The Sustainability of Wind Energy Systems: The Composite Blades Loophole

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Abstract: A key component of a wind turbine's life cycle, the decommissioning phase, is only recently being addressed by research and policy on wind energy projects' sustainability. Although end-of-life composite blades constitute minimal waste as compared to annual industrial composite waste, to date no universally accepted solution or standard commercial procedure has been found for the problem of wind blade disposal. This paper examines the US wind blade supply chain as it regards the end-of-life management of composite waste. Based on 40, in depth, semi-structured interviews with North American and European wind energy experts, this paper provides an overview of wind blade manufacturing plants, composite suppliers to the wind energy sector, and blade-design academic research and testing in the US. Regarding the recycling of composite materials this paper offers original data on what legislation and current practice tells us about end-of-life blades. Data shows that all but a few blade manufacturers and/or OEMs have been involved in research or experimental projects regarding composite wind blade recycling over the last 13–14 years. All the projects since 2000–2001 are of European origin. Interview data also shows that important steps have recently been taken in the US as a market is being established for composite recycling across the country and as the composite recycling infrastructure is continually being improved.

Keywords: Wind energy, sustainability, composite blades, decommissioning

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sustainability.[1] Modern wind blades are designed without real thought to recycling or disassembling. Specifically, while composite materials used in wind turbine blade construction lead to greater efficiencies, energy capture, cost savings, and product durability under challenging service environments, they also ultimately waste resources because damaged blades are not easily recycled. Based on 40, in depth, semi-structured interviews with North American and European wind energy experts, this paper provides an overview of wind blade manufacturing plants, composite suppliers to the wind energy sector, and blade-design academic research and testing in the US. [2]

Composite blades, the parts of a wind turbine, which are harder to decommission—present an important waste management problem.[3] Excluding its concrete

[1] Ortegon, Katherine, F., Loring Nies, and W. John Sutherland. "Preparing for end of service of wind turbines." *Journal of Cleaner Production* 39, (2013): 191–199

[2] The interviews for this article were conducted between 2012 and 2014 while the author was working as a doctoral candidate at the department of Environmental Science, Policy and Management at the University of California at Berkeley. The interviewees (engineers by training, LCA experts, renewable energy and recycling company owners, as well as sustainable materials researchers) were contacted via email and a questionnaire was provided to them after they had agreed to participate in the research. The interviews were recorded (upon interviewee's informed consent) and the data was transcribed. The research was supported by National Science Foundation award NSF #1354545. Unless the interviewees requested otherwise, the data for this article is presented anonymously. More specifically, the author spoke with representatives from the following wind companies: American Energy Innovations, Blade Dynamics, Energetx Composites, Gamesa, GBT, LM Wind Power, MFG, Modular Wind Energy, Nordex, Northern Power Systems, Siemens, Wind Power, TPI, and Vestas. Interviews with representatives of the following US recyclers also took place: Adherent Technologies Inc. (ATI) (Dr. *Jan*-Michael *Gosau*, Engineering & Environmental Projects Manager. Global Fiberglass Solutions, Inc. (GFS) (Don Lilly, President). Materials Innovation Technology (MIT-RCF) (Jim Stike, President); R. J. Marshall. Other names of individual researchers/engineers who were interviewed for this research include *but are not limited to*: Simon Joncas (wind blades expert); Zajons Logistik's Erwin Schmidl; Marian Kjærgaard from the GenVind project; sustainability/LCA consulting Barsmark's Romain Sacchi; Fiberline's Benedikte Jørgensen; EDPR Renewables' Bill Whitlock; LCA specialist Peter Garrett, Wind blades expert Steve Nolet; composites specialist Stella Job; Maurik Ankersmit of Dutch Wind; Composites expert Inderdeep Singh of the Indian Institute of Technology Roorkee; Montana University's John Mandell; Erin Hazen of Acciona Energy; Composites expert Povl Brønsted; wind blade manufacturing expert Christen Malte Markussen; James Meredith of the University of Warwick; Windflow's John Arimond and Peter Brooking; Gaoth Tec Teo's Dr. O'Bradiagh; Professor of Chemical Engineering Ica Manas-Zloczower from Case Western Reserve University; Holcim's Erwin Schmidl; Jens Henriksen of Force Technology

[3] Andersen, Per Dannemand, and Mads Borup. "Long-Term Considerations on Wind Power's Environmental Impact. Presentation at Risø International Energy Conference, 19–21 May 2003.; Andersen, Per Dannemand, Mads Borup, and Trine Krogh. "Managing

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foundations, the average recyclability of a modern industrial wind turbine was calculated to be 80% by mass.[4] Representatives from the Danish company Vestas, still the largest wind turbine manufacturer in the world and pioneer in wind turbine LCAs, claim that 80% of their turbines are recyclable, whereas "a major part of the remaining 20% are the blades which cannot be recycled in an efficient way as of yet."[5]

Although end-of-life composite blades constitute minimal waste as compared to annual industrial composite waste, to date no universally accepted solution or standard commercial procedure has been found for the problem of wind blade disposal.[6] In addition, rotor blades' composite components—due to their increasing length and complex material composition—will certainly require a different recycling approach from the methods applied to the substantially smaller composite parts found in cars or electronics.

