

Evaluating priority strategies for decarbonising offshore wind turbine blades through lifecycle assessment– Supplementary Material

1 WTB description

Table 1 Additional WTB data

Blade scenario	All blade scenarios
Rated power (MW)	15
Blade length (m)	122.2
Root diameter (m)	6.4
Root cylinder length (m)	6.1
Cut-in wind speed (m/s)	3
Rated wind speed (m/s)	10.6
Cut-out wind speed (m/s)	25

2 Description of ATOM blade design optimisation and BoM Generation

The structural design of the blade using alternative materials was performed using ATOM (Aeroelastic Turbine Optimisation Methods). ATOM co-developed under the Wind Blade 23 Research Hub (WBRH) by the Offshore Renewable Energy Catapult and Bristol University. It is an analysis and optimisation tool specifically aimed at the optimisation of aeroelastic tailored, horizontal-axis wind turbines whereby turbine topology remains fixed during the optimisation. From an analysis point of view, a set of numerical design variables (DVs) that define each aspect of a turbine can be input by the user, ATOM then performs every step from meshing of the blade and tower beams, right through to running a full set of aero-servo-elastic design load cases (DLC) and post-processing results for statistics on power, loads, cross-sectional strains, and failure indices. This analysis capability is smoothly integrated within an optimisation framework with a choice of algorithms.

A key feature of ATOM's design capabilities is the use of spline surfaces and lamination parameters. During optimisation, DVs control a number of spline surfaces that define variations in lamination parameters and laminate thickness across the blade. This framework allows for the optimisation process to be unconstrained by conventional structural configurations and stacking sequences. ATOM utilises a range of analysis modules, a brief summary is given here:

- The aerodynamic model utilises a modified blade element momentum theory with corrections for dynamic wake and dynamic stall.
- The structural models of the blade and tower utilise beam finite-elements, with linear damping. The beam elements allow for anisotropic composite laminates with fully populated stiffness and mass matrices. A cross-sectional modeller uses 2D bar elements to generate properties from the laminate spline surfaces. ATOM allows for high-order beam modelling whereby three, four or five node beam elements can be used.
- The non-linear aero-servo-elastic model combines aerodynamic and structural models with a simple controller and multiple options for time-varying wind fields. The controller is embedded into the

code and employs PI pitch control above rated and a simple optimal mode gain to control torque below rated.

- The optimisation algorithm implemented is the globally convergent method of moving asymptotes (GCMMA). GCMMA uses the function values and gradients at each step to generate a convex subproblem that approximates the real objective and constraint functions. If the solution to the subproblem is found to be inaccurate when checked against the real values, then the approximating functions are sequentially modified until they are conservative, resulting in an improved and feasible solution.

There are two main architectures to solve multi-disciplinary optimisation (MDO) problems like the one of the design of a wind turbine rotor blade, that is, the monolithic and distributed architecture.

Monolithic architecture considers the whole problem in a single optimisation procedure. All of the analysis modules are combined to produce a single set of objective and constraint functions and all of the DVs are present in a single optimisation. Monolithic architectures have the advantage of being simpler to implement as they typically mimic conventional analysis workflows whilst they can take into account all the interactions/couplings of the different aspects involved in the analysis for example aerodynamic and structural one. However, the computational cost of monolithic architectures is high.

In contrast to monolithic architectures, distributed architectures decompose the MDO problem into a number of smaller sub-problems. That is, the aerodynamic and structural design is separated into two sub-optimisation processes. In ATOM, the user has the capability to simulate either adopting a monolithic approach, in the frame of this work called “aero-structural” optimisation approach or using a distributed architecture called “frozen load” optimisation approach.

Herein, due to the high computational cost of an “aero-structural” optimisation as well as the large number of different materials to be investigated, the “frozen load” approach was adopted. In “frozen load” optimisation loop, an initial calculation of aeroelastic loads for an initial non-optimised blade design is performed. Having calculating loads, the structure is optimised. For the new optimised structure, new loads are evaluated. The loop continuous until convergence of specific metrics, e.g. tip displacement or blade frequencies. Based on previous experience, “frozen load” optimisation although it is not guaranteed that will converge, nevertheless it can give acceptable results, close to the ones obtained from an “aero-structural” optimisation approach with less computational effort.

It is important to say that a constrained optimization problem is concerned with finding the minimum (or the maximum) of a function, usually named the objective function, whilst satisfying selected constraints. The objective function in the rotor blade design context could be the mass of the blade or the Levelized Cost of Energy (LCoE) of the wind turbine machine. For the constraint requirements, these could be that any stress developed at any point in any section of the blade to be less than the allowable stress of the material or the tip displacement of the blade to be less than the distance between the tip and the tower. An optimization algorithm searches the design space in an automatic and efficient way to find minimum (or maximum) of the objective function.

In this work, the objective function of the optimisation problem was set to be a modified LCoE that takes into account the CO₂ footprint from cradle to gate of every material. More specifically, ATOM uses a cost model to estimate capital and operational expenditure costs (CAPEX and OPEX respectively) and finally to estimate the LCoE of the wind turbine machine analysed. It is assumed that only the material cost is important when comparing different blade designs that only the materials change (assuming that the cost of the technology to fabricate the blade remains the same). Making one step forward and trying to include CO₂ mass of each material in the blade optimisation process, the material cost, for example £X per [kg] of material in the cost model, was replaced by the generated mass of CO₂ in [kg] per [kg] of each material. The modified LCoE essentially sets the optimisation algorithm to search for the minimum Global Potential Warming (GWP) value associated with the structural materials in the blade. The trade off in this new

optimisation framework is between performance and environmental impact of the blade. Materials with adequate mechanical properties and smaller GWP values will be favoured by the optimisation algorithm. Design constraints imposed in the blade optimisation of this work are related to strength, buckling, fatigue, tower clearance and aeroelastic stability of the blade as well as some manufacturing constraints related to the taper of the composite plies and the core materials.

Regarding the DVs, only variables that affect the internal structure of the blade were considered, that is, the thickness of the various layers along the length of the blade structure.

A reduced set of IEC design load cases [1] (1.1 and 1.3) were examined as these have been found to offer a good estimate of ultimate blade loads without excessive computational effort [2].

The baseline design has been analysed and optimised in a previous task of this project whilst it has been thoroughly described in [2]. The initial design point for all the different designs that has been examined when changing materials is based on the optimised baseline blade design.

3 ATOM design variables

Table 2 List of design variables (PS: pressure side, SS: suction side)

Name	#DVs	Normalised location of spline control points along the blade arc-length. 0:Root, 1: Tip	Comments
UD	10	[0 0.02 0.05 0.1 0.25 0.4 0.6 0.8 0.9 0.95]	Baseline: glass
Shell Biax	10	[0 0.02 0.05 0.1 0.25 0.4 0.6 0.8 0.9 0.95]	Baseline: glass
Spar UDc (PS)	8	[0.05 0.1 0.25 0.4 0.6 0.8 0.9 0.95]	Baseline: carbon
Spar UDc (SS)	8	[0.05 0.1 0.25 0.4 0.6 0.8 0.9 0.95]	Baseline: carbon
Spar UDg	8	[0.05 0.1 0.25 0.4 0.6 0.8 0.9 0.95]	Baseline: glass
Web Biax	8	[0.04 0.1 0.25 0.4 0.6 0.8 0.9 0.96]	Baseline: glass
Web core	8	[0.04 0.1 0.25 0.4 0.6 0.8 0.9 0.96]	Baseline: foam
LE UD	5	[0.1 0.25 0.4 0.6 0.8]	Baseline: glass
LE core	7	[0.1 0.25 0.4 0.6 0.8 0.9 0.95]	Baseline: foam
TE UD	5	[0.1 0.25 0.4 0.6 0.8]	Baseline: glass
TE core	7	[0.1 0.25 0.4 0.6 0.8 0.9 0.95]	Baseline: foam

4 Lamina (UD) mechanical properties used during ATOM blade design optimisation

Table 3 Lamina (UD) mechanical properties used during ATOM blade design optimisation

Material name	GF/Epoxy	CF/Epoxy	GF/Bio-epoxy	GF/rEpoxy	GF/Bio-rEpoxy	GF/PMMA
V_f [%]	54	59	54	54	54	54
E_1 [MPa]	41214	129190	43218	24718	43218	43204
E_2 [MPa]	14883	7616	15364	9942	15364	15208
ν_{12}	0.28	0.32	0.28	0.29	0.28	0.29
G_{12} [MPa]	3019	3811	3102	2172	3102	3188
X_T [MPa]	905	1954	1105	221	1105	1105

X _C [MPa]	527	967	621	159	621	634
Y _T [MPa]	59	47	68	59	68	66
Y _C [MPa]	81	158	86	81	86	116
S [MPa]	41	55	43	41	43	43
Density [g/cm ³]	1.96	1.55	1.87	1.29	1.87	1.83

5 Micromechanical properties

Table 4 Micromechanical properties and GWP of materials used to generate lamina properties in Table 3

Material → Property ↓	GF	Epoxy	Bio- epoxy	rEpoxy ⁴	Bio- rEpoxy ⁵	PMMA
Density [gcm ⁻²]	2.62 [3]	1.19 [4]	1.08 [5]	1.19	1.08	1.01 [6]
Tensile modulus [GPa]	78.0 [3]	3.2 [4]	3170 [5]	3.2	3170	3170 [6]
Tensile strength [MPa]	1995 [3]	65 [4]	67.6 [5]	65	67.6	66 [6]
Compressive strength [MPa]	1085 [3]	85 [4]	86.3 [5]	85	86.3	116 [6]
Shear modulus [GPa]	17.2 ¹					
Shear strength [MPa]		43 ²	43 ²	43	43	43 [6]
Poisson's ratio	0.22 [3]	0.35 [3]	0.35	0.35	0.35	0.37 [6]
GWP [kg CO ₂ eq./kg]	1.49 ³	6.37 ³	3.29 [7]	6.37	3.29	3.70 [8]

¹ Empirical shear modulus data not available, GF assumed isotropic and shear modulus found by multiplying tensile modulus and Poisson's ratio

² Shear strength not specified by material producer / supplier, used generic epoxy value as proxy [3]

³ Sphera LCA database 2022 - CML2001, Global Warming Potential (GWP 100 years)

⁴ It is assumed the properties of laminates made rEpoxy are largely determined by the specific epoxy resin it is paired with. rEpoxy supplier have published performance data of their cured rEpoxy systems, which are comparable with standard epoxy systems. For consistency across blade scenarios, it has been assumed that the rEpoxy is a drop in solution to the standard epoxy resin (Epikote RIMR 135) used in other blade designs. As such, the mechanical properties of rEpoxy cured laminates are the same as the standard epoxy counterpart used throughout the study.

