ELECTRIC POWER RESEARCH INSTITUTE

# Wind Turbine Blade Recycling

## Preliminary Assessment

2020 TECHNICAL REPORT

# Wind Turbine Blade Recycling

Preliminary Assessment

**3002017711**

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THE FOLLOWING ORGANIZATIONS, UNDER CONTRACT TO EPRI, PREPARED THIS REPORT:


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**Urban Venture Group, Inc.**


## NOTE

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# ABSTRACT

In 2019, the Electric Power Research Institute (EPRI) commissioned the American Composites Manufacturers Association (ACMA) to carry out a preliminary assessment on wind turbine blade recycling. The study included the following four components: wind turbine blade scrap resource assessment; material and energy recovery technology assessment; site location considerations; and summary of existing preliminary techno-economic analysis models. This report summarizes that work, offers guidance to the wind power industry with regard to the magnitude of the issue of wind turbine blade waste, offers potential solutions, and suggests next steps.

**Keywords**
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## Product Title: Wind Turbine Blade Recycling: Preliminary Assessment

**PRIMARY AUDIENCE:** Utility solid waste managers

**SECONDARY AUDIENCE:** Wind power owners

### KEY RESEARCH QUESTION

The service life of wind turbines ranges from fifteen to twenty-five years, and the first generation of turbines are now being decommissioned. Due to expanding use of wind power and increasing numbers of turbines coming offline each year, managing wind turbine blade end-of-life issues is a growing long-term concern. Wind turbine blades are especially challenging to manage due to their size and limited recycling options. The growing challenge of recycling composites affects the wind industry as well as the entire composites market.

### RESEARCH OVERVIEW

The Electric Power Research Institute (EPRI) commissioned the American Composites Manufacturers Association (ACMA) to perform a preliminary assessment on wind turbine blade recycling. The assessment was based on global and national sources of information, interviews with industry leaders, and communications with experts.

The study included the following four components:

- Wind turbine blade scrap resource assessment
- Material and energy recovery technology assessment
- Site location considerations
- Techno-economic analysis (TEA) models

Four technologies were reviewed that are commercially available for managing end-of-life composite wind turbine blades:

- Life extension
- Pyrolysis
- Cement kilns
- Grinding and re-use as filler material in a variety of products

### KEY FINDINGS

- The projected amount of blade waste could vary from about 200,000 tons per year (based on a 15-year lifetime) up to about 370,000 tons per year (based on a 25-year lifetime) by 2050; the cumulative blade waste through 2050 is estimated at about 4 million tons.
- Availability of other sources of composite (and other types of) scrap to maintain adequate recycled material quantity and consistency is key for commercial viability of a given recycling option.
- Wind turbine blades are made of tough, fiber-reinforced polymer (FRP) composites, making them difficult and expensive to process and recycle; most recycling technologies require front-end processing to a size of 1 inch or less.

- Transportation is a large cost variable; proximity of central processing and recycling facilities to a high concentration of wind farms and to major transportation networks is important.
- Mechanical reprocessing (grinding and use as filler) faces economic and market challenges, including a current lack of high-value end-use applications.
- Cement kilns are more sustainable but currently cost about twice as much as solid waste disposal.
- Pyrolysis offers more attractive economics for recovery of carbon fiber than for glass fiber; it requires more technology development and a higher initial investment than the other options.
- Primary recommendations for research include the following:
  - A rigorous TEA comparing life extension, pyrolysis, cement kilns, and re-grind/re-use, particularly in comparison with solid waste disposal
  - Assessment and development of other emerging technologies and uses
  - Collaborative development of a commercial-scale facility for front-end processing of composites scrap

**WHY THIS MATTERS**

Management of wind turbine blades is a growing issue as wind power continues to expand and older turbine units are decommissioned. Research to develop economic technologies for recycling and reuse is needed to provide sustainable alternatives to landfill disposal.

**HOW TO APPLY RESULTS**

- To become familiar with current and projected volumes of wind turbine blades
- To understand pros and cons of commercially available recycling technologies
- To inform research priorities and collaborative efforts

**LEARNING AND ENGAGEMENT OPPORTUNITIES**

- Environmental Aspects of Renewables Program (P192)
- Renewable Energy and Battery Storage End-of-Life Strategic Initiative Supplemental Project
- American Wind Energy Association (AWEA, https://www.awea.org/)
- American Composites Manufacturers Association (ACMA, https://acmanet.org/)

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# 1 INTRODUCTION

The Electric Power Research Institute (EPRI) commissioned the American Composites Manufacturers Association (ACMA) to perform a preliminary assessment on wind turbine blade recycling. The study included the following four components, each comprising a chapter in this report:

**1. Wind Turbine Blade Scrap Resource Assessment**

- Forecast wind turbine blade scrap resources through 2050
- Estimate materials comprising wind turbine blades
- Discuss non-wind scrap sources for potential leveraging of recycling

**2. Material and Energy Recovery Technology Assessment**

- Summarize available and anticipated recycling technologies to process wind turbine blade scrap for glass fiber reinforced polymer (GFRP) and carbon fiber reinforced polymer (CFRP) materials
- Consider technology readiness level; emissions management; process management; and safety, handling throughput, and economics

**3. Site Location Considerations**

- Assess factors in site location for wind turbine blade scrap processing and handling, including logistics, regulatory, economic, and other factors

**4. Techno-Economic Analysis (TEA) Models**

- Summarize and compare TEA models for energy and material recovery technologies
- Consider the relative cost of transportation by various modes

In turn, ACMA partnered with Urban Venture Group (UVG) to prepare this report under EPRI guidance. Many global and national sources of information were reviewed, interviews with industry leaders conducted, and emails with experts exchanged. At various stages the findings were presented and discussed among ACMA, UVG, and EPRI. In addition, a special meeting was called with the team associated with the 2018-2019 project *Controlled Pyrolysis: a Robust Scalable Composite Recycling Technology*[1] to provide further feedback on the technologies discussed in Chapter 3. This report is a synthesis of that work and is intended as a tool to help guide the wind and power industry towards understanding the magnitude of the issues regarding wind turbine blade waste and presenting potential solutions.

[1] Ludwig, C. and Ginder, R., "Controlled Pyrolysis: A Robust Scalable Composite Recycling Technology," *IACMI Draft Final Technical Report*, 2019.

# 2
# WIND TURBINE BLADE SCRAP RESOURCE ASSESSMENT

## 2.1 Overview: Wind Resources and the Need for Recycling

The U.S. hosts one of the largest and fastest-growing wind markets in the world.[2] For more than twenty years, wind power has been increasingly adopted in the U.S. for electric generating capacity. By 2018, the cumulative generating capacity was about 100 gigawatts and by 2020, it is expected to supply 10% of national end-use electricity demand (Figure 2-1). Moreover, wind now comprises about 30% of new capacity nationwide.[3] Moreover, wind power is expected to grow substantially in the coming years. Using a scenario of wind power supplying 20% national end-use electricity demand by 2030 and 35% by 2050, the U.S. Department of Energy projects that the total wind generating capacity will reach 224 gigawatts by 2030 and 404 gigawatts by 2050.[4]

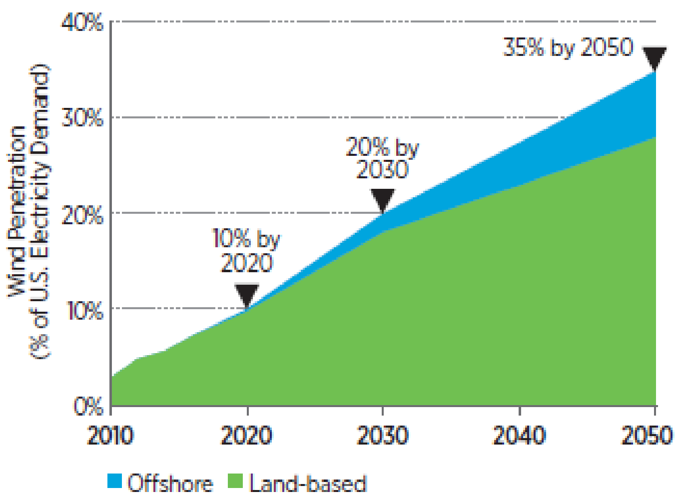


**Figure 2-1**
**U.S. Department of Energy estimates of growth in wind power generating capacity by 2050[5]**

[2] https://www.energy.gov/science-innovation/energy-sources/renewable-energy/wind

[3] https://www.energy.gov/eere/wind/downloads/2017-wind-technologies-market-report

[4] https://www.energy.gov/maps/map-projected-growth-wind-industry-now-until-2050

[5] https://www.energy.gov/eere/wind/wind-vision

However, the lifetime of wind turbines ranges from about fifteen to twenty-five years, and many of the initial generation of turbines are already reaching end-of-life. As wind energy grows, so does the issue of end-of life-disposal when the turbines are decommissioned. The giant blades are difficult and expensive to recycle, and are therefore normally disposed as solid waste since this is currently the least expensive option. For instance, the Kimball wind project, Nebraska's first wind farm, is being scrapped after about twenty years of activity, and two wind-farms in northern Iowa are arranging for disposal at a South Dakota sanitary landfill; in 2019, 101 turbine blades were trucked there.[6] As wind turbine installations grow, concerns over end-of-life management are growing as well.

A wind turbine assembly includes the rotor (typically with three blades), nacelle (turbine generator and housing), tower, and foundation (Figure 2-2, left). Today, a significant part of a turbine includes recyclable materials: the foundation is concrete; the tower is steel and concrete; and the nacelle components are primarily made of steel and copper. Currently, most components can be recycled economically at end-of-life except the blades, which are a mixture of materials that cannot be separated easily. The blades are difficult to recycle as their structure is comprised of about 80%-90% composite by weight (glass fiber [GF] and/or carbon fiber [CF]-reinforced polymer, referred to in this report as GFRP and CFRP), with the rest as foam, balsa, metal, adhesive, paint, and other materials. High-value uses for recovered blade material currently do not exist, so solid waste disposal is the management option most often selected. As larger numbers of wind turbines are decommissioned, the issue of blade disposal is becoming a greater concern (Figure 2-2, right).

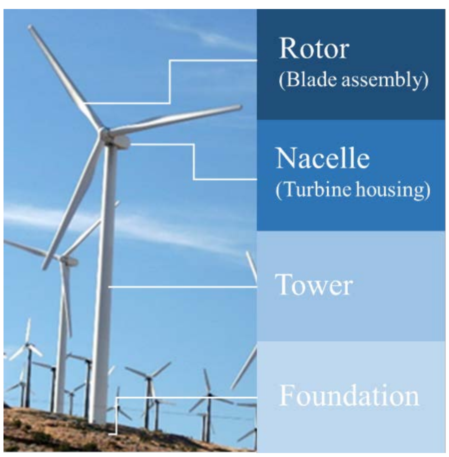


**Figure 2-2**
**Wind turbine components in service (left) and blades at end-of-life (right)**

**Left: Wind turbine components include the rotor (blades), nacelle, tower, and foundation. Right: Today, decommissioned wind turbine blades are typically cut up and transported by truck for solid waste disposal.[7]**

[6] https://www.aei.org/carpe-diem/the-environmental-fiasco-of-wind-energy/

[7] Derek Berry, NREL, used by permission.

Additionally, newer installations have all seen significant increases in turbine and rotor size and height over time, as this increases the generating capacity, growing from an average rotor diameter of 50 meters in 1998 to over 110 meters in 2017. However, disposal becomes more difficult as the blade size increases; for instance, some individual blades are now longer than a football field.

Whereas Figure 2-1 shows the magnitude of cumulative installations, Figure 2-3 shows the historical and projected capacity additions by year.