An important dimension of the challenge is that as a relatively young and labor-intensive industry, wind energy has focused almost entirely on the production and operation stages of turbines. In the US, for instance, whereas the key mechanical considerations in wind blade design such as materials' fatigue characteristics have been studied for more than 20 years, almost all government-funded research on wind systems centers on the design and manufacturing of cost-effective generators.[7] On the contrary, wind blade end-of-life considerations were not examined systematically until very recently.

long-term environmental aspects of wind turbines: a prospective case study." *International Journal of Technology, Policy and Management* 7, no.4 (2007): 339–354.

[4] Guezuraga, Begoña, Rudolf Zauner, and Werner Pölz. "Life cycle assessment of two different 2 MW class wind turbines." *Renewable Energy* 37 (2012): 37–44.

[5] Dyer, Andrew. "Innovate10 Sustainability Seminar Vestas Recycling Project." October 12, 2010. <http://www.innovate10.co.uk/uploads/04%20-%20AD%20-%20Vestas%20-%20Recycling%20Project%20121010.pdf>, Accessed October 2013.

[6] Papadakis, Nikolaos, Ramírez, Carlos, and Neil Reynolds. "Designing composite wind turbine blades for disposal, recycling or reuse." In Management, recycling and reuse of waste composites, edited by Vannessa Goodship, 443–457. Cambridge: Woodhead Publishing in Materials, 2010; Larsen, Kari. "Recycling Wind Turbine Blades." *Renewable Energy Focus* January/February (2009): 70–73.

[7] Mandell, John F., D. Daniel Samborsky, and Agastra Pancasatya. "Composite Materials Fatigue Issues in Wind Turbine Blade Construction." Presented at the 2008 SAMPE Conference, Long Beach, California, paper L238, 2008. Nolet, Stephen. "Manufacturing of Utility-Scale Wind Turbine Blades." Presented at the Iowa Wind Energy Association 2010 IAWIND Conference, March 10, 2010. In the last 2–3 years, the US Department of Energy (DOE) has funded some projects that research wind blade design also from the perspective of disposal. Regarding the early days of blade testing in the US, John Mandell from Montana State University reports: "…all you had to do was look at the blade and you could see that it was pretty crude. There was a lot of extra resin and poorly manufactured…" (personal communication).

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Developing bigger, lighter, stronger, and stiffer blades to enable maximum energy output may be adding to the sustainability challenge: longer blades—apart from creating extra requirements for virgin materials such as glass fibers (GF) or carbon fibers (CF)—presuppose greater energy consumption during the production phase of wind turbines, higher emissions during the transportation of components, and greater demand for landfill sites during their decommissioning.

Over the past decade, European experts have warned that issues pertaining to the end-of-life of wind energy systems have escaped the attention of the industry altogether: The "[r]emoval and recycling phase [of wind energy system components] is a 'blind spot' of environmental impacts analyses".[8] The problem's magnitude is captured by claims such as "nobody seriously paid attention to this topic in the last decade" or "by 2034 around 225,000 tons of rotor blade material will need to be recycled annually worldwide".[9] According to European researchers "380,000 tons of fibre composites will have to be removed and recycled each year from 2040" while "1200 t of non-recyclable post-industrial waste [from the production of new wind turbines is being] produced… [monthly]."[10]

1 Material Selection and Wind Blade Manufacturing

Today, wind blades' complex shape (the fact, for example, that over the entire surface of the blade there is not a single straight edge) and the need to optimize or minimize weight are the two main factors driving their construction. In recent years, OEMs as well as component and material suppliers have been investigating the end-of-life possibilities of decommissioned or damaged composite blades: familiarity with LCAs increases awareness of the environmental aspects of wind blade manufacturing (Table 1). One important issue with composite wind blades from an LCA perspective is the waste generated during the manufacturing process. For example, whereas recycling company R.J. Marshall is not officially working on a commercial basis with any wind energy blade molders, they are working with some FG distributors who make FG available to blade manufacturers in order to investigate the possibilities of recycling manufacturing scrap. Likewise, since 2010, Global Fiberglass Solutions, Inc. (GFS) (Bellevue, WA) is able to recycle end-of-life GF blades as well as GF manufacturing scrap. In personal communication, GFS president Don Lilly reported familiarity with LCA studies performed by ACMA (American Composites Manufacturers Association) and that his company is in the process of creating the "cradle to cradle solution for wind energy." In the same vein, CF recyclers have emphasized the need for publicly available data on the volume of manufacturing scrap generated today by CF and CFRP producers, as well as the lack of incentives for recycling by state governments.