⁵ Assumed the same as Bio-epoxy system for reasons discussed in 4 above.

6 WTB manufacturing consumables model

Given the considerable quantities of consumables used during blade production, the impact of using these materials was included in the assessment. This required the development of a consumables model to estimate the quantity of consumables used with respect to the blade geometry. Developing the model in this way allows for rapid estimation of consumables used for a range of different blade structures and geometries. The mass of consumables used was estimated, for the most part, using the model outlined by the US National Renewable Energy Laboratory (NREL) in [9].

6.1 Vacuum bagging

The mass of bagging is proportional to the surface areas of the substructures and the area weight of the bagging material. Waste mass is given as a fraction of total mass required.

Equation 1: Total mass of bagging required

$$Mass_{bagging} = Area_{weight_{bagging}}(Area_{webs} + Area_{HP\ mould} + Area_{LP\ mould} + Area_{spar\ caps} + Area_{Root}) + Waste$$

6.2 Peel-ply

The mass of peel-ply is proportional to the surface areas of the substructures and the area weight of the peel-ply fabric. Waste mass is given as a fraction of total mass required.

Equation 2: Total mass of peel-ply required

$$Mass_{peel-ply} = Area_{weight_{peel-ply}}(Area_{webs} + Area_{HP\ mould} + Area_{LP\ mould} + Area_{spar\ caps} + Area_{Root}) + Waste$$

6.3 Tackifier adhesive

Tackifier adhesive is used in small amounts to adhere layers of layup materials / consumables during the layup process, so that they do not move relative to each other. The mass is estimated proportional to the mould areas, which are the sum of the areas of the moulds of webs, spar caps, root preforms, and main shells. Waste mass is given as a fraction of total mass required.

Equation 3: Total mass of tackifier adhesive required

$$Mass_{Tackifier\ adhesive} = Density_{Tackifier\ adhesive} \times Volume\ per\ area_{Tackifier\ adhesive}(Area_{webs} + Area_{spar\ caps} + Area_{root} + Area_{LP\ mould} + Area_{HP\ mould}) + Waste$$

6.4 Release agent

The mass of release agent is proportional to the mould areas and the volume of release agent per mould area used. Volume per area is provided in [9]. Waste mass is given as a fraction of total mass required.

Equation 4: Total mass of release agent required

$$\begin{aligned}
Mass_{Release\ agent} &= Density_{Release\ agent} \times Volume\ per\ area_{Release\ agent} (Area_{webs} + Area_{spar\ caps} \\
&+ Area_{root} + Area_{LP\ mould} + Area_{HP\ mould}) + Waste
\end{aligned}$$

6.5 Flow medium

The mass of flow medium is proportional to the surface areas of the substructures and the area weight of the flow medium material. Flow medium coverage is given as the flow medium area relative to the substructure surface area and is given in [9]. When the spar caps are produced using prepregs, no flow medium is used for their production. Waste mass is given as a fraction of total mass required.

Equation 5: Total mass of flow medium required

$$\begin{aligned}
Mass_{Flow\ medium} &= Coverage \\
&\times Area\ weight_{Flow\ medium} (Area_{webs} + Area_{spar\ caps} + Area_{root} + Area_{LP\ mould} \\
&+ Area_{HP\ mould}) + Waste
\end{aligned}$$

6.6 Tubing

This model assumes the use of tubes for both vacuum and resin feed lines. The mass of tubing is estimated as proportional to blade length, with model assumptions coming from [9]. Total mass of tubing per blade is given by:

Equation 6: Total mass of tubing per blade

$$Mass_{Tubing} = Linear\ weight_{Tubing} \times Length\ per\ blade\ length_{Tubing} \times Blade\ length + Waste$$

With eight substructures (2x shell, 2x spar cap, 2x shear web and 2x root prefab), the tubing used for each substructure is:

Equation 7: Mass of tubing using per substructure

$$Mass_{Tubing}(per\ substructure) = \frac{Mass_{Tubing}}{no.\ of\ substructures} = \frac{Mass_{Tubing}}{8}$$

Waste mass is given as a fraction of total mass required.

6.7 Tacking tape

The mass of tacking tape is assumed proportional to the blade length and the linear weight of the tacking tape, using assumptions made in [9]. Total mass of tacking tape per blade:

Equation 8: Total mass of tacking tape per blade

$$\begin{aligned}
Mass_{Tacking\ tape} &= Length\ per\ blade\ length_{Tacking\ tape} \times Linear\ weight_{Tacking\ tape} \times Blade\ length \\
&+ Waste
\end{aligned}$$

Mass of tacking tape for a given substructure "X" is assumed to be proportional to the length of said component:

Equation 9: Mass of tacking tape for a given substructure

$$Mass_{Tacking\ tape-X} = Mass_{Tacking\ tape} \frac{Length_X}{\sum Length\ of\ all\ blade\ substructure}$$

Waste mass is given as a fraction of total mass required.

6.8 Masking tape

Masking tape is used to section off the area of the mould where tacking tape will be applied to for vacuum bagging. This is to protect the surface during mould release application so that the area of the mould that needs to have the tape applied does not become too slippery for tacking tape to adhere to. The length of masking tape is therefore equal to the length of the tacking tape and the mass proportional to the length and the linear weight of the masking tape.

Total mass of masking tape per blade:

Equation 10: Total mass of masking tape per blade

$$Mass_{Masking\ tape} = Length\ per\ blade\ length_{Masking\ tape} \times Linear\ weight_{masking\ tape} \times Blade\ length + Waste$$

Mass of masking tape for a given substructure "X" is assumed to be proportional to the length of said component:

Equation 11: Mass of masking tape for a given substructure

$$Mass_{Masking\ tape-X} = Mass_{Masking\ tape} \frac{Length_X}{\sum Length\ of\ all\ blade\ substructure}$$

Waste mass is given as a fraction of total mass required.

6.9 Surface filler

Filler used to close small cracks and gaps on the blade surface prior to painting and its mass is assumed proportional to the blade outer area following assumptions made in [9].

Equation 12: The mass of surface filler required

$$Mass_{Filler} = Density_{Filler} \times Volume\ per\ blade\ surface\ area_{Filler} \times Blade\ surface\ area + Waste$$

Table 5 gives the assumptions and materials used in consumables models and mass of consumables used in blade production. Given the relevant blade geometries do not change across blade designs, the mass of consumables is constant across scenarios.

Table 5 Assumptions and materials used in consumables models and mass of consumables used. All waste estimates based on NREL blade cost model [9].

Consumable	Material	Assumption(s)*
Vacuum bagging	Nylon	Waste = 15% Area weight = 0.0525 kg/m ² [10]
Peel-ply	Nylon fabric coated with 10% PTFE	Waste = 15% Area weight = 0.085 kg/m ² [11]

Tackifier adhesive	PVA adhesive	Waste = 5% Density = 1190 kg/m ³ [12] Volume per (mould) area = $3.06 \cdot 10^{-5}$ m ³ /m ² [9]
Release agent		Waste = 5% Density = 792 kg/m ³ [13] Volume per (mould) area = $2.57 \cdot 10^{-5}$ m ³ /m ² [9]
Flow medium	Polypropylene	Waste = 15% Coverage = 70% [9] Area weight = 0.088 kg/m ² [14]
Tubing	Nitrile rubber	Waste = 10% Length per blade length = 5 m/m [9] Linear weight = 0.4551 kg/m [15]
Tacking tape		Waste = 5% Length per blade length = 10 m/m [9] Linear weight = 0.0633 kg/m [16]
Masking tape	Paper and acrylic-based adhesive	Waste = 10% Length per blade length = 10 m/m (Assumed same as tacking tape [9]) Linear weight = 0.0076 kg/m [17]
Surface filler	2-component PUR adhesive based on polyether and castor oil	Waste = 10% Volume per blade surface area = 0.0000204 m ² /m ³ [9] Filler density = 1330 kg/m ³ [18]

Table 6 Mass of consumables used in all blade scenarios.

	Mass (kg/WTB)
Bagging	106
Peel ply	172
Tackifier adhesive	67
Release agent	39
Flow medium	124
Tubing	611
Tacking tape	77
Masking tape	10
Surface filler	38

7 WTB manufacturing waste disposal

During blade production, waste is generated both from the blade materials and consumables used during production. This includes materials generated during infusion (i.e. excess resin in infusion tubing, vacuum bagging materials) and during trimming (i.e. flash trimming, fabric trimming). The waste quantity model for consumable materials was informed by assumptions made in [9] whereas the model for blade materials was informed by discussion with wind turbine OEM.

Table 7 gives the mass of waste materials generated and the mass of material disposed during blade production and the assumption used in waste model. In this context “Mass wasted” is the mass of a given material / consumable that has not been used in the production of the blade directly, but none the less, has been consumed during a given process (e.g. vacuum bagging trimming that is not actually used during infusion). “Mass disposed” is the total mass of the material / consumable that must be disposed of during production phase.

For consumables, this is generally the mass of the consumables used in the production in addition to the “mass wasted”. In the case of “tackifier adhesive” and “surface filler”, the used consumable is not disposed of, and becomes incorporated with the blade itself, therefore disposal mass is simply the same as the waste mass. Excess “release agent” is assumed to evaporate over time and not require disposal whether it is used or is wasted. For blade materials, the mass wasted simply equals the mass disposed (since blade material disposal is accounted for at end-of-life phase).

Table 7 Assumption used in blade production waste model.

Material	Production stage	Waste quantity model
Glass fibre	Fabric trim, flash trim	15% of BoM
Carbon fibre	Fabric trim, flash trim	15% of BoM
Resin	Infusion, flash trim	15% of BoM
Gel coat, topcoat, primer	Coating spray up	10% of BoM
Core	Core trim	15% of BoM
Root attachments (steel)	N/A	0% of BoM
Lighting protection system (Aluminium)	N/A	0% of BoM
Vacuum bagging	Infusion / prepreg layup	15% of required mass
Peel-ply	Infusion / prepreg layup	15% of required mass
Tackifier adhesive	Infusion layup	5% of required mass
Release agent	Infusion / prepreg layup	5% of required mass
Flow medium	Infusion layup	15% of required mass
Tubing	Infusion / prepreg layup	10% of required mass
Tacking tape	Infusion / prepreg layup	5% of required mass
Masking tape	Infusion / prepreg layup	10% of required mass
Surface filler	Surface finishing	10% of required mass

Table 8 and Table 9 give the mass of consumables and blade structural waste disposed of during blade manufacturing. The mass of waste consumables is constant across the scenarios.

