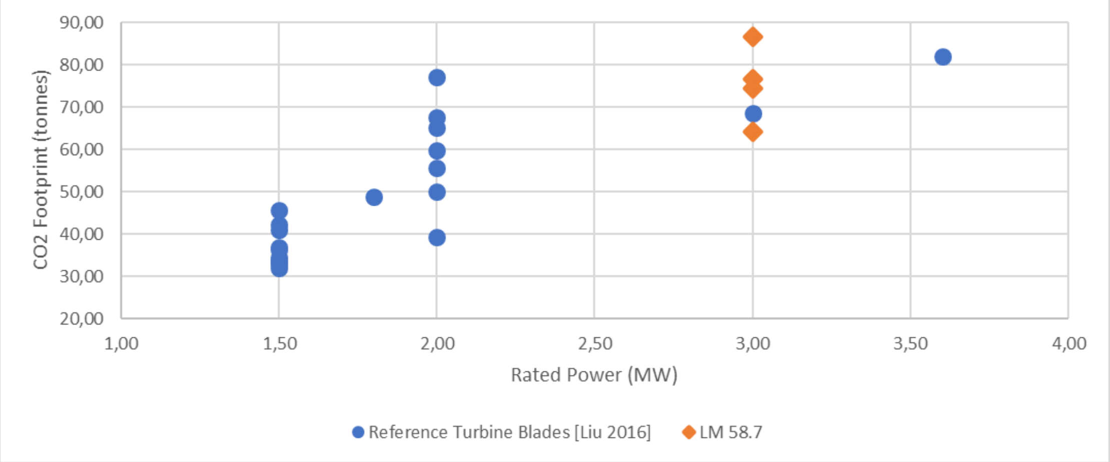


Figure 12: Comparison of CO2 footprints between 58.7 (Landfilled GF/UPR/balsa)and LCA Results from Literature. CO2 footprint used for comparison were assessed by Liu et al. [40]

The comparison of the CO2 footprints shows that the model results are of the same magnitude as the data found in literature. This ensures that no big errors were made in critical areas and adds to the validity of the results.

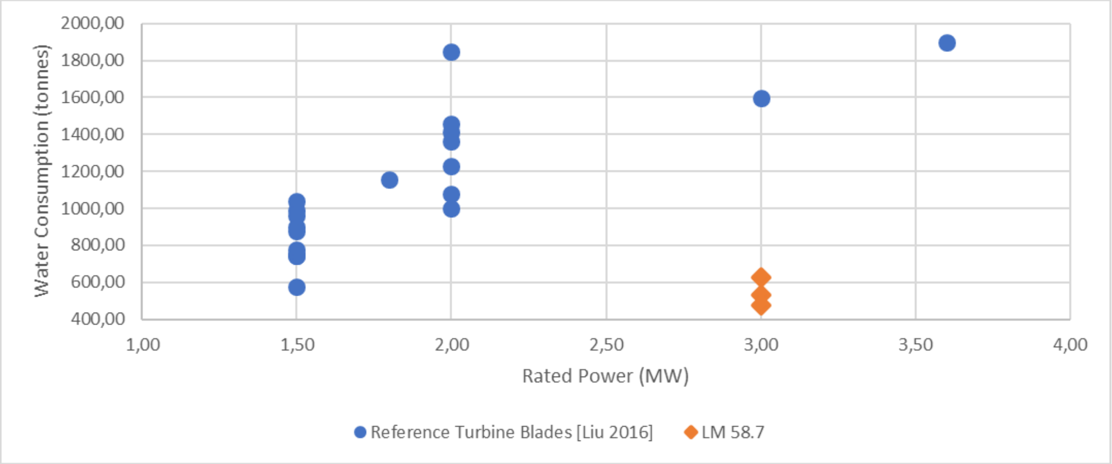


Figure 13: Comparison of Water Consumption between 58.7 (Landfilled GF/UPR/balsa)and LCA Results from Literature. CO2 footprint used for comparison were assessed by Liu et al. [40]

However, the results of the water consumption are further off. This can be because of a number of reasons. One of which is that Liu used a different database to calculate the results. Water use methodologies are less mature than those of CO2 footprint. This means larger differences are expected to be present between the databases and LCIA characterisation schemes. For this reason and since the results are still in the same order of magnitude no further action was taken.

10.1.3 Consistency

It is important that methods are applied in a consistent way for all scenarios. The results will otherwise be influenced. Care was taken that methods and modelling choices were applied in a consistent fashion throughout the research. Recycling methods for example were applied to the production waste streams in the same way for all scenarios. The same goes for the LCIA methodology used for the analysis. Transport and energy consumptions were applied in a fashion similar to all scenarios.

10.1.4 Result interaction of interested parties

LM has high interest in CO2 reduction since this is one of the companies focus point with their carbon neutrality program. This did however not interfere with the presentation of the results. Greenhouse potential was found to be one of the key drivers in the design of the blade. Focus was therefore put on the GW and FPM emissions. This was done regardless of the incentives of LM Wind Power.

10.2 Uncertainty Analyses

During the data gathering stage of this research some data was not definitive and some assumptions may have lead to uncertainty in the results. These uncertain areas are addressed in this section.

10.2.1 Chemical efficiency of PHT-solvolysis process

The amount of chemicals needed to solve the resin have not been mentioned in the literature describing the recycling process BAPP-PHT resin. Only the ratios of the chemical compounds is know. However, they can be changed to meet a desired recycling timeframe. It is also likely that the solvent can be (partially) reused for multiple batches of recyclate if the final recycling process is optimized.

To investigate the influence of the reusability of the solvent compounts and the influence of the amount of solvent needed for solving a certain amount of PHT-composite, a sensitivity analysis was done. The results of this analysis are shown in Section 10.3.1.

10.2.2 Composition of Elium Resin

The exact composition of the Elium Resin has not disclosed to the public. Some parts of the resin composition are know however. This knowledge is based on the material safety sheet. Most uncertain are the composition of the Acrylic copolymer and the mass fraction of the Methyl Methacrylate. Various resin compositions have been investigated in Section 10.3.2.

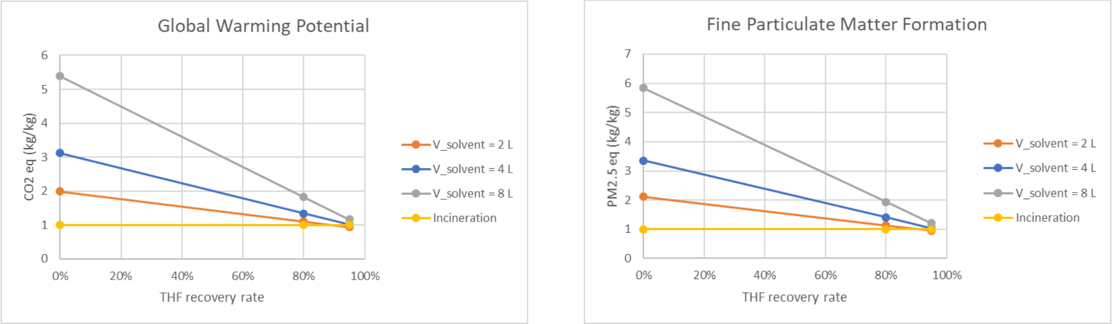
10.3 Sensitivity Analyses

10.3.1 PHT Recycling

Although the constituents and their concentrations are known for the solvolysis process, the total amount of solvent per kilogram of recyclate composite is not communicated in literature. Based on amount of solvent needed to solve the polyester resin in the SCW process (V = 4 liters per kilogram of recyclate) a range of 1 to 8 liters was set.

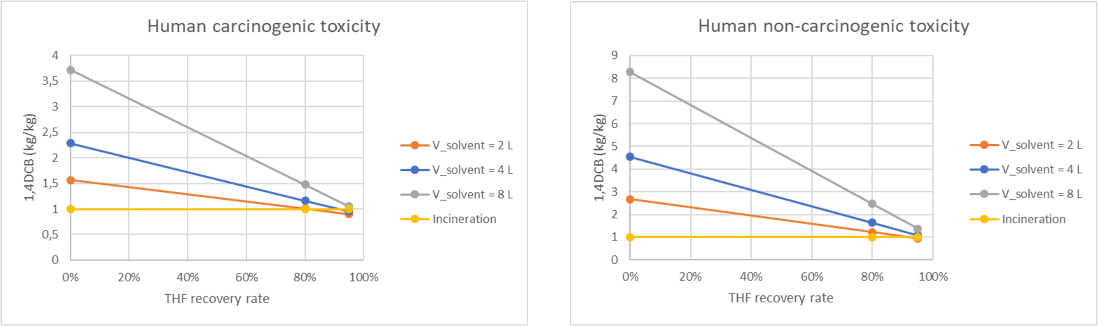
During the solvolysis process, tetrahydrofuran (THF) increases the wettability of the solvent on the PHT resin. It is however not consumed during solvolysis. The question could therfor be asked if the THF could be reused for a second or even more solvolysis cycles. The recovery rate (RR) of THF is varied from 0-95%.

The effect of these two parameters was evaluated on the predefined intervals (V = [2, 8], RR = [0, 0.95]). The response of the impacts on these variations was tested by evaluating the midpoint impact scores of complete life cycles. The responses are shown in Figures 14.



(a) GHG emissions.

(b) Particulate Matter Formation.



(c) Carcinogenic Toxicity.

(d) Non-Carcinogenic Toxicity.

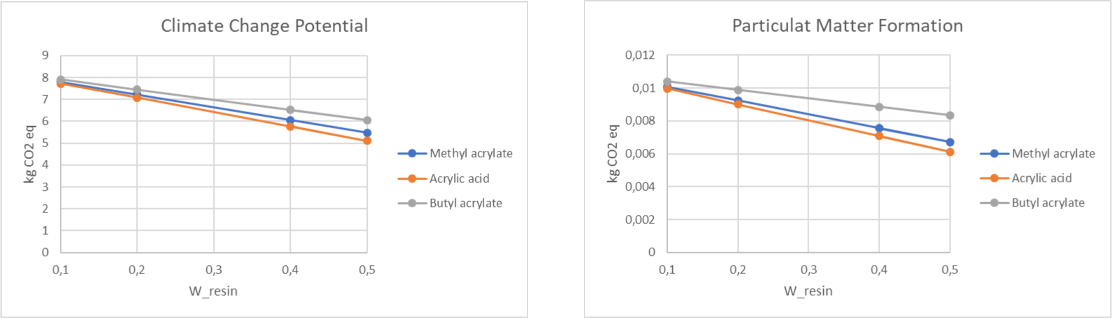
Figure 14: Variation of lifetime emissions for multiple assumptions normalized w.r.t PHT-incineration Scenario.