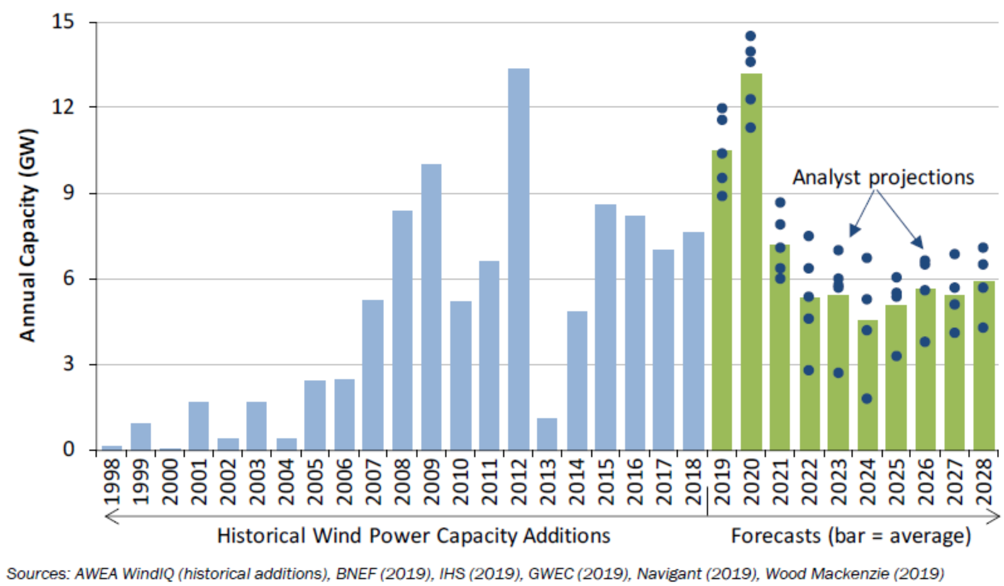


**Figure 2-3**
**Wind power capacity additions: historical installations and projected growth[8]**

The wide variations from year to year in Figure 2-3 are primarily due to changes in tax incentives such as the Production Tax Credit (PTC).[9] The PTC offers incentives to "repower" projects by upgrading existing turbines with newer, more efficient components. Repowering is intended to increase energy production of a turbine by about 25% as well as extend the lifetime. In full repowering, the original wind turbine is replaced with new and improved equipment. In partial repowering, damaged or aged parts are replaced with uprating equipment (e.g., blade or generator).[10] The PTC was renewed in 2013 and provided a tax credit for wind generation of up to 2.3 cents per kilowatt-hour (kWh) for the first 10 years of production. As it phases out, the tax credit decreases by 20% per year from 2017 through 2019. Facilities starting construction after December 31, 2019, can no longer claim the PTC.[11]

These rules are causing some early blade decommissioning and a short-term increase in the amount of blades decommissioned *en masse* from 2017-2020.  The opportunity to qualify or re-

[8] https://www.energy.gov/sites/prod/files/2019/08/f65/2018%20Wind%20Technologies%20Market%20Report%20FINAL.pdf

[9] https://programs.dsireusa.org/system/program/detail/734

[10] https://sentientscience.com/blog/is-repowering-a-viable-option-for-the-life-extension-of-aging-wind-turbines/

[11] https://www.eia.gov/todayinenergy/detail.php?id=39472

qualify a site for the PTC and tax rules essentially requires scrapping instead of re-use, which has begun to raise concerns across both the wind industry and local landfills.

## 2.2 First-Pass Estimate of Wind Turbine Blade Scrap Resources

In addition to end-of-life waste of the blades associated with turbine decommissioning, both the waste from manufacturing and replacements during the service lifetime add between 16 and 45% of the mass of the wind turbine blades requiring management.[12] Arias converted the installed and projected capacity to tonnage (using a conservative factor of 9.57 tons of blade material per megawatt)[13] and Liu and Barlow added a moderate 25% additional manufacturing waste and waste during the service lifetime.[14] If we project these numbers forward as end-of-life scenarios using turbine lifespans of 15, 20, and 25 years, the anticipated tonnage of blade waste by year is shown in Figure 2-4.

Consequently, in Liu and Barlow's end-of-life scenario, by 2050 the projected amount of blade waste could vary from about 200,000 tons per year (based on a 25-year lifetime) up to about 370,000 tons per year (based on a 15-year lifetime). Moreover, the cumulative blade waste up to 2050 is estimated at about 4 million tons. Additional scenarios based on a 20-year lifetime, discussed in the Appendix, vary from 50,000-300,000 tons per year by the year 2050.

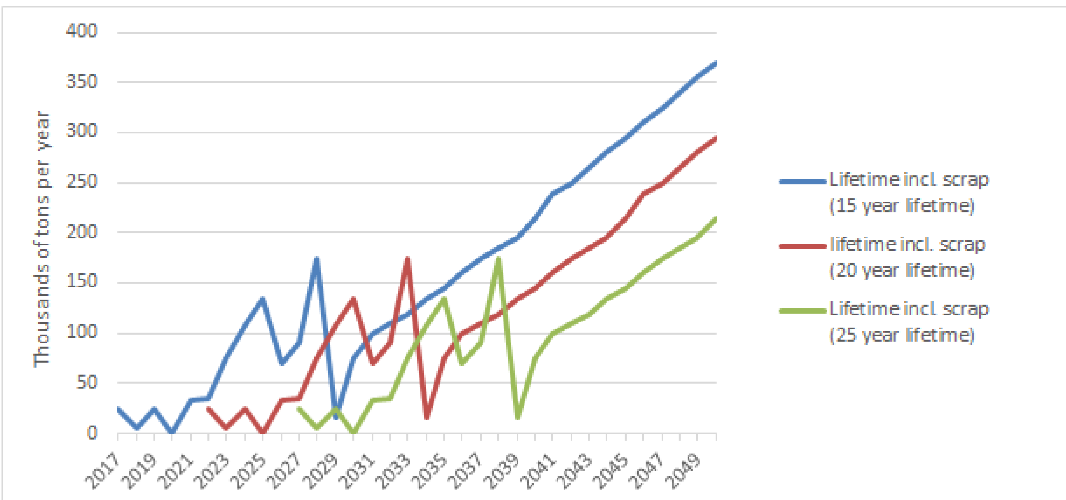


**Figure 2-4**
**Estimated annual quantities of wind turbine blade waste produced, based on Liu and Barlow estimates[15] and lifespan scenarios of 15, 20, and 25 years.**

[12] Liu, Pu, and Barlow, Claire Y., *Wind Turbine Blade Waste in 2050*, University of Cambridge Institute for Manufacturing, UK, p. 19, 33.

[13] Franco Arias, "Assessment of Present/Future Decommissioned Wind Blade Fiber-Reinforced Composite Material in the United States," submitted May 23, 2016, as *Independent Study to the City College of New York – City University of New York Department of Civil Engineering.*

[14] Liu, Pu, and Barlow, Claire Y., *Wind Turbine Blade Waste in 2050*, University of Cambridge Institute for Manufacturing, UK, p. 19, 33.

[15] Liu, Pu, and Barlow, Claire Y., *Wind Turbine Blade Waste in 2050*, University of Cambridge Institute for Manufacturing, UK, p. 19, 33.

## 2.3 Estimates of Constituent Materials

Composites (glass and/or carbon fiber in a polymer matrix) can account for 80-90% of the weight of wind turbine blades, with the remainder comprised of steel, paint, balsa wood, adhesives, cables, and other materials[16] in a complex structure, as depicted in Figure 2-5. This mixed, integrated composition presents particular challenges in recycling. Moreover, different manufacturers and blade models present further variations in material composition and structure.

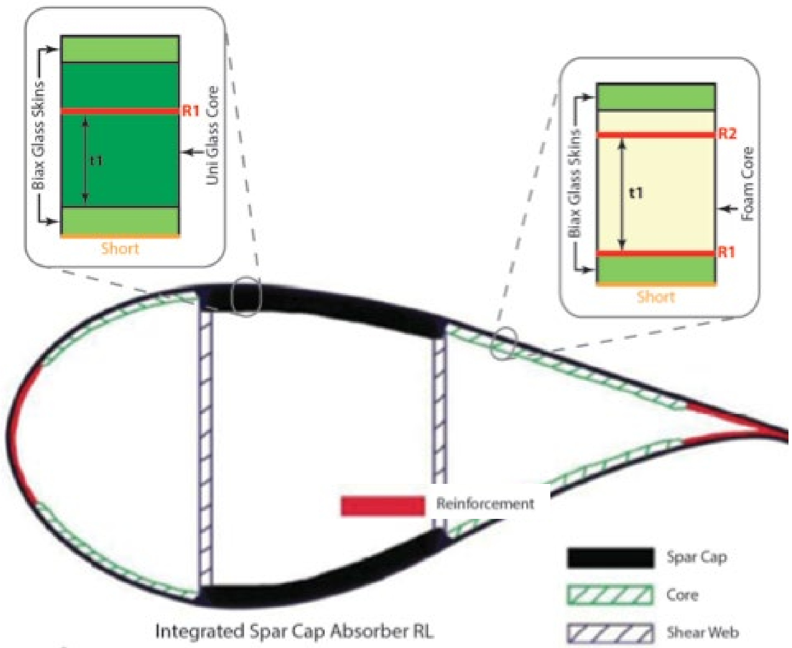


**Figure 2-5**
**Example of wind turbine blade construction (Sandia National Laboratories)**[17]

Both the integrated structure and varying composition present special challenges in recycling, as recycling processes typically require breaking down the feedstock to be recycled into separate material components. This is done in order to produce uniform end products that can be marketed and sold, such as grades of glass or carbon fiber having set specifications such as strength and fiber length.

## 2.4 Leveraging Non-Wind Scrap Material Sources

Wind power is not the only industry facing the issue of how to manage end-of-life composites. According to ACMA, in the first six months of 2019 new composites production in the U.S. plus Canada totaled 1.85 million tons.[18] This can be compared to about 100,000 tons of new composites produced for wind energy. These new composites (as well as older ones) will

[16] Liu, P. & Barlow, C., 2016, "The environmental impact of Wind Turbine Blades," *Presentation at the 37th Risoe International Symposium on Material Science*, pp.1–16.

[17] https://energy.sandia.gov/energy/renewable-energy/wind-power/wind-turbine-siting-and-barrier-mitigation/radar-friendly-blades/

[18] ACMA Total Composites Industry Report, Second Quarter 2019.

eventually reach end-of-life and can potentially be subjected to similar recycling processes as wind blades, rather than being sent to a landfill.

Recycling can be advantageous, not only for wind but for other sectors as well. Figure 2-6 (left) shows the relative composites quantities produced, of which wind comprises about 5% as part of “Other”. Figure 2-6 (right) depicts typical industrial and consumer products made from composites. Some of the factors in making composites recycling cost-effective include, among others, an economy of scale (i.e., larger quantities of feedstock can reduce the unit processing cost), as well the availability of a consistent supply source of material to recycle to allow for continuous operation at the desired scale. Thus, the wind industry might benefit from collaborating with other composites sectors. In particular, aerospace and marine enterprises can also have large composite structures with mixed materials and similar recycling needs.[19]


**Figure 2-6**
**Left: Market segmentation of annual composite product sales volumes, including glass reinforcements, resins, and gel coats. Wind turbine blades are grouped under “Other” and comprise about 5% of the total. Right: Depiction of the range of products produced from composite materials.[20] (Used by permission of ACMA, 2019.)**

## 2.5 Summary and Conclusions of Wind Turbine Blade Scrap Resource Assessment

As wind energy installations increase, so does the quantity of materials that eventually will require end-of-life management. The projected amount of blade waste could vary from about 200,000 tons per year (based on a 15-year lifetime) up to about 370,000 tons per year (based on a 25-year lifetime) by 2050. The cumulative blade waste through 2050 is estimated at about 4 million tons.