Table 8 Mass of consumables waste materials in all blade scenarios

	Mass (kg/WTB)
Bagging	106
Peel ply	172
Tackifier adhesive	3.2
Release agent	3.8

Flow medium	124
Tubing	611
Tacking tape	77
Masking tape	10
Surface filler	3.4

Table 9 Mass of blade structural material waste across the scenarios

Blade scenario	Waste mass (kg/blade)					
	Glass fibre	Carbon fibre	Laminate	Core	Adhesive	Surface coating
Baseline	5062	1361	2547	870	281	78
CF_Low impact	5062	1361	2547	870	281	78
Core_Balsa	5062	1361	2547	870	281	78
Core_rPET	5062	1361	2547	870	281	78
Matrix_Bio-epoxy	5061	1316	2526	804	277	78
Matrix_rEpoxy	5062	1361	2547	870	281	78
Matrix_Bio-rEpoxy	5061	1316	2526	804	277	78
Matrix_PMMA	4951	1343	2496	825	275	78

8 WTB manufacturing approach

A high-level process flow of the entire blade manufacturing process used in the baseline impact assessment is presented below. Offline prefabrication of blade sub-structures: shear webs, spar caps and root sections are assumed to take place prior to integration with the shell. VARTM is the most common method for producing the blade shells, with separate half shell infusion being used in the assessment. Blade manufacturing is then completed with assembly and finishing processes.

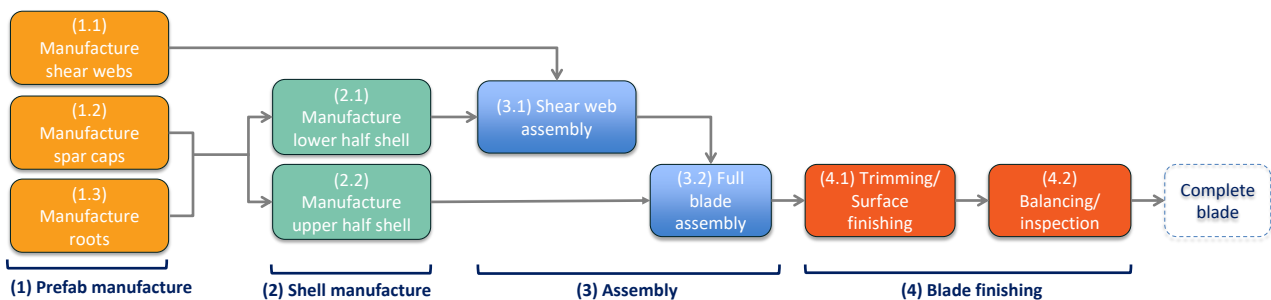


Table 10 High-level description of blade manufacturing stages and processes

Manufacturing stage	Process description
(1.1) Shear web / (1.3) Root prefabrication	VARTM alone is selected for baselines assessment.
(1.2) Shear web prefabrication	Three manufacturing processes: VARTM, prepreg and pultrusion, are selected for the baselines assessment.
(2.1) / (2.2) Shell production	Prefabricated spar cap and root sections are inserted into the shell mould as part of the layup prior to shell infusion. While consolidation through adhesive bonding, following shell curing, has been identified this does not appear to be currently used widely.

(3.1) Shear web assembly	Following blade curing, the shear webs are bonded to the spar cap, within the lower shell inner surface, using adhesive.
(3.2) Full blade assembly	Carried out by simultaneously bonding the shear webs to the upper shell, and bonding the upper and lower shell perimeters (this is achieved using “clam shell” style closed moulds). Thermal post curing of the whole blade structure is carried out using heated tooling, followed by demoulding after cooling.
(4.1) Trimming/surface finishing	The assembled blade is lifted onto a transport cart and moved to the finishing area, where flash trimming, surface finishing, painting and root machining is conducted.
(4.2) Balancing/inspection	Finally, the blade is balanced and inspected prior to transportation to onsite location.

9 WTB manufacturing energy models

9.1 Resin infusion

Energy demand for the resin infusion stages was informed by primary data obtained by NCC during a large-scale vacuum infusion trial. The total energy demand for the resin infusion step was assumed to be proportional to the mass of the resin infused which was measured to be 0.91 MJ/kg resin. The energy demand required to infuse a given blade is given below:

Equation 13: The energy demand required to infuse a given

$$Energy_{infusion} = 0.91 \times Resin\ mass$$

9.2 Flash trimming

Flash trimming involves cutting the excess fibre/resin present at the perimeter of the part. This is conducted following demoulding the shear webs, spear caps and root prefabs. The flash is trimmed from the blade shells following bonding upper and lower shell halves. Trimming is assumed to be conducted using a handheld circular saw with a max. rated power of 750 W [19]. Trim rate by a single circular saw was assumed to be 10 m/hr in line with the methodology outlined in [9]. Energy demand from flash trimming for a given substructure is a function of the time to trim and the max. rated power of the circular saw and is given as:

Equation 14: Energy demand from flash trimming for a given substructure

$$Energy_{flash\ trim} = \frac{Trim\ length\ [m]}{Trim\ rate\ [\frac{m}{s}]} \times Circular\ saw\ max.\ power\ [W]$$

Where trim length is the part/mould perimeter and is assumed to be twice the part length gives the trim lengths, cycle times and energy associated with flash trimming for each blade scenario. Note, the cycle time is the total time to trim each part but can be conducted concurrently by multiple personnel. Given the trim length does not change between blade designs, the energy demand is the same across scenarios.

Table 11 Trim lengths, cycle time and energy associated with flash trimming for all blade scenarios.

Total trim length (m/blade)	1248
Cycle time (hr/blade)	125
Total energy demand (MJ/blade)	337

9.3 Adhesive

Adhesives are commonly applied with two-component metering and mixing equipment. The resin and the hardener are mechanically pumped or extruded from their containers, through delivery pipes, to the mixer head where the two components are thoroughly blended and discharged [20]. Energy to apply adhesive was estimated based on the max. power consumption (26 kW) of a “Twin Engineers - Adhesive mixing machine” and estimated cycle time for applying adhesive [21]. Cycle time estimates were based on max. adhesive mass flow rate (20 kg/min [21]) and the mass of adhesive required for each stage. Energy associated with adhesive application was therefore given by:

Equation 15: Energy demand associated with adhesive application

$$Energy_{adhesive\ app.} = \frac{Adhesive\ mass[kg]}{Adhesive\ flow\ rate\ [kg/s]} \times Adhesive\ machine\ max.\ power\ [W]$$

Table 12 Adhesive mass and energy demand for all blade scenarios.

Blade scenario	Adhesive mass [incl. waste] (kg)	Energy demand (MJ)
Baseline	3744	292
CF_Low impact	3744	292
Core_Balsa	3744	292
Core_rPET	3744	292
Matrix_Bio-epoxy	3694	288
Matrix_rEpoxy	3744	292
Matrix_Bio-rEpoxy	3694	288
Matrix_PMMA	3661	286

9.4 Warehouse transportation

Blade structure and substructures were assumed to be transportation throughout the manufacturing facility using electric warehouse transportation carts. The power consumption of the electric carts, along with the cycle/transportation time to move the component, was used to estimate the energy associated with moving the blade/substructures. The max. power of the cart is assumed to be dependent on the carry capacity with the following two carts used depending on the mass of the component being transported:

- Cart A: AICRANE AQ-KPJ-20T – up to 20 tonne – max. power consumption = 2.5 kW [22]
- Cart B: AICRANE AQ-KPJ-150T – up to 150 tonne – max. power consumption = 15 kW [22]

The energy demand associated with transportation of a given blade structure within the warehouse is given as follows:

Equation 16: Energy demand associated with transportation of a given blade structure within the warehouse

$$Energy_{warehouse\ transport} = Cycle\ (transport)\ time \times max.\ power\ of\ cart$$

The cycle (transportation) time is found using the methodology outlined in [9]; "*Megawatt-size blades require a minimum of 10 minutes to be moved, with a premium of 1/3 minute per extra meter of blade length above 60 m due to extra complexity with larger blade lengths*". The blade production requires the transportation of large blade substructures (i.e. spar cap and shear web), the same methodology to calculate cycle (transportation) time was used for these parts, as is outline by [9] for full blade structure.

Table 13 Cycle time, cart type used and energy demand associated with component transportation within warehouse.

Cart A cycle time (min/blade)	Cart B cycle time (min/blade)	Total energy (MJ/blade)
130	123	130

9.5 Warehouse lifting

It is assumed that overhead cranes are used to lift the blade and blade substructures during manufacturing within the warehouse. This occurs during part demoulding, transferring to warehouse transportation carts as well as placement of substructures such as spar caps, shear webs and root prefabs within the blade shell. The power consumption of the crane, along with the cycle time to lift the component, was used to estimate the energy associated with lifting the blade/substructures. The max. power of the crane is assumed to be dependent on the carrying capacity with the following two cranes used depending on the mass of the component being transported:

- Crane A: AICRANE AQ-LH – up to 10 tonne – max. power consumption = 39.5 kW [23]
- Crane B: LIEBHERR LTM 1100-4.2– up to 100 tone – max. power consumption = 129 kW [24]

The energy demand associated with lifting a given blade structure within the warehouse is given as follows:

Equation 17: Energy demand associated with lifting a given blade structure within the warehouse

$$Energy_{warehouse\ lifting} = 50\% \ Cycle\ time \times max.\ power\ of\ crane$$

The cycle time to lift / insert prefabricated blade substructures, as well to demould the entire blade, have been estimated in [9] and are described in Table 14. It is assumed that the crane will not require energy input during the whole lifting cycle time, a nominal knock down of 50% is use – i.e. it is assumed the crane demands power for half the lifting time. The impact of this assumption is assessed in the sensitivity analysis.

