Wind Turbine Blades Using Recycled Carbon Fibers: An Environmental Assessment

Venkata K.K. Upadhyayula[1,2], Venkataramana Gadhamshetty[3,4], Dimitris Athanassiadis[2],
Mats Tysklind[1], Fanran Meng[5*], Qing Pan[6], Jonathan M. Cullen[5], and Dalia M.M. Yacout[7]

[1] Department of Chemistry, Umeå University, SE 90187, Umeå, Sweden

[2] Department of Forest Biomaterials and Technology, Swedish University of Agricultural Sciences, SE 90183, Umeå, Sweden

[3] Civil and Environmental Engineering, South Dakota School of Mines and Technology, 501 E Saint Joseph Blvd, Rapid City, SD 57701, United States

[4] 2-Dimensional Materials for Biofilm Engineering Science and Technology (2D BEST) Center, South Dakota School of Mines and Technology, 501 E. St. Joseph Street, Rapid City, SD 57701, United States

[5] Department of Engineering, University of Cambridge, Trumpington Street, Cambridge CB2 1PZ, United Kingdom

[6] LMAT ltd, Bristol, BS34 8RB, United Kingdom

[7] Department of Energy and Technology, Swedish University of Agricultural Sciences, E-750 07, Uppsala Sweden

***Corresponding Author**
Email: fm392@cam.ac.uk (F. Meng)

Abstract

Polymers reinforced with virgin carbon fiber (VCF) are being used to make spar caps of wind turbine (WT) blades and polymers with glass fiber (GF) to make skins of the blade components. Here, we assess the life cycle environmental performance of the hybrid blades with spar caps based on VCF and the shells and shear webs on RCF composites (RCF-hybrid). The production of the WT blades and associated reinforced polymers are assumed to occur in Sweden, their uses and end-of-life management in the European region. The functional unit is equivalent to three blades in an offshore WT with the market incumbent blades solely based on GF composite or the hybrid option. The RCF-hybrid blades offer 12-89% better environmental performance in nine out of ten impact categories and 6-26% better in six out of ten impact categories. The RCF-hybrid blades exhibit optimum environmental performance when the VCF manufacturing facilities are equipped with pollution abatement systems including regenerative thermal oxidizers to reduce ammonia and HCN emissions; spar caps are made using VCF-epoxy composites through pultrusion and resin infusion molding and the blade scrap is mechanically recycled at the end of life. The energy and carbon payback times for the RCF-hybrid blades were found to be 5%-13% lower than the market incumbents.

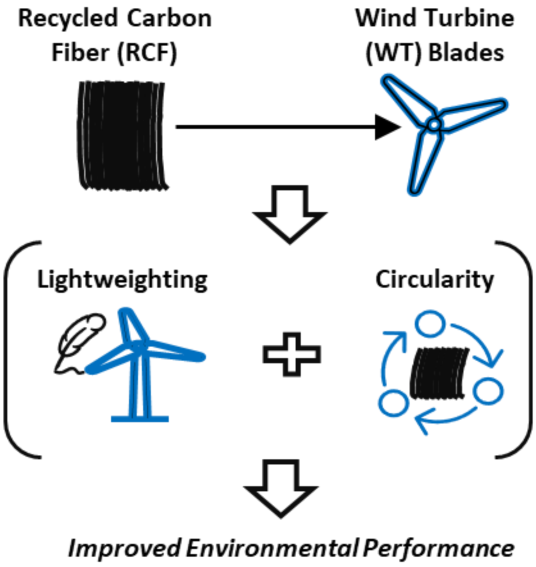
Key Words:

Recycled Carbon Fibers
Wind Turbine Blade Components
Life Cycle Assessment
Energy and Carbon Payback Time
High Performance Discontinuous Fiber Technology

Synopsis

Using recycled carbon fibers for wind turbine blade parts can be mechanically feasible and offer significant environmental benefits over glass fibers.

TOC graphic



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Nomenclature

ACF	Average Capacity Factor
AP	Acidification Potential
CFRP	Carbon Fiber Reinforced Polymer Composites
CPBT	Carbon Payback Time (Months)
EPBT	Energy Payback Time (Months)
FDP	Fossil Depletion Potential
FEP	Freshwater Eutrophication Potential
FEXP	Freshwater Ecotoxicity Potential
FU	Functional Unit
FVF	Fiber Volume Fraction
GF	Glass Fibers
GFB	All GF Blade (only GF epoxy composites used in blade manufacturing)
GFB-Opt All GF	Blade at Optimum Conditions (described in scenario analysis)
GFHB	GF Hybrid Blade (VCF and GF epoxy composites used in blade manufacturing)
GFHB-Opt	GF Hybrid Blade at Optimum Conditions (described in scenario analysis)
GFRP	Glass Fiber Reinforced Polymer Composites
GWP	Global Warming Potential
HiPerDif	High Performance Discontinuous Fiber Method
HTP	Human Toxicity Potential
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
MEP	Marine Eutrophication Potential

MEXP	Marine Ecotoxicity Potential
MW	Megawatts
MWh	Megawatt hour
OEMs	Original Equipment Manufacturers
PAN	Polyacrylonitrile
PET	Polyethylene Terephthalate
PMFP	Particulate Matter Formation Potential
POFP	Photochemical Oxidant Formation Potential
RCF	Recycled Carbon Fibers
RCFHB	RCF Hybrid Blade (VCF and RCF Epoxy composites used in blade manufacturing)
RCFHB-Opt	RCF Hybrid Blade at Optimum Conditions (described in scenario analysis)
RCFRP	Recycled Carbon Fiber Reinforced Polymer Composites
RIM	Resin Infusion Molding
SNL	Sandia National Laboratories
VCF	Virgin Carbon Fibers
WT	Wind Turbine

1 INTRODUCTION

Light-weighting is embraced as an effective strategy to design environmentally conscious products, such as light-weighted passenger cars with enhanced fuel efficiency.[1] Light-weighting can increase payload transfer capacities and reduce carbon emissions and other air pollutants.[2, 3] In the wind energy industry, material light-weighting opens up the possibility of manufacturing large wind turbine (WT) blades with higher power generation capacities.[4] This ability to design lighter products and differentiate them based on improved sustainability performance has led to the increase in demand for lighter and mechanically stronger materials like carbon fibers (CF). The global demand for CF increased from 33,000 metric tons in 2010 to 100,000 metric tons in 2020,[5] and by 2025, is projected to reach 200,000 metric tons.[6] The wind energy industry is expected to emerge as the largest consumer of CF with its market share surpassing that of the aviation sector by 2022.[5]

The brighter market prospects of CF in the wind energy industry is attributed to a growing interest among original equipment manufacturers (OEM) in the preferential manufacture of WTs designed for higher energy generation capacities.[7] This triggers the need for the fabrication of longer WT blades. CF demand has also increased because the mechanical performance (especially properties related to the number of fatigue cycles to failure) of longer WT blades can only be met when structural components (i.e. spar caps) are fabricated using CF-reinforced polymer (CFRP).[7, 8] However, the incorporation of CFRP composites into WT blades poses sustainability challenges to the wind energy industry in the long term because their predominantly cross-linked structure renders them difficult to recycle. Disposing CFRP WT blade scrap via conventional routes (landfilling or incineration is neither environmentally sustainable alternative nor beneficial from a circular economy perspective in the long run.[9-11] Mechanical recycling is an option but the recycled CF (RCF) can only be used in products without stringent structural performance requirements.[12] Advanced chemical and thermal recycling technologies have been developed in recent years to treat CFRP waste and recover

CF without significantly compromising mechanical properties. It is preferential to reuse recovered RCF in new light-weighting applications, such as manufacturing of WT blade components, where the fundamental principle of circular economy (large volumes of recycled material to be used for longer times) can be justified.