While parts of wind turbines are straightforward to recycle, the blades comprise a composite matrix with mixed materials that are difficult to recycle. Consequently, in the U.S. today nearly all blades are sent to solid waste disposal at end-of-life, as both the least expensive option and the only option that is readily available. To minimize waste in the future, composites reuse and recycling technologies are needed that are economically and environmentally sustainable.

[19] ACMA Total Composites Industry Report, Second Quarter 2019.

[20] ACMA Total Composites Industry Report, Second Quarter 2019.

Similar composite materials are found in many industries. Through collaboration it will be possible to share technology developments as well as best practices, and to help ensure adequate and consistent supply to foster a nascent composites recycling industry.

# 3
# MATERIAL AND ENERGY RECOVERY TECHNOLOGY ASSESSMENT

## 3.1 Overview of Composite Scrap Recycling Technologies

A review of recycling technologies for end-of-life or scrap composite materials that are applicable to wind turbine blades can be divided into two main categories: (1) technologies that are ready to be applied today at commercial scale, and (2) technologies that are in development but not yet ready for commercialization. This chapter emphasizes review of the former: technologies available today, which include lifetime extension, pyrolysis, cement kiln, and re-grind/re-use. Additional technologies in development are only mentioned briefly here; they are discussed further in the Appendix.

Figure 3-1 provides definitions and a general hierarchy for end-of-life materials management, which includes options to re-enter usable materials into manufacturing rather than simply discarding them. The general framework for sustainability is to maximize materials recovery, minimize environmental impacts, and minimize costs. In general, sustainability is improved moving up the arrow to lifetime extension. A discussion on each technology follows and can be contrasted with solid waste disposal, the least desirable option in this framework and the one most practiced today.

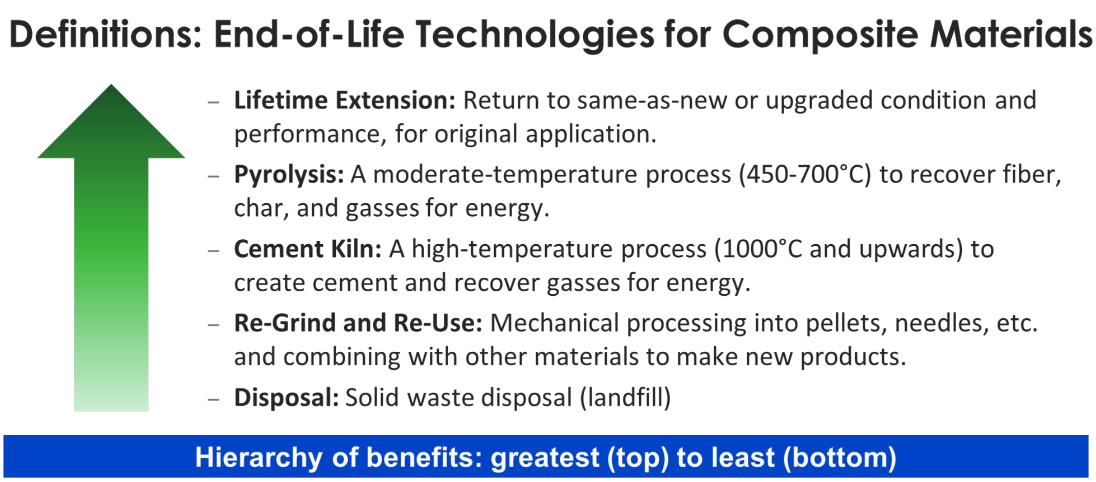


**Figure 3-1**
**General framework to maximize materials recovery, minimize costs, and minimize environmental impacts**

## 3.2 Technology Review: Lifetime Extension

An environmentally friendly means of reducing wind turbine blade waste, which is also often economically desirable, is to extend the blade lifetime past a nominal twenty years. The longer the product life, the lower the overall carbon footprint because fewer resources are used and the $CO_2$ emissions associated with blade manufacturing are reduced. Not only the blades, but also the gearboxes and generators can last longer through reconditioning or replacement of parts. Moreover, the Production Tax Credit (Repower)[21] can offer further economic incentives to update and/or upgrade older wind turbines.

In particular, exposure to sunlight, freezing temperatures, and precipitation can erode the leading edge of the blades. Blade monitoring and repair technology is improving rapidly for life extension. For instance, ACMA has developed a technician certification wind turbine blade repair module to support the wind industry (Figure 3-2). Standard blade refurbishment procedures may include visual and/or ultrasonic inspection and natural frequency measurements; then blades can be repaired, repainted, weighed and balanced as needed.[22]

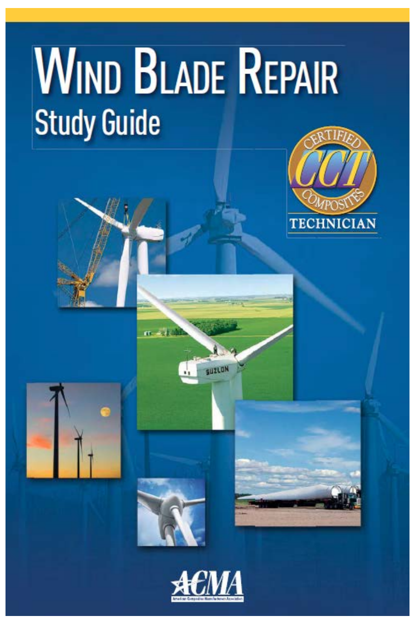


**Figure 3-2**
**ACMA wind turbine blade repair module to extend blade lifetime[23]**

## 3.3 Technology Review: Pyrolysis

Pyrolysis is a process used to recover fibers, char, and/or gases for energy. First the blades are sectioned and then re-sized to about 1-2", and then they are decomposed using conventional heating (ovens) in an inert atmosphere at 450-700°C. Both glass fiber and carbon fiber can be recovered using this process. The fiber can then be re-used as reinforcement in a wide variety of

[21] https://programs.dsireusa.org/system/program/detail/734

[22] https://backend.orbit.dtu.dk/ws/files/128071350/Wind_Turbine_Blades.pdf

[23] http://www.acmaeducationhub.org/Files/LearningProducts/9b298166f805465caf32f3655ed330dc/Wind_Blade_Repair_Preview.pdf, used by permission of ACMA.

applications. (Industrial-scale processes are already commercially available for non-wind turbine blade CFRP,[24] and are in testing for GFRP.) The resulting fiber may contain oxidation residue or char, and changes in the chemical structure are noted relative to pre-processing. To produce consistent fibers, it is important for the supply quantity and composition to be consistent. In addition to fiber, by-products include syngas, which can be combusted for electricity and heat recovery, and char, which can be recycled as fertilizer.

A pilot study was carried out in 2018-19 by ACMA and its members through the Institute for Advanced Composites Manufacturing Innovation (IACMI) with industry, trade association, and government partners. [25] A primary aim of the study was to create a business case for cost-effective recycling of end-of-life and production composite scrap materials, using CHZ Technologies' Thermolyzer™ (Figure 3-3, left). This process converts organic polymer materials into:

- Clean fuel gas to heat the primary reactor;
- Char with recoverable carbon fiber and glass fiber reinforcement, for re-use in other polymer systems; and
- Broken-down halogenated dioxins or furans (present in about 43% of carbon fiber reinforced polymers), thereby avoiding costly disposal.

**Figure 3-3**
**Left: Pilot Thermolyzer™ line used in IACMI project trials for controlled pyrolysis (used by permission of CHZ Ltd., 2019).[26] Right: Shredded composite feedstocks (clockwise starting upper left) CF epoxy wind turbine blade laminate (GE); GF/CF epoxy hybrid (John Deere); GF PE/VE automotive SMC (CSP); and GF epoxy balsa/PVC foam wind turbine blade (GE) .**

Based on the pilot study using the four feedstocks in Figure 3-3 (right), an observed limitation was that the physical form of both the glass and carbon fiber was modified from the initial bundle structure into amorphous, entangled "cotton." It also was determined that whereas the

[24] https://www.compositesworld.com/articles/carbon-fiber-reclamation-going-commercial

[25] Ludwig, C. and Ginder, R. "Controlled Pyrolysis: A Robust Scalable Composite Recycling Technology," *IACMI Draft Final Technical Report*, 2019.

[26] Ludwig, C. and Ginder, R. "Controlled Pyrolysis: A Robust Scalable Composite Recycling Technology," *IACMI Draft Final Technical Report*, 2019.

recovered CF has substantial market value, that of the recovered GF and/or GF-CF mixtures is anticipated to be significantly less. A follow-on IACMI project is planned to develop a value proposition for glass fiber recovered from this process, to create market pull in products such as insulation, gaskets, and ceramics.

## 3.4 Technology Review: Cement Kiln

Cement kilns produced 82.8 million tons of cement annually in the U.S. in 2015,[27] with a single kiln producing about 5,000 tons of cement per day. A typical process, which is highly efficient and fast (4-5 seconds of residence time) includes three stages: (1) grinding limestone with clay or shale to make a fine mixture; (2) heating this mixture in a cement kiln to up to 1000°C (some are able to process at up to 1450°C); and finally, (3) grinding the resultant "clinker" material (comprised of 1-10 mm aggregate lumps) into cement. In Germany the cement kiln process is already being used commercially for glass fiber wind turbine blade disposal, where solid waste disposal of end-of-life blades is prohibited by law.[28]

Recycling using the cement kiln eliminates the need for landfill, recovering both energy and raw materials needed for the production of cement. The composite portion of the feedstock (up to half) must be combined with other materials to provide the required consistency and BTU values. The combined stream can be in the range of at least 50,000-60,000 tons per year for a single kiln. The wind turbine blades are first re-sized into small pieces, then combined with other materials to provide a uniform high BTU content mixture. This mixture is then fed into the kiln where it is integrated with other materials into the clinker. The glass fiber content, roughly 50% of the wind blade's content, replaces raw material for cement production. The other 50% (the resin that is the organic part) replaces coal or natural gas, thereby reducing the $CO_2$ output of cement manufacturing by up to 16%.[29]

In summary, the key benefits are that the inorganic glass fiber is reprocessed into cement and the resin provides an energy offset. The limitations of this process include: (1) there is a loss of material characteristics, (2) some cement kilns cannot handle halogens, so PVC may need to be separated, (3) a high volume of composites is required to make the additional processing economical, and (4) because of the high melting point of carbon fiber this is considered an option for glass fiber-based blades only, which comprise 90% of the fiber-reinforced polymer (FRP) market.

## 3.5 Technology Review: Re-Grind and Re-Use

Once blades are decommissioned, mechanical processing can be used to cut, shred, crush, or mill wind turbine blade material to various sizes. The throughput rate can be high using an efficient waste management process. The resulting chunks, needles, or powder can be sold at low market value, to be reused for a variety of purposes. For example, the processed material can be combined with other materials to make new consumer products such as decking, insulation, and building panels.

[27] https://en.wikipedia.org/wiki/Cement_industry_in_the_United_States

[28] http://www.windfarmbop.com/circular-economy-use-of-wind-turbines-blades-as-combustible-and-mix-material-for-cement-production/

[29] https://www.materialstoday.com/composite-industry/news/recycling-of-glass-thermoset-composites-via/

However, the recyclate is mixed material, resulting in up to 40% waste such as paint and contaminants, which require solid waste disposal. Grinding can create a fine dust irritant, and shards create handling challenges. There is a large decrease in the mechanical properties of the recycled material (e.g., stiffness, strength). Moreover, it currently is not cost-effective and requires further investment to process (see Techno-Economic Analysis in Chapter 5).

Other re-use concepts in development take entire large sections of decommissioned blades and repurpose them for construction purposes, such as affordable housing or pedestrian bridges.[30] Such concepts would rank more highly in the end-of-life hierarchy in Figure 3-1 (e.g., between lifetime extension and pyrolysis) since they offer high materials recovery, low costs, and minimal environmental impacts.

