Supporting Information for

Wind Turbine Blades Using Recycled Carbon Fibers: An Environmental Feasibility Assessment

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1 Mechanical feasibility

1.1 RCF epoxy composites for WT blades- mechanical feasibility

A micromechanics model was developed to to predict the equivalent properties of RCFRP laminate with different layup angles (i.e., $[\pm 45]_2[0]_2$) which are the same layup angles with SNL Triax GF epoxy composites. Generalised compliance matrix is the inverse of generalised stiffness matrix.

$$[abd]=[ABD]^{-1}=\begin{bmatrix} a_{11} & a_{12} & a_{16} & b_{11} & b_{12} & b_{16} \\ a_{12} & a_{22} & a_{26} & b_{21} & b_{22} & b_{26} \\ a_{16} & a_{26} & a_{66} & b_{61} & b_{62} & b_{66} \\ b_{11} & b_{21} & b_{61} & d_{11} & d_{12} & d_{16} \\ b_{12} & b_{22} & b_{62} & d_{12} & d_{22} & d_{26} \\ b_{16} & b_{26} & b_{66} & d_{16} & d_{26} & d_{66} \end{bmatrix}$$

The generalised stiffness matrix are calculated using the following equations.

$$[ABD]=\begin{bmatrix} A_{ij} & B_{ij} \\ B_{ij} & D_{ij} \end{bmatrix}=\begin{bmatrix} A_{11} & A_{12} & A_{16} & B_{11} & B_{12} & B_{16} \\ A_{12} & A_{22} & A_{26} & B_{12} & B_{22} & B_{26} \\ A_{16} & A_{26} & A_{66} & B_{16} & B_{26} & B_{66} \\ B_{11} & B_{12} & B_{16} & D_{11} & D_{12} & D_{16} \\ B_{12} & B_{22} & B_{26} & D_{12} & D_{22} & D_{26} \\ B_{16} & B_{26} & B_{66} & D_{16} & D_{26} & D_{66} \end{bmatrix}$$

$$[A]=\int_{z^{bottom}}^{z^{top}}[Q']\,dz=\sum_{l=1}^{n}\int_{h_{l-1}}^{h_l}[Q']_l\,dz=\sum_{l=1}^{n}[Q']_l\left(h_l-h_{l-1}\right)$$

$$[B]=\int_{z^{bottom}}^{z^{top}}[Q']\,zdz=\sum_{l=1}^{n}\int_{h_{l-1}}^{h_l}[Q']_l\,zdz=\frac{1}{2}\sum_{l=1}^{n}[Q']_l\left(h_l^2-h_{l-1}^2\right)$$

$$[D]=\int_{z^{bottom}}^{z^{top}}[Q']\,z^2dz=\sum_{l=1}^{n}\int_{h_{l-1}}^{h_l}[Q']_l\,z^2dz=\frac{1}{3}\sum_{l=1}^{n}[Q']_l\left(h_l^3-h_{l-1}^3\right)$$

where h represents the vertical position in the ply from the midplane. $[Q^{\prime}]_{l}$ are the stiffness matrix for each ply in global coordinate system, which can be calculated as follow.

$$[Q'] = [T]\,[Q]\,[T]^{T}$$

Where, $[Q]$ is the stiffness matrix in local coordinate system, $[T]$ is the transverse matrix from local coordinate system to global coordinate system. θ is ply angle, E_1, E_2, ν_{12} and ν_{21} are equivalent elastic properties of a single layer.

$$[Q]=\begin{bmatrix} \dfrac{E_1}{1-\nu_{12}\nu_{21}} & \dfrac{\nu_{12}E_2}{1-\nu_{12}\nu_{21}} & 0 \\ \dfrac{\nu_{21}E_1}{1-\nu_{12}\nu_{21}} & \dfrac{E_2}{1-\nu_{12}\nu_{21}} & 0 \\ 0 & 0 & G_{12} \end{bmatrix}$$

$$[T]=\begin{bmatrix} \cos^2\theta & \sin^2\theta & -2\sin\theta\cos\theta \\ \sin^2\theta & \cos^2\theta & 2\sin\theta\cos\theta \\ \sin\theta\cos\theta & -\sin\theta\cos\theta & \cos^2\theta-\sin^2\theta \end{bmatrix}$$

1.2 Material substitution under stiffness-limited design

Under failure modes, face yielding can be expressed:

$$\sigma_f = \frac{Pl}{btc} \tag{1}$$

Core shear failure can be expressed as

$$\tau_c = \dot{\tau_c} = \frac{P}{2bc} \tag{2}$$

Failure index with the referenced GF material is 100%, the aligned RCF epoxy composite needs to be less than 100%.

$$f_\sigma = {}^{\sigma_f}/_{\sigma_y} \tag{3}$$

where the values of *P, l, b, t, c*, σ_f, σ_y can be found in Table S2.

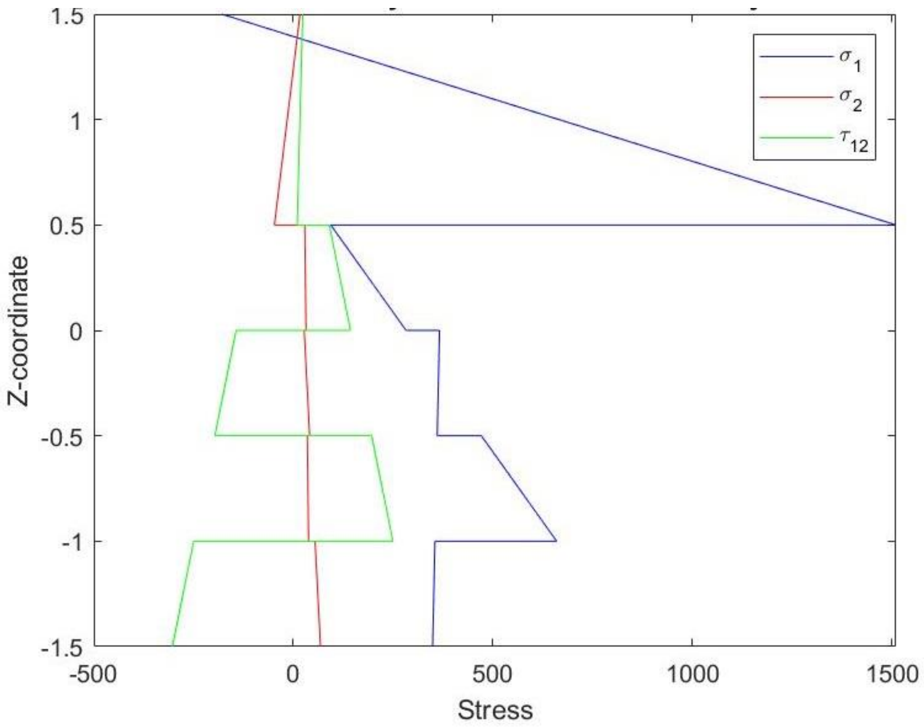
Table S1 Material mechanical properties under the base case and improved case