All four figures show comparible relations between recovery rate of THF, volume per kilo of recyclate and the magnitude of the midpoint impacts. The results show that the THF recovery rate must be well above 60% and/or the volume of solvent must be below 4 liters per kilo of recyclate for the solvolysis process to be beneficial for the environmental impact.

The dependency of the impact on the THF recovery rate and volume of the solvent is very big (i.e. total impact varies with a factor of 8 for some impact higher impact midpoint categories). Because of this big variation, no decisive conclusions can be drawn based on the results of the PHT-solvolysis process at this point.

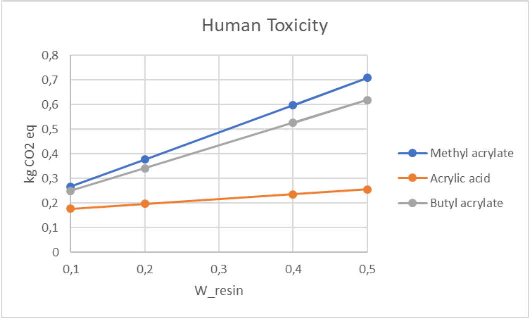
10.3.2 Elium Compostion

Since the contents of the "Acrylic Copolymer" are not disclosed by Arkema Inc. a combination of acrylic monomers were tested to find the scatter of possible impacts. Based on information on Arkema's Acrylic monomer production, Methyl Acrylate, Acrilic acid and Butyl Acrylate were considered as possible constituents. The weight fractions of the monomers were varied within the previously mentioned boundaries. To find both the positive and negative extremes of the impact per kilogram of Elium, pure monomer volumes were added to the Methyl Methacrylate. The resulting impacts per kilogram of Elium are shown in Figures 15a-15c.



(a) Climate Change Potential per Kilogram of Elium.

(b) Formation of Particulate Matter per Kilogram of Elium.



(c) Human Toxicity per Kilogram of Elium.

Figure 15: Variation of Emissions for Multiple Elium Composition per Kilo of Resin.

Based on the extremes found in the above figures the resin compositions shown in Table 18 were tested for the sensitivity analysis. The resin composition defined as the 'baseline' scenario is the composition which was used throughout the rest of the calculations.

Table 18: Elium Constituents for the evaluated Alternative Scenarios (AS)

Monomers	Baseline	AS 1	AS 2	AS 3	AS 4
Methyl Methacrylate	0,7	0,9	0,5	0,9	0,5
Methyl Acrylate	0,1	0,0	0,0	0,0	0,5
Acrilic acid	0,1	0,0	0,5	0,1	0,0
Butyl Acrylate	0,1	0,1	0,0	0,0	0,0

The lifecycle impacts were calculated for the different resin compositions and the variation on top of the baseline scenario was calculated using Equation 8. In this equation, 'var' refers to the variation of the alternative scenario w.r.t. the baseline scenario, $\mathrm{IS}_{\mathrm{AS}}$ is the impact score of the alternative scenario and $\mathrm{IS}_{\mathrm{BL}}$ is the impact score of the baseline scenario. The resulting variations are shown in Figure 16.

$$var = \frac{IS_{AS}}{IS_{BL}} - 1 = \frac{IS_{AS} - IS_{BL}}{IS_{BL}} \tag{8}$$

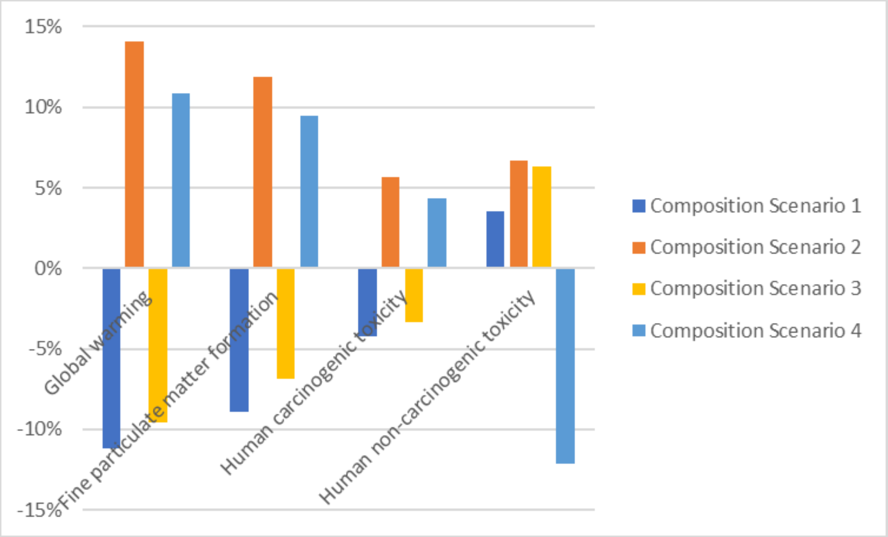
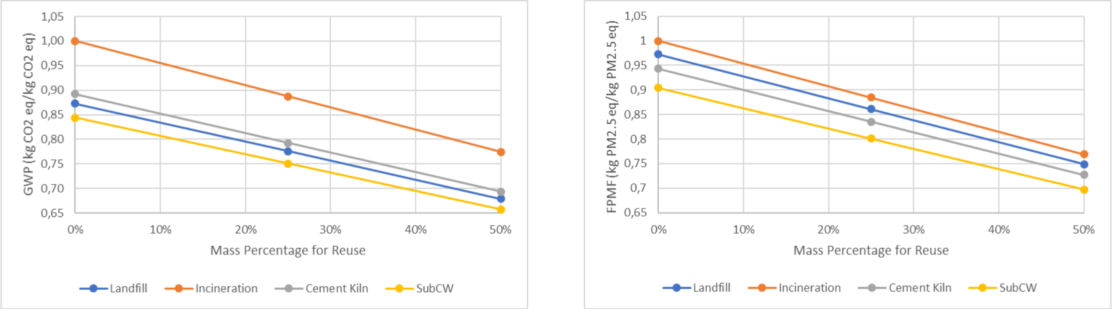


Figure 16: Midpoint Impact for Multiple Elium Compositions.

Figure 16 shows a considerable scatter in the life cycle impact of 5 to 15 percent between alternative scenarios and the baseline. Although the investigated acrylic monomers are very representative, the possibility exists that other copolymers were used. This could result in a bigger scatter.

10.3.3 Reuse Fraction and Glue Amount

The predicted impacts were calculated for the total of two times 20 years. The impact scores were then divided by two to satisfy the functional unit. Figure 17 shows the emissions of greenhouse gasses and fine particulate matter for multiple reuse weight fractions. The scenarios shown in Figure 17 assume that no extra adhesive on top of the amount used in the original design.



(a) GHG emissions.

(b) Particulate Matter Formation.

Figure 17: Most Impactfull Emissions for Varying Reuse Mass Fractions normalized w.r.t. the single use, incinerated benchmark Blade.

The GHG and FPM emissions decrease close to linearly with an increasing reuse fraction. The reduction is around 11% and 22% for reuse fractions of 25% and 50% respectively. This is on top of reductions due to the waste management method utilized at EoL. The results show that reuse is promising way to reduced the environmental impact when it is structurally viable. This need to be addressed in further analysis. Possible areas of interest are the reduction of leading edge erosion, crack growth and changes in maintenance over the increased timespan.

The dependency of the extra added adhesive was assessed an the results are shown in Tables 19 and 20. The effect of extra adhesive is small compared to the reuse fraction. However, it still leads to a variation of 2 percent point.

Table 19: Greenhouse Potential for Varying Reuse Mass Fraction and adhesive Amounts in kg CO2 eq/kg CO2 eq normalized w.r.t. the single use, incinerated benchmark Blade.

		Reuse Percentage		
	adhesive added	0%	25%	50%
Landfill	0%	87%	78%	68%
	50%	-	78%	68%
	100%	-	79%	69%
Incineration	0%	100%	89%	77%
	50%	-	90%	78%
	100%	-	90%	79%
Cement Kiln	0%	89%	79%	69%
	50%	-	80%	70%
	100%	-	81%	71%
SubCW	0%	84%	75%	66%
	50%	-	76%	67%
	100%	-	77%	68%

Table 20: Fine particulate matter formation for varying reuse mass fraction and adhesive amounts in kg PM2.5 eq/kg PM2.5 eq normalized w.r.t. the single use, incinerated benchmark blade.

		Reuse Percentage		
	adhesive added	0%	25%	50%
Landfill	0%	97%	86%	75%
	50%	-	87%	75%
	100%	-	87%	76%
Incineration	0%	100%	88%	77%
	50%	-	89%	77%
	100%	-	90%	78%
Cement Kiln	0%	94%	84%	73%
	50%	-	84%	73%
	100%	-	85%	74%
SubCW	0%	90%	80%	70%
	50%	-	81%	70%
	100%	-	82%	71%

11 Tool

Design decisions are in most cases based on a combination of cost and (performance) parameters. Environmental impact is, generally speaking, not on of them. However, LM wants to incorporate knowledge on the potential environmental impacts in the early design stage decision making processes. To start providing decision makers from LM with the necessary information in this decision making process a tool was developed to calculate potential impacts.

Next to the correctness of the calculations preformed by the tool, other important factors were addressed to increase the usability of the tool. An important part of presenting and communicating the results throughout the corporate structure is ensuring a high understandability of results for involved parties. User friendliness and adaptability of the tool are, next to this, key factors. The first is important to allow easy use throughout the organisation without extensive training (N.B. care most be taken that users are aware of the limitations of the tool). The second enables the further development of the tool without scrapping the existing tool completely. Adaptability is increased by using the OOD coding strategy.