[8] Andersen and Borup (2003).
[9] Albers *et al.* (2009): 32; Larsen (2009): 70.
[10] Andersen *et al.* (2007: 346); Papadakis *et al.* (2010).

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Table 1 Wind blade materials distribution based on data from wind system LCAs.

Vegt and Haije examined three scenarios (flaxfiber reinforced epoxy, CF reinforced epoxy, and GF reinforced polyester) for a 13.4 m rotor blade (250 Kw), which had a global mass of 300 kg. The authors assumed that the amount of any sort of fiber applied in a rotorblade amounted to 0.055 m^3. This corresponded to 78 kg flaxfiber, 100 kg carbon fiber applied in one rotorblade.[1]
Ardente *et al*. assumed that the GFRP content of one Vestas 660 kW generator was 4,950 kg.[2]
Crawford analyzed a 3.0 MW turbine whose blades weighed 20.07 t (12.04 t fiber glass and 8.03 t epoxy).[3]
Martínez *et al*. performed an LCA study of a Gamesa G8X (2MW) turbine whose rotor weighed 19.5 T (each blade 6.5 T and 39m long). This corresponded to 11.7 T resin and 7.8 T fiber glass (pre-preg).[4]
Guezuranga *et al*. analyze a 2.0 MW geared turbine (1538T) with 10T of epoxy (0.6 Wt%) and 24.3 T of fiberglass (1.6 Wt%). The second turbine they analyzed was a 1.8 MW gearless turbine (609.2 T) with 4.80 T of epoxy (1.8 Wt%) and 10.20 T glass fiber (2.6Wt%).[5]
Kabir *et al*. analyzed a 100kW Northern Power turbine, with each blade weighing 1.8T (1.08 T glass fiber and 0.72 T polyester).[6]
Rashedi *et al*. analyzed a REpower 5MW. Each blade was 61.5 m long and weighed 17.74 t and was made of composite prepreg material—70% GF and 30% epoxy resin.[7]
According to Zimmermann, the weight [t] distribution of materials for the blades of an E-82 E2 Enercon turbine are: 1.1 Steels 0.08 Aluminum 29 GFR plastic; Total 30.18 t.[8]

[1] De Vegt, Oron M., and G. Wim Haije. "Comparative Environmental Life Cycle Assessment of Composite Materials." 1997, manuscript courtesy of Dr. Wim G. Haije.
[2] Ardente, Fulvio, Marco Beccali, Maurizio Cellura, and Valerio Lo Brano. "Energy performances and life cycle assessment of an Italian wind farm." *Renewable and Sustainable Energy Reviews* 12, no.1 (2008): 200–217.
[3] Crawford, Robert. "Life cycle energy and greenhouse emissions analysis of wind turbines and the effect of size on energy yield." *Renewable and Sustainable Energy Reviews* 13, no. 9 (2009): 2653–2660.
[4] Martínez, Eduardo, Félix Sanz, Stefano Pellegrini, Emilio Jiménez, and Julio Blanco. "Life cycle assessment of a 2-MW rated power wind turbine." *International Journal of Life Cycle Assessment* 14, no.1 (2009): 52–63; Martínez, Eduardo, Félix Sanz, Stefano Pellegrini, Emilio Jiménez, and Julio Blanco. "Life cycle assessment of a multi-megawatt wind turbine." *Renewable Energy*, 34 (2009): 667–673.
[5] Guezuraga, Begoña, Rudolf Zauner, and Werner Pölz. "Life cycle assessment of two different 2 MW class wind turbines." *Renewable Energy* 37, no. 1 (2012): 37–44.
[6] Kabir, Md Ruhul, Braden Rooke, G.D. Malinga Dassanayake, and A. Brian Fleck. "Comparative life cycle energy, emission, and economic analysis of 100 kW nameplate wind power generation." *Renewable Energy* 37, (2012): 133–141.
[7] Rashedi Ahmad, Idapalapati Sridhar, and J. King Tseng. "Life cycle assessment of 50 MW wind firms and strategies for impact reduction." *Renewable and Sustainable Energy Reviews* 21, (2013): 89–101. Due to necessary cut-off during pre-pregging, the authors note that the actual fiber weight is scaled up by 10%.
[8] Zimmermann, Till. "Parameterized tool for site specific LCAs of wind energy converters." *The International Journal of Life Cycle Assessment* 18, no. 1 (2013): 49–60.

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Of course, a sustainable treatment of end-of-life composite blades from an LCA perspective requires paying attention to dismantling, sorting, cleaning and transporting of the blade, a labor intensive method that requires acquisition of suitable crushing tools. This involves machinery wear and tear, occupational safety and health protection questions regarding fine dust, and outgassing solvents. Polymer resin and GF are not completely separated—the fibers produced are short and have poor mechanical properties. Blade transportation is costly, causes road congestion and adds to pollution. Particularly from the perspective of so-called "thermal recycling"—using blades as feedstock in cement kilns (calorific value 15.3 GJ/ton)—special transportation of blades to the pre-preparation plant is required. Ground blades need to be mixed with certain material that has humidity so the dust of the processed blades will be bound into the mixture. In personal communication, Principal Engineer and Senior Director of Innovation and Technology at TPI composites (TPI/Newton, IA) reported that his company is looking for designs to minimize transportation costs, which will in turn improve the logistics of decommissioning.