	Layup	vf %	Density (kg/m3)	EL, Gpa	ET, Gpa	GLT, Gpa	vLT	UTSL, Mpa	References
Foam (PET)	-	-	200	0.256	0.256	0.022	0.3	2.41	ref[1]
SNL Triax	$[\pm 45]_2[0]_2$	50%	1820	27.7	13.7	7.2	0.39	300	ref[1]
Aligned rCF 3mm-base case	$[\pm 45]_2[0]_2$	55%	1485	24.6	16.1	14.3	0.27	507	ref[2] + own cal
Aligned rCF 3mm-upper case	$[\pm 45]_2[0]_2$	55%	1492	31.4	18.3	15.4	0.27	507	ref[2] + own cal

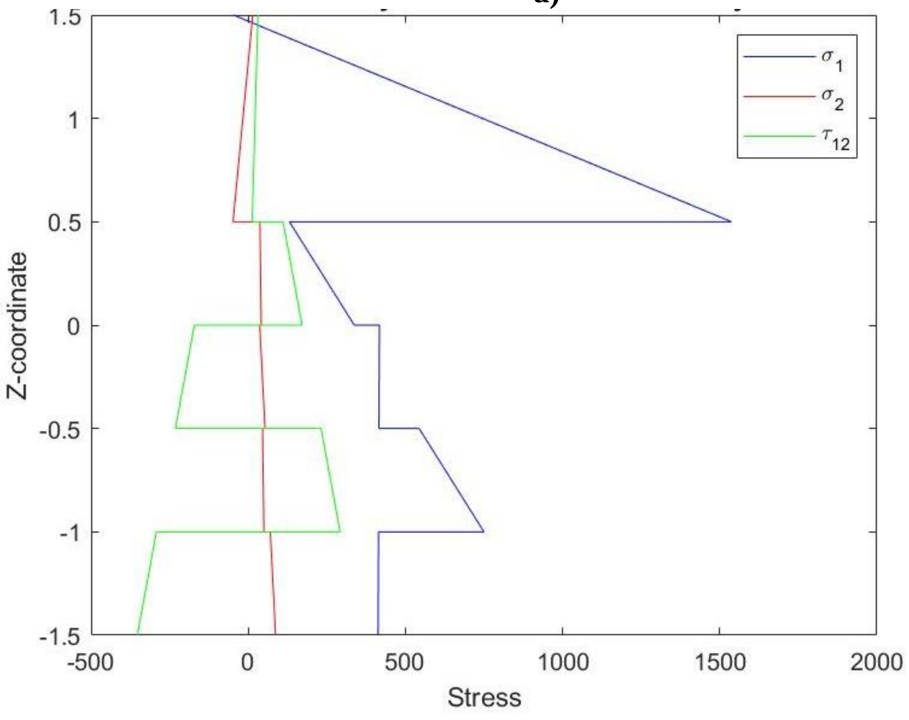
Table S2 Material substitution calculation under the base case and improved case

	SNL Triax [(a)]	Aligned rCF 3mm-base case [(b)]	Aligned rCF 3mm, improved case[(c)]
Load, *P*, [N]	1000.0	1000.0	1000.0
Length, *l*, [m]	50.0	50.0	50.0
Width, *b*, [m] for calculation purpose only	1.0	1.0	1.0
Skin Thickness, *t*, [mm]	3.0	3.3	2.7
Core thickness, *c*, [mm]	60.0	60.0	60.0
ρ_c/ρ_s (typically 0.02 to 0.3)	0.1	0.1	0.1
t/l (typically 1/2000 to 1/200 = 0.0005 to 0.005)	6.00E-05	6.92E-05	5.36E-05
Mass, sandwich panel, [kg]	11231	10918	9795
Normalised mass, sandwich panel	1.0	1.0	0.9
$(EI)_{eq}$ for calculation purpose only	169645	169644	169644
Mass, composite, [kg]	5350.8	5038.2	3915.1
Normalised mass, composite	1.0	0.9	0.7
Mass, foam, [kg]	5880.0	5880.0	5880.0
Deflection, $\delta=\delta_b+\delta_s$, [m]	216.6	108.8	106.2
Maximum bending, [Nm]	1.12E+04	1.09E+04	1.25E+06
Curvature, [m^{-1}]	0.7	0.3	0.3
Constant, *B1*	8.0	8.0	8.0
Constant, *B2*	2.0	2.0	2.0
Constant, *B3*	1.0	1.0	1.0
Constant, *B4*	2.0	2.0	2.0
Constant, *C2*	0.4	0.4	0.4
Face yielding, σf	2.78E+08	2.41E+08	3.11E+08
Failure index, $f=\sigma f/\sigma y$	93%	47%	61%
Normalised Failure index	100%	51%	66%

a) Glass fiber epoxy composite (SNL Triax) has 3.0 mm skins and 60mm foam core.
b) Aligned RCF epoxy composite under base case has 3.3 mm skins and 60mm foam core.
c) Aligned RCF epoxy composite under improved case has 2.7 mm skins and 60mm foam core.



a)



b)

Figure S1 Stress for each layer under local coordinate system ($[\pm 45]_2[0]_2$) for a) base case; b) improved case.