Table 14 Cycle time assumptions and crane type to lift, demould and insert the various structures

Manufacturing stage	Description / source	Crane type
Insert root prefab	"...it is assumed to take 15 minutes" [9]	Crane A
Insert spar cap (Upper/Lower)	"workers can insert a 30-meter-long (or less) spar cap in 15 minutes, with an additional premium of 5 minutes per extra 10 m of spar cap length above 30 meters" [9]NRE	Crane A

Insert shear web (1/2)	Assumed using same method as used for spar cap insertion.	Crane A
Insert upper shell		Crane B
Full blade demould and transfer to cart	<i>“All megawatt-size blades and above require a minimum of 15 minutes to be transferred to carts. However, because of extra complexity with larger blade lengths, a premium of 1 minute per extra meter of blade length above 60 m should be added.”</i>	Crane B
Demould root prefab	Assumed the same cycle time as inserting into shell	Crane A
Demould spar cap (Upper/Lower)		Crane A
Demould shear web (1/2)		Crane A

Table 15 Cycle time and energy demand to lift, demould and insert the various structures for all blade scenarios

Crane A cycle time (min/blade)	Crane B cycle time (min/blade)	Total energy (MJ/blade)
529	138	1163

9.6 Blade surface sanding

Surface sanding involves sanding the blade surface following surface filling in preparation for surface coating application. Sanding is assumed to be conducted using a handheld orbital sander with a max. rated power of 280 W [25]. Sanding rate by a single orbital sander was assumed to be 6 m²/hr in line with the methodology outlined in [9]. Energy demand from sanding for a given substructure is a function of the time to sand and the max. rated power of the orbital sander and is given as:

Equation 18: Energy demand from sanding for a given substructure

$$Energy_{sanding} = \frac{Blade\ surface\ area[m^2]}{Sanding\ rate\ [m^2/s]} \times Sander\ max.\ power[W]$$

Where blade surface area is the sum of the high and low pressure shell outer surface area gives the sanding area, cycle time and energy demand during blade surface sanding. Note, the cycle time is the total time to sand the blade but can be conducted concurrently by multiple personnel. Given the blade surface area does not change between blade designs, the energy demand is constant across the scenarios.

Table 16 Sanding area, cycle time and energy demand during blade surface sanding

Sanding area (m2/blade)	Cycle time (hr/blade)	Energy demand (MJ/blade)
1262	210	212

9.7 Surface coating

Surface coating are assumed to include gel coat, primer and top coat. Gel coat is applied directly onto the shell moulds prior to lay up and lamination. Primer and top coat are applied to the blade surface following sanding. In all cases it is assumed the coatings are applied via compressed air spray guns. These equipment use an electric compressor which is the source of energy demand during these processes. Power

consumption of such equipment was based on an industrial spray gun / compressor system which a max. power consumption of 2.2 kW [26]. Spray rate for a single spray gun was assumed to be 120 m²/hr based on the methodology outlined in [9]. Energy demand from surface coatings application for a given substructure is given as:

Equation 19: Energy demand from surface coatings application for a given substructure

$$Energy_{coating\ application} = \frac{Part\ surface\ area[m^2]}{Spray\ rate\ [m^2/s]} \times Spray\ gun/compressor\ max.\ power[W]$$

Table 17 gives the spray area, cycle time and energy demand during coatings application. Note, the cycle time is the total time to apply coatings but can be conducted concurrently by multiple personnel. Given the blade surface areas do not change between blade designs, the energy demand is constant across the scenarios.

Table 17 Spray area, cycle time and energy demand during coatings application

Blade scenario	Spray area (m ² /blade)	Cycle time (hr/blade)	Energy demand (MJ/blade)
All blade scenarios	3786	32	250

9.8 Thermal post curing

The energy input required to conduct the thermal post curing treatment of the blade/blade substructures was modelled. Total energy input during the post curing is assumed equal to the sum of the energies required to bring the blade/blade substructures to temperature, the tooling to temperature and the total heat lost during the post curing schedule. This is given below as:

Equation 20: Energy input associated with part thermal post curing treatment

$$Q_{cure-total} = Q_{part} + Q_{tool} + Q_{loss}$$

energy input to bring the part to temperature (Q_{part}) is given as:

Equation 21: Energy input to bring the part to post cure temperature

$$Q_{part} = mass_{part} \times Cp_{part} \times (T_{cure} - T_{amb}) \times \eta_{heater}$$

Cp_{part} was found by weighted averaging the Cp of the constituent materials in the part. η_{heater} is the heater efficiency with a nominal value of 50% selected.

The average temperature across the composite tooling “equipment wall” was found to be approximate to that of the part curing temperature therefore the energy associated with heating this part of the tooling must be included in the energy input also. This requires the mass of the tooling to also be estimated.

Table 18 Cure schedule and energy required during thermal post curing for each of the blade scenarios.

Blade scenario	Cure temperature (°C)	Cure time (hr)	Energy demand (MJ)
Baseline	60	15	17009
CF_Low impact	60	15	17009
Core_Balsa	60	15	17009
Core_rPET	60	15	17009
Matrix_Bio-epoxy	60	15	16745

Matrix_rEpoxy	60	15	17009
Matrix_Bio-rEpoxy	60	15	16745
Matrix_PMMA	40	16	7795

9.9 HVAC

The electricity and natural gas consumption required for the WTB manufacturing facility atmospheric control (using its HVAC system) was estimated based on assumptions and methodology described in [27]. Table 19 gives the estimated energy demand from facility atmospheric control (HVAC). * Workshop floor space estimated using methodology outlined in [9], assuming facility has capacity to produce 250 WTB annually. ** General office and Storage warehouse assumed to be 25% the floor space of the Workshop.

Table 19 Estimated energy demand from facility atmospheric control (HVAC)

	Electricity typical benchmark [kWh/m ²] [27]	Fossil-thermal typical benchmark [kWh/m ²] [27]	Surface area [m ²]	Total electricity per blade [kWh]	Total thermal energy from NG per blade [kWh]
Workshop	35	180	16256*	2275.891557	11704.58515
General office	95	120	4064**	1544.354985	1950.764192
Storage warehouse	35	160	4064**	568.9728893	2601.018923
Total				4389.219432	16256.36827

10 WTB commissioning model

10.1 Blade transportation

It is assumed that the blade itself is produced at a port site, i.e. the complete blade does not require any transportation from the plant to the port, prior to transporting by sea to the wind farm location. Given the logistical challenges associated with transporting blades of this size, this is a common strategy adopted by OEMs for offshore blade production.

Based on linear regression of similar reported WTB delivery operations, it was assumed that the HLV could transport 106 WTBs at once [28][29]. The total heavy fuel oil consumption of the HLV during transit was estimated assuming a transit speed of 22 km/h [30] and a fuel consumption rate of 0.93 t/hr [31]. The emissions factors for heavy fuel oil are given in Table 21.

10.2 Blade installation

The WTs consist of different components, including blades, hub, nacelle, tower. Current practice in WT installation shows that different strategies have been devised by wind farm installation companies depending on the available vessels/equipment, port facilities, and safety considerations. Figure 1 shows the different installation methods for WTs alongside their required number of offshore lifts. This report assumed Method 2 is used. In this method, the tower is assembled onshore and installed as a single part in a single lift. Then, the nacelle with a pre-attached rotor hub is mounted on the top of the tower. The installation operation is followed by three separate lifts for the blades. Thus, this method includes 5 independent lifts. It is assumed that a Jackup Vessel (JUV) is used to transport and lift the WT subsections. It is assumed that one JUV has cargo capacity of 8 total WT systems which it installs in series in a single trip at sea.

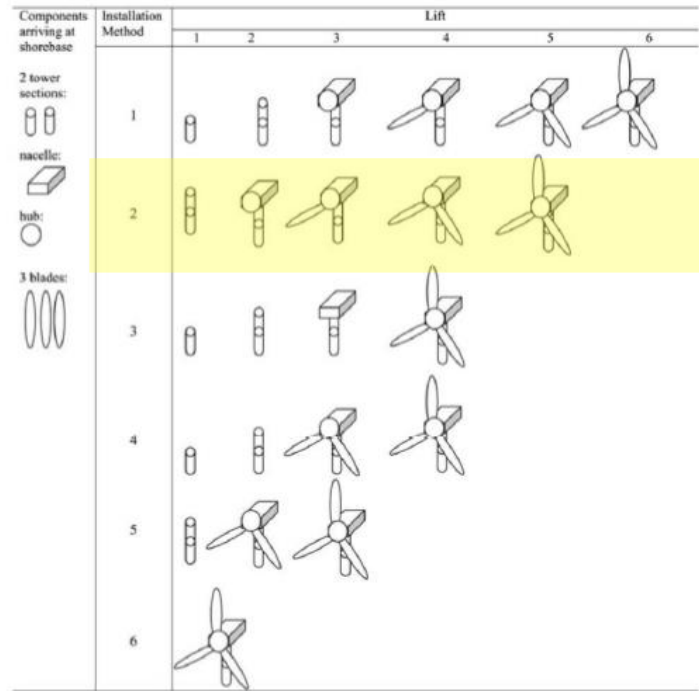


Figure 1 Different installation methods for WTs [32]

Table 20 gives the estimated durations of the various offshore installation operations.

Table 20 Installation operation duration [33]

Installation operation	Duration (hr)
JUV positioning time	3
JUV jack up time	6
Single blade installation	4
Nacelle installation	4
Tower installation	6
JUV jack down time	2
Total lift time per turbine	25

Fuel consumption of the JUV during the WT installation is estimated based on the total installation time of the WT and literature JUV fuel consumption data of 0.42 t/hr [34]. Fuel consumption of the JUV during transit is also calculated based on the known JUV transit distance during the entire trip (i.e., to install all 8 WT) (port-to-windfarm = 115 km, WT-to-WT = 1 km), known JUV transit speed of 10 knots [34], and fuel consumption of 0.42 t/hr [34]. Fuel consumption is converted into the impact indicators using emission factors taken from the GaBi model "Bulk commodity carrier, 5,000 to 200,000 dwt payload capacity, ocean going", in case of combustion of 1kg of heavy fuel oil (Table 21).

During installation operations, the JUV are lifting and transporting dissimilar structures, beyond just the WTB (as shown in Method 2 in Figure 1). The total fuel consumption of the JUV during the installation was calculated and fuel allocated to the WTB based on the time contribution of the blade installation activities to the total WT installation time. One blade installation is estimated be 17% of the total WT installation time, resulting in 2,306 kg of HFO consumed.

Table 21 Emissions factors in case of combustion of 1kg of heavy fuel oil

	Emission factors - combustion of 1kg of Heavy fuel oil (1.0 wt.% S) [Refinery products]
Carbon dioxide [Inorganic emissions to air]	3.114000000000000000
Carbon dioxide (biotic) [Inorganic emissions to air]	0.000000000000000000
Carbon monoxide [Inorganic emissions to air]	0.0027700000000000100
Dust (PM2.5) [Particles to air]	0.007280000000000000
Methane [Organic emissions to air (group VOC)]	0.000060000000000001
Nitrogen oxides [Inorganic emissions to air]	0.0903000000000001000
Nitrous oxide (laughing gas) [Inorganic emissions to air]	0.000150000000000000
NMVOC (unspecified) [Group NMVOC to air]	0.003080000000000000
Sulphur dioxide [Inorganic emissions to air]	0.050000000000000000

11 Operation and maintenance model

Given the high transit distance from the coast (115 km), it is impractical for the turbine to be serviced by a port-based work boat. It is assumed the turbine will be serviced by an offshore-based vessel with accommodation for personnel which does not need to return to port daily [35]. Such vessels are termed SOVs (Service Operation Vessels) which are large vessels designed to be a platform for wind farm support, operating within the wind farm for weeks at a time. SOVs naturally have longer endurance periods and tend to operate on 14-21 day rotations before needing to return to port [36].