The mechanical properties of chemically or thermally recovered carbon fiber reinforced polymer (RCFRP) are comparable with (or even exceed) virgin GFRP composites with fiber volume fractions (FVF) of as low as 30%.[13, 14] This explains the motivation for using RCFRPs in place of virgin GFRPs to manufacture parts of WT blades. Efforts towards the utilization of RCFRP in WT blades have already gained some commercial traction. In 2019, the Boeing company collaborated with ELG Carbon Fibre (UK based CF recycler) to explore the use of CFRP waste from retired airplane fuselages for the manufacture of WT blades.[15] Thus, the future large-scale penetration of RCFRPs in the wind energy industry is highly anticipated. A holistic understanding of the environmental sustainability aspects of reusing RCFRPs in WT blades will therefore be critical to the relevant stakeholders in the wind energy and aviation industries.

Life cycle assessment (LCA) studies of WT blades [16, 17] or WT as a whole product system have been reported in literature.[18, 19] The findings of these studies highlight two aspects that relate to the environmental performance of WT blades. First, using virgin CFRP for the fabrication of WT blade parts (spar caps) increases the life cycle carbon footprint of WT blades by 61% although they are lighter than the equivalent parts made from GFRPs.[16, 17] Second, mechanical recycling is the environmentally preferred short-term end of life management route for WT blades.[17] In this study, the technical and environmental feasibility of RCFRP for manufacturing WT blade components is systematically evaluated. The work is performed with a two-fold objective. First, cradle to grave LCA models are developed to evaluate the environmental performance of WT blades with parts manufactured using RCFRP composites.

Second (based on LCA results), the energy and carbon payback times associated with a lifetime operation of WT equipped with RCFRP based WT blade parts are calculated. To the best of our knowledge, this is the first detailed LCA study aimed to assess the environmental performance of WT blades with parts made from RCFRPs. It will enable manufacturers and policy makers to understand fully the environmental impacts of alternative market opportunities for RCF and support the development of relevant policies to encourage the sustainable use of CFRP materials over the multiple product life cycles.

2 MECHANICAL FEASIBILITY OF CONCEPTUAL RCF EPOXY COMPOSITES FOR WT BLADES APPLICATIONS

Prior to evaluating the environmental performance, the mechanical feasibility of RCFRP for use in WT blades must be established. A WT blade consists of four components: twin spar caps, shear webs, and pressure and suction side shells. Both GFRP and CFRP material can be used in the fabrication of spar caps. The market share of CFRP in the composition of smallest onshore WT blades is only 9% and increases to 55% in larger blades, when blade lengths exceed 70 m.[7] The shear webs are sandwich panels of a foam core and GFRP skins. Currently, the pressure and suction side shells (the outer body) are predominantly made from GFRP composites.

Several studies have reported that the mechanical properties of 1st pass RCF, i.e., CF recovered from CFRP waste through chemical or thermal recycling techniques, are almost comparable to virgin CF.[14, 20, 21] The tensile modulus and tensile strength of 1st pass recycled CF are 0.4% to 13% and 0.4% to 20% lower than virgin CF, respectively.[14] The 1st pass RCF can potentially replace virgin GF in the fabrication of pressure and suction side shells and shear web skins. However, the handling of RCF and its processing to CFRP are difficult due to its discontinuous 3D random filamentized form and low bulk density. Currently, the fiber volume fraction (FVF) of RCFRP can reach up to 40% for randomly aligned RCF. However, fiber alignment processes are required to achieve higher fiber volume fractions (i.e., higher mechanical properties) up to 55%. [22-24] Tensile properties (i.e., tensile modulus, strength, and impact strength) of RCFRP are comparable to those of similar materials produced with VCF and other general engineering materials such as glass fiber reinforced polymer[25-28].

2.1 Elastic Modulus of RCF Epoxy Composites

We assume Tenax®-A HT C124 CF is recycled with no reduction of modulus after recycling[29]. The theoretical elastic modulus of aligned discontinuous RCFRP can be estimated using Halpin-Tsai equations as shown in equation 1. [30]

$$\frac{M}{M_m} = \frac{1 + \xi \cdot \eta \cdot V_f}{1 - \eta \cdot V_f} \tag{1}$$

where, M represent the equivalent mechanical properties. E_1 is the longitudinal modulus (=225 GPa), $E_2$is the transverse modulus (=15 GPa), G_{12} is the in-plane shear modulus (=15 GPa), G_{23} is the out-of-plane shear modulus (=7 GPa), ν_{12} is the in-plane poison ratio (=0.27). The variable η can be expressed:

$$\eta = \frac{\frac{M_f}{M_m} - 1}{\frac{M_f}{M_m} + \xi} \tag{2}$$

where ξ is a measure of reinforcement geometry depending on the loading conditions.

$\xi_{E_1} = \xi_{\nu_{12}} = \frac{2l}{d} = 2r,\ r$ is aspect ratio of the fibre.

$$\begin{gathered} \xi_{E_2} = 2 \\ \xi_{G_{12}} = 1 \\ \xi_{G_{23}} = \frac{K_m/G_m}{(K_m/G_m+2)}, \end{gathered} \tag{3}$$

where K_m and G_m are the bulk modulus and shear modulus of the matrix (K_m=3.33 GPa, G_m=1.54 GPa).

With the equivalent elastic modulus of aligned discontinuous RCFRP, classic laminate theory (CLT) can be used to predict the equivalent properties of laminate with different layup angles (i.e., $[\pm 45]_2[0]_2$). They are the same layup angles with SNL Triax GF epoxy composites.[31]

According to CLT, the effective in-plane elastic properties can be worked out from the generalised compliance matrix as below. We have developed a micromechanics model using MATLAB R2021a. More details can be found in section 1 of the Supporting Information.

$$E_x = \frac{1}{a_{11}}$$
$$E_y = \frac{1}{a_{22}} \tag{4}$$
$$G_{xy} = \frac{1}{a_{66}}$$

where, E_x, E_y and G_{xy} are the effective in-plane elastic properties of laminate (E_x=31.48GPa, E_y=19.22GPa, G_{xy}=18.12GPa), a_{11}, a_{22} and a_{66} are elements of generalized compliance matrix (a_{11}= 1.0588e-05, a_{22}= 1.7344e-05, a_{66}= 1.8394e-05).