2 LCI Modelling details of different WT blades

Table S3 Material Input per Functional Unit (FU =3 Blades) in kgs. For Three Blades Types Studied

Material per FU (3 Blades)	**GFB** [(a)]		**GFHB** [(b)]		**RCFHB** [(c)]	
	Weight (kg)	**Wt.%**	**Weight (kg)**	**Wt.%**	**Weight (kg)**	**Wt.%**
PET Foam	7358	13.3	7648	21.6	7648	22.7
Structural Adhesive	443	0.80	461	1.30	461	1.37
GF	31689	57.2	14111	39.9	0	0
VCF	0	0.00	3371	9.5	3371	10.0
RCF	0	0.00	0	0	11750	34.9
Epoxy Resin [(d)]	15836	28.7	9818	27.7	10391	31.0
Total Weight	55326	100	35409	100	33621	100

a) GFB= All Glass Fibers (All-GF) WT Blades. Weight of one GFB (50 m length) = 18442 kg (without root studs)[3]. Thus, the weight of 3 blades is 55326 kg. The material composition of GFB obtained from Sandia National Labs report on GF WT.[1]

b) GFHB= GF-Hybrid WT Blades. Weight of GFHB is 36% lighter than GFB.[4] Its material composition obtained from Sandia National Labs report on Hybrid VCF spar epoxy spar cap enabled WT.[4]

c) RCFHB= RCF-Hybrid WT Blades. Since RCFHBs also use VCF epoxy spar caps , the weight of RCFHB is 36% lighter than GFB and on top of that using RCF reinforced epoxy composites would result in 9% weight savings compared to shear web, and shell skins made of GF-epoxy composites. Individual material composition is similar to GFHB except that RCF epoxy replaced with GF epoxy for production of other parts of WT.

d) Total epoxy resin input also includes extra resin (termed as parasitic resin[1]) consumed due to nature of infusion curing process.

2.1 Modeling Details of RCF-Hybrid WT Blades (RCFHB)

The system boundary showing major life cycle stages of RCFHB is shown in Figure 1.

Table S4 Assumptions and data sources used in building LCI model for RCF-Hybrid Blade

Life Cycle Stage	Description of Stage	Assumptions and Data Sources Used.
Raw Materials	VCF, RCF, epoxy resin, PET foam boards and structural adhesive	**VCF** • Material conversion yield of PAN precursor to VCF is 58%. Electricity, natural gas, and steam consumption include 150 MJ, 178 MJ and 31.4 kg per kg VCF produced.[5] Emission data for CF production obtained from literature. [6] **RCF** • Energy consumption for shredding CFRP scrap ranges between 16-32 kWh/ton.[7] (24 kWh/ton assumed for baseline modeling) • LCI for RCF production via pyrolysis obtained from literature. [8, 9] **Epoxy Resin and PET Foam Boards** • LCI data of epoxy (GLO dataset) and PET foam obtained from ecoinvent database.[10] **Structural Adhesive** • LCI data on structural adhesive obtained from literature.[11]
Manufacturing	Non crimp VCF Preform	• Production of 1 kg non crimp virgin CF preform consumes 5.06 kWh electricity and 9.85 KJ heat are consumed.[12] • Material loss as offcuts is 11% [13]. This is treated as post-industrial recycling (PIR) scrap and incinerated with energy recovery.
	Aligned RCF preform & RCF epoxy prepreg	• LCI data on RCF preforms is developed based on HipeDiF method.[14] LCI Data for • Energy consumption for prepreg assumed as 4 MJ/kg (with continuous usage requirement and no need to store under controlled conditions for long periods of time).[15, 16] • Material loss (offcuts) in shaping RCF epoxy prepregs assumed as 11%

		•
	Autoclave Molding	• 100% yield assumed for all blade components. • Energy consumption of auto clave molding reported as 1.375 KWh/kg[19]; 4.97 KWh/kg[20] and 6.08 KWh/kg[17] respectively by three sources. An average of 4.14 KWh/kg is taken. • FVF Content of RCF in epoxy = 55%
	Gel coating of blades and their installation in WT.	• Excluded from LCA because this life cycle stages are common for all blade options.
Use	Use of blades in a WT	• No maintenance is required for WT blades.
End of Life	Incineration with energy recovery	• Energy consumption of shredding WT blade scrap taken as 24 kWh/ton (average of 16 and 32 kWh/ton).[7] • 5% losses assumed during transport of blade scrap to incineration site (This loss applied only to fiber reinforced epoxy composites. No loss assumed material assumed for PET foam boards) • Energy recovered per kg of RCF and VCF epoxy blade scrap plus residual ash sent to landfills is obtained from literature.[21] Ecoinvent dataset on waste plastics mixture (adjusted for ash content) is used for modeling • For waste PET foams, ecoinvent dataset[10] on waste PET treatment in municipal incineration facility is used.

2.2 LCI Data of Aligned RCF Epoxy Preform and RCF Epoxy Prepregs

The LCI data for aligned RCF epoxy preform and RCF epoxy prepregs is developed based on experimental data reported by Yu et al.[2] in their work on manufacturing of aligned discontinuous fiber composites using HiPerDif method.

Based on experimental conditions reported by Yu el al.[2] six RCF epoxy prepreg specimens with dimensions of 50 mm (length) x 3mm (width) x 0.22 mm (thick) are produced. Therefore, the total weight of RCF epoxy prepregs is 294.03 mg (3.3E-08 m^3 *6 specimens* 1485 kg/m^3 (RCF epoxy composite density assuming CF density as 1800 kg/m^3; epoxy density = 1100 kg/m^3 and FVF of 55%))). The FVF of carbon fibers used in RCF epoxy prepregs is 55% (65% by weight). Thus, the weight of carbon fibers in the prepreg is 294.03 * 0.65 = 191.11 mg.

Also based on experimental conditions reported by Yu et al., to manufacture CF preforms, the carbon fibers are dispersed in water with a volume fraction of 0.003% (0.01% by weight). This amounts to dispersion rate of 0.1 mg/ml (0.01 g/100 g water). This is the initial condition for manufacturing of 191.11 mg of aligned carbon fiber preform. The dispersed carbon fibers in water solution is pumped at a controlled speed such that fibers suspended in the water get slowly aligned in a uniform direction. The aligned fibers are passed through a perforated conveyor belt and water collected at the bottom is ejected out using vacuum ejector and is returned back to the dispersion tank. A detailed method of HiPerDif method is given by Yu et al.[2] Here, the LCI data for manufacturing 191.11 mg of aligned RCF preforms via HiPerDif method is given in Table S21.

Table S5 LCI data on Aligned RCF Preforms (191.11 mg) using HiPerDif Method.