The impact of O&M was quantified by estimating the vessel fuel used during 1) regular scheduled inspections, 2) repair activities. SOV fuel consumption during regular WT inspections is given in [36]. For the baseline scenario, it was assumed that the system wide inspection rate is 1.44 WT inspection per year [37]. Repair rates for various offshore wind turbine sub-systems was measured as part of the SPARTA program, which found an average of 0.115 repair trips per month per turbine explicitly for turbine rotor repair work [37]. It was assumed that four WTs can be inspected / repaired in parallel from a single SOV [36], with each WT requiring one or two days per inspection or repair respectively. The fuel consumption of the SOV during inspection / repair works was allocated evenly across all WT substructures being inspected (assuming 15 sub-structures per WT being inspected) / repaired. The SOV fuel consumption was considered for periods where the vessel was in transit or idle on site, which each have different consumption rates as shown in Table 22.

Table 22 Fuel consumptions assumptions made in O&M model [36]

Metric	Value	Unit
Fuel consumption in transit	1000 [36]	litres/hour
Fuel consumption in idle	120 [36]	litres/hour
Fraction of time spent in transit	52% [36]	
Fraction of time spent idle	48% [36]	

Table 23 Emissions factors in case of combustion of 1kg of heavy fuel oil

	Emission factors - combustion of 1kg of Light fuel oil (0.05 wt.% S) [Refinery products]
Carbon dioxide [Inorganic emissions to air]	3.1510000000000100000
Carbon dioxide (biotic) [Inorganic emissions to air]	0.0000000000000000000
Carbon monoxide [Inorganic emissions to air]	0.0027700000000000000
Dust (PM2.5) [Particles to air]	0.0042600000000000100
Methane [Organic emissions to air (group VOC)]	0.0000600000000000001
Nitrogen oxides [Inorganic emissions to air]	0.0903000000000001000
Nitrous oxide (laughing gas) [Inorganic emissions to air]	0.0001500000000000000
NMVOC (unspecified) [Group NMVOC to air]	0.0030799999999999900
Sulphur dioxide [Inorganic emissions to air]	0.0010000000000000000

12 WTB decommissioning model

The WT decommissioning is assumed to be the reverse of the installation with the only difference being that, as the WT sub-structures (e.g., blades, hub, nacelle, tower) are removed using a JUV, they are loaded onto a barge vessel [33]. The barge vessel is then tugged (using a tugboat) back to port for unloading. Decommissioning activity times are given in Table 24. It is assumed that one barge vessel has the capacity to transport one full disassembled WT. The fuel consumption of the tugboat during transit is based on the known transit distance (port-to-windfarm = 115 km), known tugboat transit speed of 8 knots [38], and fuel consumption of 0.32 t/hr [39]. Fuel consumption is converted into the impact indicators using emission factors taken from the GaBi model in case of combustion of 1kg of light fuel oil (Table 23).

The total fuel consumption of the JUV during the decommissioning was calculated and fuel allocated to the WTB based on the time contribution of the blade decommissioning activities to the total WT decommissioning time. One blade installation is estimated be 21% of the total WT installation time, resulting in 2,954 kg of fuel consumed.

Table 24 Decommissioning operation duration [33]

Installation operation	Duration (hr)
JUV positioning time	3
JUV jack up time	6
Single blade removal	2
Nacelle removal	3
Tower removal	4
JUV jack down time	2
Total lift time per turbine	20

13 WTB EoL assumptions

13.1 Downsizing

It was assumed that some level of downsizing of the blade is required regardless of the EoL scenario. Two methods for downsizing are considered depending on the EoL scenario. It is assumed for all EoL scenarios that the blade is initially shredded. This is assumed to be carried out on the port site via a low speed, high torque shredder.

The energy demand required to conduct the shredding was estimated based on the energy demand provided by a supplier of industrial shredding equipment with data presented in Figure 2 for a range of shredder sizes. The energy demand was found assuming actual shredder power is equal to 60% of maximum rated power under conditions of maximum throughput, as suggested in communications with shredder supplier “Summit Solutions”. It is assumed that the shredding will be conducted using large scale equipment therefore the energy consumption will, at most, be that of the Zerma ZXS 3000 at 0.11 MJ/kg of FRP.

Equation 22: Shredder energy consumption

$$Energy_{shredder}[MJ] = 0.11 \times Mass_{blade}[kg]$$

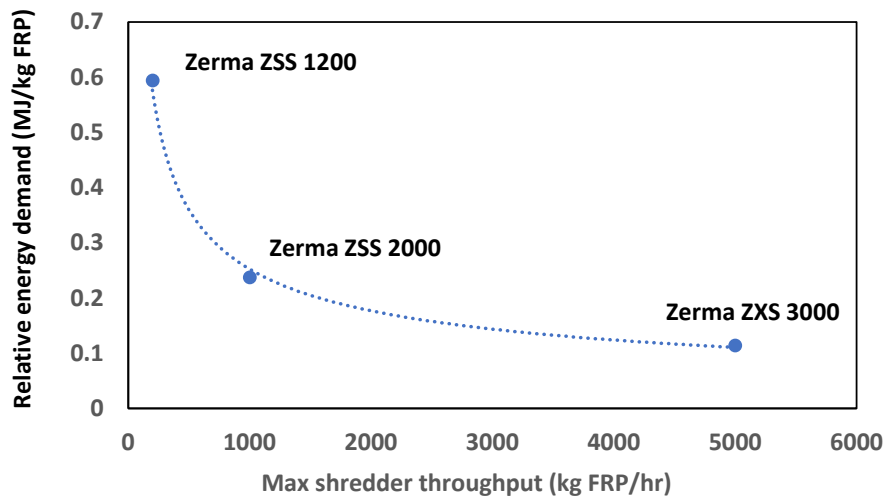


Figure 2 Maximum throughput and relative energy demand of a range of shredders with differing capacities as provided by Summit System

13.2 Waste transport

The transportation from the coast to the landfill site has been modelled using the GaBi LCI secondary dataset “Articulated lorry transport incl. fuel, Euro 0-6 mix, 40 t total weight, 27 t max payload”. It is an aggregated LCI dataset that includes the LCI data about the fuel production used by the lorry (“well to tank” impact) and by the tailpipe emissions (“tank to wheel” impact).

The mass transported has been considered equal to the whole blade waste mass. The assumed transportation distances are given in Table 25. Waste by-products generated during the recycling EoL scenarios have assumed transportation distance to final waste disposal (either landfill or incineration) equal to 100 km.

Table 25 Assumed transportation distances for WTB waste

EoL scenario	Transportation distance (km)	Description
• Landfill	100	It is assumed that a landfill / EfW facility will be in close proximity regardless of location of waste.
• Chemical recycling	500	It is assumed that recycling facilities for EoL WTBs will be more sparsely distributed across the UK, therefore, nominally larger waste transportation distance has been selected.

13.3 Metallics

The following metallic components will be present in the decommissioning blade:

- Blade root attachment inserts (steel)
- Lightning protection system (aluminium)

Following blade shredding it is assumed these metallics will be recovered from the shredded blade waste and will be sent for recycling. It is believed that this is a reasonable assumption given the widespread recycling of steel and aluminium, and the financial opportunity for a blade recycler to resale metal scraps.

The extraction and recycling of the metals is out with the scope of this LCA and therefore the impact associated with any processes to reclaim and recycling the metals has not been considered. In balance, no avoided burden has been attributed to the blade at EoL (as has been done for other recycled materials e.g. carbon / glass fibre). The metallic components therefore do not incur any impact at EoL, and as a consequence, no additional credit has been awarded to the blade despite being a source of valuable scrap metals.

13.4 Landfill

Table 26 Assumptions and datasets used for landfilling the various blade materials

Material	Assumption / landfill dataset
Glass fibre	A data set specifically for glass or basalt fibre landfilling was not available in the GaBi LCI dataset, therefore the “EU-28 - Inert matter (Glass) on landfill” dataset was used as a proxy, as it is assumed this will have similar impact given comparable composition and stability in landfilling.
Carbon fibre	A data set specifically for carbon fibre landfilling was not available in the GaBi LCI dataset, therefore the “EU-28- Plastic waste on landfill” dataset was used as a proxy, as it is assumed this will have similar impact given comparable composition and stability in landfilling.
Balsa	A data set specifically for Balsa landfilling was not available in the GaBi LCI dataset, therefore the “EU-28 - Untreated wood on landfill” dataset was used as a proxy, as it is assumed this will have similar impact given comparable composition and stability in landfilling.
Epoxy/Bio-epoxy	A data set for landfilling specific polymer types was not available in the GaBi LCI dataset, therefore the “EU-28 - Plastic waste on landfill” dataset was used for all polymers.
PET/rPET core	
Adhesive	
Surface coatings	

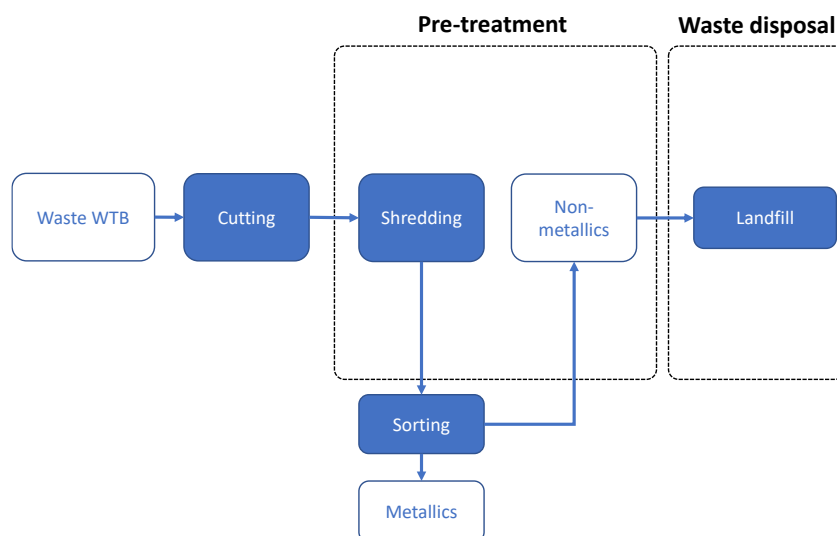


Figure 3 Process flow for WTB disposal in landfill

13.5 Chemical Recycling: Recycling 1 (rEpoxy)

The recycling process for rEpoxy composites can reclaim the fibrous fractions and thermoset matrix as a thermoplastic. The process for recycling rEpoxy based composites is detailed in an LCA, where all the required primary data was collected and is used to populate the LCI in this work [40]. The composites are placed in a dilute (25 %vol.) acetic acid recycling bath of 70 °C for 1 hour. Once the matrix is fully dissolved, fibres can be removed from the recycling solution, rinsed in water, and dried. To reclaim the thermoplastic, the acidic recycling solution is neutralised with sodium hydroxide. The thermoplastic then precipitates out of solution, is filtered, rinsed, and then dried into a powder. Figure 4 gives the process flow outlining the recycling of rEpoxy based WTB, informed by [40].