Presently, state-of-the-art wind blades have an essentially mixed material structure, making it particularly challenging to extract value from them once they reach their end-of-life because the presence of mixed materials significantly reduces the value of the recyclate.[11]

1.1 Carbon Fiber and Sustainable Wind Blade Design

Incorporating carbon into wind turbine blade design has been shown to achieve cost-effectiveness in wind energy systems—particularly for blades produced in longer lengths intended for use in off-shore projects.[12] Some of the first carbon fiber started showing up in blades in 2002–2003—both in research and development blades as well as in utility-scale designs by European companies like Vestas and Spanish OEM Gamesa.[13] Although there are some unresolved issues with CF properties—particularly compression—and sometimes the fabrics are more difficult to process by infusion, interview data for this chapter supports the case that carbon is very attractive from a property point of view. Presently, the incorporation of CF in blade design is more popular amongst European than US blade manufacturers and OEMs.

[11] Recyclates are waste materials that are collected and/or sorted for the purpose of material recovery.
[12] Ashwill, Thomas D. and A. Joshua Paquettte. "Composite Materials for Innovative Wind Turbine Blades," *SAMPE 2008*, Los Angeles, CA, May 2008.
[13] Vestas and NEG Micon, which merged in 2004, were the first companies to use CF in blade production.

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Another factor which may affect the future trajectory of wind blade design and manufacturing is that there is little financial incentive to recycle GF composites due to the limited application and low value of the recyclate.

The carbon market is volatile due to its dependence on the price of fossil fuels, and the heavy investments needed in machinery and energy for scaling up its manufacturing; nevertheless, several commercial applications for CF recyclate currently exist and demand is expected to increase in the future. Having collaborated with Vestas on a recent wind blade recycling project, James Meredith of the University of Warwick argues that until the recovery cost for CF comes down, adding recyclate to new blade design will not be a cost-efficient program for wind companies.[14]

1.2 Thermoset Versus Thermoplastic Technology for the Design of Wind Blades

On the one hand, modern wind blade design depends largely on thermoset resin matrices that are not easily recycled. The debate over which materials are better suited for wind blade manufacturing runs parallel to the industry's recently initiated efforts to address composite-waste recycling.

Importantly, thermoplastics could be more easily recycled than thermosets because they remain malleable when heated and could thus be re-melted into something else.

On the other hand, there is a whole field of reworkable thermosets that is attempting to address some of the major issues regarding recycling composites. Some of the most notable examples of commercially functional recycling processes for composites and other projects involving composite recyclates include (in chronological order): a) PRECOM Project, 1994–97 (UK) that developed technology for reusing ground thermoset recyclate as filler. b) R. J. Marshall (Southfield, MI) R.J. Marshall has been recycling thermoset varieties since the late 1990s—grinding them into a specified particulate material and then selling that regrind back to molding manufacturer who can put it into virgin compound at a percentage not to exceed ten percent.[15] More recently, Alpine Milled Glass—a division of R.J. Marshall–is buying offset fiberglass from Owens-Corning and PPG Industries to process it into milled fiberglass, which is a filler in many plastic compounds. c)

[14] Personal communication.

[15] After a brief collaboration project with General Motors (GM), GM moved that process to China and R.J. Marshall had to pull out of the market between 1998 and 2000. During that time the company kept the research up and worked with colleagues in Europe and Japan—basically waiting "for the time here in the US when either driven by carbon footprint, green focus, or government regulation, that there would be a time…where thermosets would need to be recycled" (Tim Price, Vice President of R J Marshall, personal communication).

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FibreCycle Project 2007–2011 Umeco (UK) and other contributors Funded by the UK Government, the project developed methods to apply CF recyclate in thermoplastic and thermoset applications. d) EUROCOMP Project (2009–2012), EU, various collaborators Funded by the European Union, EURECOMP focused on recycling thermosets via solvolysis and Life Cycle Assessment.

Although thermoplastic technologies are being applied successfully to commercially produce small size blades for "micro" turbines, currently no available thermoplastic material can be used to produce wind blades for industrial-size machines.

2 The US Wind Blade Supply Chain and End-of-Life Management of Composite Waste

2.1 Wind Blade Manufacturing Plants, Composite Suppliers to the Wind Energy Sector, and Blade-design Academic Research and Testing in the US: An Overview

The global wind blade market is linked to the wind energy industry as a whole. Most of the large turbine owners—except GE[16]—like Vestas, Siemens, Gamesa and Enercon are designing, manufacturing, and holding all of the blade technology in-house. For the remaining companies, however, particularly the newer ones, like Netherlands-based GBT, one company owns the technology and another one finishes the blades. The second important distinction, as far as outsourced blades are concerned, is between standard designs and custom-designed blades. On the one hand, "standard" blades can be bought off the shelf—and the manufacturer that serves the largest piece of that market is Danish LM Wind Power. On the other hand, the custom design blade market is much more fragmented with different, smaller, companies doing design, tooling, etc.[17] The industrial and non-industrial wind industries are largely unconnected.