Parameter	Amount	Description/Notes.
Pumping energy for carbon fibers dispersed water solution	0.0002107 KWh	• CF dispersion in water is 0.1 mg/ml. For 191.11 mg the amount of water to be pumped is 1911.1 ml = 1.911 liters. • Specific energy consumption of typical low solids metered pumping is 0.09 KWh/m^3 as per literature.[22, 23] Thus for pumping 1.911 liters the energy is 0.0001719 KWh
Movement of carbon fibers on perforated conveyor	9.36 E-08 KWh	• Specific energy consumption for moving 1 kg of material to one meter for conveyor with 0° inclination is 0.4 Wh.[24] Thus the energy required to convey 191.11 mg of material is 7.64 E-08 KWh
Power Consumption for Vacuum Ejector	5.59E-06 KWh.	• Power rating of a typical vacuum ejector is 0.35 W with air consumption rate of 24 l/min.[25] • Air flow rate needed to eject 1.911 liters water can be estimated using the below formula obtained from literature.[26] $$\eta = \frac{1}{1 + \left(\frac{t \times Q}{V}\right)}$$ Where η = Efficiency of vacuum generator at low pressure = 0.5 at -0.4 bar.[26] t = exhaust time in min. For ZK2 vacuum series unit mentioned above, the exhaust time is 5 seconds (0.0833 min).[26] Q = air flow rate in liters/min. V = Volume of water to be evacuated (liters) = 1.911 liters of water. By rearranging, above equation, the air flow rate Q is calculated as 23.04 l/min. This requires 0.96 minutes of operation of vacuum ejector. The power consumption of vacuum ejector unit = (0.96/60 min/hr.)* (0.35W/1000 W/KW) = 5.59 E-06 KWh.

The aligned RCF preforms are pre impregnated (prepreg) in epoxy resin. The amount of RCF epoxy prepreg produced by Yu et al.[2] is 294.33 mg and LCI data of 191.11 mg (65 wt.% , i.e. 294.33 mg) is RCF preforms and obtained Table 15S. The specific energy consumption of the process is 40 MJ/kg.[15, 16] The amount of energy consumer for 294.33 mg is 0.00038 kWh. These values are scaled up for the weight of All-RCF WT blade

2.3 Modeling Details of All Glass Fibers (All-GF) WT Blades (GFB)

The system boundary showing major life cycle stages of All-GF WT blades is shown in Figure S2.

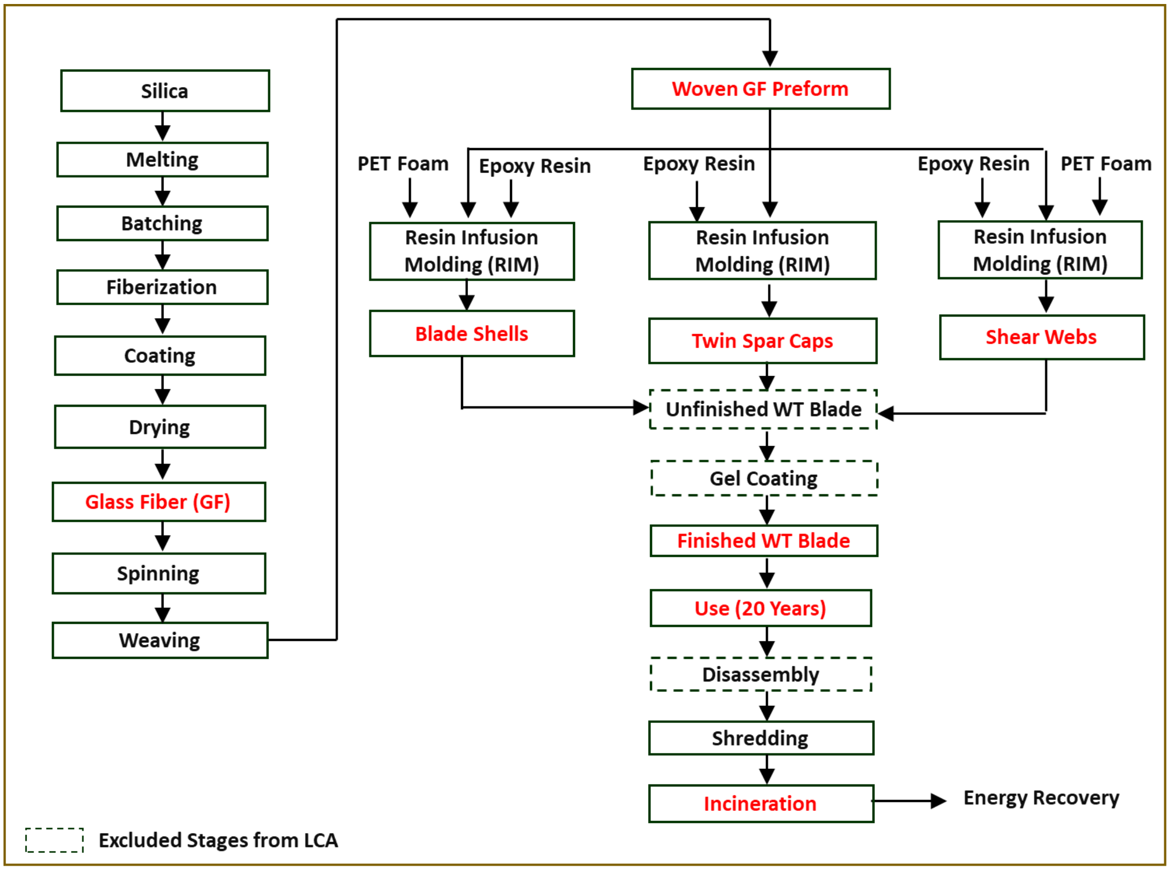


Figure S 2 Life Cycle Stages of All-GF WT Blade

The important assumptions made, and key data sources used for the construction of foreground LCI dataset of All-GF blade is shown in Table S5.

Table S 6 Assumptions and Data sources used in Building LCI Model for All-GF Blade

Life Cycle Stage	**Description of Stage**	**Assumptions and Data Sources Used.**
Raw Materials	GF, Epoxy resin, PET foam boards and Structural Adhesive	• LCI data of GF, Epoxy resin and PET foam obtained from ecoinvent database.[10] • LCI data adhesive obtained from literature.[11]
Manufacturing	Woven GF Preform	• Production of 1 kg woven GF preform consumes 5.06 kWh electricity and 9.85 kJ heat are consumed.[12] • Material loss due to offcuts while making non crimp virgin CF preform is 11%.[13] Also, off cuts are incinerated and energy recovery credit is taken.
	Resin Infusion Curing (RIM) of WT Blade Components	• 100% yield assumed for all blade components. • Energy consumption of RTM is 10.2 MJ/kg.[17] • LCI data for consumables required for RIM is prepared based on literature data[27] and given as Table 2S.
	Gel Coating of Blades and Their Installation in WT.	• Excluded from LCA because this life cycle stages are common for all blade options.
Use	Use of Blade in a WT	• No maintenance is required for WT blades
End of Life	Incineration with Energy Recovery	• Disassembly of blade is excluded from LCA • Energy consumption of shredding WT blade scrap taken as 24 kWh/ton (average of 16 and 32 kWh/ton).[7] • 5% losses assumed during transport of blade scrap to incineration site (This loss applied only to fiber reinforced epoxy composites. No loss assumed material assumed for PET foam boards) • Energy recovered per kg of GF- epoxy blade scrap plus residual ash sent to landfills is obtained from literature.[21] Ecoinvent dataset on waste plastics mixture (adjusted for ash content) is used for modeling • For waste PET foams, ecoinvent dataset[10] on waste PET treatment- municipal incineration facility is used.