Section 11.1 describes how the tool is build up, Section 11.2 describes the assumption on which the tool is based and the effect of these assumptions, Section 11.4 elaborates on the choices made on how the present the results in a very understandable way, and Section 11.3 describes the calculation methods of the different parameters.

11.1 Code Description

11.1.1 Development Strategy

The tool was built using a object orientated development (OOD) strategy in Python. A OOD strategy uses modules based on classes of objects, which are manipulated by the system, to build up a program [42]. Benefits of using an OOD strategy is that it allows reuse of encapsulate tested code in future projects [19] or within the same project. An side benefit of the reusability is easier adaptation of the code. This originates from the reduced redundancy within the code.

11.1.2 Layout

This section describes the way the tool was built up and what libraries were used to enable the functions of the tool. The layout of the tool is shown graphically in Figure 18. The front-end and back-end codes are found in Appendix **??**.

To calculate potential environmental impacts the tool makes use of impact data generated by an existing LCA tool. In this existing tool certain processes (e.g. extraction of glass fibre or transportation using a 16-32 ton truck) are modelled using a life cycle inventory database and LCIA method. Currently, the ReCiPe Endpoint Hierarchist is used to calculateed the impact scores per category. For the weighting set A is chosen, this set has a relatively high contribution of human health impacts. The impact of the processes are exported in csv (Comma-Separated Values) format.

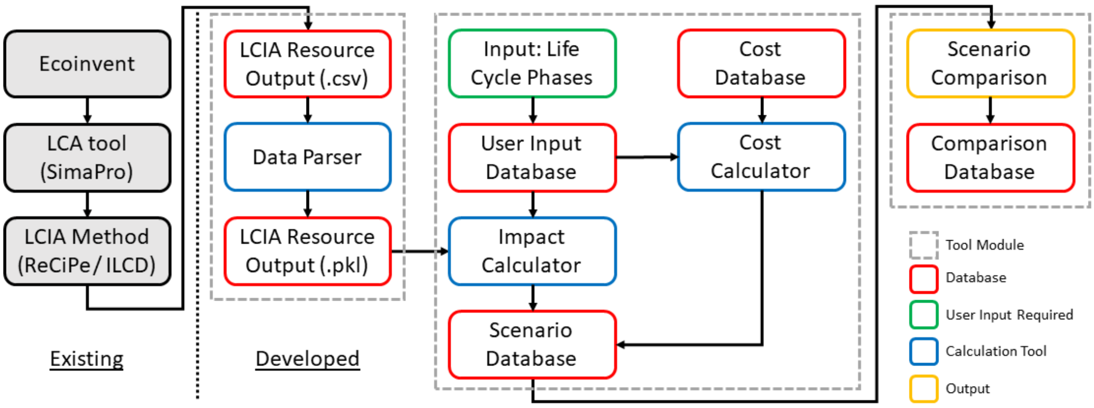


Figure 18: Code Block Layout of the Tool

The ”Pandas” library is used in the tool to handle the data. A Pandas DataFrame can be stored easily as a pickle (.pkl) file. The first part of the tool reads the csv file, parses the data and saves it in a pkl file.

The second module of the tool generates a Graphical User Interface (GUI) which allows users to enter what processes take place in the life cycle and in what quantities. After this it calculates the output parameters of a single scenario. The GUI is build using the kivy and the different screens are shown in Appendix E.1. Kivy is an open source library which allows rapid development of applications that run on most broadly used operation systems. These include Linux, Windows, OS X, Android, iOS, and Raspberry Pi [37, 61]. This extended compatibility increases the usability of the tool. After the user has entered all required inputs the tool stores the user inputs and calculates the output parameters. The calculation methods used to calculate the environmental impact and other output parameters are described in Section 11.3. The output parameters are stores in a scenario database.

Figures and numerical outputs can later be generated individual scenarios or then can be compared. The output files show (the difference in) the environmental impact, estimated cost, blade weight and recyclablility. Examples of output files generated for a comparison between two scenarios are shown in Appendix E.2.

11.2 Assumptions

The tool is based on a number of assumptions. These assumptions and their possible impact on the results are discussed in the sections below.

All scenarios have the same functionality. This tool does not take into account different functions of the evaluated systems. The user must therefore be aware that the different systems may not satisfy the functional unit in the same way (e.g. two systems with the same average power output but different lifespans). Systems with different functions without accounting for this can lead to wrong conclusions.

To account for this numerical output files (csv format) should be manually modified to satisfy the the functional unit. Graphical outputs do not support this, but this functionality can added by modifying multiple_screens.py, output_plotter.py and style_file.kv.

Environmental impact and cost increase linearly with recourse quantity. Cost and environmental impact may not increase linearly with the used quantity of resources. The give an example for each: cost per quantity may decrease if larger quantities are purchased, and environmental balances may be distorted if emissions pass a certain threshold this can lead to a knock-on effect resulting in higher impacts than the impact just from the emissions.

Cost effects are likely to be accounted for since variations in a single design will hardly impact the total procurement portfolio of LM. If databases are kept up-to-date the environmental impact the linearity assumption should not yield big differences.

Impacts of the production only consist of materials and energy usage. This is in line with what happens in the current system.

Impacts of the use phase only consist of material and transport. The installation and de-installation of the blades is excluded from the system. This is in line with the exclusions in the LCA study.

11.3 Description of Output Calculations

To facilitate the decision making, a selection key parameters need to to be calculated. These parameters include environmental impact scores, blade weight, blade cost, recycling weight fractions. The following subsections will discuss how these parameters are calculated.

11.3.1 Environmental Impact

The environmental impacts are calculated using data from an calculate impacts of different materials, means of transport, energy inputs, and waste management methods.

$$\overline{\mathrm{IS}}_{total} = \sum_{i=1}^{n} \left(\overline{\mathrm{IS}}_{m,i} + \overline{\mathrm{IS}}_{w,i} \right) \cdot w_i + \sum_{j=1}^{m} \overline{\mathrm{IS}}_{nm,j} \cdot q_j \tag{9}$$

where $\overline{\mathrm{IS}}_{\mathrm{total}}$ is a vector containing the environmental impact of the entire life cycle, $\overline{\mathrm{IS}}_{\mathrm{m}}$ and $\overline{\mathrm{IS}}_{\mathrm{nm}}$ are vectors containing the environmental impact per unit of quantity of material extraction and non-material extraction related processes respectively, $\overline{\mathrm{IS}}_{w}$ is a vector containing the impact of a waste management process. q and w are the quantity of the process and material weight. n and m are the amount of input processes.

Based on their contribution to the single score weighted endpoint impact global warming potential, fine particulate mater and (non-)carcinogenic toxicity are explicitly shown in the graphical output. The rest of the impacts are summed and shown as one. The individual impact categories are distinguished in the numerical output.

11.3.2 Weight

To calculated the blade weight, the weights of all materials that end up in the finished blade are summed. As shown in Equation 10, where $\mathrm{m}_{\mathrm{blade}}$ is the blade weight, $\mathrm{m}_{\mathrm{material}}$ is the weight of a single material which is used in the blade and n is the total amount of used materials.

$$m_{blade} = \sum_{i=1}^{n} m_{material,i} \tag{10}$$

11.3.3 Cost

The cost is build up out of 2 parts: The material cost and the extra cost (e.g. man hours or mould depreciation expenses of the mould). The cost is than calculated by adding those, as shown in Equation 11. Where $\mathrm{c}_{\mathrm{blade}}$ is the blade cost, c_{m} is the material cost, $\mathrm{w}_{\mathrm{m,i}}$ is the material weight, and c_{e} the extra cost.

$$c_{blade} = \sum_{i=1}^{n} c_{m,i} * w_{m,i} + \sum_{j=1}^{m} c_{e,j} \tag{11}$$

11.3.4 Recycle, Recover and landfill Weight fractions

The recycle, recover and landfill weight fractions show how the blade performs when looked at the waste management hierarchy. These weight fractions are calculated using Equations 12-14. Is these equations $\mathrm{M}_{\mathrm{recycle}}$, $\mathrm{M}_{\mathrm{recover}}$, $\mathrm{M}_{\mathrm{landfill}}$, and $\mathrm{M}_{\mathrm{total}}$ are the weights of the recycled portion, recovered portion, landfilled portion and the total weight of all material used during the life cycle respectively.

$$m_{recycle} = \frac{M_{recycle}}{M_{total}} \tag{12}$$

$$m_{recover} = \frac{M_{recover}}{M_{total}} \tag{13}$$

$$m_{landfill} = \frac{M_{landfill}}{M_{total}} \tag{14}$$

11.4 Communicating Results

Generally communications should be clear and unambiguous. This is one of the reasons the message should be adapted to the audience. From internal audits it is known the audience will not always have a background in LCA or (environmental) engineering. To reduce the complexity of the output and make it more understandable, a single score output was chosen. This still shows the contributions of the selected impact categories, while giving a single total score which form a basis for easy comparison between scenarios.

The results will be presented in an intuitive way. This is facilitated by assigning specific visualisation styles to individual parameters (i.e. not in a single complex graph). The final visualisation is shown in Figure 19.

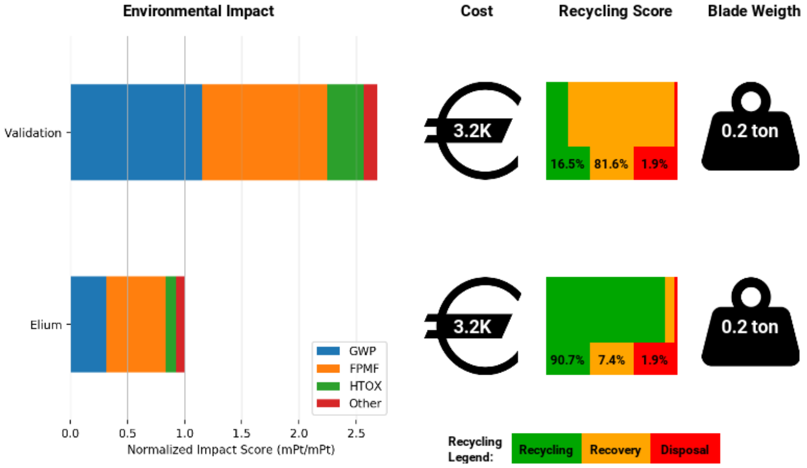


Figure 19: Graphical Comparison of two Hypothetical Blades.