## 3.6 Other Technologies

Other technologies that are under consideration for recycling of FRPs, but are currently at less advanced stages of technology development for wind turbine blade recycling, include the following:[31]

- Chemical Solvolysis
- Vacuum Cracking
- Wet Chemical Breakdown
- Fluidized Bed Pyrolysis (Gasification)
- Electrochemical
- High-Voltage Fragmentation (HVF)
- Microwave Pyrolysis
- Ultra-High Temperature Gasification

These technologies are described further in the Appendix.

## 3.7 Comparison of Near-Term End-of-Life Technologies

The four technologies examined in this chapter for end-of-life composites are summarized in Table 3-1 comparing cost, environmental impact, inputs, and outputs or recycled material value. A techno-economic analysis (TEA) with further emphasis on cost is provided in Chapter 5.

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[30] https://www.researchgate.net/publication/322567019_Concepts_for_Reusing_Composite_Materials_from_Decommissioned_Wind_Turbine_Blades_in_Affordable_Housing

[31] https://windeurope.org/wp-content/uploads/files/policy/topics/sustainability/Discussion-paper-on-blade-waste-treatment-20170418.pdf

**Table 3-1**
**Comparison of Near-Term Composite Recycling Technologies**

| Technology | Process Costs | Environmental Impact | Inputs | Outputs *Material Value* |
|---|---|---|---|---|
| **Lifetime Extension** | $ | Low: longer lifetime means lower carbon footprint over time | New paint, epoxy, etc. to refurbish | Continued power generation<br>*Avoided cost of new blades* |
| **Pyrolysis** | $$ | Low: recovered energy offsets power requirements; contaminants burn off | Both CF and GF blades: electricity or gas | Modified fibers and gas power<br>*High value for CF*<br>*Low value for GF* |
| **Cement Kiln** | $ | Low: recovered energy in resin partially offsets power requirements; most contaminants burn off | GF blades only, plus electricity, gas, or coal; clay and limestone | Cement clinker, gas power<br>*Inorganic glass strengthens the cement, reduces materials mining needed for raw materials* |
| **Re-Grind and Re-Use** | $ | Moderate: 40% requires solid waste disposal | Both CF and GF blades, electricity | Pellets, recycled fiber, powder<br>*Low value* |

## 3.8 Summary and Conclusions of Wind Turbine Blade Scrap Resource Assessment

Four technologies were reviewed that are commercially available for dealing with end-of-life composite wind turbine blades: life extension, pyrolysis, cement kiln, and re-grind/re-use. All are options today; however, profitability is an important consideration that can follow this simplified formula, in the event that recycling is the preferred option:

(Sales of recycled materials + value of energy recovery)

– (<u>Amortized capital costs + operating costs</u>)

Profit

In the event of negative profit (loss), the wind farm owner would need to subsidize (pay) to process the end-of-life material. If this is more expensive than solid waste disposal, most wind farm owners will (and currently do) choose the least-cost option: solid waste disposal. In addition, transportation is also a major cost component that is explored in Chapter 4, although most reviews consider the transportation cost roughly equal for all options (except life extension)—that is, the cost is about the same to cut and transport a blade for solid waste disposal as to a recycling facility.

Other important factors to consider when exploring technology options are the environmental impacts of each technology, especially the net greenhouse gases and other pollutants that may be generated in the recycling process, as well as available quantities and consistency of materials to be recycled.

# 4
# SITE LOCATION CONSIDERATIONS

## 4.1 Overview of Site Location Considerations for Wind Turbine Blade Scrap Processing and Handling

Currently in the U.S., wind turbine blade scrap is transported from the decommissioning site to the disposal facility via truck. In general, the transportation cost by truck increases linearly with distance; thus, the further the distance the higher the cost. According to the sources interviewed for this report, transportation and handling is currently the highest single cost in blade scrap processing and handling. This means that optimally, a facility for processing and handling would be located close to the source of blade scrap.

Other site location considerations include, for instance, the availability of utilities, road networks, and other transportation options; availability of a labor force; ease of permitting; and reduced regulatory burden.

## 4.2 Wind Turbine Blade Decommissioning Process

To better understand the requirements for site location considerations, it can be helpful to understand the steps involved in decommissioning wind turbine blades. In the first step the blades are removed from the turbine towers, broken down for transport, and moved to the processing site.[32] As shown in Figure 4-1, crane(s) are brought on-site to the wind farm to lower the blades following their detachment from the turbine. Typically, blades are then cut to size to fit the truck bed, loaded, moved to the processing site, and unloaded for processing. Costs can vary widely. For example, for a single 37-meter blade that is already lowered, the cost can be $1,000-$2,000 per blade to cut the blade into three pieces, transport 100 miles by truck, and handle the pieces at both ends. In contrast, if the same 37-meter blade is not cut but left in a single piece, it can cost $7,000-$9,000 to transport 100 miles in the central U.S.[33] Costs can increase by a factor of 2 to 5 at transport distances greater than 100 miles.

In the second step, the scrap material is first shredded into appropriate sizes such as 1” x 1”, then processed as discussed using one of the options in Chapter 3.

[32] Englund, Karl, “Wind Turbine Blade Recycling,” Composites Recycling Conference, April 10-12, 2018, American Composites Manufacturers Association, Knoxville, TN.

[33] Email from Michelle Simpson (GE Renewable Energy) to Paula Stevenson (Urban Venture Group) on 7/30/2019.

**Figure 4-1**
**Wind turbine blade decommissioning**

**Wind turbine blades are detached, lowered with a crane, and broken down for transport. Credit: (right) Don Lilly, GFSI, used by permission.**

## 4.3 Site Location Considerations

In selecting a site location for processing the wind turbine blade waste, some of the leading considerations include:

- Proximity to a high concentration of wind farms;
- Proximity to a cement kiln when that is the technology of choice;
- Proximity to transportation networks (highways, railroads, and/or inland waterways);
- Proximity to decommissioned power plants as potential reprocessing sites (e.g., former coal, gas plants);
- Proximity to tribal lands as potential reprocessing sites;
- Availability and proximity of other sources of composite (and other types of) scrap, such as auto and boat manufacturing waste and end-of-life waste, in order to maintain adequate volumes and consistent availability of recylate (discussed in Section 2.4); and
- Availability of labor force, and availability of utilities such as electricity and water.

### *4.3.1 Proximity to Wind Farms*

To minimize transportation costs, it would be desirable to locate manufacturing facilities in close proximity to large installations of wind farms, especially those set for decommissioning in the near future. The National Renewable Energy Laboratory's *2017 Wind Technologies Market Report* summarizes the locations of installed capacity in Figure 4-2, in which the darker colors indicate a higher concentration of wind power. In 2017 the state of Texas led with 22,599 MW of installed capacity, with Oklahoma next at 7,495 MW and Iowa at 7,308 MW, out of a total of 88,973 MW nationally.[34]

[34] https://www.energy.gov/eere/wind/downloads/2017-wind-technologies-market-report

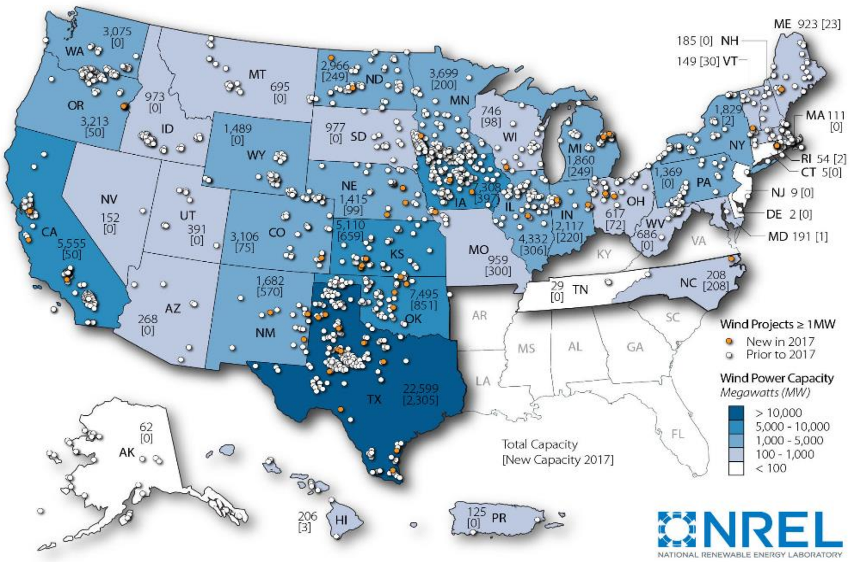


**Figure 4-2**
**Cumulative installed wind capacity by state as of 2017 (darker color denotes higher capacity)[35]**

### *4.3.2 Proximity to Cement Kilns*

Also due to high transportation costs, proximity to cement kilns may be a consideration when this is the technology of choice. The U.S. is the site of 96 integrated cement plants, plus 8 clinker grinding plants. Most cement plants are located close to limestone deposits because limestone is typically used in processing, with access to efficient transportation such as ship or railroad. Figure 4-3 shows the location of cement kiln plants in the U.S.

[35] https://www.energy.gov/eere/wind/downloads/2017-wind-technologies-market-report


**Figure 4-3**
**Cement plants located in the United States (Copyright International Cement Review / www.CemNet.com)[36]**

The color markers indicate the plant locations and company. For instance, dark red indicates LafargeHolcim Ltd. with 16 plants, red indicates Lehigh Hanson, Inc. with 15 plants, and orange indicates Cemex with 12 plants.[37,38]

### *4.3.3 Proximity to Transportation Networks*

According to the 2011 GAO report on surface freight transportation,[39] the U.S. transportation infrastructure includes over 4,000,000 miles of public highways and roads, over 140,000 miles of railroad networks, and 25,000 miles of commercially navigable waters. Trillions of dollars in freight move annually through these networks. Using ton-miles (the aggregate weight of freight times the distance the weight is carried), Table 4-1 shows the amount of domestic surface freight shipped in 2007. Figure 4-4 depicts the major transportation networks of highways, railroads, and inland waterways.