2.2 Material substitution under stiffness-limited design.

Traditionally, the blade would be modelled as a simple cantilever beam with equivalent point or uniformly distributed loads used to calculate the bending stiffness.[32, 33] This offers intial insight into the global structural loading of a wind turbine blade. A more detailed computational analysis (using finite element analysis) and experimental work would be completed including local analysis of individual features, bonds and material laminates in the future work. The flexural rigidity D (or $(EI)_{eq}$) of the sandwich panel is given by:

$$(EI)_{eq} = \frac{E_f b t^3}{12} \times 2 + \frac{E_c b c^3}{12} + E_f b t \left(\frac{c+t}{2}\right)^2 \times 2 = \frac{E_f b t^3}{6} + \frac{E_c b c^3}{12} + \frac{E_f b t}{2}(c+t)^2 \tag{5}$$

where the first and second terms are the bending stiffnesses of the faces about their own centroidal axis and that of the core about its centroidal axis. The third term is the bending stiffness of the faces about the beam's centroidal axis and is usually much larger than the sum of the other two terms. E_f is the elastic modulus of sandwich skin material (=27.7 GPa for the reference material), E_c is the elastic modulus of sandwich core material (=0.256 GPa for PET foam), and *b*, *c*, *t* are the width (constant for all materials), thickness of core material (=60 mm for all materials) and thickness of skin material (=3 mm for the reference material), respectively.

The weight of the sandwich beam is given by

$$W = 2\rho_f blt + \rho_c blc \tag{6}$$

Where: ρ_f= density of sandwich skin materials (either GF epoxy composite or RCF epoxy composite); ρ_c= density of foam core structure (=200 kg/m^3); *l* is the length of sandwich beam (=50 m); $\rho_{RCF\ Epoxy} =$ density of RCF reinforced epoxy composite (at 55% FVF) = 1485kg/m^3 (with density of CF = 1800 kg/m^3 and density of epoxy resin = 1200 kg/m^3); $\rho_{GF\ Epoxy} =$ density of GF (FVF of 50%) epoxy composite is 1820 kg/m^3 (density of GF = 2560 kg/m^3); $E_{GF\ Epoxy}$ = longitudinal modulus of GF epoxy composite (for given FVF) (= 27.7 GPa [31]); $E_{RCF\ Epoxy}$ = longitudinal modulus of RCF epoxy composite (= 31.5 GPa for sandwich panel made from aligned RCF laminate [23, 24, 34]).

By applying a variable skin material thickness principle while keeping the thickness of the core material the same, the amount of RCF epoxy composites needed to replace GF epoxy in a WT blade can be estimated as in Table S1.

3 LIFE CYCLE ASSESSMENT METHODOLOGY

3.1 Goal and Scope

An LCA study is performed to evaluate the environmental performance of RCF-Hybrid Blades (RCFHB) equipped in a wind turbine. VCF reinforced epoxy is used in the manufacture of structural components, i.e., the twin spar caps and RCF epoxy composites for nonstructural parts (sandwich panel skins of outer body and shear webs). The LCA results of RCFHB are compared with two incumbent WT blade configurations: (a) conventional GF-Blade (GFB) manufactured solely using GF epoxy composites; and (b) state-of-the-art GF-Hybrid Blade (GFHB), with a structure similar to RCFHB except that the nonstructural components are produced from GF epoxy composites.

3.2 Functional Unit

The functional unit (FU) chosen for this LCA is three fiber- composite blades installed on a WT with a power rating of 3MW and an operational lifespan of 20 years. Each blade has a length of 50 m and diameter of 3.4 m at root area,[35] i.e., on the leading-edge side at the insertion of root studs (typical values of a 3 MW power rated WT blade).

3.3 System Boundary

The system boundary defining the major life cycle stages of RCFHB is shown in Figure 1. Europe is specified as a geographical boundary condition for this study with a key assumption that RCFHBs are manufactured in Sweden, while their use and end of life occurs in any European region.

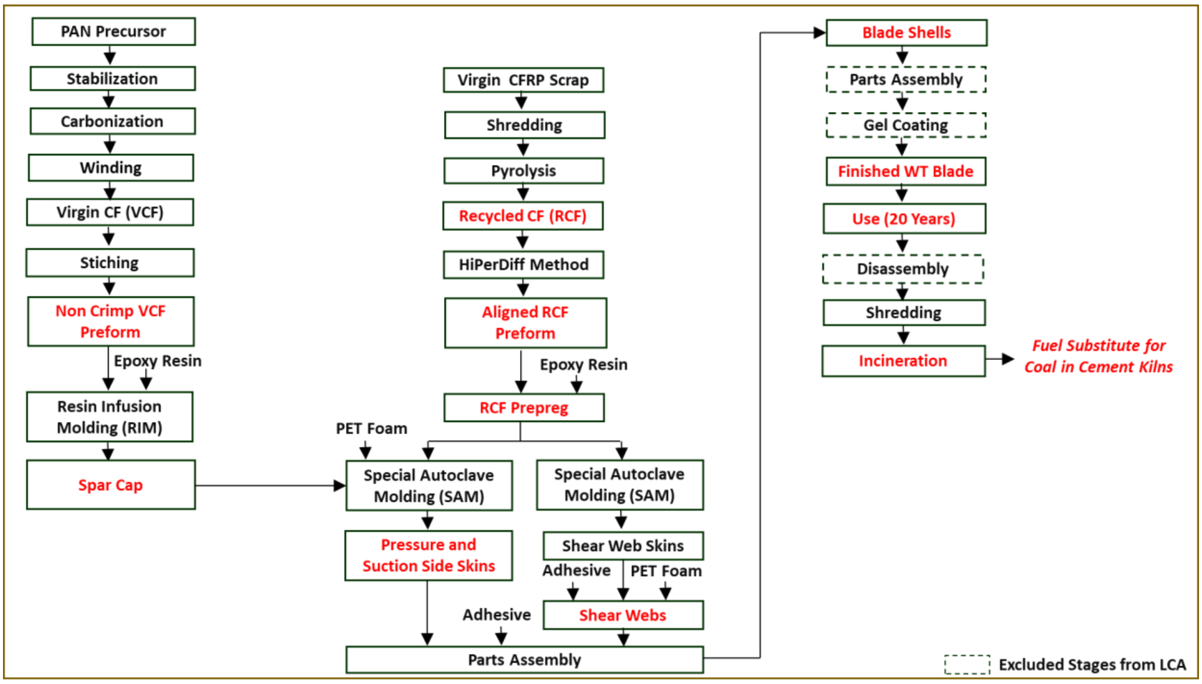

Figure 1 Life Cycle of RCF Hybrid WT Blade (Major stages shown in red)

A detailed description of the life cycle stages associated with RCFHB is given in Section 2 of the Supporting Information. Briefly, the manufacturing process includes production of individual parts (spar caps, outer body shells and shear webs) and their assembly into a finished WT blade. PAN based VCF and epoxy resin are raw materials used in the production of twin spar caps. The fabrication of caps is done by an established resin transfer molding (RIM) technique. The woven VCF is first stitched into non-crimp preforms before its use in RIM process. The manufacturing of caps is carried out by infusing epoxy resin onto non-crimp VCF preforms (layered uniformly on mold surface) and subsequently initiating a curing cycle at atmospheric pressure.

RCF is used for production of outer body shells and shear web skins The study treats RCF as a separate material value chain, meaning, virgin CFRP composite scrap (i.e., not subjected to any prior recycling) sourced from selective waste streams, (e.g., structural parts such as fuselage of retired aircrafts) is considered as a raw material. Thus, the environmental burdens of RCF manufacturing are allocated to shredding of CFRP scrap and pyrolysis process. The uniformly shredded CFRP scrap undergoes pyrolysis and RCF recovered. The RCF is processed into RCF preforms via HiperDiff method.

