Comparative Life Cycle Assessment: Reinforcing Wind Turbine Blades with Carbon Nanofibers

Laura A. Merugula, Vikas Khanna, and Bhavik R. Bakshi

Abstract—**Wind energy conversion (WEC) is dependent on wind power density, which increases with elevation and swept area of the rotor. Many components are readily scalable and size-independent; whereas, turbine blades have presented a new frontier in aerodynamic design. As the limits of glass fiber-reinforced plastics (GFRP) have been reached in this field, there is now a materials development problem in achieving outlooks for larger, more resilient WEC systems. A hybrid material is under development, which uses vapor-grown carbon nanofibers (VGCNF or CNF) to reinforce the interface of a glass fiber/epoxy matrix. This research aims to determine life cycle effects of substituting GFRP in large turbine blades with the hybrid material. A review of literature, databases, and industry reports on life cycle data for wind turbines helped to establish a baseline descriptive life cycle assessment (LCA). Trends of new installations were assessed to determine appropriate boundaries for comparison. Results indicate that cradle-to-gate processing energy of the new material is 1.4-7.7 times greater than for the original GFRP material on a MJ/kg basis under implicit assumptions of weight savings. Effects on energetic return on investment (EROI) vary from insignificant to substantial according to upstream process choices for CNF manufacture and solvent handling. All conclusions inherently assume that CNF-incorporation would lead to realizable technologies for substantially increasing either size or life span of turbine blades concomitant with weight savings. It is not yet substantiated whether replacement of long carbon fibers is advantageous both mechanically and energetically.**

***Index Terms*—carbon nanofibers (CNF), life cycle assessment (LCA), sustainability, wind energy**

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I. Introduction

GENERATION of electricity from coal and other fossil fuels requires continuous mining or drilling, transportation, and feedstock combustion over the life of a power plant. Although some negative effects can be mitigated with proper pollution control schemes, this mitigation, too, must be continuous and requires additional material and energy inputs. Electricity from renewable resources is not benign, but promising in that continuous energy input is free.

The U.S. Energy Information Administration (EIA) [1] reported that electricity generation contributed to 2,359.1 million metric tons carbon dioxide equivalents (MMT CO_2-eq) in 2008. EIA researchers also reported a 1.0% decline, or 38.7 TWh, of power generated in the same year, implying a total generation of 3870 TWh. The U.S. greenhouse gas intensity is apparently 610 g CO2eq/kWh for the current electrical mix.

True social and environmental costs of energy conversion are not often translated into consumer prices. However, a cap-and-trade program is already in effect in Europe to begin to address such issues; the European Wind Energy Association (EWEA) [2] reports that the European price of 25 euros per metric ton greenhouse gas (€/MT GHG) emissions has avoided €2.3 billion in 2008. California's program will go into effect this year at an estimated rate of 15.5 ₵/MT CO_2-eq [1].

Water scarcity will likely be the front-line in acknowledging climate changes [3]. Wind energy does not rely on large volumes of water as do thermal energy conversion systems. Domestic thermoelectric-power in 2000 contributed to withdrawals of 136 billion gallons fresh water per day, where 88% of these withdrawals were reported for use in once-through cooling systems [4]. While this figure assumes direct water use, total water use estimation using an input-output approach indicated that less than 1% additional water use for thermoelectric power generation is attributed to indirect use [5]. Even taking an input-output approach, this updated assessment considers only water use and not further ecological impacts on water. For example, the EPA [6] estimates that unreclaimed aspects of surface coal mining operations in Tuscawaras County, Ohio USA have caused an estimated 437.4 tons soil lost annually through erosion. This affects downstream sediment and bioavailability of pollutants in the soil compartment. Reclamation agreements to reduce this loss by about 74% will "compensate for unavoidable project impacts" as part of permit approval for continued mining [6].

In order to substantially complement such efforts and to substitute for fossil-based electricity generation, designers of utility-scale wind energy converters are aiming for ratings of 8-10 MW per turbine [7]. Economies of scale are apparent in wind turbines, where cost of delivering electricity decreases as turbine size increases on a per kWh basis. Several components of wind turbines and costs for foundations, building roads, connecting electrical grids are relatively size-independent [8]. Tall turbines utilize existing resources more efficiently and have a lesser impact on land use than smaller turbines of equivalent total delivery. The Danish Wind Industry Association [9] predicts that 12% of global electricity consumption can come from wind energy by 2020.