Table S 7 Consumables Required for 1 m^2 Resin Infusion Curing of WT Blade Components

Material Used	**Amount (grams)**	**Notes**
Peel Ply	82	• Nylon 6-6 used as peel ply. Weight of peel ply is 82 g/m^2 of material cured.[27] • Nylon 6-6 and weaving LCI datasets from ecoinvent are used for modeling.[10]
Release film	21.46	• Polypropylene (PP); 0.025 mm thick films.[27] Density of PP = 855 kg/m^3. PP granulate and film extrusion (99.6% yield) datasets from ecoinvent database[10] used.
Vacuum bagging	57.22	• Nylon bag with 0.05 mm thick is extruded.[27] Density = 1140 kg/m^3. Nylon and extrusion (99.6% yield) datasets from ecoinvent database[10] are used.
Sealant Tape	32.53	• Synthetic rubber (12 mm wide and 3 mm thick tape).[27] Density of rubber = 900 kg/m^3. Synthetic rubber and extrusion plastic film (99.6% yield) datasets from ecoinvent[10] are used.
Breather Fabric	178	• PP based fabric 178 g/m^2 used.[27] Density of PP = 855 kg/m^3. PP granulate and weaving datasets from ecoinvent database[10] are used.
Polyester Tape Adhesive	261.88	• Tape contains polyester resin (0.125 mm thick, density = 1400 kg/m^3) and silicone adhesive (0.037 mm thick, density = 2320 kg/m^3).[27] Data for polyester, silicone and extrusion (film with 99.6% yield) are obtained from ecoinvent.[10]
PTFE Coated Glass Fabric	235	• PTFE coated glass fabric used is 234 g/m^2 with 54% PTFE.[28] Data for PTFE, glass fiber and weaving are obtained from ecoinvent.[10]
Vacuum Hose	2429	• Silicone hose Outer diameter = 10 mm, Inner diameter = 9 mm.[27] Thickness of hose = 1 mm. Density of silicone = 2420 kg/m^3. LCI data for silicone and hose extrusion (pipe dataset with 99.6 %) are obtained from ecoinvent.[10]

The consumables shown in Table S4 is for 1 m^2 of mold area undergoing RIM. For a 50 m long blade and a width of 3.4 m, consumables are needed to cure 170 m^2 of mold area per WT blade. Thus, for 3 blades the mold area is 510 m^2. This area includes RIM of pressure and suction side shells and shear web skins. The total mold area may be slightly higher (considering molding of shear webs is done separately but the width of the blade is tapered, i.e. maximum width (3.4

mm) at root area (pressure side) and reduces towards trailing edge. Therefore, an area of 510 m^2 to be resin infusion molded is a good approximation.

2.4 Modeling Details of GF-Hybrid WT Blades (GFHB)

The system boundary showing major life cycle stages of All-GF WT blades is shown in Figure S3.

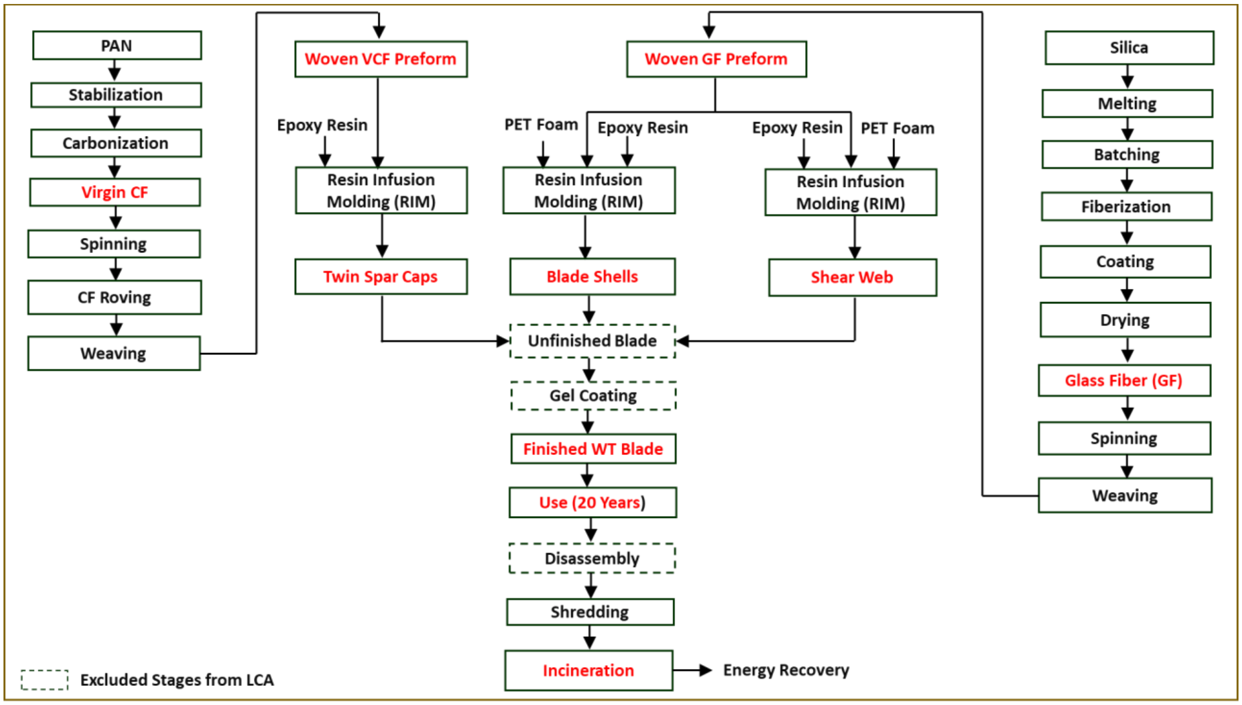


Figure S 3 Life Cycle Stages of GF-Hybrid WT Blade

The important assumptions made, and key data sources used for the construction of foreground LCI dataset of All-GF blade is shown in Table S7.