The outer body (pressure and suction side shells) shells and shear web skins are fabricated separately using a special autoclave molding (SAM) method. For the outer body shells, PET foam boards sandwiched between layers of RCF prepregs. The VCF-epoxy twin spar caps are then bonded to the pressure and suction side shells using a structural adhesive. For the manufacturing of shear webs, PET foam boards are sandwiched between RCF epoxy composite skins obtained from special autoclave molding of RCF prepregs. The shear webs are then bonded to outer body shells, and a gel coating is applied on the outer surface to finally deliver a finished RCFHB. Three such blades of the same size are manufactured and assembled into a WT installed in an offshore wind farm to generate electricity for 20 years. After its useful life, the blades are disassembled from the WT, shredded into pieces and the scrap subjected to incineration with energy recovery.

The system boundaries associated with the life cycles of market incumbent GFB and GFHB are shown in the SI-Section 2.

3.4 Life Cycle Inventory (LCI)

The material composition of RCFHB and incumbent WT blades options (GFB and GFHB) modeled in the study are given in Table S2. The important assumptions made, and key data sources used, for the construction of foreground LCI dataset of RCFHB, are shown in Table S3.

The LCI model is developed based on the establishment of a production facility in Sweden to take advantage of the country's low carbon electricity for manufacturing. This will have a positive impact on the overall environmental performance of RCFHBs. In support of this argument, RCFHBs are considered to be produced in Sweden. To reflect the manufacturing conditions of Sweden in our inventory models, ecoinvent LCI data corresponding to Sweden's electricity grid mix (SE/Medium voltage[36]) and thermal energy from wood chips (heat from softwood chips from forest at furnace[36]) are used to build all foreground LCI datasets. This includes energy consumption for the production of VCF (carbonization and stabilization of PAN precursor), RCF (pyrolysis), and the conversion stages of RCFHB (VCF preforms, RCF epoxy prepregs, RIM).

For incumbent configurations, the European average electricity mix, i.e., ecoinvent/RER is used for all manufacturing operations involving fabrication of GF parts of GFB and GFHB. However, VCF epoxy spar caps of GFHB are assumed to be manufactured in Sweden, therefore, LCI modeling conditions similar to RCFHB are applied. All LCIs are built within SimaPro LCA software package (version 9.00).[37]

3.5 Impact Assessment Methodology

ReCiPe world (H),[38] a midpoint impact assessment methodology, is used to quantify the life cycle environmental performance of ten selected midpoint impact categories. The impact categories reported in this study include: (a) Global Warming Potential (GWP) as kg CO_2 eq.; (b) Acidification Potential (AP) as kg SO_2 eq.; (c) Freshwater Eutrophication Potential (FEP) as kg P eq.; (d) Marine Eutrophication Potential (MEP) as kg N eq.; (e) Human Toxicity

Potential (HTP) as kg 1-4 DB eq.; (f) Photochemical Oxidant Formation Potential (POFP) as kg NMVOC.; (g) Particulate Matter Formation Potential (PMFP) as kg PM_{10} eq.; (h) Freshwater Ecotoxicity Potential (FEXP) as kg 1-4 DB eq.; (i) Marine Ecotoxicity Potential (MEXP) as kgP 1,4 DBeq.; (j) Fossil Depletion Potential (FDP) as kg oil eq.

3.6 Uncertainty Analysis

An uncertainty analysis is performed to understand the extent of the change in environmental impacts of three WT blade types studied in baseline scenario. The details of key modeling parameters of GFB, GFHB, and RCFHB scenarios are summarized in Table S14. Monte Carlo simulation was performed with 5000 steps and a 95% level of confidence.

3.7 Scenario Analysis

A scenario analysis is performed by altering certain assumptions of baseline LCI models to optimize the environmental performance of three blade types. Four scenarios were considered: under optimum conditions (GFB-Opt, GFHB-Opt, RCFHB-Opt) and all RCF scenario (RCFHB-Future). The details are summarized in Table S16.

4 ENERGY PAYBACK TIME (EPBT) AND CARBON PAYBACK TIME (CBPT) OF WIND TURBINES WITH DIFFERENT BLADE VARIANTS

Blades constitute the moving parts of WT and make an appreciable contribution towards overall the environmental performance of a WT. Therefore, the installation of blades made from different materials (i.e., GFB/GFHB/RCFHB) as moving parts in a WT can profoundly influence its life cycle environmental performance. The EPBT and CBPT for a WT (3 MW capacity) comprised of blades with different material composition will be of particular interest to the OEMs of the wind energy industry. Detailed calculation can be found in Section 3 in the Supporting Information.

5 RESULTS

5.1 Baseline Scenario

The LCA results comparing the environmental performance of RCFHB with GFB and GFHB are shown in Figure 2.

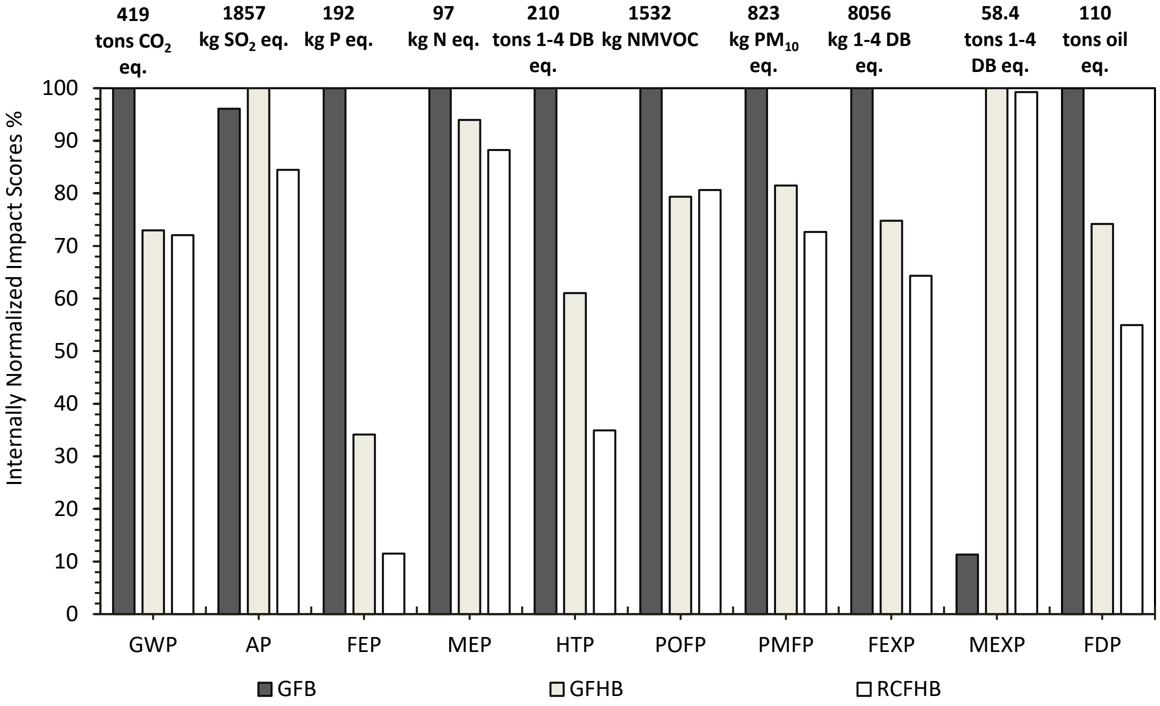

Figure 2. Life Cycle Environmental Performance Comparison of GFB, GFHB and RCFHB (Maximum scores in each impact category shown in top). GFB=GF Blade, GFHB =GF-Hybrid Blade, RCFHB=RCF-Hybrid Blades.