11.5 Tool Verification and Validation

To verify the tool did what was expected from the tool, unit testing was performed on the different different code blocks. Various test data files (e.g. files containing zero, unit or increasing impacts scores) were used during the code verification steps. After all code blocks were verified to work properly, validation was started.

Validation was performed using a case study. This case study was on a simplified model of a wind turbine and it contains all major processes. Quantities were chosen to reflect weight ratios which are in the right order of magnitude. The processes and chosen quantities are shown in Table 21. This case was analysed by both the developed tool and SimaPro. The results from SimaPro were used to validate the tool.

Table 21: Inputs of the Validation

Life Phase	Recourse / Process	Quantity	Unit	Waste Management
Mat. Ext.	Glass Fibre	100	kg	Incineration
	UPR	100	kg	Incineration
	Balsa Wood	20	kg	Recycling
	Steel	10	kg	Recycling
Production	Glass Fibre	10	kg	Recycling
	UPR	10	kg	Incineration
	Balsa Wood	2	kg	Recycling
	Steel	1	kg	Recycling
	Polypropylene	5	kg	Landfill
	Electricity EU mix	100	MJ	-
Use	Glass Fibre	5	kg	Incineration
	UPR	5	kg	Incineration
	Balsa Wood	1	kg	Recycling
	Steel	0.5	kg	Recycling
	Freigth, Lorry 16-32 ton	1000	tkm	-
	Passenger Car	200	km	-

The resulting impacts were calculated using both a dedicated SimaPro model and the developed tool. The numerical results are shown in Appendix E.2. They are also shown in Figure 20. This shows the results follow each other closely. A difference is observed between the results of the marine eutrophication, freshwater ecotoxicity, marine ecotoxicity, and human non-carcinogenic toxicity. The error is calculated using Equation 15 and equates to an error of 0.12%. This falls well within the uncertainty margins of LCA studies.

$$\epsilon = \frac{\sum_{i=1}^{n} |IS_{Tool,i} - IS_{SimaPro,i}|}{\sum_{i=1}^{n} IS_{SimaPro,i}} \tag{15}$$

Combined, the global warming impacts, the impact due to fine particulate matter formation and the human carcinogenic and non-carcinogenic toxicity impacts make up for 93.1% of the total impact. The next biggest contribution is form the land use which makes only up for 2.5%. This justifies highlighting the GW, FPMF and H(n)CT categories in the graphical output.

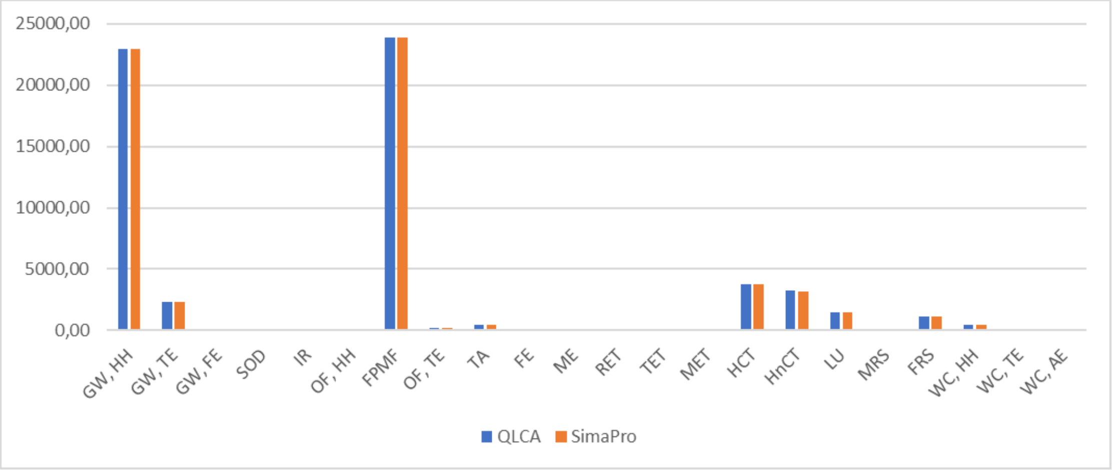


Figure 20: Results of validation case study.

12 Conclusions, limitations and recommendations

This comparative case study of material substitution in wind turbine blades to reduce environmental impact shows that the biggest part of the environmental impact is caused by the resin and secondly the glass fibre fraction. This is in line with literature. The resin variation allows for different recycling techniques which may result in the reduction of the environmental impact. This is largely because of the avoided production of the recyclate material. However, the impact of the waste management techniques is highly dependent on the resources during the process.

First looking at the core variation, exchanging the balsa wood core with PET foam results in a comparable greenhouse potential, but decreases the released amount of fine particulate matter. As a result the environmental impact of 58.7 is slightly reduced. The effect of the core change is small compared to fibre or resin changes, because of the relatively small weight of the core. If recycling of the PET core would be enabled in the future, the benefits of switching from balsa to PET are likely to increase.

Next to the higher weight of the resin fraction, specific resin types allows for specific recycling techniques. These show to have a big impact on the total environmental impact. First looking at the UPR resin blade. The recycling technique with the lowest impact which is currently available on industrial scale is the cement kiln route. A big advantage of this technique is it availability; i.e. TRL and capacity are high and this technique is allowed. Next to this, the environmental impacts of both the greenhouse gas emissions and the fine particulate matter are lower than for incineration of this blade, as is the total impact. The cement kiln route is the advised method of disposal for the blades which are currently in operation.

However, sub critical water hydrolysis method yields better results than the cement kiln route and should be considered as the better option for currently used blades after further development of this technique. Sub critical water hydrolysis can also be considered to be a recycling technique since usable substances come out of this process. These substances can be used for comparable purposes as before and are not recovered or lost as heat. This may be a big advantage depending on regulatory changes, as seen in the automotive industry. It is however not possible to conclude sub critical water hydrolysis is lower impact recycling method than the cement kiln route with certainty since the difference is only marginal (4%). It is however likely that an optimized sub critical water hydrolysis is better than the incineration of the UPR blade since the difference in total endpoint impact is bigger (10%).

When the change is made to different resin types, i.e. BAPP-PHT and Elium, other recycling methods become available and material extraction impacts change. The latter is especially true for the BAPP-PHT. This resin has lower impact in the material extraction phase than the UPR resin. This is apparent when the landfill scenarios are compared.

The incineration of the PHT blade shows better results than the UPR blade largely because of the contributions of the material extraction phase. When looking at the chemical recycling process of PHT resin, a big dependency on the reusability of the chemicals is observed. The impact strongly decreases in case the Tetrahydrofuran (THF), which only serves the purpose of increasing the wettability and is not used up in a chemical reaction, can be reused in more reactions. This is the case for both the greenhouse gas emission and the fine particulate matter formation. For very effective recovery of the THF (95% or higher), the chemical recycling process of BAPP-PHT results in environmental impacts comparable with the UPR blade when solved using sub critical water hydrolysis or used in the cement kiln. Although the hydrolysis of PHT is the only true and high efficiency recycling method, with a recovery rate of around 90% of all raw chemicals, its potential is not reflected to the fullest in the LCA results.

For Elium the environmental impact of the material extraction phase is harder to determine with certainty. This is very much dependent on the composition of the Elium resin, which is disclosed in a precise manner. The GWP and the FPMF impact scores of the resin may vary. As a result of this is not possible to conclude the landfilled or incinerated Elium blades result in lower impacts.

It is however possible to conclude that the mechanical granulation process shows much lower impacts than all other material and recycling options. This is because of the avoided production of fibre reinforced thermoplastic resin. This is true for both the greenhouse gas and fine particulate matter emissions even when taking into account the possible variations in the resin composition. I.e. the most impactfull resin combination results is at least comparable and likely better than the subcritical water hydrolysis process of the UPR blade.

Next to material variations, a reuse scenario was investigated. In the waste management hierarchy developed by the European Union, reuse and remanufacturing are seen as a method superior to recycling. The results of this research confirm this method is promising for the GF/UPR/balsa blade and it is applicable to more material scenarios.

The results have a high dependency on reuse fraction. The higher the reusable fraction, the lower the impact. High reuse fractions (close to 50% or higher) are not likely to be obtained. The reduction of the environmental impact does not show a big dependency on the recycling method at EoL and is around 11% for all recycling scenarios when 25% of the blade is reused. This is on top of the reduction because of the waste management method at EoL.

Although not part of the main research, exchanging glass fibre to carbon fibre may lead to big changes in the impact of wind turbine blades according to literature. Also, bio fibres, have a big potential when in comes to reducing the impacts of the material extraction phase. However there are practical challenges which make their implication unlikely in the near future.

UPR was used as a baseline for this comparative study. Epoxy makes up the other big part of the resin used in the wind turbine industry.

No Monte Carlo analysis was available within the resources of this project. The Monte Carlo analysis allows the determination of statistical significance of the results. This would have allowed for a better comparison of the results. However, resin compositions and recycling processes need to be known with more certainty for the Monte Carlo analysis to be most effective.

It is known that the material extraction phase of the wind turbine blade is the most impactfull life phase and that resin is the biggest contributor to this. However, exact resin compositions are often strictly confidential. This was the case for the Elium resin. This made it more difficult to analyse the material extraction impact of the Elium resin and results in a high amount of uncertainty.

A similar difficulty was found for the BAPP-PHT resin. This is largely because the production process of the raw materials used to synthesize BAPP were not included in the Ecoinvent database. The production processes of the BAPP and formaldehyde where however known and could be modelled using stoichiometric relations.