Primarily located in the Midwest, the US blade manufacturing industry has an expected capacity of 12,500 blades per year (AWEA, 2012) and is expected to grow. The US wind blade supply chain features a considerable number of composite suppliers (Table 3). MFG and LM Wind Power launched the industry in 1997–1998, while most currently active manufacturing plants opened between 2006 and 2008. Amidst lay-offs in US blade factories, a third generation of plants came online

[16] GE holds the technology in-house but TPI Composites is the manufacturer.

[17] This means that when a company wants a custom-designed blade, first they have to go to a blade designer and order a design; then, they have to go to a different company to order the tooling; and, finally, they have to go yet again to a different company to have the blades manufactured. A third distinction in the blade market, therefore, is that between custom blade industry companies that perform all of those steps in-house and companies that do not.

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Table 2 Indicative list of companies supplied by US-based wind blade manufacturing plants (interview data).

Company/plants (US)	Supplies blades to
LM Wind/ Grand Forks, ND and Little Rock, AR	Acciama, Impresta, GE Wind, Gold Wind, Gamesa, Nordex
MFG/Gainesville, TX Aberdeen, SD	GE Wind
TPI/Newton, IA	GE Wind and Mitsubishi

Table 3 US composite suppliers to the global wind blade industry (interview data and data compiled online)

Ashland Performance Materials (Ashland, OH)	Ashland makes the Derakane 601-200 series resins (epoxy vinyl ester resin for infusion) and the Aropol G300/M300 series resins (unsaturated polyester infusion resin).
Bayer MaterialScience LLC (Pittsburgh, PA)	Supplier of carbon nanotube reinforced polyurethane composites.
Cyclics Corporation (Schenectady, NY)	Supplier of fiber-reinforced cyclic butylene terephthalate (CBT) thermoplastic resins.
Cytec (previously Umeco, Woodland Park, NJ)	Supplier of advanced CF and GF reinforced epoxy and polyester resin impregnated composites.
Dow Chemical Company (Midland, MI)	Supplier of the Dow AIRSTONE™ system of epoxy resins.
Hexcel (Stamford, CT)	Supplier of pre-pregs (e.g. HexPly® Prepregs) as well as reinforcements and laminates.
Huntsman Advanced Materials (McIntosh, AL)	Supplier of the Araldite® epoxy adhesives and laminating resin systems.
Momentive Performance Materials Inc. (previously Hexion, Columbus, OH)	Supplier of the EPIKOTE MGS RIMR 145 epoxy resin systems for wind blades that allows the incorporation of CF in wind blade design. Supplier of Epikure™ epoxy systems.
Owens Corning Composite Materials (Toledo, Ohio)	Supplier of the Ultrablade™ and Rapidblade™ fabric solutions.
PPG Industries (Pittsburgh, PA)	Supplier of GF.
Zoltek Inc (Bridgeton, MO)	Supplier of Panex 35 (a 50K Continuous Tow product) for use in wind blades. Zoltek's St. Peters, MO factory also makes CF prepreg.

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Table 4 Current and past wind blade and wind blade manufacturing waste recycling projects (interview, literature and online data).

REACT project (2003–2005)	DNV KEMA, Aerpac and Hanze Milieu collaborated on a project that looked at several end-of-life management options for the turbines of the Dutch Eemshaven wind farm. The project built and tested a hybrid shredder, which was able to reduce fiber reinforced plastics to 15–25 mm. According to DNV KEMA, from the various thermal processing methods and material recycling options considered, "two processing methods turn out to offer the best prospects. In the short term, thermal processing of the turbine blades in the cement industry will be possible. In the longer term, mechanical recycling is to be preferred" (Larsen, 2009; interview data).
Project "Sustainable Utilization of Lager Blades in the LagerDörf Cement Plant" (Holcim, Ltd., (2006-onwards)	Holcim started working on this issue in collaboration with German OEM Enercon in 2006, and the project became commercial in 2010. Holcim's process—the cost of which is 800–900 euros per ton—works as follows: 1. Size reduction (10m pieces) at the wind power plant with mobile saws; 2. Transport to the pre-preparation platform where further reduction in an encapsulated system takes place—recycling of ferrous and non-ferrous metals; 3. Pre-cut blades are sent to the encapsulated plant (max size 50mm); 4. Homogenization of the shredded blade with a wet material to make fuel (calorific value approximately 15MJ/Kg)—the rotor blade ashes are incorporated into the clinker matrix (ash content approximately 50%). Zajons Logistik is responsible for the collection and pre-processing of the blades—including size reduction on site. In 2010 Holcim processed 100–150 tons, in 2012, 400 tons and in 2013, 1000 tons. The company expects to process some 10,000 tons per year of end-of-life blades from Germany alone for the years 2015–2016. According to Erwin Schmidl "every blade that Vestas has will be processed by us" (personal communication).
i Composites consortium (2010–2011)	Andrew Dyer and Amaury Vuillaume, then with Vestas Technology UK and Vestas Recycling, led a project whose goal was "to manufacture and test wind blade sub-structures from recycled composite materials and importantly, to assess the viability of using recyclates in the design *and* manufacturing process." According to Vestas, this project of "[i]ncorporating recycled fibres in demanding structures could have a real impact on the lifecycle of composites and is seen as an important sustainable development for these materials" (Dyer, 2010; interview data). Concurrently, Vestas was also collaborating with Boeing Company on mapping the possibilities for CFRP recycling (Marian Kjærgaard, personal communication).[1]