The conceptual RCFHB proposed in this study exhibits a superior overall environmental performance compared to incumbent GFB in nine out of ten impact categories, except MEXP. RCFHB is 12% to 89% less damaging to the environment than its counterpart, GFB, in nine impact categories. The environmental impacts of RCFHB are significantly lower (by 65% to 89%) in HTP and FEP; moderately lower (by 27% to 45%) in GWP, PMFP, FEXP and FDP; and marginally lower (by 12% to 19%) than GFB in AP, MEP and POFP impact categories respectively. The poor overall environmental performance of GFB is largely attributed to a combination of three factors: (a) material consumption (GF and epoxy resin); (b) energy demand of blade manufacturing; (c) landfilling residual ashes after incineration of GF composite scrap at the end of life.

The higher FEP impact of GFB results from WT blade manufacturing and the end-of-life stages. Electricity consumed during production of GF preforms is mainly responsible for the FEP impact during the production stage. The components of incumbent GFB are assumed to be manufactured anywhere in Europe and therefore the electrical energy required for weaving GF preforms is drawn from the EU-27 average grid mix (RER). The RER fuel mix contains 20% of its electricity generated from coal which mainly drives the EP impact.[39] The end of life of GFB - precisely the disposal of incineration ash residues - also partly contributes to FEP impact. The residual ash obtained from the incineration of GF epoxy composite is 70% (0.7 kg of ash per kg composite incinerated) and this is much higher than ash (8%) remaining after incinerating CF composite [40]. Depositing higher quantities of residual ash is likely to increase the probability of leachate formation in landfills, and its subsequent leakage into natural water systems increases eutrophication.[41, 42] This is the main reason why the FEP impact of RCFHB is 89% lower than GFB.

The end-of-life stage accounts for 20% to 50% of HTP, FEXP and MEXP impacts due to landfilling of ashes. The disposal of incineration ash residues into landfills is known to have negative human health and ecotoxicological implications.[40, 43] In addition, the higher HTP impact (45%) of GFB is also driven by the consumption of glass fibers (15,837 kg per FU (3 blades) and release of heavy metal pollutants (arsenic and cadmium) from their production sites, which induces toxicity effects in humans.[44] The POFP, PMFP and FDP impacts of GFB are 19% to 45% higher than RCFHB. These impacts are mainly associated with epoxy resin. The consumption of epoxy in manufacturing of GFB (due to heavy weight) is 1.5 times higher than RCFHB. Bisphenol A (a precursor of epoxy resin) and the epoxy resin production process, where other volatile organic compounds emissions are released, are responsible for PMFP and

POFP impacts respectively.[45, 46] On the other hand, the higher FDP impact of GFB is directly related to the requirement of resin in higher quantities compared to RCFHB.

A comparison of life cycle environmental performance is also made between RCFHB and GFHB. RCFHB shows a 20% to 26% lower environmental burden than state-of-the-art GFHB in FDP, FEP and HTP, and a marginal reduction (6% to 16%) in MEP, PMFP, FEXP and AP impact categories. The GWP, POFP and MEXP impacts remain the same for both blade types. As explained above, airborne metal emissions from GF production facilities and large quantities of ash generation (0.76 kg per kg of GF epoxy) upon incineration of GF epoxy composite scrap drive FEP and HTP impacts. Replacing GF with RCF in body shell and shear web skins of WT blades can achieve a significant reduction of these impacts. In the case of FDP impact, RCFHB performs 19% better than GFHB. Although epoxy resin consumption in RCFHB manufacturing is slightly higher than GFHB (10,392 versus 9,818 kg per FU) and the amount of VCF used is the same in both blade types, the use of GF in the latter contributes to a higher FDP impact. The amount of GF used in GFHB is 14,111 kg per FU and, owing to 9% weight savings, the mass of RCF in RCFHB is 11,750 kg per FU. The FDP is 0.774 kg oil eq. per kg GF whereas it is -0.392 kg oil eq. per kg RCF. The net negative value is because of impact credit given for pyrolysis byproducts which explains why GFHB causes 20% higher FDP than RCFHB.

Figure 3 shows the GWP of RCFHB and GFHB is 27-28% lower than GFB. The hybrid WT blades (i.e., GFHB and RCFHB) which incorporate energy intensive VCF in their spar caps are anticipated to have higher GWP impact than GFB if the caps are manufactured elsewhere. The GWP of both hybrid WT blades, despite using VCF epoxy composite spar caps, is 27-28% less than GFB. This is because the study assumes that spar caps are made in Sweden and their production can benefit from the less carbon-intensive (39 g CO_2 per kWh[47]) energy grid. Finally, the MEXP of GFHB and RCFHB is much higher (89%) than GFB, which is exclusively driven by the VCF production stages associated with the life cycle of both hybrid WT blades.

VCF manufacturing sites (using PAN precursor) release hydrogen cyanide (HCN) gas as an atmospheric pollutant which is aerosolized and eventually transported into marine water bodies which serve as a sink for these compounds.[48] These cyanide compounds are proven to be toxic to marine dwelling species, especially to molluscs, annelids, and crustaceans.[49] To avoid environmental impacts arising from HCN release, VCF manufacturing facilities increasingly rely on air pollution control equipment such as regenerative thermal oxidizers with high emission control efficiencies (97%) and operate with negligible energy requirements.[50]

5.2 Contribution Analysis of RCF-hybrid WT Blade

The contribution of major life cycle stages of RCFHB towards overall impact is shown in Figure 3.