Also, the focus of this research is mainly on the reduction of emission by utilizing reuse and recycling techniques. This is however only one way to approach the matter of impact reduction. Future research could focus on the reduction of the impact of the material extraction phase. The material extraction phase accounts for the biggest impact of wind turbine blades and avoiding impact is known to be effective. It must be determined however how applicable low impact materials are to the production of wind turbine blades. This development is therefore mainly dependent on developments in novel, low impact materials.

Next to this, a high volume of research is done into newly developed resins (including Elium). Future publication may describe these resins more distinctive manor which will allow for better modelling of the material extraction phase. The same is true for recycling processes.

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A Avoided production per material

Table 22: Avoided Production of recyclate. (P), (M), and (E) refer to production, maintenance, and EoL waste.

Recyclate	Avoided product	Unit
Glass Fibre (P)	Glass Fibre	kg
Glass Fibre (M)	-	-
Glass Fibre (E, Incineration)	-	-
Glass Fibre (E, Mechanical)	Glass Fibre	kg
Glass Fibre (E, Chemical)	Glass Fibre	kg
BAPP-PHT (P)	BAPP-PHT	kg
BAPP-PHT (M)	BAPP-PHT	kg
BAPP-PHT (E, Chemical)	BAPP-PHT	kg
BAPP-PHT (E, Incineration)	Power and Heat Energy	MJ
Elium (P)	Nylon 6	kg
Elium (M)	Nylon 6	kg
Elium (E, Incineration)	Power and Heat Energy	MJ
Elium (E, Mechanical)	Nylon 6	kg
Polyester (P)	Power and Heat Energy	MJ
Polyester (M)	Power and Heat Energy	MJ
Polyester (E, Chemical)		kg
Polyester (E, Incineration)	Power and Heat Energy	MJ
Balsa (M)	Wood for board production	kg
Balsa (E, Extracted)	Wood for board production	kg
Balsa (E, Incinerated)	Power and Heat Energy	MJ
PET (M)	Power and Heat Energy	MJ
PET (E, Incineration)	Power and Heat Energy	MJ
Steel (E, Extracted)	Steel	kg
Aluminum (E, Extracted)	Aluminum	kg
Paint (E)	-	-

B Midpoint Impact Indicator Scores

Table 23: MidPoint Impact of the GF/UPR/balsa Scenario.

Impact category	Material Extraction	Munufactoring	use	landfill	Incineration	Cement	SubCW
GW	0,617	0,172	0,075	0,006	0,137	0,026	-0,023
SOD	0,888	0,051	0,053	0,000	0,008	-0,009	0,002
IR	1,465	2,461	0,110	-0,037	-3,036	-1,609	1,572
OF, HH	0,740	0,220	0,066	-0,051	-0,026	-0,079	-0,172
FPMF	0,775	0,232	0,065	-0,100	-0,072	-0,129	-0,169
OF, TE	0,743	0,216	0,066	-0,050	-0,025	-0,079	-0,206
TA	0,767	0,287	0,066	-0,133	-0,119	-0,187	-0,173
FE	0,961	0,320	0,068	-0,573	-0,349	-0,529	-0,602
ME	0,879	0,285	0,059	-0,272	-0,223	-0,301	-0,264
TET	0,592	0,102	0,306	-0,019	0,000	-0,036	-0,002
FET	0,731	0,221	0,081	0,047	-0,033	-0,117	-0,094
MET	0,735	0,214	0,091	0,036	-0,040	-0,129	-0,109
HCT	0,652	0,137	0,050	-0,269	0,161	-0,156	-0,170
HnCT	0,864	0,174	0,100	-0,041	-0,138	-0,236	-0,268
LU	0,882	0,079	0,059	-0,033	-0,020	-0,041	-0,033
MRS	1,083	0,152	0,091	-0,322	-0,326	-0,563	-0,331
FRS	0,804	0,191	0,095	-0,107	-0,090	-0,249	-0,318
WC	1,184	0,225	0,077	-0,326	-0,485	-0,466	-0,353

Table 24: MidPoint Impact of the GF/UPR/PET Scenario.

Impact category	Material Extraction	Munufactoring	use	landfill	Incineration
GW	0,626	0,172	0,075	0,141	0,102
SOD	0,886	0,051	0,053	0,006	0,001
IR	1,497	2,461	0,111	-3,623	-3,957
OF, HH	0,711	0,220	0,064	-0,028	-0,041
FPMF	0,662	0,232	0,060	-0,074	-0,088
OF, TE	0,715	0,216	0,065	-0,027	-0,040
TA	0,770	0,287	0,066	-0,126	-0,148
FE	0,988	0,320	0,069	-0,344	-0,421
ME	0,893	0,285	0,060	-0,241	-0,299
TET	0,616	0,102	0,307	-0,005	-0,022
FET	0,753	0,221	0,082	-0,043	-0,089
MET	0,757	0,214	0,092	-0,049	-0,094
HCT	0,664	0,137	0,051	0,186	0,093
HnCT	0,890	0,174	0,101	-0,142	-0,181
LU	0,082	0,079	0,019	-0,022	-0,025
MRS	1,095	0,152	0,092	-0,335	-0,354
FRS	0,830	0,191	0,096	-0,093	-0,108
WC	1,216	0,225	0,078	-0,529	-0,578

Table 25: MidPoint Impact of the GF/PHT/balsa Scenario.

Impact category	Material Extraction	Munufactoring	use	landfill	Incineration	Chemical
GW	0,504	0,172	0,069	0,006	0,119	0,975
SOD	0,452	0,051	0,032	0,000	0,001	-0,124
IR	1,223	2,461	0,097	-0,102	-4,675	-1,676
OF, HH	0,694	0,220	0,063	-0,052	-0,039	0,768
FPMF	0,712	0,232	0,062	-0,100	-0,087	0,938
OF, TE	0,701	0,216	0,064	-0,051	-0,038	0,754
TA	0,687	0,287	0,062	-0,134	-0,151	0,958
FE	0,852	0,320	0,062	-0,575	-0,394	1,566
ME	0,673	0,285	0,049	-0,275	-0,306	1,643
TET	0,476	0,102	0,300	-0,020	-0,022	1,120
FET	0,709	0,221	0,080	0,046	-0,088	1,090
MET	0,632	0,214	0,086	0,035	-0,092	1,174
HCT	0,638	0,137	0,050	-0,269	0,152	0,708
HnCT	0,742	0,174	0,094	-0,041	-0,172	1,227
LU	0,862	0,079	0,058	-0,033	-0,026	0,140
MRS	1,022	0,152	0,088	-0,323	-0,360	0,476
FRS	0,709	0,191	0,090	-0,108	-0,107	0,984
WC	0,928	0,225	0,064	-0,331	-0,625	6,889

Table 26: MidPoint Impact of the GF/Elium/balsa Scenario.

Impact Category	Material Extraction	Munufactoring	use	landfill	Incineration	Granulation
GW	0,643	0,172	0,076	0,005	0,102	-0,335
SOD	0,124	0,051	0,015	-0,001	0,001	-1,060
IR	0,925	2,461	0,083	-0,076	-3,957	-0,483
OF, HH	0,780	0,220	0,068	-0,052	-0,041	-0,558
FPMF	0,792	0,232	0,066	-0,101	-0,088	-0,426
OF, TE	0,785	0,216	0,068	-0,051	-0,040	-0,550
TA	0,898	0,287	0,073	-0,135	-0,148	-0,575
FE	0,643	0,320	0,052	-0,577	-0,421	-0,576
ME	1,379	0,285	0,084	-0,275	-0,299	-0,912
TET	0,362	0,102	0,295	-0,021	-0,022	-0,136
FET	0,504	0,221	0,069	0,035	-0,089	-0,163
MET	0,511	0,214	0,080	0,024	-0,094	-0,179
HCT	0,632	0,137	0,049	-0,272	0,093	-0,150
HnCT	0,599	0,174	0,087	-0,055	-0,181	-0,339
LU	0,851	0,079	0,057	-0,033	-0,025	-0,044
MRS	0,872	0,152	0,081	-0,323	-0,354	-0,565
FRS	0,796	0,191	0,094	-0,108	-0,108	-0,548
WC	0,758	0,225	0,056	-0,330	-0,578	-0,824

C Endpoint Impact Indicator Scores

Table 27: EndPoint impact scores of the benchmark scenario.

Impact category	Unit	Assembly bench	landfill	Incineration	Cement	SubCW
Total	kPt	3,28E+00	-2,03E-01	9,84E-02	-2,33E-01	-3,72E-01
Global warming, Human health	kPt	1,15E+00	8,62E-03	1,78E-01	3,54E-02	-3,03E-02
Global warming, Terrestrial ecosystems	kPt	1,15E-01	8,62E-04	1,78E-02	3,54E-03	-3,04E-03
Global warming, Freshwater ecosystems	kPt	3,15E-06	2,36E-08	4,87E-07	9,67E-08	-8,29E-08
Stratospheric ozone depletion	kPt	2,52E-03	-4,07E-07	1,70E-05	-2,17E-05	5,08E-06
Ionizing radiation	kPt	1,23E-03	-1,12E-05	-9,98E-04	-4,89E-04	4,78E-04
Ozone formation, Human health	kPt	3,08E-03	-1,54E-04	-8,37E-05	-2,37E-04	-5,18E-04
Fine particulate matter formation	kPt	1,43E+00	-1,33E-01	-9,94E-02	-1,73E-01	-2,26E-01
Ozone formation, Terrestrial ecosystems	kPt	1,51E-02	-7,40E-04	-4,05E-04	-1,16E-03	-3,03E-03
Terrestrial acidification	kPt	3,33E-02	-3,95E-03	-3,69E-03	-5,56E-03	-5,15E-03
Freshwater eutrophication	kPt	7,82E-03	-3,32E-03	-2,07E-03	-3,07E-03	-3,49E-03
Marine eutrophication	kPt	1,81E-06	-4,03E-07	-3,49E-07	-4,45E-07	-3,91E-07
Terrestrial ecotoxicity	kPt	1,16E-03	-2,24E-05	-4,04E-06	-4,13E-05	-2,49E-06
Freshwater ecotoxicity	kPt	6,10E-04	2,75E-05	-2,45E-05	-6,94E-05	-5,58E-05
Marine ecotoxicity	kPt	1,30E-04	4,46E-06	-5,99E-06	-1,60E-05	-1,36E-05
Human carcinogenic toxicity	kPt	1,86E-01	-5,96E-02	3,50E-02	-3,46E-02	-3,77E-02
Human non-carcinogenic toxicity	kPt	1,75E-01	-6,36E-03	-2,21E-02	-3,63E-02	-4,12E-02
Land use	kPt	5,55E-02	-1,79E-03	-1,15E-03	-2,20E-03	-1,81E-03
Mineral resource scarcity	kPt	4,12E-04	-9,98E-05	-1,03E-04	-1,75E-04	-1,03E-04
Fossil resource scarcity	kPt	5,89E-02	-2,82E-03	-1,73E-03	-1,30E-02	-1,60E-02
Water consumption, Human health	kPt	2,66E-02	-3,28E-04	-3,89E-04	-1,35E-03	-2,78E-03
Water consumption, Terrestrial ecosystem	kPt	5,11E-03	-3,32E-04	-4,35E-04	-5,80E-04	-7,67E-04
Water consumption, Aquatic ecosystems	kPt	2,69E-07	-3,29E-09	-1,84E-09	-1,24E-08	-2,75E-08

Table 28: EndPoint impact scores of the PET scenario.