**Table 4-1**
**Estimated Ton-Miles of Domestic Freight Shipping by Mode in 2007[40]**

| Mode | Ton-miles (in millions) | Source |
|---|---|---|
| **Trucking** | 2,040,000 | Federal Highway Administration (FHWA), Freight Analysis Framework |
| **Railroad** | 1,819,633 | Bureau of Transportation Statistics, National Transportation Statistics |
| **Waterways** | 553,151 | U.S. Army Corps of Engineers, Waterborne Commerce of the United States |

[36] https://www.cemnet.com/global-cement-report/country/united-states
[37] https://www.cemnet.com/global-cement-report/country/united-states
[38] https://en.wikipedia.org/wiki/Cement_industry_in_the_United_States
[39] https://www.gao.gov/assets/320/315230.pdf
[40] https://www.cemnet.com/global-cement-report/country/united-states

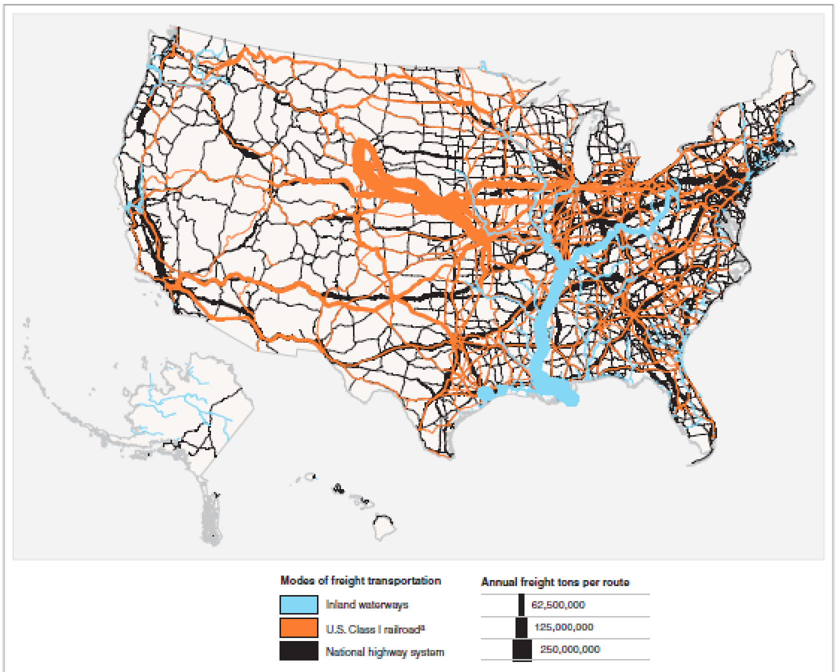


**Figure 4-4**
**Tonnage of freight on highways, railroads, and inland waterways (2007)[41]**

Transportation costs (especially by truck) are generally related to the distance traveled, although the further the distance, the more affordable waterway and rail become. Figure 4-5 offers a relative comparison of the transportation costs for truck, railway (CSXT-single car), and barge (waterway), as a function of distance traveled from the Midwest U.S. to Eastern and Southeastern U.S. for wood chips (roughly comparable to shredded composites).[42] The cost of transportation by truck is roughly proportional to distance, meaning optimal location of recycling facilities is critical to overall economics. The costs of rail and barge transport modes are less distance-dependent, as seen in Figure 4-5, such that access to rail and barge makes the recycling site location less critical to overall cost. The figure also does not take into account additional transportation costs that may be required on one or both ends for trucking to a terminal, for instance.

[41] https://www.gao.gov/assets/320/315230.pdf

[42] Gonzales, D., Searcy, E., and Eksioglu, D., "Cost analysis for high-volume and long-haul transportation of densified biomass feedstock," *Transportation and Research Part A: Policy and Practice*, Volume 49, March 2013, pp. 48-61, https://doi.org/10.1016/j.tra.2013.01.005.

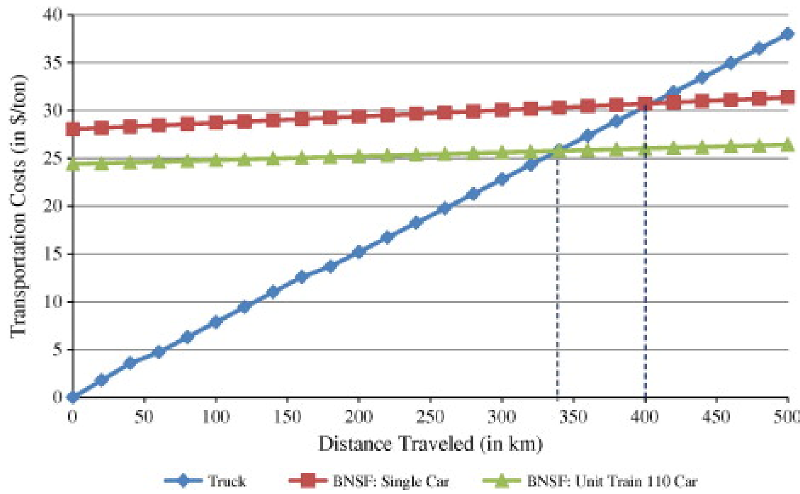


**Figure 4-5**
**Comparison of transportation costs by distance for truck, rail, or barge.[43] Image appears courtesy of Elsevier, Copyright Elsevier (2013).**

### *4.3.4 Proximity to Retired or Decommissioned Power Plants*

The locations of retired or decommissioned power plants may offer significant advantages to repurpose as manufacturing facilities for processing wind turbine blade waste. Retirement occurs when power production ceases, while decommissioning involves removing equipment and materials, demolishing buildings, and remediating any contaminated soils. Another option is to repower an existing coal power plant with natural gas-fired technology (e.g., combined-cycle), which requires significantly less space than coal-fired configurations that can cover hundreds of acres.[44] The excess space may then be considered for blade processing.

Some advantages of using retired or decommissioned power plants include space, and infrastructure access to roads, rail, (sometimes) waterways, and electric substations. The site owners are potentially amenable to collaboration and knowledgeable in repurposing power plant properties (e.g., utilities, municipalities).[45]

An overriding concern in repurposing a decommissioned power plant is that the site is returned to an economically viable operation. For municipalities, maximizing the tax base is important. Other concerns include hazardous material remediation such as asbestos; restrictions on land use per the original power plant agreements; permitting requirements and constraints; and competing interests for use of the space (commercial, industrial, residential, etc.).[46]

Figure 4-6 shows the generating capacity of actual and planned power plant retirements from 2008-2020. Of the total retired capacity, coal power plants and natural gas steam turbines accounted for the highest percentages at 47% and 26%, respectively. Coal power plants retired since 2008 were relatively old and small, averaging 52 years and 105 MW, compared with the

[43] Gonzales, D., Searcy, E., and Eksioglu, D., "Cost analysis for high-volume and long-haul transportation of densified biomass feedstock," *Transportation and Research Part A: Policy and Practice*, Volume 49, March 2013, pp. 48-61, https://doi.org/10.1016/j.tra.2013.01.005.
[44] https://www.eia.gov/todayinenergy/detail.php?id=40212
[45] Phone interview of Jeffrey Clock (EPRI) by Paula Stevenson (Urban Venture Group) on 10/18/2019.
[46] Phone interview of Jeffrey Clock (EPRI) by Paula Stevenson (Urban Venture Group) on 10/18/2019.

fleet of coal plants still operating, at 39 years and 319 MW. Other factors in retirement included changes in regional electricity use, federal or state policies that affect plant operation, and state policies that require or encourage use of certain fuels such as renewables.[47]

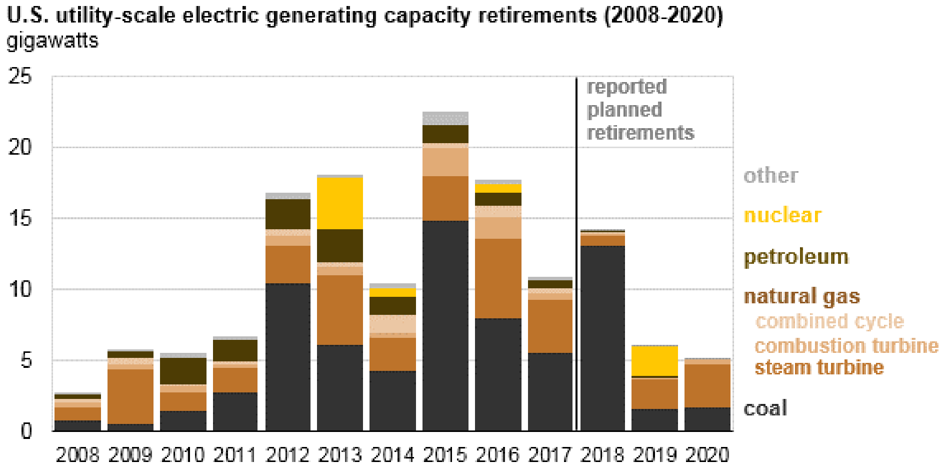


**Figure 4-6**
**Power plant retirements: 2008-2020[48]**

One example of the widespread availability of retired and retiring power generating facilities is shown in Figure 4-7, which highlights the locations of upcoming and potential coal unit retirements and conversions to gas, although this does not include many facilities that are already retired.

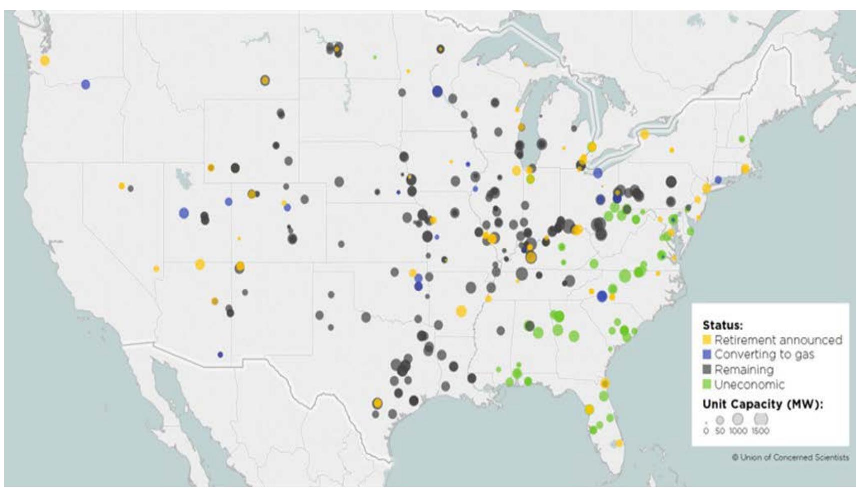


**Figure 4-7**
**Upcoming and potential coal unit retirements and conversion to gas as of 2018[49]**

[47] https://www.eia.gov/todayinenergy/detail.php?id=34452

[48] https://www.eia.gov/todayinenergy/detail.php?id=34452

[49] *A Comprehensive Approach to Repurposing Retired Coal Power Plant Sites: Transforming Liabilities to Assets.* EPRI, Palo Alto, CA: 2019. 3002016691.

### 4.3.5 Proximity to Tribal Lands

Native Americans hold more than 100 million acres of land in the U.S. The tribal wind power potential in the Great Plains alone exceeds 300 GW across 6 states, equivalent to half of the installed electrical generating capacity in the U.S. Many initiatives are underway to install wind facilities on tribal lands. In addition, the U.S. Department of Energy's EERE Tribal Energy Program supports energy development programs. Figure 4-8 shows the locations of tribal lands in the U.S.[50,51] As further wind capabilities are installed, with local approval it may be feasible to locate recycling facilities nearby to minimize transportation costs, as well as provide outside investment opportunities for local economic benefit.

## 4.4 Summary and Conclusions of Site Location Considerations

Many factors can be considered in determining the optimal location of facilities to process wind turbine blade scrap. These include, for instance:

- Availability of other sources of composite (and other types of) scrap to maintain adequate recycled material quantity and consistency for commercial viability of a given recycling option.
- Transportation, which is a large cost factor in recycling. Proximity to a high concentration of wind farms and to major transportation networks is important, as well as proximity to the processing site and to existing cement kilns when that is the technology of choice.
- Availability of decommissioned power plants (e.g., former coal, gas plants).
- Tribal lands potential (investment opportunity, regulatory approval).
- Availability of labor force, plus availability of utilities such as electricity and water.

Examples of additional factors to consider include local regulations, regional/local interests, and public and private investment opportunities.