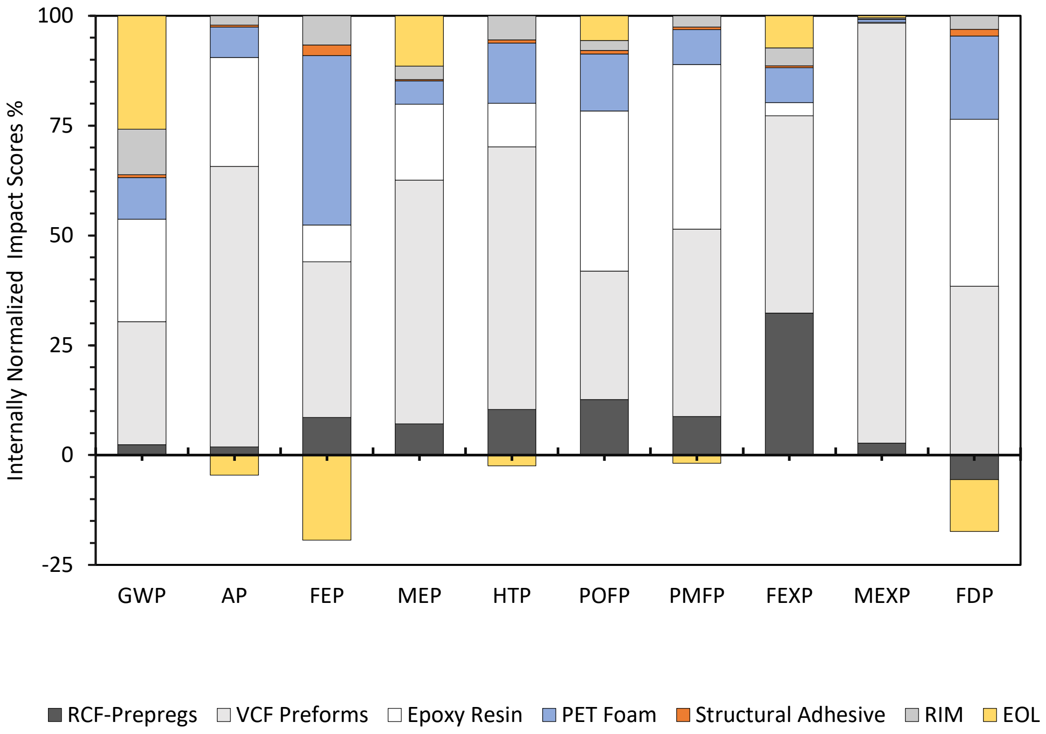

Figure 3. Contribution Analysis of Different Life Cycle Stages of RCF-Hybrid Blade

The production of VCF preforms for twin spar caps (VCF production plus their stitching into non crimp preforms) dominates the life cycle environmental performance of RCFHB. The VCF preforms, alone, contribute 28% to 96% of the total impact in all ten categories quantified, due to highly energy intensive VCF manufactured from PAN precursor for the fabrication of spar caps. RCF prepregs—the production of RCF via pyrolysis, processing staple RCF into preforms using HiPerDiF method and Prepreg preparation (resin not included)—is responsible for less than 13% (between 2% and 13%) of the total environmental impact of RCFHB in eight out of ten categories, except FEXP and FDP. The contribution is minimal due to credits associated with pyrolysis byproducts (methanol and ethyl acetate). For the same reason, the FDP shows a negative score (-5.6%), implying that the RCF prepreg reduces the overall environmental impact of RCFHB in this category. The RCF prepreg production step contributes to 32% of the total FEXP impact due to the incineration of residual char, a waste byproduct from pyrolysis chamber, during the production of RCF. Interestingly, the amount of RCF prepregs used in making hybrid RCFHB is threefold higher than VCF preforms. However, the share of the environmental burden imposed by RCF prepregs is smaller compared to VCF preforms. This suggests that the environmental impacts of RCFHB blades can be significantly reduced if, in future, the technology allows the production of RCFRP that have sufficient structural strength to replace VCF in the fabrication of spar caps.

Next to VCF preforms, epoxy resin is the second highest contributor with its consumption for RCFHB manufacturing responsible for 24% to 38% of the total environmental impact in GWP, AP, POFP, PMFP and FDP categories. The petroleum-derived epoxy resin (especially from bisphenol-A) manufacturing sites are understood to cause these impacts.[51] The RIM process only accounts for 0.3% to 10.3% of total impact in all ten categories. The environmental impacts associated with RIM are mainly electricity-related and because of its coal free nature (from SE grid), the process makes little contribution.

Finally, adapting incineration as an end-of-life management strategy for the disposal of RCFHB proves less environmentally beneficial because the impact credit is only 19% and 12% in FEP and FDP impact categories, respectively. Moreover, this comes with a tradeoff as the incineration of RCFHB scrap contributes to 26% of the GWP impact, with EOL incineration occurs anywhere in Europe. Other EOL management techniques, e.g. mechanical recycling, can reduce the environmental impacts caused by the incineration of RCF-hybrid blades.[17]

5.3 Uncertainty Analysis

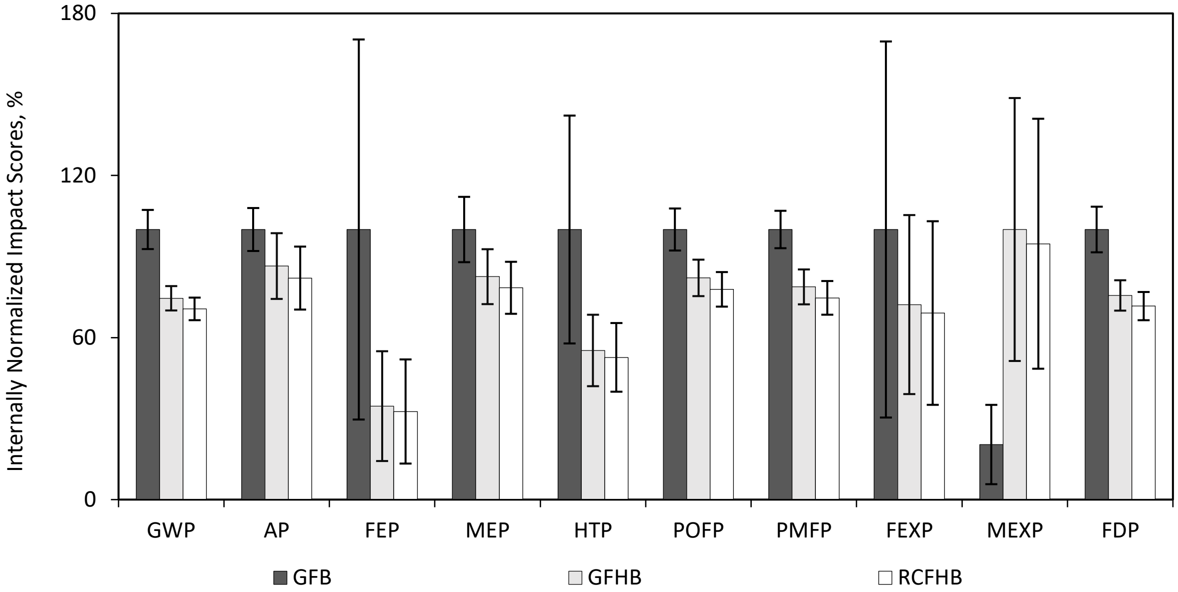

Figure 4. Uncertainty Analysis Results of GFB, GFHB and RCFHB. GFB= GF Blade, GFHB= GF-Hybrid Blade, RCFHB=RCF-Hybrid Blades (uncertainty analysis performed with 95% confidence level using Monte Carlo Simulation (5000 steps) in SimaPro).

Uncertainty in model parameters (see Table S14) does not alter the finding that RCFHB achieve the lower environmental performance than GFB in GWP, POFP, PMFP, and FDP impact categories. Similarly, the MEXP impact of GFB will be lower than RCFHB. The likelihood of RCFHB exhibiting lower AP, HTP and MEP impacts than GFB is high, although a minor overlap is seen between the scores in their respective impact categories. However, introducing data uncertainty affects FEP and FEXP impacts as a large variation is observed in the scores of both WT blade types. In particular, FEP and FEXP of GFB vary significantly because these impacts are sensitive to the energy input of weaving (2.1- 5.6 kWh/kg) and RIM (0.7056- 2.83 kWh/kg) processes. A similar variation pattern is also seen in the scores of GFHB and RCFHB in all impact categories (Figure 4). The impacts of both GFB and RCFHB are profoundly affected by data uncertainties associated with VCF production. Also, the data changes (e.g., weight savings realized from replacing GF epoxy with RCF epoxy composites in outer body shells and shear web skins) pertaining to other life cycle stages of RCFHB exert only a minor influence on its overall environmental performance. The outcome of this uncertainty analysis implies two things. First, hybrid WT blades, if manufactured in Sweden, will always have better environmental performance than GF-only WT blades produced elsewhere in Europe. Second, hybrid WT blades manufactured in Sweden using either GF or RCF epoxy composites in conjunction with VCF epoxy (for spar caps) will have similar environmental impacts. However, from a circular economy perspective, using RCF epoxy composites for manufacturing the body shell and shear web skins of hybrid WT blades is prioritized.