Power per square meter, P/A (W/m^2), in wind is proportional to the cube of wind velocity, v (m/s), and air density, ρ_a (kg/m^3), as shown in (1). As kinetic energy is extracted from the wind, it is slowed down, so extracting 100% of the energy would be impossible as it would mean no more air can pass through the turbine.

$$P/A = 1/2 \bullet \rho_a \bullet v^3 \tag{1}$$

The limit of converting wind's kinetic energy to mechanical energy via a disc-like rotor is 16/27, or 59%, by what is known as Betz' limit. A discussion of this proof and an introduction to wind power is available in [10]. Industry experience with materials, design, and testing has led to innovations in horizontal axis wind turbines (HAWTs) that are operating near this physical limit and are increasing in size [11].

Rotor blades made of polymer matrix composite materials (PMC) are generally anisotropic and have failure mechanisms that are less well-understood than for metals. These materials are attractive for wind turbine blades because of their high strength-to-weight ratio, high stiffness-to-weight ratio, exceptional vibration damping, and fatigue resistance [12].

As power density is proportional to swept area of the rotor, remaining components are more readily scaled than blades themselves. These rotors will undergo over 10 million flexural cycles in their lifespan where a combination of aerodynamic, inertial, and gravitational forces are experienced at each turn. Thus, much attention is spent on understanding and designing out PMC blade failure as turbine size and demand increase. Seven types of damages to turbine blades are discussed in [13]. These failures' order of magnitude in size varies with tears having a characteristic length of 10 nm.

PMCs reinforced with vapor-grown carbon nanofibers (VGCNF or CNF) have exhibited improvements of tensile strength and modulus for CNF loadings between 1 and 5 percent by weight (wt%) compared to neat samples [14]-[17]. Reduction in mechanical properties is exhibited at loadings beyond 5 wt% with current methods, and some studies suggest 2-4 wt% as an optimal loading range [14]-[16].

Generally, CNFs are premixed into the resin, which significantly increases resin viscosity and affects molding time and processing energies [14], [15], [17]. Prebinding CNFs to glass fibers before resin infusion is less impacting on mold filling time without requiring new working models for flow behavior [16]. Prebinding additionally enhances mechanical properties over premixing, where interface reinforcement may address microscale (fiber/matrix) failure more effectively. Researchers continue to develop these hybrid PMC materials for wind turbine blades that will extend the mechanical limits of glass fiber-reinforced plastics (GFRP) currently used.

This paper considers life cycle effects of a possible decision to incorporate the hybrid PMC material into wind turbine blades. Section II describes the overall system, highlighting materials issues in representative modern turbine blades followed by those issues relevant to integration of the new material. Section III introduces the components of life cycle assessment and energy analysis. Section IV presents results offers a brief discussion.

II. Boundary Development

A 3-blade HAWT of 2 MW nominal rating with GFRP blades of 40 m length is selected as representative of current installations. Larger blades tend to be locally reinforced with long carbon fibers [18]. Fig. 1 shows trends in turbine ratings and rotor diameters. Companies will optimize a system for local conditions such that an installed turbine will have more or less the nominal rating indicated in the picture.

GE Wind Energy's 3.6 MW (50.5m blades) and LM Glasfiber's 4.5 MW 54P (54m) have no carbon fiber reinforcement and are notable exceptions to apparent GFRP limits [19], [20]. Vestas V90 3.0MW (44m) are constructed of GFRP with some carbon fiber reinforcement, resulting in blades that are lighter than the V80 2.0MW series, but are 5m longer with a 50% increase in nominal output [19], [21]. LM Glasfiber has introduced a 5MW design with blades of 61.5m and what is considered a modicum of carbon fiber [20]. This design is said to represent true limits of glass fiber in blade construction. Land transportation of blades beyond about 61m