Table S 8 Assumptions and Data sources used in Building LCI Model for GF-Hybrid WT Blade

Life Cycle Stage	Description of Stage	Assumptions and Data Sources Used.
Raw Materials	VCF, Epoxy resin, PET foam boards and Structural Adhesive	**VCF** • Conversion yield of PAN precursor to VCF is 58% LCI data for VCF obtained from literature.[6] **Epoxy Resin and PET Foam Boards** • LCI data of epoxy and PET foam obtained from ecoinvent database.[10] **Structural Adhesive** • LCI data adhesive obtained from literature.[11]
Manufacturing	Non Crimp VCF Preform and Woven GF Preforms	• Production of 1 kg non crimp virgin CF preform and Woven GF preform consumes 5.06 kWh electricity and 9.85 kJ heat are consumed.[12] • Material loss due to offcuts while making non crimp virgin CF of GF preform is 11%.[13] Also, off cuts are incinerated and energy recovery credit is taken.
	Resin Infusion Molding (RIM) of Blade Components	• 100% yield for all blade components. • Energy consumption of RIM is 10.2 MJ/kg.[17] • LCI data for consumables required for RIM is prepared based on literature data[27] and given as Table 2S. (Consumables calculated for a total mold area of 510 m2. Please see calculation associated with Table 2S).
	Gel Coating of Blades and Their Installation in WT.	• Excluded from LCA because this life cycle stages are common for all blade options.
Use	Use of Blade in a WT	• No maintenance is required for WT blades
End of Life	Incineration with Energy Recovery	• Disassembly of blade is excluded from LCA • Energy consumption of shredding WT blade scrap taken as 24 kWh/ton (average of 16 and 32 kWh/ton).[7] • 5% losses assumed during transport of blade scrap to incineration site (This loss applied only to fiber reinforced epoxy composites. No loss assumed material assumed for PET foam boards) • Energy recovered per kg of GF and VCF epoxy blade scrap plus residual ash sent to landfills is

	obtained from literature.[21] Ecoinvent dataset on waste plastics mixture (adjusted for ash content) is used for modeling • For waste PET foams, ecoinvent dataset[10] on waste PET treatment in municipal incineration facility is used.

2.5 Baseline Scenario of Three WT Blades

The amounts of individual materials used in fabricating All-GF WT blade per functional unit (FU) and supporting calculations is shown in Tables S9 and S10 respectively.

Table S 9 Material Composition of All-GF WT Blade

Material	Amount/Blade kg	% Composition	Amount for Three Blades kg
PET Foam	2453	13.3	7358
Adhesive	148	0.8	443
Glass Fibers for Shear Webs	418	2.268	1255
Epoxy Resin for Shear Webs	246	1.332	737
Glass Fibers for Shells	10145	55.008	30434
Epoxy Resin for Shells	3945	21.392	11835
Parasitic Resin	1088	5.9	3264
Total Weight	18442	100	55326

1) Total weight from Cost Study of Large Wind Turbine Blades. Sandia Report. Blade (50m) Weight of 18856 minus root studs (414 kg).[3] Material Composition obtained from Griffith and Ashwill report on glass fiber wind turbine blade.[1]

Table S 10 Material Input Calculations for All-GF WT Blade (All GFB)

Material Input for Three All GFB Blades	**Amount**	**Comments**
Amount of Glass Fibers in 3 Blades	31688.52	
Woven Preform Yield	0.89	89% Weaving Yield
Total Amount of GF Needed for 3 Blades	35605.08	
Offcuts from Woven GF Preform Making	3916.56	
Losses (L1)	195.83	5 % loss during transport
Off Cut Waste for Incineration (PIS)	3720.73	PIS = Post Industrial Scrap
Epoxy Resin for 3 Blades	15836.51	
PET Foam for 3 Blades	7358.36	
Structural Adhesive	442.61	
Material of Weaving	35605.08	
Material for Resin Infusion Curing	55326.00	
Total Material Input (TMI)	59242.56	
Total Amount for 3 GFWT Blades	55326.00	
Total Amount without PET Foam	47967.64	
GFWT Blade Scrap at EOL	47967.64	
Material Loss During Shredding and Transport (L2)	2398.38	5% losses
GFWT Blade Scrap at EOL for Incineration (PCS1)	45569.26	PCS= Post Consumer Scrap
PET Foam for Incineration (PCS2)	7358.36	
Total Scrap for Incineration	49289.99	
PIS Reycle %	6.28	(PIS/TMI)*100
PCS Recycled %	89.34	((PCS1+PCS2)/TMI)*100
Total Losses (TL) = (L1+L2)	2594.21	
Loss%	4.378	(TL/TMI)*100
Total Material Percentage	100	

The amounts of individual materials used in fabricating GF-Hybrid WT blade per FU and supporting calculations is shown in Tables S11 and S12 respectively.

Table S11 Material Composition of GF-Hybrid WT Blade

Material	Amount/Blade kg	% Composition	Amount for Three Blades kg
PET Foam	2549	21.60	7648
Adhesive	154	1.30	461
Glass Fibers Shear Webs	446	3.78	1338
Epoxy Shear Webs	262	2.22	786
Glass Fibers Shells	4258	36.07	12773
Epoxy Shells	1656	14.03	4967
Virgin Carbon Fibers	1124	9.52	3371
Epoxy for Laminate	482	4.08	1445
Epoxy Resin Parasitic	873	7.40	2620
Total Weight	**11803**	**100**	**35409**

1) 6% blade mass with 44% FVF which is 62.6% by weight% (GF for shear webs). 50.1% blade mass with 55% with 72.28% by weight (for glass fiber shells).[29]

Table S12 Material Input Calculations for GF Hybrid WT Blade (GFHB)

Material Input for Three GFHB	Amount (in kg)	Comments
Amount of Glass Fibers for 3 Blades	14111.17	
Amount of Carbon Fibers for 3 Blades	3370.92	
Woven GF Preform Yield	0.89	89% Yield
Woven VCF Preform Yield	0.89	89% yield
Total Glass Fiber Input	15855.25	
Precured Offcuts of Glass fibers	1744.08	
Losses (L1)	87.20	5 % loss during transport
Off cured Glass Fiber Cuts for Incineration (PIS1)	1656.87	
Total Carbon Fiber Input	3787.55	
CF Waste from Weaving	416.63	
Losses (L2)	20.83	5% losses
Waste from CF Woven Preforms (PIS2)	395.80	
Total Glass Fiber Input	15855.25	
Total Carbon Fiber Input	3787.55	
Epoxy for Laminates	1444.68	
Amount of Resin Infused	8373.51	
Total Epoxy Resin Input	9818.19	
PET Foam	7648.34	
Adhesive	460.62	
Total Material Input (TMI)	37569.94	
Total Weaving	19642.80	
Amount for Resin infusion Curing	35409.24	
Total Blades at EOL	35409.24	
Total Blades without PET Foam	27760.89	
Total Blade Scrap at EOL	27760.89	
Material Loss During Transport (L3)	1388.04	
Blade Scrap sent for Incineration (PCS1)	26372.85	
PET Foam for Incineration (PCS2)	7648.34	
PIR Reycle %	5.46	((PIS1 + PIS2)/TMI)*100
PCR Recycled %	90.55	((PCS1 + PCS2)/TMI)*100
Total Losses TL = (L1 + L2 + L3)	1496.08	(TL/TMI)*100
Loss%	3.98	
Total Material Percentage	100	

The amounts of individual materials used in fabricating RCF-Hybrid WT blade per FU and supporting calculations is shown in Tables S13 and S14 respectively.