[50] https://openei.org/wiki/Wind_Projects_on_Native_American_Lands

[51] https://www.nrel.gov/docs/fy13osti/57748.pdf

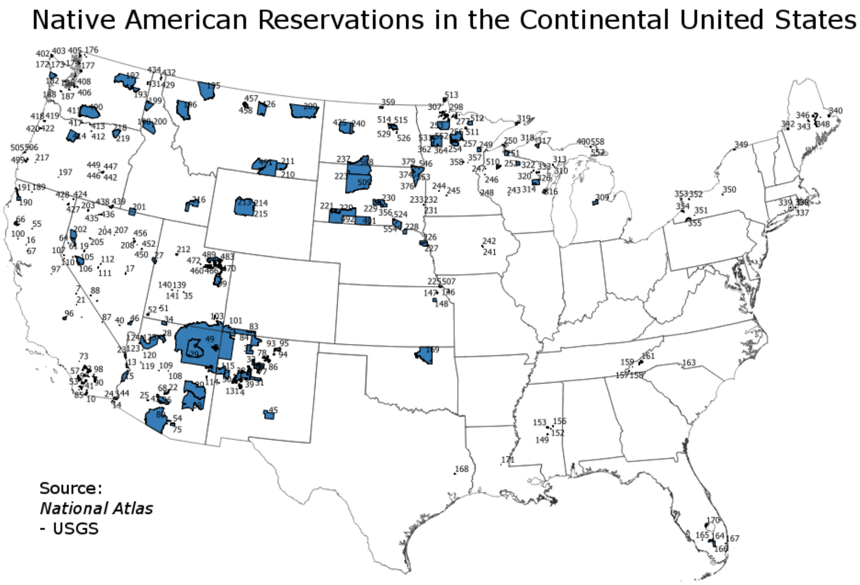


**Figure 4-8**
**Tribal lands in the U.S.: potential locations for processing facilities**[52]

[52] https://www.nrel.gov/docs/fy13osti/57748.pdf

# 5 TECHNO-ECONOMIC ANALYSIS (TEA) MODELS

A techno-economic analysis (TEA) evaluates technologies in terms of costs, benefits, risks, uncertainties, and timeframes.[53] In this chapter we examine and compare several TEA models for three near-term technologies of interest that avoid solid waste disposal—namely, pyrolysis; cement kiln; and mechanical processing (re-grind/re-use).

## 5.1 Overview of Techno-Economic Analysis (TEA) Models

Due to the recent emergence of the comparison technologies, in general only partial models are available. The three primary models and/or cost data that are available for each of these methods are described below, along with a discussion of the baseline costs for transportation and solid waste disposal. It can be noted that the processing cost varies significantly with each technology, and the value of the recycled material also varies widely with the end product.

### *5.1.1 Overall Model Assumptions*

All of the TEAs assume that the turbine blades are already lowered by crane as part of the decommissioning process, since this step is required for all modes of disposal or recycling. The models assume that the material is moved only a single time, although in many cases an intermediate processing step (with additional transportation costs) may be required. In the event that some of the processing is at an intermediate site (such as shredding or crushing), additional transportation costs would be incurred that are not included in the models.

## 5.2 Baseline Costs for Transportation and/or Solid Waste Disposal

Transportation costs and costs for solid waste disposal (tipping fees) can vary widely, depending on the number of turbines being decommissioned in an area, size of blades, distance to be transported, mode of transportation, and area of the country, among other factors. However, the relative cost can be envisioned using an example: as part of decommissioning a wind farm of 72 turbines that are each 82 meters high, it costs about $5,000 to cut three blades into three pieces each (nine pieces total) to fit on a truck bed, plus $8,000 for solid waste disposal for each set of three cut blades, or a total of about $13,000 for three blades.[54]

[53] https://www.nrel.gov/analysis/techno-economic.html

[54] https://puc.sd.gov/commission/dockets/electric/2018/EL18-003/appendixp.pdf

In another example, the costs for cutting, handling, and/or transporting (but not solid waste disposal) a single 37-meter blade that is already lowered include:[55]

- $1000-$2000 per blade to cut into three pieces, transport 100 miles by truck, and handle the pieces at both ends, or

Or, if the 37-meter blade is not cut but left in a single piece:[56]

- $7000-$9000 to transport 100 miles by truck in the central U.S., or
- In the northeastern U.S., $11,000-$16,000 to transport 100 miles.

Costs can increase by a factor of 2 to 5 if transport distances are greater than 100 miles. Currently end-of-life blades are transported by truck, although rail and waterway transportation are under consideration for the future.

## 5.3 TEA Model by Hoefer – 2015

The first TEA by Hoefer in 2015 assumes decommissioning of a 28-turbine wind farm, in which each turbine has three blades that weigh seven tons each. The blades are assumed to be shredded into fine material in the field using a Vermeer horizontal grinder (used by the forest products industry to turn wood into sawdust in the field). The model assumes that only a given percentage of the blade can be sold to the post-consumer market, with the remainder going to solid waste disposal. The TEA focuses on the cost to wind farm owners and the factors causing the owner to decide to use solid waste disposal or recycle a blade.[57]

Hoefer's methodology compares two different models. The objective for both models is to minimize the total cost, which is the sum of the cost for solid waste disposal ($71/ton) and the processing cost ($60/ton to recycle vs. $25/ton to pre-process for solid waste disposal). The only transportation cost included is to transport the processing equipment to the wind farm. The selling price for the recyclate is assumed to be $10/ton, or half the price of crushed rock. The first model is binary and assumes that the blade is either all landfilled or all recycled. The second model is continuous in terms of the percent yield from the recycling process, ranging from 0% if no recycling is attempted to 100% if all of the blade material is recovered. In the second model, material that is not recycled is landfilled.[58]

Both of Hoefer's models conclude that solid waste disposal is a less expensive option than recycling. Assuming no government intervention, wind farm owners would recycle only if it were less expensive than solid waste disposal. Hoefer concludes that a government subsidy of $36-$55 per ton would be needed to make recycling attractive to the owner.[59]

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[55] Source: Email from Michelle Simpson (GE Renewable Energy) to Paula Stevenson (Urban Venture Group) on 7/30/2019.

[56] Source: Email from Michelle Simpson (GE Renewable Energy) to Paula Stevenson (Urban Venture Group) on 7/30/2019.

[57] Hoefer, Michael, "Wind Turbine Blade Recycling: An Economic Decision Framework," Technical Report, The Boeing Company, May 2015, DOI: 10.13140/RG.2.2.28393.90723.

[58] Hoefer, Michael, "Wind Turbine Blade Recycling: An Economic Decision Framework," Technical Report, The Boeing Company, May 2015, DOI: 10.13140/RG.2.2.28393.90723.

[59] Hoefer, Michael, "Wind Turbine Blade Recycling: An Economic Decision Framework," Technical Report, The Boeing Company, May 2015, DOI: 10.13140/RG.2.2.28393.90723.

Additionally, Hoefer suggests that recycling technology improvements would offset the cost, because a greater percent of the blade could be recycled than with current technology. With an increase in the quantity of recyclate, more revenue can be generated, as there is more recyclate to sell, and the overall cost is reduced since less material goes to solid waste disposal. However, Hoefer's model suggests that even in the event of most of the blade being recycled, government subsidy would still be required to make this a preferable option over solid waste disposal.[60]

## 5.4 TEA Model by Owens Corning (Hartman and Szegner) – 2018-19

Through a study carried out in 2018-2019 by Owens Corning (Hartman and Szegner, 2019) for the Institute for Advanced Composites Manufacturing Innovation (IACMI), three recycling options were considered for fiber reinforced polymers (FRPs) as alternatives to solid waste disposal (landfill) and/or incineration (L/I). The three options were Thermolyzer™ (pyrolysis), Re-Grind/Re-Use (mechanical processing), and Cement Kiln, as follows:[61]

- Pyrolysis – can accept both GF and GF/CF hybrid material and converts organics to syngas and sellable fibers. Processing by pyrolysis would require new investment, preferably at the industry level (i.e., business/industry consortium) versus individual company level.
- Re-Grind and Re-Use – can accept both GF and GF/CF hybrid material; FRP scrap is ground and pelletized to make sellable composites. The start-up cost is low, but the value of the recycled material is also low.
- Cement Kiln – can only accept GF (90% of North American FRP market) and can be used to generate an enriched cement silica, but does not return any revenue as there is no increased value in the end cement product from using the composite feedstock. Some incremental investment may be required to adapt an existing cement kiln for composite feedstock.

The Owens Corning TEA assumed that: (1) the Life Cycle Analysis (LCA) of the alternative processing of recovered end-of-life (EoL) material and scraps shows a lower carbon footprint over L/I; (2) the strategy must be financially viable and economically sustainable without government or non-government subsidies to drive adoption and investment; and (3) that markets have been developed for recycled fibers recovered from the pyrolysis option. The cost model assumes first-pass shredding at the end-of-life site and transportation to above ground storage and to the L/I alternative facilities (e.g., Thermolyzer™, Re-grind/Re-Use, and Cement Kiln) located within 200 miles, and that these costs are comparable for all options.

Figure 5-1 provides a relative summary of the LCA benefits and economic impacts and drivers of the various options.[62] In *LCA impact* when compared to landfill or incineration, the Thermolyzer™ offers the best LCA benefit, followed by re-grind/re-use, with the cement kiln offering the least LCA benefit. In *economic impact*, the Thermolyzer™ provides a high value of recyclate but requires a high investment cost; re-grind/re-use provides a low value for recycled

[60] Hoefer, Michael, "Wind Turbine Blade Recycling: An Economic Decision Framework," Technical Report, The Boeing Company, May 2015, DOI: 10.13140/RG.2.2.28393.90723.

[61] Hartman, Dave, and Szegner, John, "NA Composite Recycle Options and Recommendations: LCA & Techno-Economic Analysis," presentation to IACMI on June 22, 2019.

[62] Hartman, Dave, and Szegner, John, "NA Composite Recycle Options and Recommendations: LCA & Techno-Economic Analysis," presentation to IACMI on June 22, 2019.

material and a low investment cost; and the cement kiln provides no recycled product but also requires little additional investment.

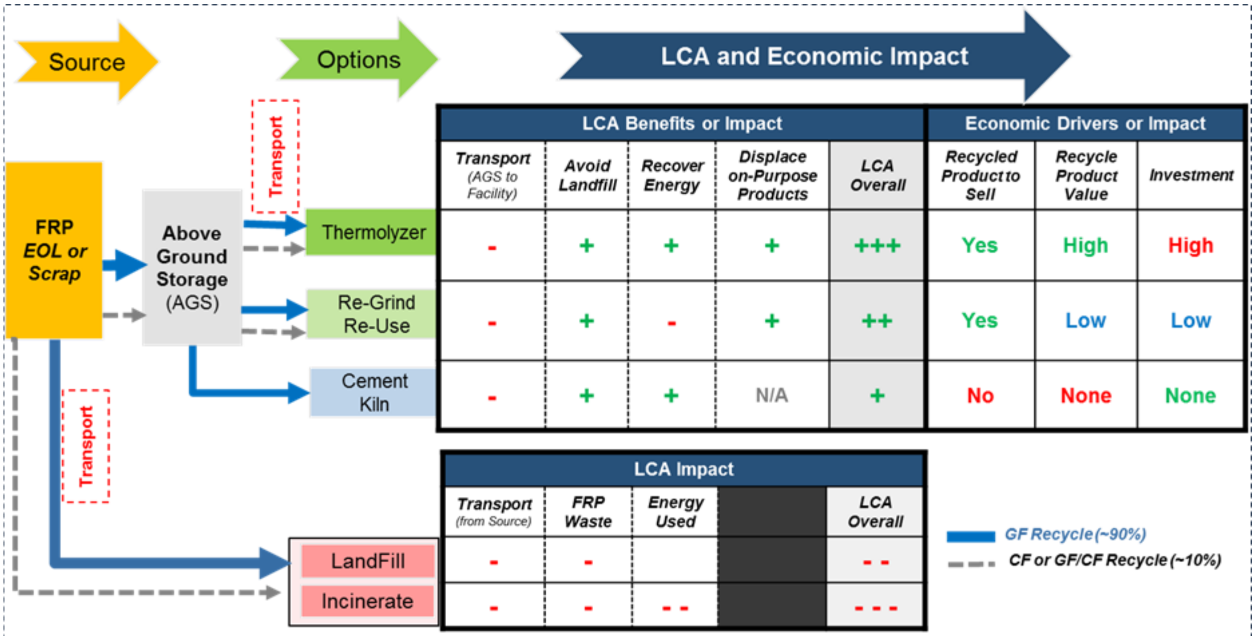


**Figure 5-1**
**North America composite recycle options and recommendations: LCA and techno-economic analysis**[63]

### *5.4.1 TEA Model by Owens Corning (Hartman and Szegner) for Thermolyzer™ (Pyrolysis)*

The Owens Corning study went into considerable detail on the Thermolyzer™ option, using a TEA model to evaluate and frame different scenarios to recycle and sell the recovered fibers. Each of four Thermolyzer™ scenarios included variable and fixed costs. A price to value ratio was assigned to account for performance loss from virgin fibers. The four scenarios and their respective payback periods, based primarily on the scaled value of the recovered GF and CF fibers, are summarized in Figure 5-2 and include:[64]

- Scenario 1 – GF only: 63 kta (kilotons per annum) sales volume by Year 5
  - 4.7 year payback @ $0.60/kg for GF only
- Scenario 2 – CF lean: 63 kta sales volume by Year 5
  - 2.0 year payback @ $1.80/kg for long CF lean/GF (8/92)
- Scenario 3 – GF/CF hybrid, CF rich: 16 kta sales volume by Year 5
  - 1.8 year payback @ $2.80/kg for milled CF rich/GF (30/70)

[63] Hartman, Dave, and Szegner, John, "NA Composite Recycle Options and Recommendations: LCA & Techno-Economic Analysis," presentation to IACMI on June 22, 2019.
[64] Hartman, Dave, and Szegner, John, "NA Composite Recycle Options and Recommendations: LCA & Techno-Economic Analysis," presentation to IACMI on June 22, 2019.