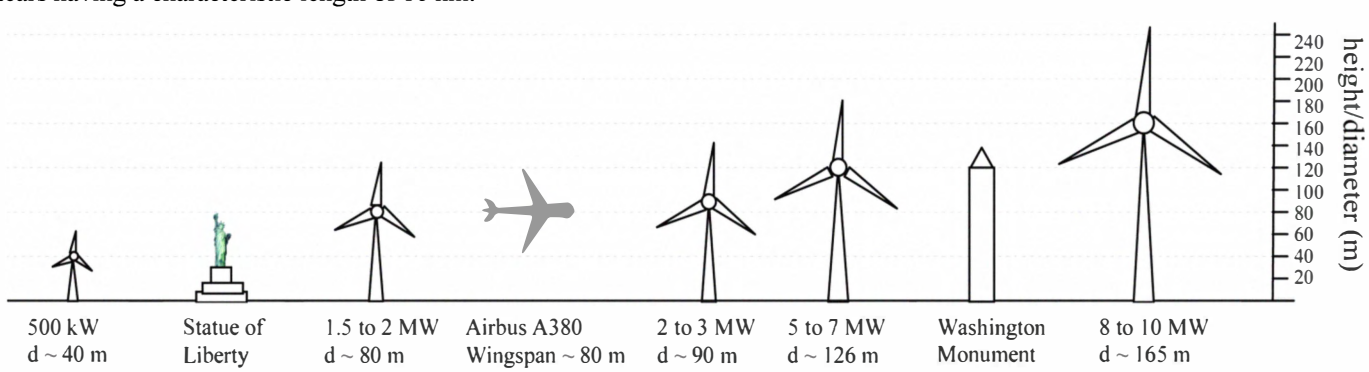

Figure 1. Relative sizes of turbines with average nominal ratings

(200ft) becomes a cost-prohibitive factor in growth [23]. These considerations lend to the decision to consider a 5 MW turbine with blades of 61.5 m for the alternative assessment.

Stiffness becomes a driving criterion for blades of this size. Edgewise fatigue resistance, a critical design factor for blades longer than 45m, is improved by carbon fiber reinforcement, but introducing carbon fibers requires re-engineering of blade molds to compensate for waviness that can be induced in the carbon fibers by processing with vacuum-assisted resin transfer molding (VARTM) [19]. LM Glasfiber's use of carbon fiber is mostly for reinforcement of the shell laminate on the trailing edge [21]. Weight savings from reinforcement with the less dense material results in a blade of 17.7 tons for the 61.5 m length [24].

The models for comparison consider these two systems, 2 MW and 5 MW, having been reinforced with CNF at loadings of 1-5 wt%. It is assumed that the addition of CNFs would result in similar benefits as long carbon fiber reinforcement: including increased fatigue resistance that could facilitate an increase in life span and weight savings up to 20%.

III. METHODS AND DATA

Life cycle assessment (LCA) is an evaluation tool based on the premise that all stages in a product or process are interdependent. It provides an estimation of cumulative impacts, including contributions from raw material extraction, transportation, and other stages not traditionally included in analyses [25]. An LCA can be either attributional, which profiles impacts of a product or process, or decision-oriented as in this study where the aim is to assess effects of a change in processing or technology. The LCA methodology can be used for other purposes, such as identifying data gaps and ranking relative contributions of processes, more of which is described in [25]. LCA has four major components: goal and scope definition, inventory analysis, impact assessment, and interpretation. Each of these components will be described in the subsections that follow.

A. Goal and scope definition

The intended application of this study is to highlight whether or not incorporation of the hybrid material into current production technology may result in a substantial change in energetic efficiency of the entire system. A recently published process-based life cycle inventory (LCI) of VGCNF indicated that life-cycle energy requirements are significantly greater than for traditional materials on a kilogram basis [26], yet further analysis exemplified potential savings over the life of an automobile where substitution of steel body panels with CNF-enabled polymer nanocomposites was considered [27]. The reason for this study is to assess life-cycle effects of polymer nanocomposites in a different technology in keeping with scientific and governing communities' calls for applying LCA methodologies to emerging technologies, specifically nanotechnology and nanoproducts [28].

The wind energy market is already marked by a greater demand than supply of constructed materials, and developers have recently experienced delays of about 12 months for turbines ordered [29]. Yet the world wind market continues to grow at 25-30% per year, doubling in capacity every 3 years [30]. In such an emerging field, material decisions that will increase production are likely to be quick and pervasive once shown to be technically viable. Thus, the intended audience is the general research community for consideration of product/process design and is meant to provide preliminary information to guide decisions of material choice.

The product system to be studied is a single wind energy plant. One scenario will consider a basis plant rated at 2 MW with rotor blades of 40 m length and the potential for increasing the life span of this standard system from 20 years to 30 years by the material substitution in consideration. The other scenario will take a 5 MW system with blades of 61.5 m length and substantiate potentials for extending this mechanical limit of GFRP by using the new material. The functional unit is activity per kilowatt-hour electricity generated (x/kWh_{el}). No allocation is necessary as wind energy generates no byproduct in operation.

Reported life cycle information from government, industry and scientific literature was reviewed to determine the boundary and life cycle inventories for the two bases. Fig. 2 shows the system boundary development. The boundaries would be affected in the regions indicated: production of materials and process concentration.

All material production is assumed to be static except for additional units for producing CNFs and the solvent acetone used for dispersion and application. Once the glass fibers are pre-bound, it is assumed that either vacuum-assisted resin transfer molding (VARTM) or Seemann Composites Resin Infusion Molding Process (SCRIMP) would be employed in the same way as with neat, or unmodified, fiberglass composites. This is the most common technology employed molding of large turbine blades [31].