Impact category	Unit	Assembly PET	landfill	Incineration
Total	kPt	3,09E+00	-1,10E-01	2,16E-01
Global warming, Human health	kPt	1,17E+00	2,34E-02	2,07E-01
Global warming, Terrestrial ecosystems	kPt	1,17E-01	2,34E-03	2,07E-02
Global warming, Freshwater ecosystems	kPt	3,19E-06	6,39E-08	5,67E-07
Stratospheric ozone depletion	kPt	2,52E-03	2,65E-06	2,13E-05
Ionizing radiation	kPt	1,24E-03	-2,64E-06	-1,03E-03
Ozone formation, Human health	kPt	2,99E-03	-1,14E-04	-4,28E-05
Fine particulate matter formation	kPt	1,28E+00	-1,10E-01	-7,50E-02
Ozone formation, Terrestrial ecosystems	kPt	1,47E-02	-5,41E-04	-2,06E-04
Terrestrial acidification	kPt	3,34E-02	-3,59E-03	-3,27E-03
Freshwater eutrophication	kPt	7,99E-03	-3,03E-03	-1,66E-03
Marine eutrophication	kPt	1,83E-06	-3,74E-07	-3,11E-07
Terrestrial ecotoxicity	kPt	1,19E-03	1,70E-05	3,69E-05
Freshwater ecotoxicity	kPt	6,24E-04	7,59E-05	2,46E-05
Marine ecotoxicity	kPt	1,33E-04	1,48E-05	4,51E-06
Human carcinogenic toxicity	kPt	1,89E-01	-2,24E-02	0,07907475
Human non-carcinogenic toxicity	kPt	1,79E-01	0,007964937	-7,78E-03
Land use	kPt	9,80E-03	-8,53E-04	-1,00E-03
Mineral resource scarcity	kPt	4,16E-04	-2,75E-05	-3,03E-05
Fossil resource scarcity	kPt	6,04E-02	-2,49E-03	-1,31E-03
Water consumption, Human health	kPt	2,72E-02	-7,91E-05	-0,000114815
Water consumption, Terrestrial ecosystem	kPt	5,23E-03	-0,000281425	-3,84E-04
Water consumption, Aquatic ecosystems	kPt	2,75E-07	3,11E-10	1,84E-09

Table 29: EndPoint impact scores of the PHT scenario.

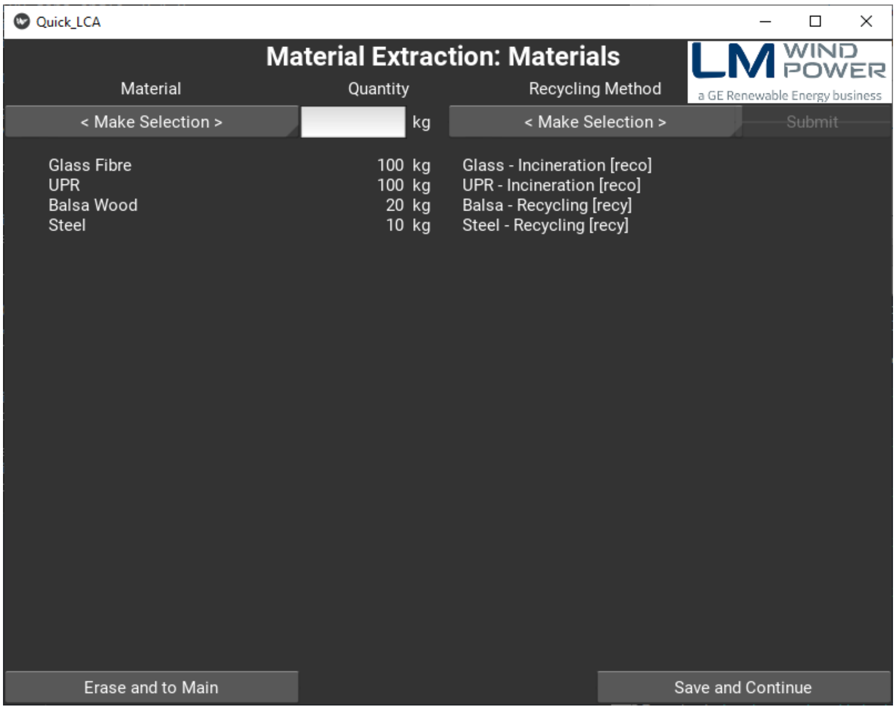
Impact category	Unit	Assembly PHT	landfill	Incineration	Chemical
Total	kPt	2,9717398	-0,2050277	0,052565511	6,9890309
Global warming, Human health	kPt	0,99460529	0,007793109	0,15921739	2,6064162
Global warming, Terrestrial ecosystems	kPt	0,099520212	0,000778843	0,015929274	0,26083204
Global warming, Freshwater ecosystems	kPt	2,72E-06	2,13E-08	4,35E-07	7,12E-06
Stratospheric ozone depletion	kPt	0,001358636	-1,06E-06	2,59E-06	-4,04E-05
Ionizing radiation	kPt	0,001150473	-3,10E-05	-0,001416152	0,000454554
Ozone formation, Human health	kPt	0,00293746	-0,000155095	-0,000115643	0,005097042
Fine particulate matter formation	kPt	1,3466645	-0,1340819	-0,115543	2,7819882
Ozone formation, Terrestrial ecosystems	kPt	0,014468907	-0,000745914	-0,000558271	0,024692268
Terrestrial acidification	kPt	0,030780331	-0,003989308	-0,00447829	0,065317596
Freshwater eutrophication	kPt	0,007157151	-0,003332457	-0,00228163	0,021641938
Marine eutrophication	kPt	1,49E-06	-4,07E-07	-4,52E-07	5,55E-06
Terrestrial ecotoxicity	kPt	0,001021301	-2,32E-05	-2,54E-05	0,002697759
Freshwater ecotoxicity	kPt	0,000596654	2,72E-05	-5,17E-05	0,001461424
Marine ecotoxicity	kPt	0,000116334	4,42E-06	-1,14E-05	0,000323293
Human carcinogenic toxicity	kPt	0,1829235	-0,059602797	0,033824305	0,31236656
Human non-carcinogenic toxicity	kPt	0,15520639	-0,006235298	-0,026443759	0,42934535
Land use	kPt	0,054328759	-0,001796332	-0,001385067	0,017984593
Mineral resource scarcity	kPt	0,000391841	-0,000100256	-0,000111806	0,000445738
Fossil resource scarcity	kPt	0,052597594	-0,002839042	-0,002327445	0,10499434
Water consumption, Human health	kPt	0,021770196	-0,000357405	-0,001052498	0,29409181
Water consumption, Terrestrial ecosystem	kPt	0,004139804	-0,000339798	-0,000605959	0,058905074
Water consumption, Aquatic ecosystems	kPt	2,23E-07	-3,58E-09	-8,33E-09	2,75E-06

Table 30: EndPoint impact scores of the Elium scenario.