- Scenario 4 – CF only: 10 kta sales volume by Year 5
  - 1.2 year payback @ $8.00/kg for milled CF only

The Owens Corning TEA concluded that pyrolysis offers a financially viable and economically sustainable operation with highly attractive investment economics for recovered CF. Pyrolysis further offers reasonably attractive economics for GF and/or mixed CF/GF if sufficient market pull is established, without reliance on or need for government or non-government subsidies.[65]

| | Scenario | Finished Product (FP) (GF, GF/CF, CF) | Price(1) | Demand (5YRS) | Capacity(2) | Invest (3) | Financial Summary (un-subsidized) | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | LCP - Long CF Price<br>MCP - Milled CF Price | % wt /% wt | $/kg | kta FP | kta FP | $mm | NPV6 ($mm) | CF(4) 5YRS ($mm/yr) | XIRR (%) | Payback (YRS) | ROCC(5) (%) |
| 1 | GF only | GF - 100 | GF = 0.6 | 63 | 67 | 57 | 50 | 18 | 25% | 4.7 | 13% |
| 2a | CF Lean - LCP | CF/GF - 8/92 | CF/GF = 1.8 (CF= 16.0/GF = 0.6) | 63 | 67 | 57 | 384 | 70 | 97% | 2.0 | 84% |
| 2b | CF Lean - MCP | CF/GF - 8/92 | CF/GF = 1.2 (CF = 8.0/GF = 0.6) | 63 | 67 | 57 | 211 | 43 | 64% | 2.7 | 50% |
| 3a | CF rich - LCP | CF/GF - 30/70 | CF/GF = 5.2 (CF = 16.0/GF = 0.6) | 16 | 17 | 18 | 313 | 52 | 198% | 1.1 | 171% |
| 3b | CF rich - MCP | CF/GF - 30/70 | CF/GF = 2.8 (CF = 8.0/GF = 0.6) | 16 | 17 | 18 | 150 | 27 | 108% | 1.8 | 98% |
| 4a | CF only - LCP | CF - 100 | CF = 16.0 | 9 | 17 | 18 | 616 | 100 | 415% | 0.7 | 261% |
| 4b | CF only - MCP | CF - 100 | CF = 8.0 | 9 | 17 | 18 | 290 | 49 | 184% | 1.2 | 163% |

(1) Price - Assumes Price to Value, which takes into account possible loss in performance of recovered Fibers from "Thermolyzer" vs "on-purpose" fibers produced through
(2) Capacity - FRP recycle or Raw Material (RM) and Recovered Fiber or Finished Product (FP).
FP from RM capacity based on CHZ mass balance from the four different products tested on pilot line
(3) Investment - Greenfield Investment (Thermolyzer™ Process and required infrastructure)
(4) CF - Cash Flow
(5) ROCC - Return on Capital Consumed (5 YR avg)

**Figure 5-2**
**Owens Corning TEA summary of four Thermolyzer™ (pyrolysis) scenarios and payback periods[66]**

## 5.5 Simplified TEA for Re-Grind and Re-Use (Wegman) – 2019

A simplified TEA is shown here for the re-grind/re-use option, which includes approximate costs for grinding, as well as approximate values for the recycled fibers and powders: [67]

- Grinding to 1-3 cm: $90-$120/ton
- Further grinding to fibers and powders: Additional $110-$150/ton
- Roughly 20%-40% is waste that needs to go to solid waste disposal: ~$60-$250/ton (solid waste tipping fee can vary significantly by country, e.g., in Germany the fee can be $220-$250/ton.)

[65] Hartman, Dave, and Szegner, John, "NA Composite Recycle Options and Recommendations: LCA & Techno-Economic Analysis," presentation to IACMI on June 22, 2019.
[66] Hartman, Dave, and Szegner, John, "NA Composite Recycle Options and Recommendations: LCA & Techno-Economic Analysis," presentation to IACMI on June 22, 2019.
[67] Interview of Thomas Wegman (AOC) by Paula Stevenson (Urban Venture Group) on 8/30/2019, followed by email on 9/3/2019.

- Value of recycled fibers and powders: $220-$275/ton

Thus, it is clear from these numbers that commercial profitability would be difficult in the re-grind and re-use option, thus requiring user fees or subsidization.

## 5.6 Simplified TEA for Cement Kiln (Wegman) – 2019

A simplified TEA is provided here for the cement kiln option, including grinding and transportation costs. Since there is no economic return (i.e., no recycled material), only the costs are included. A potential challenge for this technology is the ability to achieve sufficient composite waste within 300 miles to provide relatively constant feedstock quantities and consistency.[68]

- Grinding to 1-3 cm: $90-$120/ton
- Transportation cost: ~$55/ton for 300 miles (10-ton load)
- 1 cement kiln produces 5000 tons (11 million pounds of cement) per day
- Up to 2500-3000 tons per day feedstock can be composite materials, or about 1100 kT/yr (~2,500 MM lbs/yr)

## 5.7 Comparison of TEA Models

A comparison of costs used in the various TEA models is provided in Table 5-1.

## 5.8 Examples of Commercial Recycling Initiatives

Several U.S. companies have already developed commercial business models for recycling end-of-life and scrap composites (including wind turbine blades). Some recent examples include:

- **Re-Grind and Re-Use**: *Global Fiberglass Solutions, Inc.* (GFSI) is the first U.S.-based company to commercially recycle wind turbine blades into viable products. The wind farm owner lowers the blades and GFSI cuts the blades in the field and then transports the material to a GFSI processing facility for further processing. The wind farm owners pay for the blade removal process; GFSI estimates that their process can cost the wind farm owner less than solid waste disposal. GFSI reuses 100% of the ground blades using a patented formula to make GF pellets and composite materials, such as fiberboard.[69]
- **Cement Kiln**: *Veolia North America* is spearheading an effort to utilize recycled wind turbine blades as an engineered fuel for use in cement kiln facilities across the U.S. Recycling the wind turbine blade as an engineered fuel product eliminates the need to landfill a material that has low value and is otherwise very difficult to recycle as a fiberglass product. There are potential $CO_2$ and carbon offsets available as some of the material is biogenic.[70]

[68] Interview of Thomas Wegman (AOC) by Paula Stevenson (Urban Venture Group) on 8/30/2019, followed by email on 9/3/2019.

[69] Interview of Karl Englund (GFSI) by Paula Stevenson (Urban Venture Group) on 10/16/2019.

[70] Interview of Chris Howell (Veolia) by Paula Stevenson (Urban Venture Group) on 10/16/2019; Veolianorthamerica.com; e-mail update on 12/10/2019.

- **Pyrolysis**: *CHZ Technologies, LLC* is establishing several processing facilities in the U.S. for controlled pyrolysis using their patented Thermolyzer™ technology. Currently used for tires, circuit boards, and carpets, the technology is being adapted for composite processing. The CHZ business model assumes a daily volume of at least 100 tons per day, and suggests co-locating wind turbine blade composite processing with other compatible materials such as end-of-life utility poles, railroad ties, and plastics.[71]

**Table 5-1**
**TEA Models: Economic Comparison of End-of-Life Technologies**

| Processing Step | Solid Waste Disposal | Re-Use/ Recycle (Hoefer) | Re-Use/ Recycle (Wegman) | Cement Kiln (Wegman) | Pyrolysis/ Thermolyzer™ (Owens Corning) |
|---|---|---|---|---|---|
| **Decommission/Lower Wind Turbine Blades** | * | * | * | * | * |
| **First-Pass Cutting or Shredding** | $1,000-$2,000 per blade for 100 miles | $25/ton | ** | ** | $25-$50/ton |
| **Transportation** | | ** | $55/ton for 300 miles | $55/ton for 300 miles | ~$40/ton for 300 miles |
| **Grinding to 1-3 cm** | N/A | $60/ton | $83-$110/ton | $90-$120/ton | Included in first-pass |
| **Solid Waste Disposal Fee** | $62/ton*** | $71/ton | 20%-40% waste: $$60-$250/ton (depending on country) | N/A | $61/ton |
| **Processing to Recycle** | N/A | N/A | $110-$150/ton for further grinding to fibers/powders | N/A | $230-$450/ton (variable and fixed costs) |
| **Minimum Processing Volume** | ** | ** | ** | 2500-3000 tons/day | 100 tons/day |
| **Recycled Material Value** | N/A | $10/ton | $220-$275/ton | $0 | $600-$5,200/ton for recovered GF and GF/CF |

* Not included: cost is assumed to be the same for all end-of-life technologies.
** Not included in this review.
*** Average cost from other studies for US.

[71] Ludwig, Chuck, "EoL Options with Utility Poles & More," *EPRI Environmental Aspects of Renewables Workshop*, September 16-17, 2019, Rosemont, IL, CHZ Technologies, LLC, a wholly-owned subsidiary of Aliquippa Holdings LLC.

## 5.9 Summary and Conclusions of TEA Models

Currently most end-of-life wind turbine blades are sent to solid waste disposal. To avoid this, mechanical recycling (re-grind/re-use) and the cement kiln are options in the short term; however, they are not self-supporting and require the wind farm owner or responsible authority to pay for cutting to size, transportation, and processing. According to the Thermolyzer™ TEA by Hartman and Szegner, the controlled pyrolysis technology offers a favorable self-supporting investment option. An up-front investment is required, with Return on Investment (ROI) occurring in about 1-5 years depending on the ratio of recovered GF and CF obtained from the process. The TEA assumes that sufficient markets exist for the recycled fiber.

Mechanical reprocessing (re-grind/re-use) faces steep challenges, including a lack of attractive end-use applications and poor economics. Cement kilns are more sustainable, but cost about twice as much as solid waste disposal. Pyrolysis offers more attractive economics for recovery of carbon fiber than for glass fiber; however, collaborative development is needed to create market pull for recycled glass fibers to support a business case for recycling through pyrolysis.

# 6
# CONCLUSIONS AND RECOMMENDATIONS

## 6.1 Conclusions

This study examined four main topics: (1) U.S. wind turbine blade scrap resource assessment, (2) material and energy recovery technology assessment, (3) site location considerations, and (4) techno-economic analysis (TEA) models. The report is offered as a tool to help guide the wind and power industry towards understanding the magnitude of the issue regarding wind turbine blade waste and to present potential, practical solutions.