The use phase is affected in considerations of energy production by the system with no change in operation and maintenance (O&M), assuming O&M differences are not substantial in considering extension of the system's life span. Transportation of system components is considered only insofar as it is accounted for in baseline scenarios.

Though a dearth of information exists on end-of-life issues of nanotechnology, it is assumed that disposal of the system parts would remain unchanged.

Preliminarily, the impact category selected has been cumulative energy demand (CED) expressed as the number of kilowatt-hours of energy required per kilowatt-hour electricity produced (kWh_{in}/kWh_{el}). The figures will also be reported as energy payback period (EPBT) and energy return on investment (EROI). Thus, the data will be interpreted so as to note any trends in these energy indicators, which will guide further iterations of the LCA components for considering expanded impact assessment or for taking an alternative view on the product system.

Data quality requirements are met by estimated, referenced and averaged data as well as best-engineering judgments as is in accordance with the goal of a preliminary assessment.

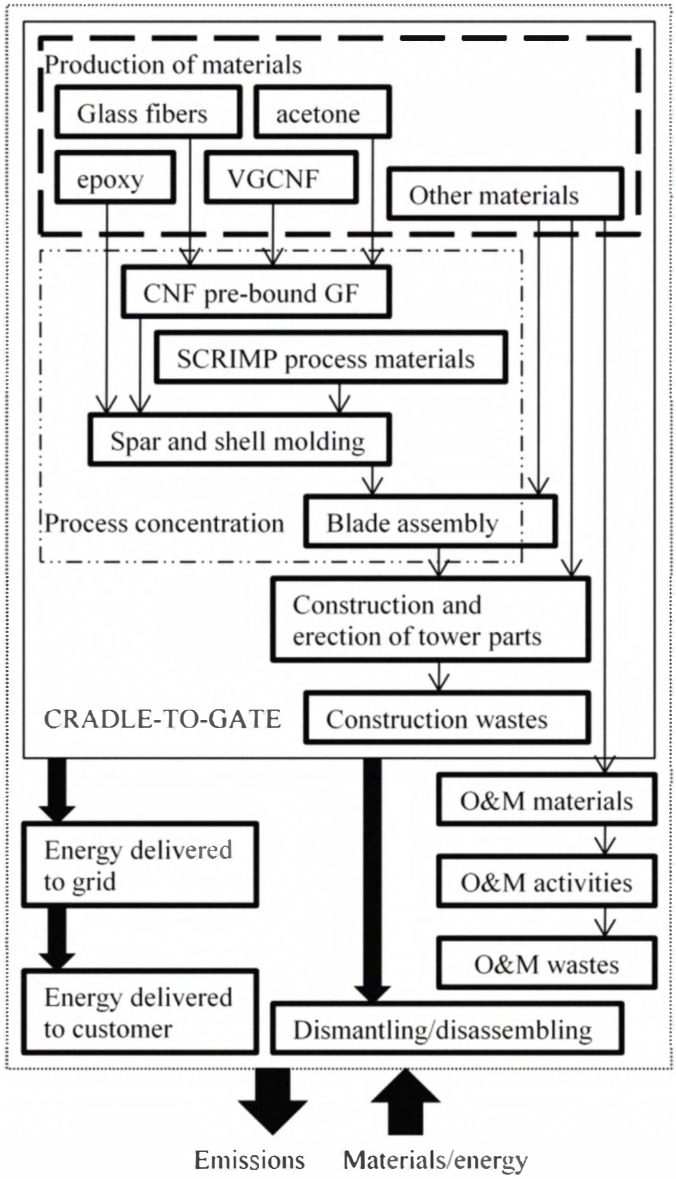

Figure 2. System boundaries: variations occur in material production and processing.

Cumulative energy demand for 2 MW and 5 MW systems are assumed to be 24 000 GJ/turbine and 85 000 GJ/turbine with blades accounting for 10% and 6%, respectively, of the systems' CED [21], [32]-[34]. All reported calculations are based on blades that are 40% epoxy by vol (vol%) and 60 vol% glass fiber with specific gravities of 1.2 and 2.5, respectively. For consideration of material substitution, primary material savings were applied followed by calculating the required mass of CNF for weight loadings from 1% to 5% along with the amount of acetone needed for CNF application. Energy production of each turbine was based on a capacity factor of 30 for 2 MW and 40 for 5 MW.