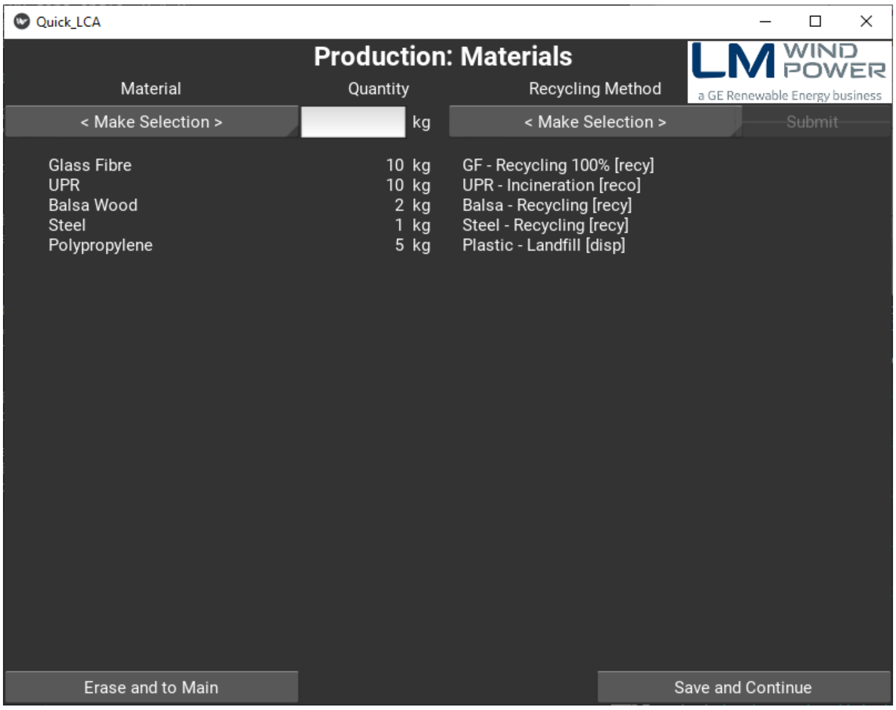
Impact category	Unit	Assembly elium	landfill	Incineration	Granulate
Total	kPt	3,283591	-0,2105453	0,29175203	-1,2240969
Global warming, Human health	kPt	1,1901554	0,006166962	0,19769937	-0,44742798
Global warming, Terrestrial ecosystems	kPt	0,1191055	0,000616142	0,019780074	-0,044758275
Global warming, Freshwater ecosystems	kPt	3,25E-06	1,69E-08	5,40E-07	-1,22E-06
Stratospheric ozone depletion	kPt	0,000484879	-1,31E-06	5,31E-06	-0,002693474
Ionizing radiation	kPt	0,001055192	-2,30E-05	-0,001887942	-0,000146993
Ozone formation, Human health	kPt	0,003208337	-0,000157112	2,66E-05	-0,001675992
Fine particulate matter formation	kPt	1,4587788	-0,13470644	-0,000333028	-0,57011053
Ozone formation, Terrestrial ecosystems	kPt	0,015761408	-0,000755612	0,00011402	-0,00810848
Terrestrial acidification	kPt	0,037353096	-0,003999299	-0,000989485	-0,017072886
Freshwater eutrophication	kPt	0,005890011	-0,003343105	0,001089786	-0,003342893
Marine eutrophication	kPt	2,59E-06	-4,08E-07	-8,09E-08	-1,35E-06
Terrestrial ecotoxicity	kPt	0,000881691	-2,48E-05	-2,74E-05	-0,00015846
Freshwater ecotoxicity	kPt	0,000469261	2,06E-05	-4,17E-05	-9,66E-05
Marine ecotoxicity	kPt	0,000100458	3,01E-06	-7,56E-06	-2,23E-05
Human carcinogenic toxicity	kPt	0,18153473	-0,060347811	0,079655267	-0,033267599
Human non-carcinogenic toxicity	kPt	0,13211999	-0,008490533	-0,002458509	-0,052109319
Land use	kPt	0,053664445	-0,001812384	-0,000237783	-0,002411394
Mineral resource scarcity	kPt	0,00034305	-0,000100311	-0,000112473	-0,000175538
Fossil resource scarcity	kPt	0,06042571	-0,002880977	0,000860943	-0,028707183
Water consumption, Human health	kPt	0,018723102	-0,000367722	-0,001008177	-0,009607095
Water consumption, Terrestrial ecosystem	kPt	0,003529822	-0,000341136	-0,000375655	-0,002201244
Water consumption, Aquatic ecosystems	kPt	1,90E-07	-3,69E-09	-7,78E-09	-9,09E-08

E Decision Assist Tool

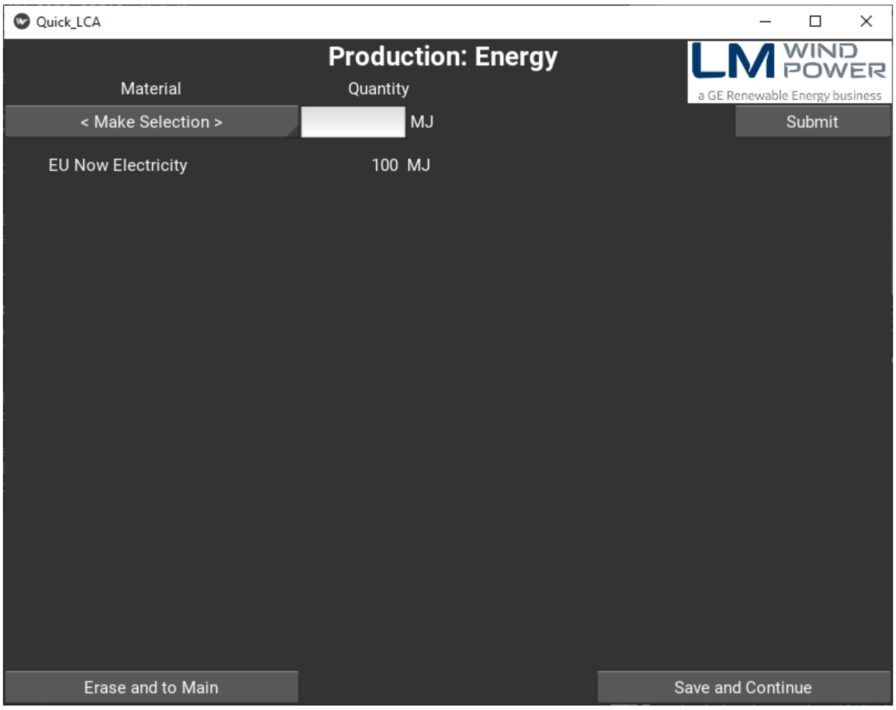
E.1 GUI



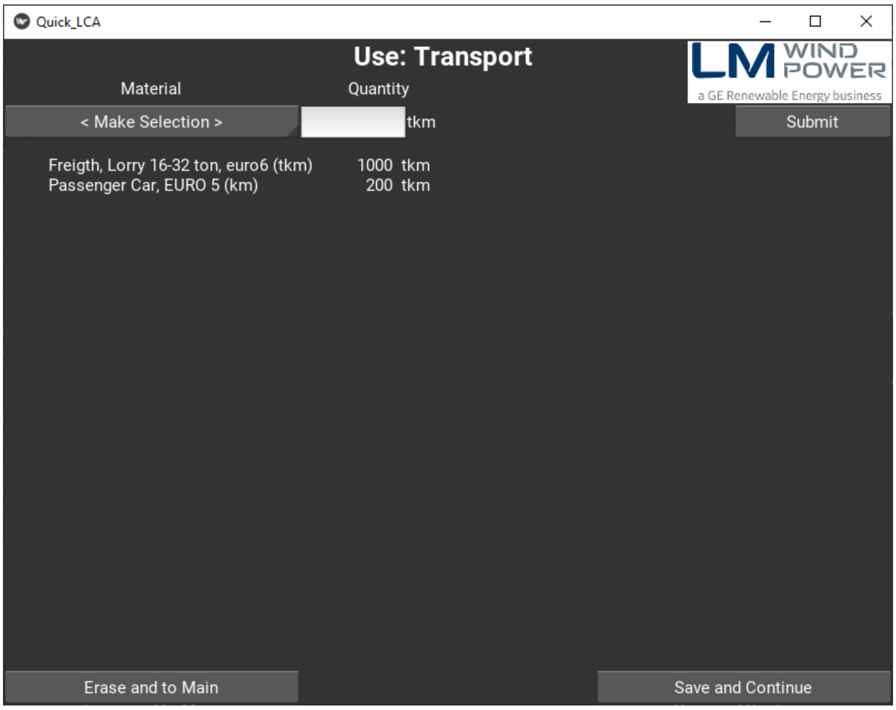
Material	Quantity	Recycling Method
Glass Fibre	100 kg	Glass - Incineration [reco]
UPR	100 kg	UPR - Incineration [reco]
Balsa Wood	20 kg	Balsa - Recycling [recy]
Steel	10 kg	Steel - Recycling [recy]



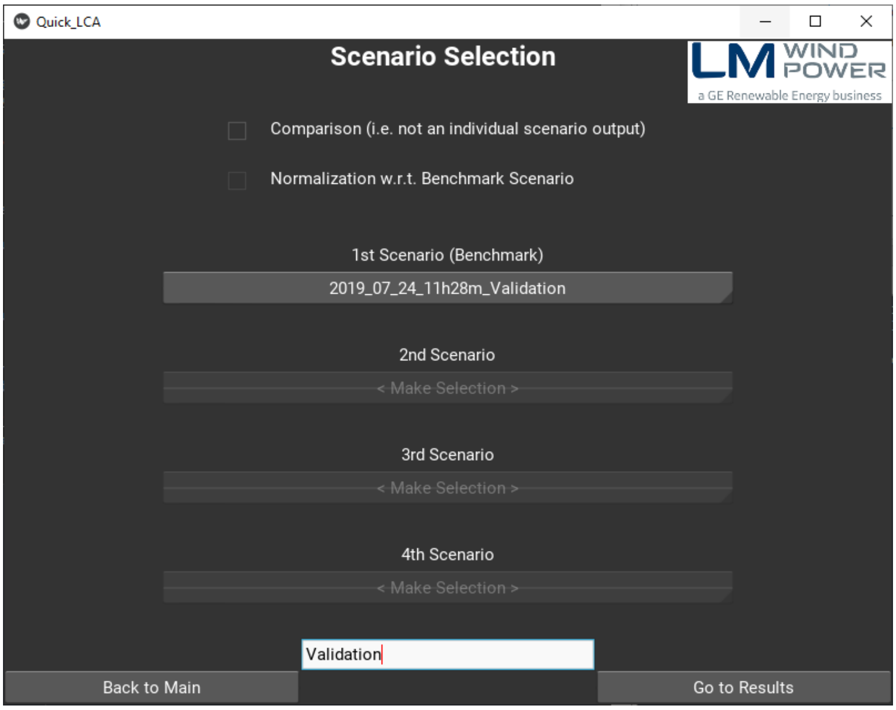
Glass Fibre	10 kg	GF - Recycling 100% [recy]
UPR	10 kg	UPR - Incineration [reco]
Balsa Wood	2 kg	Balsa - Recycling [recy]
Steel	1 kg	Steel - Recycling [recy]
Polypropylene	5 kg	Plastic - Landfill [disp]



EU Now Electricity	100 MJ



Freigth, Lorry 16-32 ton, euro6 (tkm)	1000 tkm
Passenger Car, EURO 5 (km)	200 tkm