Growing quantities of fiber-reinforced polymer (FRP) composites scrap are becoming an issue, not just in the wind industry (comprising about 5% of overall composites production in the U.S.) but in other composites sectors as well. Although estimates vary, up to 50,000 tons of blades will be available as scrap in the U.S. by 2023, increasing to as much as 370,000 tons per year by 2050. Today most composites scrap is landfilled; sustainability concerns, as well as the increasing numbers and sizes of blades, undermine the viability of solid waste disposal. New solutions are needed; recycling is a promising option. Several technologies for composite recycling were examined, along with their respective economic prospects and environmental impacts, and show promise for potential adoption.

The issue of recycling composites is increasing over time and is one faced not only by the wind industry as it grows, but by other composites sectors as well. The electric power sector can collaborate with other industries to take advantage of the economies of scale and reduce cost.

## 6.2 Discussion of Technology and Business Gaps That Need to Be Addressed

In the three current technologies that were evaluated, gaps were seen in the following areas:

- **Pyrolysis** – The technical and economic feasibility of this process has been well established for carbon fiber, but applications development of the resulting glass fiber is needed to generate market pull for the recycled glass fiber.
- **Cement Kiln** – Commercial facilities exist in Europe, and a successful pilot project has been carried out in the U.S. (with composite boat material). No commercial facility yet exists in the U.S. for this purpose, although one company is seeking funding to start up processing facilities to provide a front-end for the use of composites with cement kilns. Assistance with start-up funding for a commercial facility may be helpful.
- **Re-Grind/Re-Use** – One source reported that this recycling option is not economically feasible (i.e., it is more expensive than solid waste disposal), while another source reported that it was less expensive—and therefore more appealing—than solid waste disposal. A rigorous TEA would help clarify the affordability of this option.

- **Other Developing Technologies** – Many alternative composites recycling technologies are in development, as discussed in the Appendix. Consideration may be given to partnering with other organizations (U.S. Department of Energy, ACMA, etc.) to sponsor research, development, and demonstration funding to advance these emerging technologies.

## 6.3 Recommendations for Next Steps

As discussed in Section 6.2, recommendations for next steps center on further assessment of the economics and logistics of options for wind turbine blade management, including:

1. A rigorous TEA comparing life extension, pyrolysis, cement kilns, and re-grind/re-use, particularly in comparison with solid waste disposal.
2. Collaborative development of a commercial-scale facility for front-end processing of composites scrap for use in recycling, cement kiln feedstock, and/or pyrolysis demonstration.
3. Applications for recycled glass fiber resulting from the controlled pyrolysis project.
4. Other composites recycling technologies that are in development.
5. Analysis of supply chain requirement for sustainable recycling.
6. Development of materials and programs for education and engagement of stakeholders at all stages of the process.

Such support may include collaborating with other organizations, supporting government efforts to fund R&D funding programs targeted to composites recycling, and providing direct support to technology developers.

# A
# APPENDIX A

## A.1 Alternative Scenarios for Projecting Quantities of Blade Scrap

Three scenarios were examined to estimate quantities of scrap anticipated from wind turbine blades from about 2023 to 2050:

### *Scenario 1*

Liu and Barlow estimated growth rates using these three scenarios: [72]

- *The base growth rate* follows current directions in national and international energy and climate policy.
- *The moderate growth rate* assumes that government targets and commitments for emissions reductions will be implemented, although on the modest side, and adds these targets to the base growth rate.
- *The advanced scenario* is ambitious and represents the best case following wind energy vision, but within the capacity of the industry as it is likely to grow in the future.

By applying these respective growth rates to historical capacity, Liu and Barlow calculate the future availability of end-of-life composite material. The red line in Figure A-1 corresponds to their estimates in the moderate growth rate scenario.

### *Scenario 2*

Arias projected cumulative wind power capacity[73] by taking the best-fit curve of past installed capacity, obtaining the formula

$$y = 261.59x^2 + 1198.1x - 377.85$$

This formula was used to project installed capacity into the future. Using the equivalency of 9.57 megawatts per ton of composite blade, Arias's projected values for each year are shown as the blue line in Figure A-1.

### *Scenario 3*

This scenario was projected in the U.S. Department of Energy's 2018 Wind Vision report, seen earlier in Figure 2-3 showing historical and projected wind power capacity. After converting the

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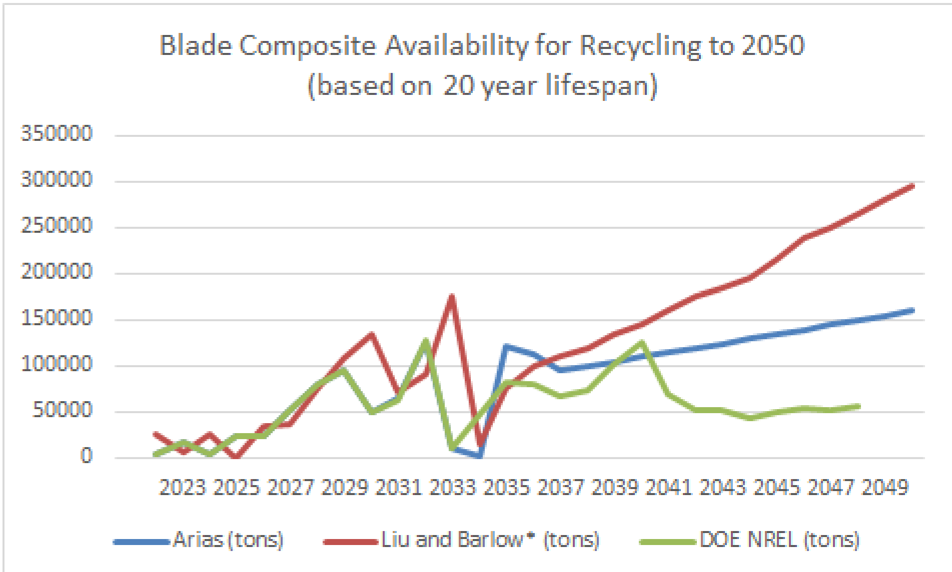
[72] Liu, Pu, and Barlow, Claire Y., *Wind Turbine Blade Waste in 2050*, University of Cambridge Institute for Manufacturing, UK, 2015.

[73] Franco Arias, *"Assessment of Present/Future Decommissioned Wind Blade Fiber-Reinforced Composite Material in the United States,"* submitted May 23, 2016, as Independent Study to the City College of New York – City University of New York Department of Civil Engineering.

power capacity to blade weight and assuming end-of-life at twenty years from the date of install, this is represented in the green line in Figure A-1.[74]

Out of the three scenarios, Liu and Barlow's moderate case was used to obtain the projections of blade waste scrap given in Chapter 2, as it includes manufacturing and service waste and follows a rigorous estimation scheme.




*includes additional 25% for manufacturing scrap and maintenance.

**Figure A-1**
**Comparison of three different estimates of available wind turbine blade composite scrap, assuming a 20-year lifespan**[75,76,77]

## A.2 Composite Recycling Processes in Development

Other technologies that are potential future candidates for recycling of wind turbine blades are currently at less advanced stages of development. These include:[78]

- **Chemical Solvolysis** – Involves thermo-chemical depolymerization using solvents such as water, alcohol, or acid, typically at a temperature of 300-650° C and high pressure. The fiber is recovered, while resins can be combusted for energy recovery. Most research at the laboratory scale focuses on carbon fibers, since glass fibers are degraded in the process.

[74] https://www.energy.gov/eere/wind/downloads/2017-wind-technologies-market-report

[75] Franco Arias, *"Assessment of Present/Future Decommissioned Wind Blade Fiber-Reinforced Composite Material in the United States,"* submitted May 23, 2016, as Independent Study to the City College of New York – City University of New York Department of Civil Engineering.

[76] Liu, Pu, and Barlow, Claire Y., *Wind Turbine Blade Waste in 2050*, University of Cambridge Institute for Manufacturing, UK, 2015.

[77] https://www.energy.gov/eere/wind/downloads/2017-wind-technologies-market-report

[78] https://windeurope.org/wp-content/uploads/files/policy/topics/sustainability/Discussion-paper-on-blade-waste-treatment-20170418.pdf

  - Concerns include high energy consumption, low throughput, potentially toxic gas emissions, disposal of spent solvents and catalysts, and high water consumption.[79]

- **Vacuum Cracking** – Plastics are heated in a vacuum to break down polymer-containing solids into liquid raw materials or fuels. The process has been demonstrated at pilot scale on various materials, including mixed plastic waste. Vacuum cracking reduces the need for off-gas treatment.
  - Current limitations are that the parts must be no more than 1 inch in any dimension, the process has apparently not been tested on wind turbine blades, and the pilot plant for e-waste can process only 25-50 pounds per hour.[80]

- **Wet Chemical Breakdown** – The composite matrix resin is broken down in a liquid to reclaim the fibers. Testing on carbon fiber reinforced polymer (CFRP) shows that the recovered carbon fiber is over 99% clean and retains over 95% of the virgin fiber strength. The current pilot plant can process 100 pounds per batch.
  - Although the process is suitable for all fiber-reinforced composites, so far only reclaimed carbon fiber is economically viable.[81]

- **Fluidized Bed Pyrolysis (Gasification)** – The process passes size-reduced FRP composite through a bed of sand, fluidized by a stream of hot air. The process can be used to treat mixed and contaminated materials, and results in clean fibers with good stiffness retention. The process is available at pilot scale for CFRP, and treatment of GFRP is in development.
  - However, the process consumes a high amount of energy and yields fiber with lower mechanical properties compared to other pyrolysis methods.[82]

- **Electrochemical** – Electrical current is applied through an electrolyte solution to degrade the polymer matrix. There is limited availability of the process, even at laboratory scale. [83]

- **High-Voltage Fragmentation (HVF)** – HVF uses high voltage to create an intense shockwave with high-pressure waves ($10^9$~$10^{10}$ Pa) and high temperature (> $10^4$ K) along plasma channels, with a pulse rise time <500 ns, causing materials to disintegrate in water. The process has been tested at laboratory and pilot scales on both CFRP and GFRP.[84]
  - A safety concern is working with these high voltages. Moreover, the process heavily decreases the mechanical properties (modulus) of glass fibers, leading to lower value for the recycled fiber.

- **Microwave Pyrolysis** – In this process, material is heated with microwave radiation at its core. The thermal transfer is very fast and potentially energy saving compared to other pyrolysis methods. It has limited availability even at the laboratory scale.

[79] https://baxcompany.com/wp-content/uploads/2019/06/wind-turbine-circularity.pdf
[80] https://www.adherent-tech.com/recycling_technologies
[81] https://www.adherent-tech.com/recycling_technologies
[82] compositesuk.co.uk
[83]https://www.researchgate.net/publication/281198090_Recycling_of_carbon_fibers_from_carbon_fiber_reinforced_polymer_using_electrochemical_method
[84] https://www.sciencedirect.com/science/article/pii/S000785061630107X, https://cordis.europa.eu/project/rcn/106311/reporting/en

  - Microwave pyrolysis has similar concerns as pyrolysis: the recycled fiber may retain oxidation residue or char; the glass fiber is degraded due to change in the chemical structure; and it is not economically viable for glass fibers.[85]

- **Ultra-High Temperature Gasification –** This process is a promising technique based on hydrolysis and does not require combustion. All organic matter is converted into a clean synthesized gas, typically ~40% of the material by weight. Most of the rest is converted into 1-2 cm GF pieces that can be reused, with the final 2-5% comprised of carbon black residual. Both the GF pieces and the carbon black can be used in the hollow glass industry.[86]

[85] http://www.iccm-central.org/Proceedings/ICCM18proceedings/data/3.%20Poster%20Presentation/Aug24%28Wednesday%29/P3-64~70%20Recycling/P3-65-IF1815.pdf

[86] https://windeurope.org/wp-content/uploads/files/policy/topics/sustainability/Discussion-paper-on-blade-waste-treatment-20170418.pdf

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