Table S13 Material Composition of RCF-Hybrid WT Blade (RCFHB)

Material	**Amount/Blade kg**	**% Composition**	**Amount for Three Blades kg**
PET Foam	2549	0.23	7648
Adhesive	153	0.01	460
RCF for Shear Webs	419	0.04	1257
Epoxy for Shear Webs	226	0.02	677
RCF for Shells	3498	0.31	10493
Epoxy for Shells	1883	0.17	5650
Virgin Carbon Fibers	1124	0.10	3371
Epoxy for Laminate	482	0.04	1445
Epoxy Resin Parasitic	873	0.08	2620
Total Weight	11207	100	33621

1) Material composition of RCFHB Similar to GFHB except that use of RCF epoxy composites would result in additional 9% savings

Table S14 Material Input Calculations for RCF Hybrid WT Blade (RCFHB)

Material Input for Three RCFHB	**Amount (in kg)**	**Comments**
Amount of RCF for 3 Blades	11749.77	
Amount of Carbon Fibers for 3 Blades	3370.94	
Woven Preform Yield	0.89	89% Yield
Pultrusion Yield	0.89	89% yield
Total RCF Input	13201.99	
Precured Offcuts of RCF	1452.22	
Losses (L1)	72.61	5% Losses during transport
Off cured RCF Cuts for Incineration (PIS1)	1379.61	
Total Carbon Fiber Input	3787.57	
CF Waste from Pultrusion	416.63	
Losses (L2)	20.83	5% losses
Waste from CF Woven Preforms (PIS2)	395.80	
Total RCF Input	13201.99	
Total Carbon Fiber Input	3787.57	
Epoxy for Laminates	1444.68	
Amount of Resin Infused	8947.06	
Total Epoxy Resin Input	10391.74	
PET Foam	7648.34	
Adhesive	460.32	
Total Material Input (TMI)	35489.95	
Total Weaving	3787.57	

Amount for Resin infusion Curing	33621.10	
Total Blades at EOL	33621.10	
Total Blades without PET Foam	25972.76	
Total Blade Scrap at EOL	25972.76	
Material Loss During Transport (L3)	1298.64	
Total Blade Scrap sent for Incineration (PCS1)	24674.12	
PET Foam for Incineration (PCS2)	7648.34	
PIR Reycle %	5.00	((PIS1 + PIS2)/TMI)*100
PCR Recycled %	91.07	((PCS1 + PCS2)/TMI)*100
Total Losses (TL) = L1 + L2 + L3	1392.08	(TL/TMI)*100
Loss%	3.92	
Total Material Percentage	100	

2.6 Uncertainty Analysis of RCF-Hybrid WT Blade

The model parameters varied for uncertainty analysis is shown in Table S15.

Table S15 Model Parameters Varied for Uncertainty Analysis

Parameters Varied	**Description**	**WT Blade Types Affected**
Blade Weight	• Varied from 30046 kg (with maximum 15% weight savings if RCF has no mechanical performance loss as calculated in section 2.3) to 33621 kg (no weight savings considered).	RCFHB
VCF Production	• Electricity consumption varied from 90-272 MJ/kg; Heat from wood chips: 108-323 MJ/kg and Steam: 19-57 kg.[5] • VCF production yield varied from 55-62% • HCN and NH_3 emissions released from VCF production site is controlled by a regenerative thermal oxidizer (RTO) with a destruction efficiency of 98%.[30] HCN emissions varied from 0.0056 to 0.283 kg and NH_3 emissions from 0.00152 to 0.076 kg/kg VCF production LCI for RTO obtained from literature.[31]	GFHB and RCFHB
GF/VCF Preforms	• Electricity consumption varied from 2.1 to 5.06 kWh/kg and heat from 8.3 to 17 kJ/kg.[32]	GFB and GFHB
RIM	• Electricity consumption of RIM varied from 0.7056[18] to 2.83 kWh/kg.[17]	GFB, GFHB and RCFHB
Shredding WT Blade	• Electricity consumption of RIM varied from 16 to 30 kWh/kg.[7]	GFB, GFHB and RCFHB

The amounts of individual materials used in fabricating RCF-Hybrid WT blade per FU with maximum lightweight savings and supporting calculations is shown in Tables S16 and S17 respectively. For minimum weight savings, the blade weight and material composition are the same as those of GFHB (except that RCF used instead of GF).

Table S16 Material Composition of RCF-Hybrid WT Blade (Maximum Weight Savings)

Material	**Amount/Blade kg**	**% Composition**	**Amount for Three Blades kg**
PET Foam	2549	25.46	7648
Adhesive	153	1.53	460
RCF for Shear Webs	336	3.36	1008
Epoxy for Shear Webs	181	1.81	543
RCF for Shells	2806	28.02	8418
Epoxy for Shells	1511	15.09	4533
Virgin Carbon Fibers	1124	11.22	3371
Epoxy for Laminate	482	4.81	1445
Epoxy Resin Parasitic	873	8.72	2620
Total Weight	10015	100	30046

Table S17 Material Input Calculations for RCF Hybrid WT Blade (RCFHB with Max Weight Savings)