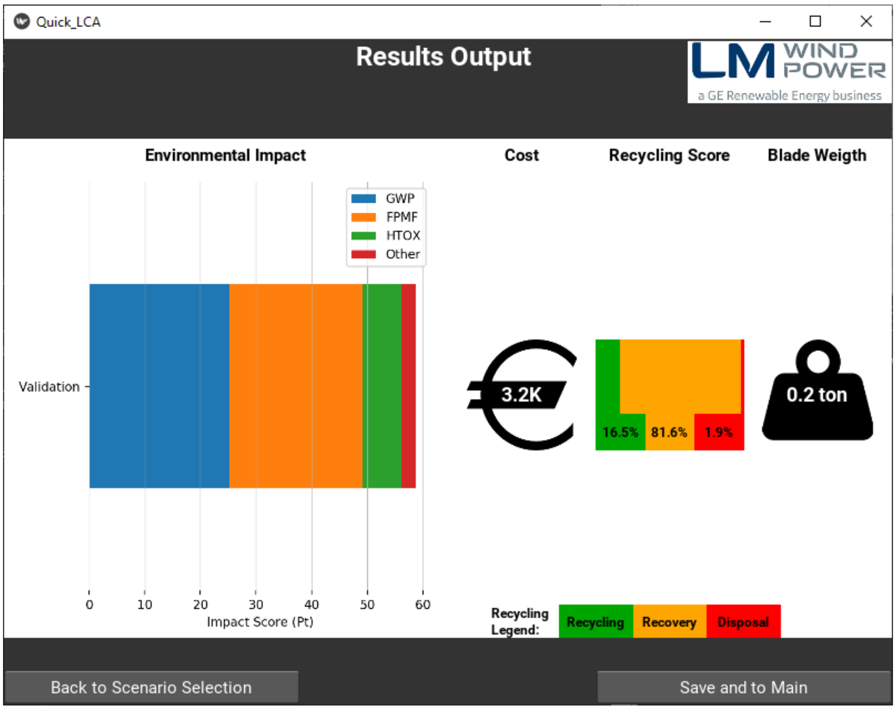
☐ Comparison (i.e. not an individual scenario output)

☐ Normalization w.r.t. Benchmark Scenario

1st Scenario (Benchmark)

2019_07_24_11h28m_Validation

Validation


Quick_LCA
Results Output
LM WIND POWER
a GE Renewable Energy business
Environmental Impact
Cost
Recycling Score
Blade Weigth
GWP
FPMF
HTOX
Other
Validation
0
10
20
30
40
50
60
Impact Score (Pt)
3.2K
16.5%
81.6%
1.9%
0.2 ton
Recycling Legend:
Recycling
Recovery
Disposal
Back to Scenario Selection
Save and to Main

E.2 Output Files

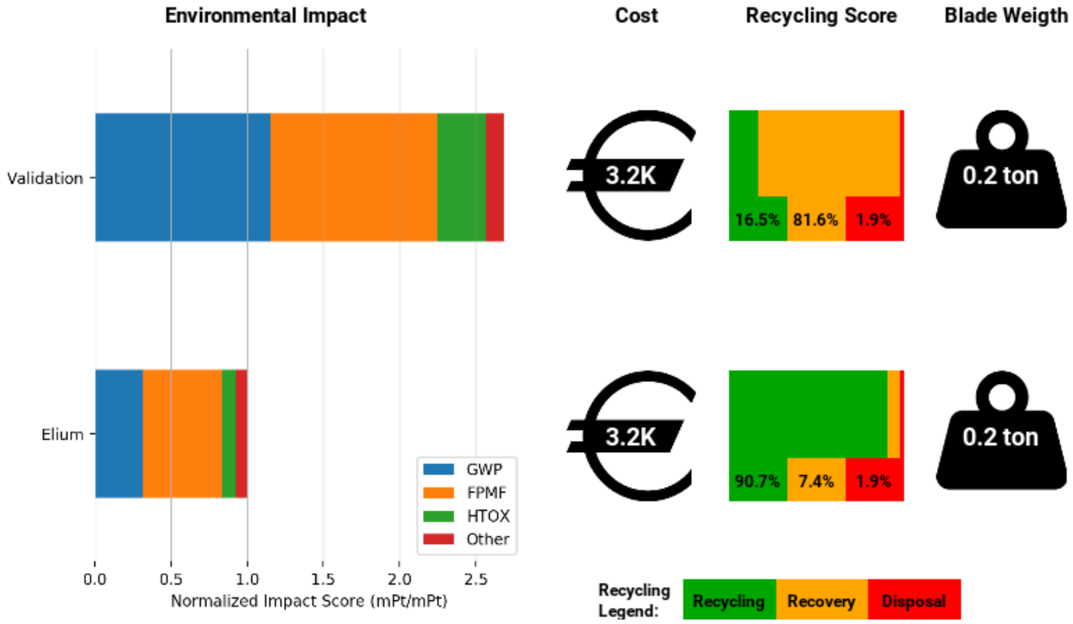


Figure 21: Graphical Comparison of two Hypothetical Blades.

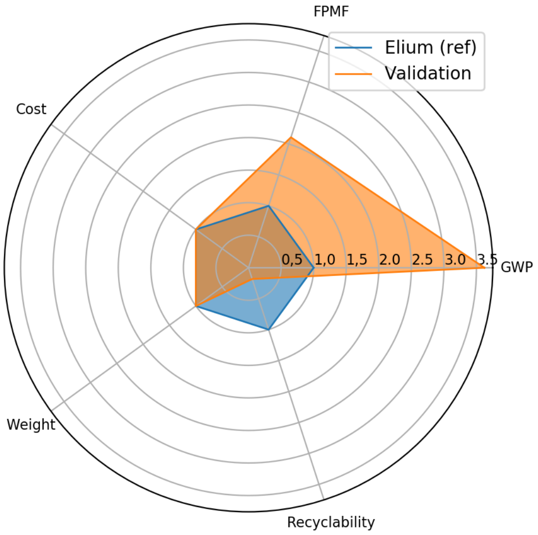


Figure 22: Radar plot of Two Hypothetical Cases.

Table 31: Non-Normalised, Numerical Output of the Tool for Two Hypothetical Cases.

Output Categories	Unit	Elium	Validation
Global warming, Human health	mPt	6317,23	22878,97
Global warming, Terrestrial ecosystems	mPt	632,81	2288,81
Global warming, Freshwater ecosystems	mPt	0,02	0,06
Stratospheric ozone depletion	mPt	-59,30	61,77
Ionizing radiation	mPt	4,12	-2,81
Ozone formation, Human health	mPt	9,33	46,87
Fine particulate matter formation	mPt	11351,24	23917,10
Ozone formation, Terrestrial ecosystems	mPt	51,42	230,00
Terrestrial acidification	mPt	220,41	488,98
Freshwater eutrophication	mPt	18,09	135,32
Marine eutrophication	mPt	0,02	0,03
Terrestrial ecotoxicity	mPt	16,48	28,99
Freshwater ecotoxicity	mPt	5,42	11,78
Marine ecotoxicity	mPt	1,15	2,55
Human carcinogenic toxicity	mPt	711,95	3765,44
Human non-carcinogenic toxicity	mPt	1156,12	3278,04
Land use	mPt	1418,79	1487,50
Mineral resource scarcity	mPt	1,30	5,37
Fossil resource scarcity	mPt	561,22	1107,86
Water consumption, Human health	mPt	13,39	459,87
Water consumption, Terrestrial ecosystem	mPt	2,88	91,42
Water consumption, Aquatic ecosystems	mPt	0,00	0,00
Weight	kg	230	230
Reuse Percentage	-	0	0
Recycle Percentage	-	0,91	0,17
Recover Percentage	-	0,07	0,82
Disposal Percentage	-	0,02	0,02
Cost	EURO	3230	3230

E.3 Validation Data

Table 32: Impact Scores from the Quick-LCA Tool and SimaPro for the Validation Case.

Impact Category	Unit	QLCA	SimaPro	Difference
Global warming, Human health	mPt	2,29E+04	2,29E+04	0,0%
Global warming, Terrestrial ecosystems	mPt	2,29E+03	2,29E+03	0,0%
Global warming, Freshwater ecosystems	mPt	6,25E-02	6,25E-02	0,0%
Stratospheric ozone depletion	mPt	6,18E+01	6,18E+01	0,0%
Ionizing radiation	mPt	-2,81E+00	-2,81E+00	0,0%
Ozone formation, Human health	mPt	4,69E+01	4,69E+01	0,0%
Fine particulate matter formation	mPt	2,39E+04	2,39E+04	0,0%
Ozone formation, Terrestrial ecosystems	mPt	2,30E+02	2,30E+02	0,0%
Terrestrial acidification	mPt	4,89E+02	4,89E+02	0,0%
Freshwater eutrophication	mPt	1,35E+02	1,35E+02	0,0%
Marine eutrophication	mPt	3,15E-02	2,86E-02	9,2%
Terrestrial ecotoxicity	mPt	2,90E+01	2,90E+01	0,0%
Freshwater ecotoxicity	mPt	1,18E+01	1,15E+01	2,5%
Marine ecotoxicity	mPt	2,55E+00	2,49E+00	2,4%
Human carcinogenic toxicity	mPt	3,77E+03	3,77E+03	0,0%
Human non-carcinogenic toxicity	mPt	3,28E+03	3,21E+03	2,1%
Land use	mPt	1,49E+03	1,49E+03	0,0%
Mineral resource scarcity	mPt	5,37E+00	5,37E+00	0,0%
Fossil resource scarcity	mPt	1,11E+03	1,11E+03	0,0%
Water consumption, Human health	mPt	4,60E+02	4,60E+02	0,0%
Water consumption, Terrestrial ecosystem	mPt	9,14E+01	9,14E+01	0,0%
Water consumption, Aquatic ecosystems	mPt	4,57E-03	4,57E-03	0,0%

F Public: Restriction on ”Bisphenol A”

ECHA
EUROPEAN CHEMICALS AGENCY

ANNEX XVII TO REACH – Conditions of restriction

Restrictions on the manufacture, placing on the market and use of certain dangerous substances, mixtures and articles

Entry 66
Bisphenol A CAS No 80-05-7 EC No 201-245-8

Conditions of restriction
Shall not be placed on the market in thermal paper in a concentration equal to or greater than 0,02 % by weight after 2 January 2020.