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GENVIND innovation consortium (Denmark, 2012–2016).	With a budget of 14 million kroner, financed by The Danish Agency for Science, Technology and Innovation, GENVIND was created to address the full circle of wind blade decommissioning for both thermosetting and thermoplastic blades. In the next few years, Danish wind farms alone are expected to decommission approximately 5000 turbines. The project seeks different ways of treating wind blade composite waste and investigates possible applications for both high and low tech components that could potentially be produced out of the recyclate. The various partners of the consortium—including manufacturers (LM Wind, Siemens and Vestas), recyclers, universities, chemical companies, etc.—will also collaborate with the Danish authorities regarding potential relevant legislation. By rethinking end-of-life management of wind blades, GENVIND will consider ways to optimize production. Some of the project's steps include: 1. Filling knowledge gaps in resin/fiber separation technology; 2. Evaluating the properties of recovered fibers; 3. Researching possible end-uses of reclaimed fibers. In the context of GENVIND, all participants are bounded by a consortium agreement and a nondisclosure agreement (interview data).	
Refiber Aps (Denmark)	Has been using pyrolysed GRP wind blade waste in insulation slabs since 2000–2001(Larsen, 2009).	
Companies which have been reusing wind blade production waste: Barsmark Building Solutions (Denmark) and Fiberline.	Since 2000–2001, Barsmark has been reusing production waste from blades made with prepreg epoxy GF composite materials, collecting from various production sites in Europe [Vestas, LM Wind, Gamesa] while the resin is still uncured. Barsmark uses that waste to make flat laminate sheets in their facility in Germany, but is also working on expanding their range of products. Barsmark—whose technology is strictly based on pre-preg—is "more interested in reusing the blades instead of trying to recover the energy or recycle the material" (Romain Sacchi, personal communication).	Fiberline—a pultrusion company—makes composite profiles for the wind industry. Since 2010 they have been collaborating with Zajons Logistics EmbH, and Holcim Ltd. to recycle their profiles in cement production. According to Fiberline's Benedikte Jørgensen, "it is important that you start building the business or the industry to handle production waste. That way you can have the volumes and you can get the experience and you can be ready for the day to come where you have to handle [end-of-life] blades" (personal communication).

[1] According to Kjærgaard, this was the first time that Vestas looked into composite recycling systematically—at the time, the main driver was to find potential technologies to reuse the CFs in new blade manufacturing (personal communication).

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Table 5 Composite Recyclers in the US (interview data unless noted otherwise).

Company	Composite recycling	LCA-blades recycling
Adherent Technologies Inc. (ATI) (Albuquerque, NM)	ATI successfully separates and recovers CF from carbon-reinforced epoxies. The company has been recycling composites since 1995. ATI has tested pyrolysis and chemical treatments but currently employs a low temperature, low-pressure technology.	Interviewee states that "any end of life cycle development [for composites] is really important"; has doubts whether "the wind industry, with their relatively small quantities [of decommissioned blades] is the place where I would start putting these [LCAs] out"; believes that once blades reach a content of at least 50% CF it might be worth trying to mechanically remove glass and then process the material (Jan Gosau, personal communication).
Firebird Advanced Materials Inc. (Raleigh, NC)	Firebird features a continuous microwave CFRP recycling process.	NA
Global Fiberglass Solutions, Inc. (GFS) (Bellevue, WA)	Since 2010, GFS is able to recycle end-of-life GF blades as well as GF manufacturing scrap.	Interviewee reports that it is in the process of creating the "cradle to cradle solution for wind energy" (Don Lilly, personal communication).
Materials Innovation Technology (MIT-RCF) (Fletcher, NC)	MIT-RCF is an advanced materials company that has processed technology which can reclaim, re-engineer, and repurpose chopped CFs. Reports are that since 2011 MIT-RCF has created a production facility which has kept over two million pounds of composite scrap out of the landfill. This scrap will yield about fifty percent fiber—so, about a million pounds of carbon fiber—that MIT can reintroduce back into the supply chain.	Interviewee reports that their technology is "100% applicable" to end of life CF-reinforced plastic wind blades; reports to have worked with processing CF from Gamesa's (Fairless Hills, Pennsylvania) plant. MIT-RCF's Jim Stike feels that it is imperative that LCA data or tools can be made available to the industry, to help quantify and justify the benefits and negative aspects of landfilling composites (personal communication).