A limitation is difficulty in decoupling life cycle energy for material manufacture from other aspects unique to wind turbine construction, which may lead to undercounting substitution effects. More detailed publicly available LCAs or collaboration with suppliers would correct this.

Sensitivity analyses are conducted for variability in reported life cycle values of primary materials, solvent reduction from maturity of application technology and/or recovery and reuse, weight reduction goals, and weight percent loadings of CNF.

Uncertainty remains from predicting material choices from laboratory results. It is unknown whether substitution of CNFs can achieve the degree of weight savings now seen with long carbon fibers. Weight savings by CNFs may implicitly assume a prohibitively thin blade. More details are needed on substitution or complementary use of CNFs with carbon fibers if extending beyond the scope of a preliminary study.

B. Inventory analysis

The inventory analysis for preliminary iterations consists of determining basis systems' energy requirements and that of the blades and their primary materials. The inventories were collected from values reported in literature and the LCA software SimaPro [35].

C. Impact assessment

Life cycle impact assessment (LCIA) transforms the LCI into impact categories so that environmental issues inherent to inputs and outputs of the product or process can be categorized and interpreted [36]. Various levels of complexity exist in methods of LCIA, where CED can be viewed as a predictor for environmental burdens, the case for which has been made in [37]. It is arguable that the predictive abilities of CED may lessen as a nation's energy mix decreases its proportion of fossil-based energy technologies. However, the current global mix is heavily based in fossil fuels, making this argument quite plausible for immediate use of CED as a preliminary indicator.

Energy intensity (η) can be defined as a ratio of required cumulative energy demand (E, MW) to a turbine's power rating, P (MW), load or capacity factor, λ, and lifespan, T (yrs), as shown in (2). The results are converted for reporting in accordance with the functional unit, kWh_{in}/kWh_{el}.

$$\eta = E/(P \bullet 8670h \cdot y^{-1} \bullet \lambda \bullet T) \tag{2}$$

Energy return on investment (EROI) is calculated according to (3). Since kinetic energy from the wind is free, continuous energy input (E_{ic}) and direct energy costs (E_d) are zero. The simplified equation requires only the life span (t_s), cumulative energy demand (E_{iot}), and useful energy generated (E_0). For renewable energy systems, energy payback time (EPBT) is the inverse of EROI multiplied by the life span as shown in (4).

$$\begin{aligned} EROI &= (t_s \bullet E_0)/(t_s \bullet (E_d + E_{ic}) + E_{iot}) \\ &= E_0/(E_d + E_{ic} + E_{i0t}/t_s) \\ &= t_s \bullet E_0 / E_{iot} \end{aligned} \tag{3}$$

$$EPBT = E_{i0t} / E_0 = t_s / EROI \tag{4}$$

While the energy in consideration is end-use, primary energy calculations would account for original energy that would have been required had it been generated by conventional means. The United States primary energy ratio calculated average for 2001-2005 is 3.340 [38]. That is, for each MJ of

end-use energy in the US, 3.34 MJ of primary energy is required. Assuming that energy generated from wind turbine plants will substitute an equal amount of end-use energy from the traditional mix, the reported EPBT has been divided by the US primary energy ratio.

D. *Interpretation*

This term "iterative" is used throughout with respect to the fourth component of LCA: interpretation. As the first three components are developed, findings are evaluated for consistency with goals and the scope in the interpretation phase. Notwithstanding this determination, further iterations of the four components may redefine the scope and data requirements and will eventually result in a construct for making recommendations for the intended audience [36]. This aspect of the analysis is developed further in the results section.

IV. RESULTS AND DISCUSSION

Initial calculations considered assumptions of blade mass and material proportions along with reported values of material CEDs. On a mass basis, the CED was calculated for blades of the two systems. The calculated values were found to be consistent with reported CEDs for blade contribution to wind energy converters of both magnitudes. From there, several iterations were performed to apply major assumptions, including sensitivity analyses.

Energy payback periods for 2 MW and 5 MW turbines are not substantially different, both reported consistently as less than 1 year [21], [32]-[34]. Incorporation of the new material was not found to alter this trend *per se*. Best-case scenarios indicated no change in EPBT while potential technology choices integral to the new material could cause an increase in the EPBT of either system, but remaining under 1 year.

To further understand the results of the analyses, consider Fig. 3. The bases of CED for 2 MW (a) and 5 MW (b) systems are shown as having zero CNF (0 wt%). The range of values superimposed on the main column rise from variability in reported life cycle energies of the primary materials in the blades. For 1-5 wt% CNF, overall weight savings of 0-20% were assessed with 20% reported in the figure commensurate with effects of competing long carbon fibers.