It is assumed that non-rEpoxy based polymeric materials (i.e. PET core, PU surface coating, epoxy based adhesive) are unchanged when exposed to the recycling process, therefore these materials are not recycled alongside the rEpoxy based components. These materials are therefore considered a contaminant which is either removed 1) during a sorting process between downsizing and chemical recycling, or 2) following the dissolution of rEpoxy and prior to thermoplastic precipitation (most likely using a filtration process). In practice a process combining both may be used, with classification steps used to redirect larger / more easily sortable materials (such as core material) away from the chemical recycling and post-recycling filtration used to remove small contaminant (such as surface coatings). Whatever approach is adopted in the future, it is likely to be a mechanical process and as such may have relatively low energy demands and not significantly increase the overall impact of the blade recycling. Given there is a lack of information regarding how organic contaminants will be removed in practice, the impact of this stage(s) could not be assessed in the LCA. The sorting / removal of contaminant organics in the blade waste is therefore considered out of the scope of this LCA.

Recovery rate of rEpoxy based polymeric materials is assumed to be 90% [40], with unrecovered fraction considered a waste product from the process. It is assumed that all non-rEpoxy based polymeric materials (PET core, PU surface coating, epoxy based adhesive) are a waste product from the process and assumed to be landfilled. Following neutralisation, it is assumed that acetic acid and NaOH is disposed of in standard wastewater treatment facilities.

Fibre recovery rate is assumed to be 95%, with “waste fibres” assumed to be landfilled. It is assumed that recycled glass and carbon fibre can offset the production of their respective counterparts. No loss in performance of carbon fibre reinforcement was observed following the rEpoxy recycling process. Due to low operating temperatures, no mechanical performance loss of the glass fibre is anticipated either. Offset knockdown factors for each of the fibres is given below, which are driven by anticipated reduction in fibre-polymer adhesion due to sizing degradation during the chemical recycling. The novel thermoplastic that is recovered from the process has properties analogous to polycarbonate, it was therefore assumed that it could offset the production of virgin polycarbonate with 0% offset knockdown factor.

Table 27 gives the energy data assumptions recycling of rEpoxy based WTB. The energy demand of each of the recycling stages was measured and reported in [40] for a batch of 35 kg of composite waste, this was normalised to per kg of waste composites and is presented in Table 27.

Table 27 Energy input during rEpoxy (chemical) recycling

Stage	Process	Energy	Energy source
Downsizing	Shredder	0.11 MJ/kg WTB	UK mains electricity
Recycling	Solvolysis	0.78 MJ/kg WTB [40]	UK mains electricity
	Thermoplastic precipitation	Negligible [40]	UK mains electricity
	Thermoplastic washing	0.45 MJ/kg WTB [40]	UK mains electricity
	Thermoplastic drying	9.7 MJ/kg WTB [40]	UK mains electricity
	Fibre drying	8.2 MJ/kg fibre [41]	UK mains electricity

Table 32 gives the material data assumptions used for recycling of rEpoxy based WTB. The input material masses of each of the recycling stages was measured and reported in [40] for a batch of 35 kg of composite waste, this was normalised to per kg of waste composites and is presented in Table 32.

Table 28 Material input during rEpoxy recycling [40]

Material	Mass
Acetic acid	0.52 kg/kg WTB
NaOH	0.34 kg/kg WTB
Water	10.8 kg/kg WTB

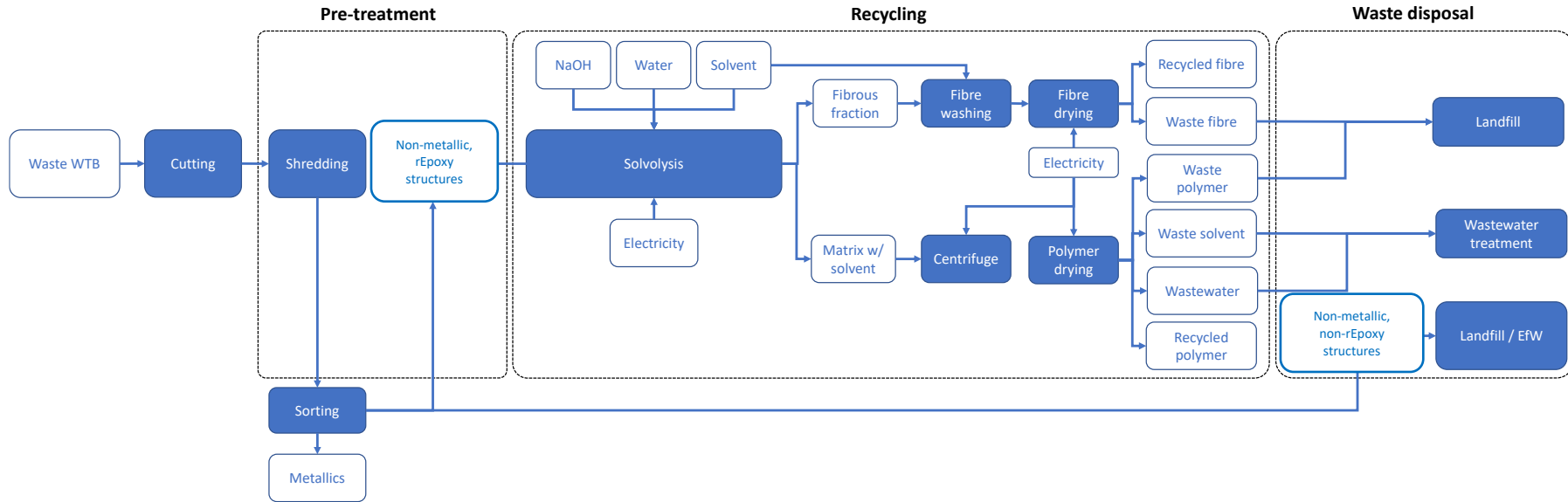


Figure 4 Process flow for recycling rEpoxy based WTB (Recycling 1)

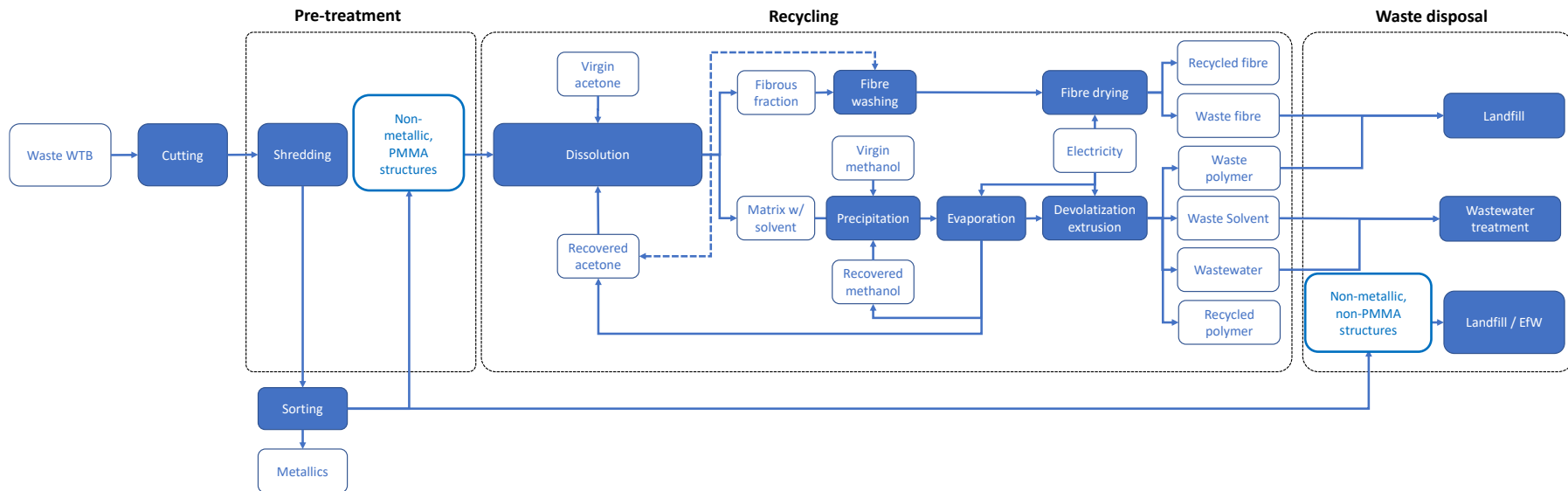


Figure 5 Process flow for recycling PMMA based WTB (Recycling 2)

13.6 Chemical Recycling: Recycling 2

The process for recycling PMMA based composites is detailed in [42], where all the required primary data was collected and is used to populate the LCI in this work. The composites are immersed in room temperature acetone (solvent) which dissolves the PMMA over several hours (time dependent on laminate thickness). Once the PMMA is fully dissolved, fibres can be removed from the recycling solution, simply rinsed in acetone, and dried. It is assumed that recovered acetone alone is used for fibre rinsing prior to use in the dissolution phase and does not add any additional demand for acetone on the recycling process. To reclaim the thermoplastic, the dissolved polymer is precipitated from the solvent in methanol. The acetone and methanol are then recovered separately using evaporation. After sufficient evaporation, diffusion limits the transport of the solvent out of the polymer. Past this point, devolatilization extrusion is used to further dry the polymer. The reclaimed polymer is then dried under vacuum at 60 °C for 12 hours. Figure 5 gives the process flow outlining the recycling of PMMA based WTB, informed by [42].

It is assumed that non-PMMA polymeric materials (i.e. PET core, PU surface coating, epoxy based adhesive) are unchanged when exposed to the PMMA dissolution process, therefore these materials are not recycled alongside the PMMA components. These materials are therefore considered a contaminant which are removed using processes before and/or after the PMMA recycling, as was discussed for rEpoxy recycling above. Given there is a lack of information regarding how organic contaminants will be removed in practice, the impact of this stage(s) could not be assessed in the LCA. The sorting / removal of contaminant organics in the blade waste is therefore considered out of the scope of this LCA.