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R. J. Marshall (Southfield, MI)	R.J. Marshall has been recycling thermoset varieties since the late 1990s—grinding them into a specified particulate material and then selling that regrind back to molding manufacturer who can put it into virgin compound at a percentage not to exceed ten percent.[1] Alpine Milled Glass—a division of R.J. Marshall–is buying offset fiberglass from Owens-Corning and PPG Industries to process it into milled fiberglass, which is a filler in many plastic compounds.	Although R.J. Marshall is not officially working on a commercial basis with any wind energy blade molders, they are working with some FG distributors who make FG available to blade manufacturers in order to investigate the possibilities of recycling manufacturing scrap. Interviewee reports familiarity with LCA studies performed by ACMA (American Composites Manufacturers Association).
Ecowolf Inc. (previously Seawolf Design/ FRP Equipment Inc., Edgewater, Florida).	The company employs a mechanical recycling technique—invented by Wolfgang Unger in 1973—for GFRP scrap that uses their ECO-Grinder™ to grind the material, which is then reintroduced as dry spray. The company's ECO-Dispensing Macerator™ transports the grind material to the spray-up equipment.	NA

[1] After a brief collaboration project with General Motors (GM), GM moved that process to China and R.J. Marshall had to pull out of the market between 1998 and 2000. During that time the company kept the research up and worked with colleagues in Europe and Japan—basically waiting "for the time here in the US when either driven by carbon footprint, green focus, or government regulation, that there would be a time…where thermosets would need to be recycled."

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in 2011–2012—about the same time (2011), Gamesa closed their Fairless Hills, PA plant.[18]

Substantial research on composite materials engineering as it pertains to wind blade design and manufacturing is currently taking place in the US (Table 6).

2.2 *Recycling of Composite Materials: What Legislation and Current Practice Tells us About End-of-Life Blades*

The aim of the recycling process for composite materials, which began taking shape in the late 1980's is to reclaim polymer content (resin) and find a second home for fiber composites. Once separated, the resins are usually used for energy production, while the fiber recyclates can be reused or recycled. Presently, the majority of composite recycling goes into lower value products.

3 Conclusion: The Past and Future of Composite Blade Recycling

Based on interview data collected for this article, it appears that all but a few blade manufacturers and/or OEMs have been involved in research or experimental projects regarding composite wind blade recycling over the last 13–14 years. All the projects since 2000–2001 are of European origin. Around this time, the Danish company Barsmark Building Solutions started reusing production waste from blades made with prepreg epoxy GF composite materials, collecting from various production sites in Europe.[19] Interview data also shows that important steps have recently been taken in the US as a market is being established for composite recycling across the country and as the composite recycling infrastructure is continually being improved.

All but one of the major composite recyclers in the US recycle CF; this chapter, however, shows that this particular GF recycling company, Global Fiber Solutions, Inc., may in fact revolutionize future end-of-life blade treatment. GFS' major challenge in the next 5–10 years is to develop a solid supply chain including blade collection, sorting and categorization of recyclates. CF recyclers have emphasized the need for publicly available data on the volume of manufacturing scrap generated today by CF and CFRP producers, as well as the lack of incentives for recycling by state governments. Other significant challenges that US composite recyclers

[18] In January 2009, Gamesa announced that they would be laying off 184 workers at their Fairless Hills facility due to the inability to produce the blade sizes that are in demand. In the summer of 2012, LM Wind Power laid-off a total of more than 300 workers from its two US-based wind blade plants. Lay-offs progressively turned Suzlon's blade plant in Pipestone Minnesota into a blade service and customer service facility only (interview data).

[19] Around 2010, LM Wind began implementing a program called "Fuel for Growth" to treat GF manufacturing scrap (LM Wind, personal communication).

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Table 6 Centers of research on composite materials and wind blade manufacturing (interview and online data).