5.4 Scenario Analysis

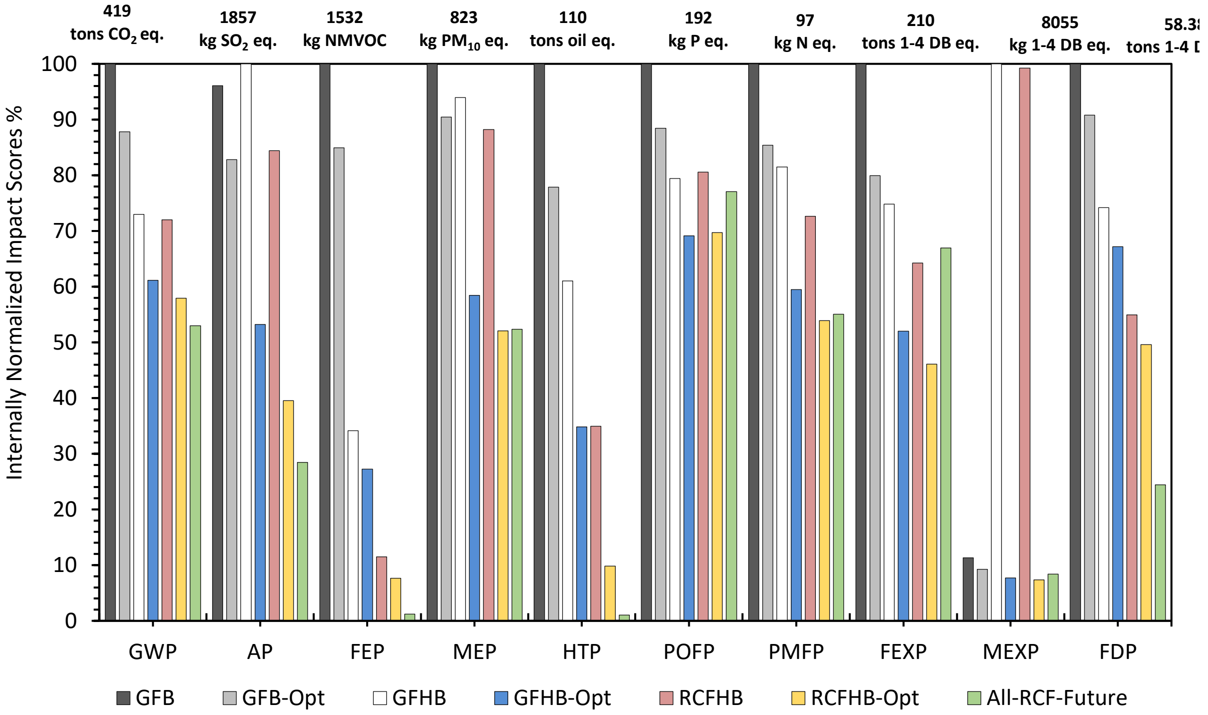

Figure 5. Life Cycle Environmental Performance of WT blade variants modeled for optimum conditions (GFB-Opt, GFHB-Opt, RCFHB-Opt) and All-RCF-Future (Maximum impact scores in each category shown on top)

The results shown in Figures 5 indicate that the environmental performance of all three optimum WT blade variants exceeds their respective baseline counterparts. GFB-Opt performs better by 9% to 22% in nine impact categories in comparison with baseline GFB because of two factors. Firstly, the impacts (mainly FEP, HTP and FEXP) of the disposal of residual ashes obtained from incinerating GF-epoxy composite portions of blade scrap can be avoided if it undergoes mechanical recycling. Secondly, virgin GF credits (0.32 kg recovered per kg scrap) associated with mechanical recycling will also contribute to the lowering of environmental impacts. The GFHB-Opt and RCFHB-Opt also perform environmentally better by 7% to 92% and 4% to 92% respectively, compared to their baseline variants. These results conclusively indicate that the environmental performance of hybrid WT blade types improves when the: (a) emissions, especially NH_3 and HCN, released from VCF manufacturing sites are controlled using an abatement technology such as RTO; (b) VCF epoxy spar caps are pultruded and then resin infusion molded; and (c) composite scrap at the end of life is subjected to mechanical recycling rather than incineration. With the use of pollution abatement technology such as RTO, MEXP and AP, impacts of hybrid WT blade variants (based on difference in the impact scores of GFHB-Opt versus GFHB; RCFHB-Opt versus RCFHB) can be reduced by 92% and 45% to 47% respectively. These two impacts are predominantly caused by NH_3 and HCN emissions. The toxicity and eutrophication impacts (FEP, MEP, HTP, and FEXP) of both optimum WT blade variants is lower than their baseline counterparts because of multiple factors. The need for landfilling of post incineration ash is avoided with optimum hybrid WT blade types as the scrap undergoes mechanical recycling. The VCFRP spar caps are pultruded in optimum hybrid variants and pultrusion has a higher processing yield (97%[52]) compared with weaving VCF preforms (with a lower yield of 89%) and subsequent molding in conjunction with epoxy resin, as is the case with the baseline types. Further, pultrusion of spar caps also means a lower overall material input to RIM process and a combination of these two factors reduces the net energy required for manufacturing hybrid WT blades in the case of optimum variants. The Swedish renewable electricity causes less human toxicity and eutrophication[53]. For GWP, PMFP, POFP, and FDP impact categories, GFHB-Opt and RCFHB-Opt exhibit higher performance by 7% to 22% and 5% to 19% than GFHB and RCFHB respectively, which is mainly attributed to virgin GF recycling credits associated with the mechanical recycling of composite scrap in optimum variants.

In addition, RCFHB-Opt clearly exhibits an overall environmental advantage over the group of baseline and other optimum WT blade variants. Therefore, hybrid WT blades manufactured in Sweden can significantly improve the environmental performance of the wind energy industry, with 1) VCF composites used for structural (spar caps) and RCF epoxy composites used for non-structural (shear web skins and body shells) components; 2) mechanical recycling of hybrid blades to recover VCF and RCF at end of life.

Finally, we evaluate the environmental impacts of a potential WT blade scenario (All-RCF-Future) in which RCF-epoxy prepregs produced via HiPerDiF technology are used for manufacturing both structural and non-structural components. We conservatively assume no weight savings, with the weight of All-RCF-Future WT blade assumed the same as GFB, i.e., 55,326 kgs per FU (18,442 per blade). The environmental impact scores for this All-RCF-Future WT blade scenario are lower compared to all other blade variants in all impact categories except POFP and PMFP. Thus, in the future, using all RCF-epoxy composites for WT blades would: (a) reduce GWP by almost 50%; (b) result in negligible FEP and HTP impacts; and (c) reduce all other impacts, except MEXP, by 23% to 76% compared to conventional GFB. However, we notice an increase in FEXP impact for All-RCF-Future scenario, which is higher than RCFHB and RCFHB-Opt scenario. This is primarily due to the increased landfill disposal of ashes from incinerating pyrolysis char derived from the increased demand for RCF.