Material Input for Three RCFHB	Amount (in kg)	Comments
Amount of RCF for 3 Blades	9425,68	
Amount of Carbon Fibers for 3 Blades	3370,94	
Woven Preform Yield	0,89	89% Yield
Pultrusion Yield	0,89	89% yield
Total RCF Input	10590,65	
Precured Offcuts of RCF	1164,97	
Losses (L1)	58,25	95% Yield
Off cured RCF Cuts for Incineration (PIS1)	1106,72	
Total Carbon Fiber Input	3787,57	
CF Waste from Pultrusion	416,63	
Losses (L2)	20,83	5% losses
Waste from CF Woven Preforms (PIS2)	395,80	
Total RCF Input	10590,65	
Total Carbon Fiber Input	3787,57	
Epoxy for Laminates	1444,68	
Amount of Resin Infused	7695,63	
Total Epoxy Resin Input	9140,31	
PET Foam	7648,34	
Adhesive	460,32	
Total Material Input (TMI)	31627,19	
Total Weaving	3787,57	
Amount for Resin infusion Curing	30045,59	
Total Blades at EOL	30045,59	
Total Blades without PET Foam	22397,25	
Total Blade Scrap at EOL	22397,25	
Material Loss During Transport (L3)	1119,86	
Total Blade Scrap sent for Incineration (PCS1)	21277,38	
PET Foam for Incineration (PCS2)	7648,34	
PIR Reycle %	4,75	((PIS1 + PIS2)/TMI)*100
PCR Recycled %	91,46	((PCS1 + PCS2)/TMI)*100
Total Losses (TL) = L1 + L2 + L3	1198,94	(TL/TMI)*100
Loss%	3,790859511	
Total Material Percentage	100,00	

2.7 Scenario Analysis of WT Blades (For All -Optimum Scenarios)

The description of scenarios considered in the study are shown in Table S18.

Table S18 Description of Scenarios Considered in the Study of Different WT Blades

Scenario	**Description**
GFB-Opt	• Modeling conditions of manufacturing remain same. At the end of life, GF Epoxy composite scrap blade is mechanically recycled.
GFHB-Opt	• The CF Epoxy twin spar caps are pultruded (unlike resin infusion curing in baseline scenario). At the end of life, blades are shredded and mechanically recycled. Credit taken (0.3 kg virgin GF credit taken/ kg scrap recycled). • The HCN and NH_3 emissions from VCF manufacturing sites is controlled by use of RTO with a destruction efficiency of 98%
RCFHB-Opt	• Scenario same as GFHB-Opt
RCFHB-Future	• All WT blade parts including structural spar caps are made of RCF epoxy composites. This scenario assumes that the production of uniformly aligned RCF epoxy composites (with High 55% FVF) using HiPerDiF technology will be commercialized and suitable to be used for fabrication of structural components of WT blades such as spar caps. • Weight of RCFHB-Future is assumed to be same as conventional GFB

3 Energy and carbon payback time calculations

For WTs, EPBT is determined as the ratio of renewable energy generated by a WT in its entire lifetime to the energy invested in the life cycle (i.e., manufacturing, use and end of life) of the WT itself. The lifetime energy generated by a WT is given by equation 3.[33, 34]

$$Energy_{lifetime-WT} = WT_{RP} \times ACF \times 8760\,\frac{hours}{Year} \times Time_{Yrs} \times CF_{Mwh\ to\ kg\ oil\ eq.} \qquad (3)$$

where $Energy_{lifetime=}$ Lifetime energy generated by WT (MWh).

WT_{RP} = Wind turbine rated power = 3 MW

ACF = Average Capacity Factor = 0.411 (European Average ACF[35])

$Time_{Yrs}$ = 20 years; $CF_{Mwh\ to\ kg\ oil\ eq.}$ = Conversion factor of energy in MWh to kg Oil eq. = 85.98 (1MWh = 85.98 kg oil eq.).

Thus, EPBT of WT with different blade options considered in this study are calculated using equation 4.

$$EBPT_{Months=} \left[\left(\frac{FDP\ Impact\ of\ WT_{kg\ Oil\ eq.}}{Energy\ Lifetime_{WT}}\right) \times 240\ Months\right]_{Blade\ Type} \qquad (4)$$

where $FDP_{Impact-WT}$ = Fossil depletion impact (obtained from ReCiPe) in kg oil eq. of WT

The lifetime energy generated by WT for all WT blade variants is calculated according to equation 3

The CBPT of a WT with a specific type of blades is determined according to procedure described in literature[36] using equations 5,6 and 7.

$$(LCE_{WT})_{Blade\ Type} = \left(Energy_{Lifetime}\right)_{WT} \times (GHG\ Intensity_{WT})_{Blade\ Type} \qquad (5)$$

$$(EOCE_{WT})_{Blade\ Type} = \left(\frac{LCE_{WT}}{Avg\ GHG\ \ Intensity_{Region}}\right)_{Blade\ Type} \qquad (6)$$

$$(CPBT_{WT})_{Blade\ Type} = \frac{(EOCE_{WT})_{Blade\ Type} \times WT\ Lifetime}{\left(Energy_{Lifetime}\right)_{WT}} \qquad (7)$$

where $(LCE_{GHGWT})_{Blade\ Type}$ = Life cycle carbon emissions of a WT for specific blade type; $(GHG\ Intensity_{WT})_{Blade\ Type}$ = Carbon Intensity of entire WT (for specific blade type installed as fixed parts (kg CO_2 eq./MWh);

$(EOCE_{WT})_{Blade\ Type}$ = Energy required to be produced by a WT (of specific blade type) to offset the life cycle carbon emissions generated.

$Avg\ GHG\ \ Intensity_{Region}$ = Average GHG intensity of electricity generation of European Region = 281 kg/MWh.[37]

In addition to EPBT and CPBT, the energy and carbon emissions ratios of blades (for specific blade type) to the entire WT infrastructure is determined using equations 8 and 9 respectively.

$$FDP_{Blades\ to\ WT\ Ratio} = \frac{Life\ Cycle\ FDP_{WT\ Blades}}{Life\ Cycle\ FDP_{WT}} \tag{8}$$

$$GHG_{Blades\ to\ WT\ Ratio} = \frac{Life\ CycleGWP_{WT\ Blades}}{Life\ Cycle\ GWP_{WT}} \tag{9}$$

Table S19 EBPT, CBPT, Percentage Contribution of FDP and GHG Emissions of Blades to Wind Turbine of Different Blade Types.

Blade Type Used in Wind Turbine	**EBPT of Wind Turbine**	**CBPT of Wind Turbine**	**FDP of Blades to Turbine %**	**GHG of Blades to Turbine%**
GFB	10.8	14.0	13.12	12.52
GFHB	10.1	13.0	10.45	9.83
RCFHB	9.5	13.0	8.19	9.71
GFB-Opt	10.6	13.5	12.2	11.36
GFHB-Opt	9.9	12.5	9.67	8.54
RCFHB-Opt	9.4	12.4	7.53	8.15
All-RCF-Future	8.6	12.2	4.02	7.57

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