Academic research (US)	Academic research (non-US)	Government-sponsored (US)	Blade testing centers (US)
Case Western Reserve University	Composites Centre at Cranfield University (Cranfield, UK)	The group leading wind blade research in the US is the Wind Energy Technology Department at Sandia National Laboratories (SNL).	AEWC (Advanced Structures and Composites Center) at the University of Maine—testing up to 70m.
Iowa State University	National University of Ireland, Galway		NREL (testing up to 50m)
Montana State University[1]	Risø National Laboratory for Sustainable Energy at the Technical University of Denmark, Risø DTU, (Roskilde, Denmark)[2]		TPI Composites Fall River Blade Development Center in Fall River, Mass., which also has access to WTTC.
Polytechnic Institute of New York University	University of Technology (Delft, The Netherlands)		Virginia Polytechnic Institute and State University's Stability Wind Tunnel.
Rochester Institute of Technology	University of Sheffield (Sheffield, U.K)		Wind Technology Test Center in Charlestown, Massachusetts (WTTC) at the Massachusetts Clean Energy Center.
University of Maine/Advanced Structures and Composites Center (AEWC)	University of Twente (Enschede, The Netherlands)		
University of Massachusetts at Lowell, Wind Energy Research Group	Indian Institute of Technology Roorkee (India)[3]		
University of Pennsylvania			
Virginia Polytechnic Institute and State University			

[1] Wind blade-related research at Montana State University primarily evaluates fatigue performance of blades and simple laminates. Another focus of the research is on improving methodologies for estimating the performance of blade materials in service (John Mandell, personal communication).
[2] The National Laboratory has a fiber component that deals with basic material science questions such as process and development of fiber composites (Christen Malte Markussen, personal communication).
[3] The researchers Inderdeep Singh and Pramendra Kumar Bajpai are investigating the challenges and opportunities of using biocomposites in wind blade manufacturing (personal communication).

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Table 7 Examples of commercially functional recycling processes for composites and other projects involving composite recyclates (interview data unless noted otherwise).

AFRECAR Project, University of Nottingham, (UK)	AFRECAR is one of several projects that used solvolysis to recycle thermoset composites (Job, 2010).
E3 Comp Project (2008–2010), University of Birmingham, (UK)	The project focused on developing a method to use recycled short-fibers to produce hybrid filament wound components (Job, 2010).
ERCOM (Germany)	In Germany in the early 1990s, ERCOM Composite Recycling GmbH developed a mechanical method (e.g. mobile shredder) of material recycling that was later used by other companies—including R.J. Marshall Company (US).
EUROCOMP Project (2009–2012), EU, various collaborators	Funded by the European Union, EURECOMP focused on recycling thermosets via solvolysis and LCA (Job, 2010).
FibreCycle Project 2007–2011 Umeco (UK) and other contributors	Funded by the UK Government, the project developed methods to apply CF recyclate in thermoplastic and thermoset applications.
Filon (UK)	Ever since 2009–2010, the GRP building product manufacturer has used a two-step (first small flakes, then fine powder) mechanical recycling method to incorporate recycled waste into its product lines.
Formax (UK)	Beginning May 2013, Formax UK, the composite reinforcements manufacturer, claims to be able to reprocess the majority of its GF and CF waste.
Hambleside Danelaw (UK)	Besides mechanically recycling their own GFRP roofing products, the company has been involved in recycling GF end-of-life blades—to be used as additives to concrete.
HIRECAR Project 2005–2009 University of Nottingham and various contributors	Used reclaimed short carbon fibers to produce BMC (Job, 2010).
Miljotek (Norway)	Mechanical recycling of GFRP.

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Mixt Composites Recyclables, MCR (France)	Grinding process and valorization of GFRP.
Mitsui Mining and Smelting Co., ltd. (Japan)	Mitsui has formed a collaboration with members of the Recycling Committee of the Japanese Carbon Fibre Manufacturers Assn. (JCMA) to recycle carbon fiber; the recyclate is targeted at the electronics and automotive industries.
Pearl Baths (US) and Royaline Industries (US)-Minnesota Technology Inc.	Following a report written by Minnesota Tech Inc., the two companies experimented with mechanical recycling in two spray-up processes.
Phoenix Fiberglass (Canada)	In the early 1990s, Ontario-based Phoenix Fiberglass operated a plant in Oakville, Ontario that was processing 6,000 tons/year of FG waste material. The company was selling its products to automobile part manufacturers, as well as to the construction and home-building industries.
Plastic Omnium Auto Exterieur (France)	Uses GFRP ground recyclate as filler in composite parts (e.g. radiator brackets) (Job, 2010).
PRECOM Project, 1994–97 (UK)	Developed technology for reusing ground thermoset recyclate as filler.
RECCOMP Project (2005–2008)	RECCOMP was a three-year, UK government-sponsored program to develop SMC/BMC [sheet and bulk molding compounds] from recycled SMC/BMC through a granulation process.
Recycled Carbon Fibre (UK)	The company offers a commercially active pyrolysis method to recycle cured CFRP.
RECYCOMP (1 and 2), 2002–2005, France, various collaborators	In this project, several French composite products manufacturers collaborated to conclude that incineration in cement kilns is the most appropriate waste management treatment for polyester/GF.
3B Fiberglass and Reprocover (both in Belgium)	The two companies collaborated to use GF waste (3B) in original composite applications.

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Picture 1 Old test blades at LM Wind Power, Lunderskov, Denmark. (Photo courtesy of LM Wind and the GENVIND innovation consortium).

are currently facing include standardization (for both waste and product certification), and requalification of any materials, particularly because qualifying composites requires time and investment.

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