Recovery rate of PMMA based polymeric materials is assumed to be 90% [42], with unrecovered fraction considered a waste product from the process which are landfilled. It is assumed that all non-PMMA polymeric materials (PET core, PU surface coating, epoxy-based adhesive) are a waste product from the process and landfilled. It is assumed that all unrecovered acetone and methanol are lost to the atmosphere during the evaporation process.

Fibre recovery rate is assumed to be 95%, with “waste fibres” assumed to be landfilled. It is assumed that recycled glass and carbon fibre can offset the production of virgin fibre counterparts. Glass fibre recovered using the described dissolution are shown to have equal tensile strength (with only 12% modulus reduction) [42]. A number of studies have investigated the impact of the dissolution process on reclaimed carbon fibre mechanical performance [43], concluding that *“barely any influence on the mechanical properties of the fibres and can be regarded as approximately similar in structural integrity to the virgin fibres”* [42]. Offset knockdown factors for each of the fibres is given below, with fibre knockdown factor influenced by anticipated reduction in fibre-polymer adhesion due to sizing degradation during the chemical recycling. The thermoplastic that is recovered from the process has properties analogous to virgin PMMA, it was therefore assumed that it could offset the production of virgin PMMA with 0% offset knockdown factor.

Table 29 gives the energy data assumptions for recycling of PMMA based WTB. The energy demand of each of the recycling stages was measured for a small scale WTB section and reported in [42].

Table 29 Energy input / output during PMMA recycling

Stage	Process	Energy	Energy source
Downsizing	Shredder	0.11 MJ/kg WTB	UK mains electricity
Recycling	Dissolution	Negligible [42]	UK mains electricity
	Thermoplastic precipitation	Negligible [42]	UK mains electricity
	Solvent evaporation / recovery	15 MJ/kg resin [42]	UK mains electricity
	Devolatilization extrusion	2.6 MJ/kg resin [42]	UK mains electricity

	Fibre drying	8.2 MJ/kg fibre [41]	UK mains electricity
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The input material masses of each of the recycling stages was measured and reported in [42] for a batch of 0.924 kg of WTB composite waste, this was normalised to per kg of waste PMMA and is presented in Table 30.

Table 30 Material input during PMMA recycling [42]

Material	Mass
Acetone	0.60 kg/kg PMMA
Methanol	1.56 kg/kg PMMA

13.7 Fibre knockdown factors

Fibre knockdown factors were calculated for fibres reclaimed from Recycling 1 and Recycling 2 EoL scenarios. Since The knockdown factor approach described below aims to quantify impact of this recycled fibre property degradation on resulting relevant performance characteristics of composites reinforced with said fibres. The method calculates the required increase in fibre weight fraction needed for a composite made with recycled fibre to achieve the same mechanical performance as that made with virgin fibre. This is given in Equation 23 as a function of the ratio between the fibre weight fractions of composites made with virgin and recycled fibres. The knockdown factor is used as a proxy for virgin fibre replacement rate when using recycled fibres to offset virgin fibre production.

Equation 23 Fibre knockdown factor approach

$$\text{Fibre knockdown factor} = 1 - \frac{W_{vF}}{W_{rF}}$$

Where W_{rF} and W_{vF} are the fibre weight fractions of model composites made with recycled and virgin fibre respectively and which meet the condition that both composites have identical relevant selected mechanical performance characteristic. To achieve this, the performance of a model composite reinforced with virgin fibre is calculated, then, using the degraded fibre properties following recycling, the performance of a composite reinforced with recycled fibres is calculated. The fibre weight fraction is then increased until the same performance is achieved with recycled fibre composites as was found using virgin counterpart. Tensile strength was selected to evaluate fibre knockdown. The method used to calculate these for the model composites is described below. It was assumed that recycled fibres are to be used as reinforcement in secondary bulk moulding compound.

Table 31 Composition of model composite used in fibre knockdown assessment.

Fibre application	Polymer type	Weight fraction in virgin model composite			Fibre length
		Fibre	Polymer	Filler	
Bulk moulding compound	Unsaturated polyester resin	16%	34%	50%	6 mm [44]

The extended Kelly-Tyson model describes the tensile strength of discontinuous fibre composites. According to the Kelly-Tyson model the composite strength can be expressed in Equation 24.

Equation 24 Tensile strength of discontinuous fibre composites according to Kelly-Tyson model

$$\sigma_{cu} = \eta_o \left(\sum_{L_i < L_c} \left(\frac{\tau L_i}{D_f} \right) v_i + \sum_{L_i > L_c} \left(\frac{2\tau L_c}{D_f} \right) \left(1 - \left(\frac{L_c}{2L_j} \right) \right) v_j \right) + \sigma_m (1 - v_f)$$

Table 32 Input data used to calculate composite tensile strength using recycled fibres.

Symbol	Definition		Value
τ	Interfacial shear strength	GF	vGF: 105 MPa [45] rGF: 30 MPa [45]
		CF	vCF: 82 MPa [46] rCF: 82 MPa
L_f	Fibre length in model composite		6 mm
L_c	Critical fibre length		$L_c = \frac{\sigma_{fu} D_f}{2\tau}$
L_i	Fibre length shorter than critical fibre length		All fibres supercritical, $L_i = 0$ $L_j = L_f$
L_j	Fibre length longer than critical fibre length		
v_i	Volume fraction of fibres with subcritical length		All fibres supercritical, $v_i = 0$ $v_j = v_f$
v_j	Volume fraction of fibres with supercritical length		
σ_m	Matrix tensile strength		33 MPa [47]
E_m	Matrix tensile modulus		3400 MPa [47]
D_f	Fibre diameter	GF	17 μm [3]
		CF	7 μm [3]
η_o	Fibre orientation factor		3D random, $\eta_o = 0.2$
σ_{fu}	Fibre tensile strength	Virgin	GF - 1995 MPa [3] CF - 4900 MPa [48]
		Recycling 1	GF - 100% retention GF - 100% retention
		Recycling 2	GF - 100% retention CF - 100% retention

Table 33 gives the calculated fibre knockdown factors for each of the fibre types and recycling routes.

Table 33 Fibre knockdown factors calculated for each recycling routes.

Fibre type	Recycling 1	Recycling 2
Glass fibre	3.4%	3.4%
Carbon fibre	0.0%	0.0%

14 Allocation

WTB manufacture: In this study the blade manufacture is assumed to not be a multifunction process; therefore, there is only one output and no allocation needed to be considered. No economic value was attributed to waste produced during the blade manufacture phase and the impact of all production waste was attributed to the WTB itself.

WTB delivery: Multiple WTB are delivered from the manufacturer to the wind farm support port on the same HLV. The total fuel consumption of the delivery vessel was calculated and allocated equally across all WTBs being delivered.

WTB installation: During installation, the JUV is lifting and transporting multiple components, beyond just the WTB. The total fuel consumption of the JUV during the installation was calculated and fuel allocated to the WTB based on the time contribution of the WTB installation activities to the total WTG installation time.

WTB O&M: The fuel consumption of the SOV during inspection was allocated evenly across all WTG substructures being inspected (assuming 15 sub-structures per WTG being inspected). The fuel consumption of the SOV during repair works was allocated evenly across all WTG substructures being repaired.

WTB decommissioning: During decommissioning operations, multiple different components are being lifted (JUV) and transported (barge vessel and tugboat). The total fuel consumption of the JUV and tugboat during the decommissioning was calculated and fuel allocated to the WTB based on the time contribution of the blade decommissioning activities to the total WTG decommissioning time.

WTB EoL: In scenarios where the WTB is recycled at EoL, there are always multiple secondary material products produced during the recycling process (GF, CF, polymer, waste). The following are allocated to the blade only: 1) the burden of the blade recycling / secondary material production, 2) the burden of disposing of waste by-products, 3) the avoided burden of all secondary material products.

15 Assumptions in PET foam production LCI dataset

Datasets for virgin PET foam (used as core materials in wind blade structures) was not available in GaBi Sphera or Ecoinvent 3. To overcome this, an LCI dataset for this material was prepared to enable the wind blade LCA to be conducted. This section described the assumptions made in generating the dataset for PET core production.

Production of polyethylene terephthalate (PET) foams can occur through many methods, and one of the most used is through reactive extrusion [49]. This process is based on the reaction between PET and an appropriate blowing agent. The next step is the creation of foam by closing gas cells in the polymer matrix. Reactive processing of PET in order to extend macromolecular chains is undertaken at the polymer's melting point using in the same equipment as is used during the melting process. Chain extenders agents like pyromellitic dianhydride or epoxy compounds are commonly used for producing PET foams.

In this LCA, which has the goal to assess the environmental impact of manufacturing 1kg of PET foam, it has been considered the use of an epoxy resin compound. According to D. Misiura et al. [49] it is efficient in a proportion of 0.43%.

In order that the foaming process could occur it is necessary the use also a foaming agent, which might be in a solid, liquid, or gaseous form. According to D. Misiura et al. [49], the agents most often used in PET foaming are chemical compounds like hydrocerol CT534 or carbon dioxide used under high pressure. In this LCA carbon dioxide has been considered as a foaming agent, because its use is widely used, it has environmentally friendly properties and it presents high solubility in the polymer.

Considering the raw material densities listed in Table 34 and considering the percentage of epoxy resin compound of 0.43%, it has been calculated the amount of PET granulate, epoxy resin and carbon dioxide that are needed in input in order to produce 1kg of PET foam. These mass flows have been reported in the Life Cycle Inventory (LCI) input-output Table 35. It has also assumed that 10% of carbon dioxide is lost during the foaming process. The energy intensity of the foaming process has been considered similar to the

same of an injection moulding process and sourced from the GaBi database, as also in this case the polymer needs to reach the melting point.

Table 34 – Raw materials densities.

Raw material	Density [kg/m ³]
PET granulate	1370
CO ₂ (@ 1atm 25° C)	1.145
Epoxy resin	1100

Table 35 – LCI input-output table to produce 1 kg of PET foam.

	Flow	Quantity	Amount	Units
INPUT	PET granulate	Mass	0.989	kg
	CO ₂	Mass	6.957E-03	kg
	Epoxy resin	Mass	4.255E-03	kg
	Electricity	Energy	2.222	kWh
OUTPUT	PET foam	Mass	1	kg
	CO ₂	Mass	6.325E-04	kg

Table 36 contains information about geographical area, source and reference year of the individual LCI secondary datasets that have been used in this LCA.

Table 36 – LCI secondary datasets used in the GaBi model of PET foam manufacture.