The 2 MW assessment in Fig. 3a assumes increased fatigue resistance could facilitate an increase in blade life span from 20 to 30 years, where reconstruction or replacement of these parts under that time span would be characterized as O&M. The best-case scenario is indicated by the lower limit of the range lines. A key for interpreting Fig. 3 is shown as Table I, which gives a description for the column indicator and ranges as they are dependent on inherent upstream unit operations. Based on engineering judgment and knowledge of process technologies, the column values indicate the predicted set of process choices. Note that the limit lines inherently include a relative contribution from variability in reported life cycle energies for the primary materials as mentioned.

Results show that choices of solvent application and CNF production are dominant in the potential for energetic benefits.

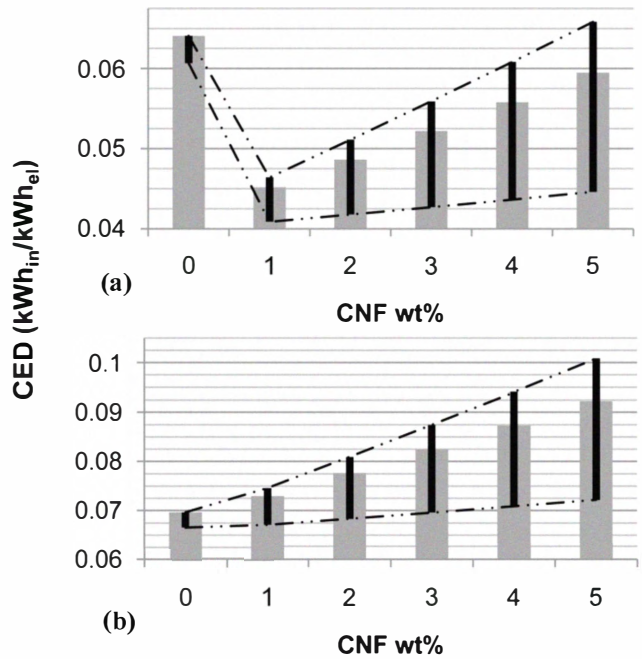

Figure 3. Cumulative energy demand results assuming 20% weight reduction for (a) 2 MW plant with life span 30 years, and (b) 5 MW plant with life span 20 years

Table I: Key to Fig. 3 - properties governing results' spread

	Upstream choices
Lower limit	90% solvent reduction, C_6H_6 feedstock with recycle of H_2 and C_6H_6 in CNF production
Upper limit	No solvent reduction, CH_4 feedstock with no recycle of H_2 or feed in CNF production
Column	90% solvent reduction, CH_4 feedstock with no recycle of H_2 or feed in CNF production

While blades contribute to 10% or less of wind turbine CED, changes to blade materials in meeting higher capacity could cause a shift in blades' relative energy intensity. The lower limit, or best-case scenario, follows the expected trend of a life span increase as substitution of the new material is balanced by savings in traditional materials. However, as CNF amount approaches 5 wt%, all reductions in CED are lost with upper limit process choices. Approximately 30% CED reduction is lost for predicted process choices as indicated by the columns. Whereas EROI increases proportionately to life span increases, a reduction in this gain of 10-100% results from various upstream conditions.

This trend is apparent also in Fig. 3b, which assumes a 5 MW system with a rated life span of 20 years can be constructed using the hybrid GFRP. Material substitution in this case could be facilitative, though accompanied by 0-30% EROI reduction from the base case.

The LCI of CNFs is dependent on feedstock with methane-based production having over 3 times the CED than benzene-based [26]. CNF-supplier Pyrograf Products have tried CNF-generation from coal [39] to meet increases in supply from 32 MT/yr to 1360-2270 MT/yr [40]. It is unknown how this would affect the LCI and allocation. With current production

rates, the Midwest-based supplier could contribute to a 160 MW installation of 5 MW turbines with 2 wt% CNF. This is less than 2% of the added US capacity for 2009 [41].

REFERENCES

[1] J. Conti, "Emissions of Greenhouse Gases in the United States 2008," U.S. EIA, Washington, D.C., Rep. DOE/EIA-0573(2008), Dec. 2009.

[2] A. Zervos and C. Kjaer (2009, Nov.). Pure Power: Wind Energy Targets for 2020 and 2030. EWEA. Brussels, Belgium [Online]. Available: http://www.ewea.org/fileadmin/ewea_documents/documents/publications/reports/Pure_Power_Full_Report.pdf

[3] J. L. Schnoor, "Three myths about water," *Env. Sci. Tech.*, vol. 44., no. 5, pp. 1516-1517, Mar. 2010.