5.5 EBPT and CBPT of Different WT Blade Variants

The EPBTs and CBPTs are calculated for different WT blade variants as shown in Table S18. The corresponding energy demand and GHG emission ratios of blades to entire WT can be found in Section 3 of the Supporting Information.

The EPBTs of seven WT blade types range between 10.8 and 8.6 months while their respective CPBTs span from 14.0 to 12.2 months. The EBPT of All-RCF-Future blade is the lowest, followed by RCFHB-Opt. This is because the contribution from FDP and GWP in these two blade types to the total CBPT is less compared to other blade variants. The results suggest that using RCFHB-Opt type blades in a 3 MW capacity WT will reduce EPBPT and CPBT by 1.4 and 1.6 months respectively, compared to GFB. In other words, using RCFHB-Opt type for a 3 MW capacity WT can generate 108 tons oil eq. (1,260 MWh) renewable energy and reduce 367 tons of CO_{2e} relative to a 3 MW WT using GFB, over a 20-year time. It is noted that EPBT and CPBT results are specific to EU offshore wind generation conditions and the payback times can be entirely different for other regions.

6 DISCUSSION

RCF (55% FVF) epoxy composites, owing to their mechanical advantage over GF, can be introduced into WT blades for manufacturing nonstructural components, i.e, skins of sandwich structures used in outer body shells and shear webs. Replacing GF-reinforced epoxy composites with their RCF counterparts results in 9% weight saving (i.e., skin to skin replacement on equivalent stiffness) and 4% weight saving across the whole sandwich structure. Together with the use of VCF-epoxy composites for spar caps, this achieves weight savings of 39.2% per blade installed in a 3 MW capacity WT (RCFHB scenario). This saving is 3.2% higher than the All-GF WT Blade scenario. However, the incorporation of RCF-epoxy composites into WT blades depends on fiber alignment technology development such as HiPerDiF technology and subsequent composite manufacturing technology which was assumed to be special autoclave moulding. Future work is suggested to perform a more detailed computational analysis and experimental work to evaluate the implications of composite manufacture and material substitution using RCF in blades.

In this study, we assume Sweden to be the geographical locations for the cradle to gate manufacture of all hybrid WT blades, including raw material production (VCF and RCF), manufacturing intermediate components (weaving VCF preforms, producing RCF prepregs with uniformly aligned RCF preforms), and final conversion processes (RIM and pultrusion), to make use of Sweden's low carbon electricity. The assumption can be justified for several reasons: firstly, the low carbon intensity of Sweden's national electricity gird would make production of PAN based CFs more sustainable [54], and secondly, forest biomass is abundant in Sweden, which serves as feedstock for the production of lignin precursor, and subsequently lignin-based CFs though it is still in lab scale. Thirdly, existing research is being carried out in Sweden to produce CFs from alternative precursors such as biogas or biomethanol (converted to propylene and then to acrylonitrile, a feedstock used for PAN precursor production[54]). Lastly, Sweden is expected to double its wind power installed capacity from 14.8 GW in 2019 to 30.4 GW by 2030.[55] The demand for locally manufactured CFs will increase correspondingly and PAN based CFs manufacturing plants are already in planning for northern Sweden[54] to meet the future demands. Therefore, we believe multi-precursor processing (PAN, lignin, virgin CFRP waste) capacities will increase, and different types of CFs (i.e., PAN-based CF, lignin-based CF, RCF)) will potentially be manufactured in Sweden in near future. Our LCA study demonstrates that the overall environmental performance of hybrid WT blade variants (GFHB and RCFHB) is better than conventional GFB. It is therefore significant for industrial stakeholders and policy makers to design the best production/recycling capacity to obtain the maximum potential environmental benefits for the wind power sector.

From scenario analysis, we find that mechanical recycling is the preferred end-of-life treatment for WT blades, when compared to incineration, with reduced environmental impacts, as also found by Liu et al[17]. Using air pollution abatement technologies like RTO at VCF production facilities is strongly recommended to reduce certain environmental impacts (e.g., MEP and AP) if VCF is used in spar caps. Further, the pultrusion of VCF epoxy spar caps performs environmentally better than RIM because the scrap rate is smaller in pultrusion while in RIM process a significant portion is wasted as offcuts in weaving VCF preforms.

RCFHB and RCFHB-Opt variants have lower energy and carbon payback times than GFHB and GFHB-Opt, which in turn are lower than GFB and GFB-Opt. The All-RCF-Future WT blade exhibits both the lowest overall environmental performance and the lowest EPBT and CPBT. However, its practical success depends on the commercialization of HiPerDiF technology (e.g., process efficiency improvements) and its ability to produce spar caps that have competing mechanical properties to enable the replacement of VCF epoxy composites. Future work shall comprehensively monitor the environmental and financial impacts of RCF in real wind energy installations to ensure opportunities are pursued that provide the greatest overall net benefit.

ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: XXX.

Supporting Information includes additional details on material properties, life cycle inventory, uncertainty analysis and scenario analysis. Figure S1 presents stress for each layer under local coordinate system ([±45]2[0]2), S2 presents system boundary of All GFWT Blade (All GFB), S3 presents life cycle stages of GF Hybrid WT Blade (GFHB). Tables S1 Material mechanical properties under the base case and improved case. Table S2 is material substitution calculation under the base case, Table S3 is material input per functional unit (FU =3 Blades) in kgs. for three blade types studied (All GF, GFHB and RCFHB), Table S4 is assumptions and data sources used in building LCI model for RCF-Hybrid blade, Table S5 is LCI data on aligned RCF preforms and RCF epoxy prepreg using HiPerDif method. Table S6 is five assumptions and data sources used in building LCI model for All-GF Blade, Table S7 is consumables required for 1 m^2 resin infusion curing of WT blade components, Table S8 is assumptions and data sources used in building LCI model for GF-Hybrid WT blade, Tables S9 to S14 are material composition and material input calculations of: (a) All GF (GFB); (b) GFHB; and (c) RCFHB baseline scenarios, Table S15 is model parameters varied for uncertainty analysis, Table S16 and S17 are material composition and material input calculations of RCFHB with maximum weight savings (as described in Table S14), Table S18 is description of scenarios considered in the study of different WT blades, and Table S19 is EBPT, CBPT, percentage contribution of FDP and GHG emissions of blades to wind turbine of different blade types.

AUTHOR INFORMATION

Corresponding Author

* Email: fm392@cam.ac.uk

ORCID

Venkata K.K. Upadhyayula: 0000-0002-8418-3515

Venkataramana Gadhamshetty: 0000-0002-8418-3515

Dimitris Athanassiadis: 0000-0002-6116-9913

Mats Tysklind: 0000-0001-8709-6970

Fanran Meng: 0000-0002-9014-1231

Jonathan M. Cullen: 0000-0003-4347-5025

Dalia M. M. Yacout: 0000-0003-2454-6879

Notes

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