LCI dataset name	Geographical area	Source	Reference year
Polyethylene terephthalate bottle grade granulate (PET) via PTA	EU-28	Sphera	2021
Carbon dioxide by-product ethylene oxide (EO) via O ₂ /methane	DE	Sphera	2021
Epoxy Resin (EP)	DE	Sphera	2021
Electricity grid mix	GB	Sphera	2021
PET foaming (density 160 kg/m ³)	Global	Literature data [49]	2018

In Figure 6 is reported the GaBi Plan related to the manufacturing of 1kg of PET foam.

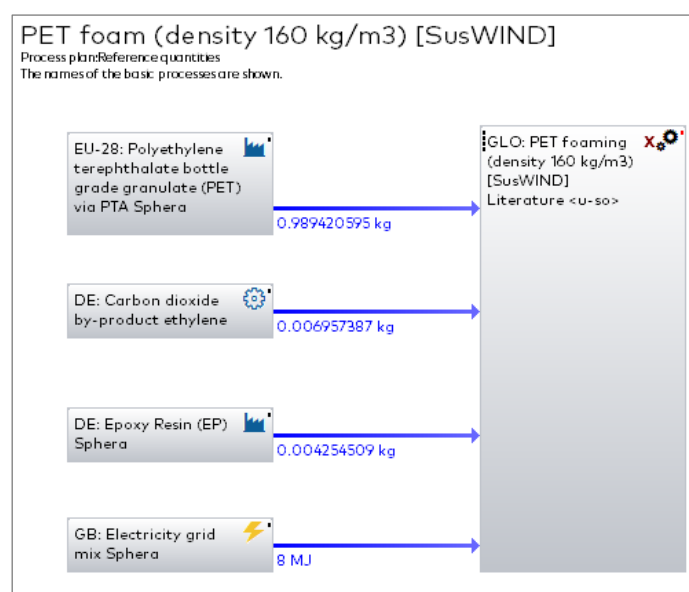


Figure 6 – GaBi Plan for the production of 1kg of PET foam.

The LCA results that comes from the Life Cycle Impact Assessment are reported in Table 37.

Table 37 - LCA results related to the production of 1kg of virgin PET foam.

Indicator	Total
CML2001 – Aug. 2016, Abiotic Depletion (ADP elements) [kg Sb eq.]	8.971E-07
CML2001 – Aug. 2016, Abiotic Depletion (ADP fossil) [MJ]	85.325
CML2001 – Aug. 2016, Acidification Potential (AP) [kg SO ₂ eq.]	4.859E-03
CML2001 – Aug. 2016, Eutrophication Potential (EP) [kg Phosphate eq.]	5.908E-04
CML2001 – Aug. 2016, Freshwater Aquatic Ecotoxicity Pot. (FAETP inf.) [kg DCB eq.]	1.775E-02
CML2001 – Aug. 2016, Global Warming Potential (GWP 100 years) [kg CO ₂ eq.]	3.530
CML2001 – Aug. 2016, Global Warming Potential (GWP 100 years), excl biogenic carbon [kg CO ₂ eq.]	3.528
CML2001 – Aug. 2016, Human Toxicity Potential (HTP inf.) [kg DCB eq.]	1.308E-01
CML2001 – Aug. 2016, Marine Aquatic Ecotoxicity Pot. (MAETP inf.) [kg DCB eq.]	197.231
CML2001 – Aug. 2016, Ozone Layer Depletion Potential (ODP, steady state) [kg R11 eq.]	4.198E-14
CML2001 – Aug. 2016, Photochem. Ozone Creation Potential (POCP) [kg Ethene eq.]	6.463E-04
CML2001 – Aug. 2016, Terrestrial Ecotoxicity Potential (TETP inf.) [kg DCB eq.]	6.936E-03
Primary energy demand from ren. And non ren. Resources (gross cal. Value) [MJ]	111.058
Primary energy demand from ren. And non ren. Resources (net cal. Value) [MJ]	103.402
Primary energy from non renewable resources (gross cal. Value) [MJ]	100.262
Primary energy from non renewable resources (net cal. Value) [MJ]	92.607

Primary energy from renewable resources (gross cal. Value) [MJ]	10.795
Primary energy from renewable resources (net cal. Value) [MJ]	10.795

16 LCI datasets

Table 38 LCI datasets used from Gabi Sphera

Material	Nation	Name	Source	GUID
Glass fibre	EU-28	Glass fibres	ts	{894AB0C2-A408-4824-8983-F886248F65BB}
Carbon fibre (Standard production)	GLO	Carbon fiber (CF; PAN-based; HT)	Fraunhofer	{AA2BD1E0-7797-480B-88C4-82E56ED454E5}
Carbon fibre (Low impact production)	HU	Carbon fiber (CF; PAN-based; HT)	Fraunhofer	{21C5051A-3379-45E4-8BD8-DD2A7899CBAA}
Surface filler	EU-28	2-component PUR adhesive based on polyether and castor oil (approximation)	Sphera	{F17F4B67-08BD-485C-AFFC-ADF347E0D65B}
Gel coat	DE	Reactive resins based on polyurethane, unfilled/solventfree, polyol-free - DBC/IVK/VdL (A1-A3)	Sphera-EPD	{549EF33D-4107-46EF-BEC8-957C8B664BC2}
Primer	DE	Base coat/primer water-based (windows, white) (EN15804 A1-A3)	Sphera	{D69CBF67-A418-4C4D-860F-94DD82CC369E}
Top coat	EU-28	Top coat water-based (windows, white) (EN15804 A1-A3)	Sphera	{CA8A19AE-3429-47D5-9BAD-197149D9A413}
Adhesive	EU-28	Simple 2-component epoxy adhesive (approximation)	Sphera	{326d32e2-3478-41a7-984e-39236c0fe8ec}
Steel (bushings)	EU-28	Steel pipe (EN15804 A1-A3)	Sphera	{35599B72-6FE6-46D1-9F04-946F1D191AA9}
Aluminium (LSP)	EU-28	Aluminium foil	Sphera	{8DD54976-0163-4D6E-9FE4-FA09F72545ED}
Tackifier adhesive	EU-28	PVAc adhesive (approximation)	Sphera	{EA2CCC46-400B-4587-BC94-E42141AFCBCF}
Flow medium (infusion mesh)	EU-28	Polypropylene fibers (PP)	Sphera	{DB00901B-338F-11DD-BD11-0800200C9A66}
Landfill (plastic)	EU-28	Plastic waste on landfill	Sphera	{64197300-3307-11DD-BD11-0800200C9A66}

Landfill (glass)	EU-28	Inert matter (Glass) on landfill	Sphera	{ED41D893-EDCD-4B2A-B5E4-E1A992A8A04A}
Landfill (wood)	EU-28	Untreated wood on landfill	Sphera	{64197302-3307-11DD-BD11-0800200C9A66}
Electric energy	GB	Electricity grid mix	Sphera	{00043BD2-4563-4D73-8DF8-B84B5D8902FC}
Articulated lorry transport incl. fuel, Euro 0-6 mix, 40 t total weight, 27 t max payload	EU-28	Articulated lorry transport incl. fuel, Euro 0-6 mix, 40 t total weight, 27 t max payload	Sphera	{B444F4D1-3393-11DD-BD11-0800200C9A66}
Light fuel oil at refinery	GB	Light fuel oil at refinery	Sphera	{71D08EEF-D96C-4AC0-9AF9-10D86E2F8316}
Heavy fuel oil at refinery	GB	Heavy fuel oil at refinery (1.0 wt.% S)	Sphera	{97C0F3B2-6C68-4D1C-A505-ACDACF789ED3}
Amine hardener	GB	Ethyleneamines (EDA, DETA, TETA, TEPA, PEHA)	Sphera	{32449A6A-E517-4EF9-A5B7-C0826A166878}
Epoxy resin	DE	Epoxy Resin (EP)	Sphera	{30DF02E7-D183-4EBA-987E-351AE4E42455}
Acetone	EU-28	Acetone	Sphera	{85B900E2-428E-4B18-8886-393F9956317D}
NaOH	EU-28	Sodium hydroxide (caustic soda) mix	Sphera	{8034F0FF-D0B9-47A8-86E8-ECE772F56871}
Acetic acid	DE	Acetic acid from methanol (low pressure carbonylation) (Monsanto process)	Sphera	{80C0F36B-9089-4058-9940-3FA073E8BFC5}
Waste water	EU-28	Municipal waste water treatment (mix)	Sphera	{9805E7EE-B500-46B4-A0F0-37B09E00A3FA}
Polycarbonate	DE	Polycarbonate Granulate	Sphera	{E8BC146D-4278-4B64-A6E5-ED9847528338}
Poly(methyl methacrylate) (PMMA)	DE	Polymethylmethacrylate granulate (PMMA)	Sphera	{0314DDE5-385C-4F3F-91B3-FEB2248F98FD}
Rail transport, average train, gross tonne weight 1,000t / 726t payload capacity	EU-28	Rail transport, average train, gross tonne weight 1,000t	Sphera	{DB009023-338F-11DD-BD11-0800200C9A66}

		/ 726t payload capacity		
Transoceanic ship, containers, 27,500 dwt payload capacity, ocean going	GLO	Transoceanic ship, containers, 27,500 dwt payload capacity, ocean going	Sphera	{69ADE038-68AA-44CF-8753-E49C3E7CADC5}

Table 39 LCI datasets used from Ecoinvent 3

Material	Nation	Name	Last change	Process identifier
Methanol	GLO	methanol production GLO	25/01/2021	EI3ARUNI000011519600560

Table 40 Literature LCI datasets

Material	Type	Source	Year	Material production GWP (kg CO ₂ eq./kg)
Bio-epoxy	Literature	Entropy bio-resin LCA [7]	2020	3.3
rEpoxy	No reported cradle-to-gate GWP for rEpoxy hardeners could be found in the literature or from supplier. It is understood that rEpoxy hardener is a modified amine-based hardener and similar in structure to typical ethyleneamine hardeners used in standard epoxy systems. As a proxy to rEpoxy hardeners, Gabi secondary dataset for production of ethyleneamines was used in the absence of product specific data (see Table 38). Standard liquid epoxy resin is used in conjunction with rEpoxy hardener (as described in Table 38).			
Bio-rEpoxy	Assumed the same data as Bio-epoxy system			
Infusable PMMA	Literature	ELIUM® 191 O/SA LCA, Arkema S.A. [8]	2021	3.7
Dibenzoyl peroxide*	Literature	DACOMAT project deliverable [50]	2019	3.6
Recycled PET (rPET)	Literature	ARMAFORM® PET LCA, Armacell Benelux S.A. [51]	2015	3.0

* LCI data for Dibenzoyl peroxide could not be found in literature therefore LCI data for Benzoyl peroxide was used as a proxy. Given the similarity in chemical composition it is assumed there will be close parity in impact between the two chemicals.

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