[4] S. S. Hutson, N. L. Barber, J. F. Kenny, K. S. Linsey, D. S. Lumia, and M. A. Maupin, "Estimated Use of Water in the United States in 2000," USGS, Reston, VA, Circular 1268, 2004.

[5] M. Blackhurst, C. Hendrickson, and J. S. I. Vidal, "Direct and indirect water withdrawals for U.S. industrial sectors," *Env. Sci. Tech.*, to be published.

[6] T. G. Hyde. Letter to G. Mullins of U.S. Army CoE. Mar. 5, 2010. Available: http://www.epa.gov/owow/wetlands/guidance/pdf/Kaiser_Mathias_030510.pdf

[7] "UpWind: Finding design solutions for very large wind turbines," [Online]. Available: http://www.upwind.eu/default.aspx.[Accessed: Feb. 1, 2010].

[8] H.-J. Wagner and J. Mathur, "Design considerations," in *Introduction to Wind Energy Systems: Basics, Technology and Operation* (Green Energy and Technology Series), Berlin, Germany: Springer, 2009, ch. 5, pp. 41.

[9] J. Hylleberg, (2008). Denmark – Wind Power Hub: Profile of the Danish Wind Industry. DWIA. Frederiksberg, Denmark [Online]. Available: http://www.e-pages.dk/windpower/10/

[10] "Guided Tour on Wind Energy," Jun. 8, 2003. [Online]. Available: http://windwithmiller.windpower.org/en/tour. [Accessed: Feb. 1, 2010].

[11] W.E. Leithead, "Wind Energy," *Phil. Trans. R. Soc. A*, vol. 365, no. 1853, pp. 957-970, Apr. 2007.

[12] R. F. Gibson, "Introduction," in *Principle of Composite Material Mechanics*, 2nd ed., New York: Marcel Dekker, Inc., 2007, ch. 1.

[13] B. Sørensen, E. Jørgensen, C. Debel, F. M. Jensen, H. M. Hensen, T. K. Jacobsen, and K. M. Halling, "Improved design of large wind turbine blade of fibre composites based on studies of scale effects (Phase 1) – Summary Report," Risø National Laboratory, Roskilde, Denmark, Rep. Risø-R-1390(EN), Sep. 2004.

[14] Y.-K. Choi, K.-i. Sugimoto, S.-M. Song, Y. Gotoh, Y. Ohkoshi, and M. Endo, "Mechanical and physical properties of epoxy composites reinforced by vapor grown carbon nanofibers," *Carbon*, vol. 43, no. 10, pp. 2199-2208, Aug. 2005.

[15] Y. Zhou, F. Pervin, S. Jeelani, and P. K. Mallick, "Improvement in mechanical properties of carbon fabric-epoxy composite using carbon nanofibers," *J. Mat. Process. Tech.*, vol. 198, no. 1-3, pp. 445-453, Mar. 2008.

[16] S. Movva, G. Zhou, D. Guerra, and L. J. Lee, "Effect of carbon nanofibers on mold filling in a vacuum assisted resin transfer molding system," *J. Comp. Mat.*, vol. 43, no. 6, pp. 611-620, Mar. 2009.

[17] M. H. G. Wichmann, J. Sumfleth, F. H. Gojny, M. Quaresimin, B. Fiedler, K. Schulte, "Glass-fibre-reinforced composites with enhanced mechanical and electrical properties – benefits and limitations of a nanoparticle modified matrix," *Eng. Frac. Mech.*, vol. 73, no. 16, pp. 2346-2359, Nov. 2006.

[18] E. Hau, "Rotor Blades," in *Wind Turbines: Fundamentals, Applications, Economics*, Berlin, Germany: Springer, 2006, ch. 7, pp. 248.

[19] K. Mason, "Carbon/glass hybrids used in composite wind turbine rotor blade design," *Comp. Tech.*, Apr. 2004.

[20] G. Marsh, "Wind turbines: how big can they get?" *Re*-Focus, vol. 6, no. 2, pp. 22-24, 27-28, Mar./Apr. 2005.

[21] "Life Cycle Assessment of offshore and onshore sited wind power plants based on Vestas V90-3.0 MW turbines," Jun. 21, 2006. [Online]. Available: http://www.vestas.com/en/about-vestas/principles /sustainability/wind-turbines-and-the-environment/life-cycle-assessment-(lca).aspx

[22] G. Gardiner, "Carbon fiber in the wind," *High Performance Comp.*, Jul. 2007.

[23] D. A. Griffin and T. D. Ashwill, "Alternative composite materials for megawatt-scale wind turbine blades: design considerations and recommended testing," presented at 41st AIAA Aerospace Sciences Meeting and Exhibit, Reno, NV, 2003, Paper AIAA-2003-0696.

[24] "The world's longest wind turbine blades in series production," LM Glasfiber. [Online]. Available: http://www.lmglasfiber.com/Products/Blade%20summary/5000/LM%2061.5.aspx. [Accessed: Mar. 1, 2010].

[25] M. A. Curran, "Life Cycle Assessment: Principrles and Practices," U.S. EPA NRMRL, Cincinnati, OH, Rep. EPA/600/R-06/060, May 2006.

[26] V. Khanna, B. R. Bakshi, and L. J. Lee, "Carbon Nanofiber Production: life cycle energy consumption and environmental impact," *J.Ind. Ecol.*, vol.12, no.3, pp. 394-410, Jun. 2008.

[27] V. Khanna and B. R. Bakshi, "Carbon nanofiber polymer composites: evaluation of life cycle energy use," *Environ. Sci. Technol.*, vol. 43, no. 6, pp. 2078-2084, Mar. 2009.

[28] A. D. Maynard (2006, Jul.). Nanotechnology: A Research Strategy for Addressing Risk. PEN. Washington, D. C. [Online]. Available: http://www.nanotechproject.org/publications/archive/nanotechnology_research_strategy_for/

[29] A. Pullen and M. G. Eneland, Eds. "Global Wind Energy Report 2006," GWEC. Brussels, Belgium. [Online]. Available: www.gwec.net/fileadmin/documents/Publications/gwec-2006_final_01.pdf. [Accessed: Feb. 1, 2010].

[30] "World Wind Energy Report 2009," Mar. 2010. WWEA. Bonn, Germany. [Online]. Available: http://www.wwindea.org/home/images/stories/worldwindenergyreport2009_s.pdf. [Accessed: Mar. 15, 2010].

[31] B. Hayman, J. Wedel-Heinen, and P. Brøndsted, "Material challenges in present and future wind energy," *MRS Bull.*, vol. 33, no 4, pp. 343-353, Apr. 2008.

[32] B. Tremeac and F. Meunier, "Life cycle analysis of 4.5 MW and 250 W turbines," *Ren. Sust. Ener. Rev,*, vol. 13, no.8., pp. 2104-2110, Oct. 2008.

[33] J. Weinzettel, M. Reenaas, C. Solli, and E. G. Hertwich, "Life cycle assessment of a floating offshore wind turbine," *Renew. Ener.*, vol. 34, no. 3, 742-747, Mar. 2009.

[34] "LCA V80-2.0 MW - Life Cycle Assessment of onshore and offshore sited wind farms," Oct. 20, 2004. [Online]. Available: http://www.vestas.com/en/about-vestas/principles /sustainability/wind-turbines-and-the-environment/life-cycle-assessment-(lca).aspx

[35] Pré Consultants, *SimaPro Demo 7.1*. [Online]. Amersfoort, The Netherlands: Pré Consultants, 2008. Available: www.pre.nl/simapro/default.htm. [Accessed: Feb. 1, 2010].

[36] *Environmental management – Life cycle assessment – Principles and* framework, ISO Standard 14040, 2006.

[37] M. A. Huijbregts, S. Hellweg, R. Frischknecht, H. W. M. Hendricks, K. Hungerbühler, and A. J. Hendriks. "Cumulative energy demand as a predictor for the environmental burden of commodity production," *Env. Sci. Tech.*, vol. 44, no. 6, pp. 2189-2196, Mar. 2010.

[38] "Energy Star Performance Ratings Methodology for Incorporating Source Energy," Aug. 2009. [Online]. Available: www.energystar.gov/ia/business/evaluate_performance/site_source.pdf. [Accessed: Feb. 1, 2010].

[39] T. W. Hughes, "Ohio Coal Development Office Annual Project Abstract as of December 2004," 2004. [Online]. Available: www.ohioairquality.org/ocdo/pdf/2004d-99-14.pdf. [Accessed: Feb. 1, 2010].

[40] "PPI: Subsidiary of Applied Sciences," 2001. [Online]. Available: www.apsci.com/ppi-about.html. [Accessed: Feb. 1, 2010].

[41] J. Mouawad, "Wind power grows 39% for the year," *The New York* Times, para. 3, Jan. 26, 2010. [Online]. Available: www.nytimes.com/2010/01/26/business/energy-environment/26wind.html?scp=6&sq=wind +energy&st=nyt. [Accessed: Feb. 1, 2010].