Feature Article

Unsustainable Wind Turbine Blade Disposal Practices in the United States: A Case for Policy Intervention and Technological Innovation

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Abstract

Finding ways to manage the waste from the expected high number of wind turbine blades in need of disposal is crucial to harvest wind energy in a truly sustainable manner. Landfilling is the most cost-effective disposal method in the United States, but it imposes significant environmental impacts. Thermal, mechanical, and chemical processes allow for some energy and/or material recovery, but they also carry potential negative externalities. This article explores the main economic and environmental issues with various wind turbine blade disposal methods. We argue for the necessity of policy intervention that encourages industry to develop better technologies to make wind turbine blade disposal sustainable, both environmentally and economically. We present some of the technological initiatives being researched, such as the use of bio-derived resins and thermoplastic composites in the manufacturing process of the blades.

Keywords

wind energy, recycling, sustainability, environment, occupational safety

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Introduction

Globally, more than seventy thousand wind turbine blades were deployed in 2012[1] and there were 433 gigawatts (GW) of wind installed capacity worldwide at the end of 2015.[2] Moreover, the United States' installed wind power capacity will need to increase from 74 GW to 300 GW[3] to achieve its 20% wind production goal by 2030.[3] To meet the increasing demand, not only are more blades being manufactured, but also blades of up to 100 meters long are being designed and produced.[4] The wind turbine blades are designed to have a lifespan of about twenty years, after which they would have to be dismantled due to physical degradation or damage beyond repair. Furthermore, constant development of more efficient blades with higher power generation capacity is resulting in blade replacement well before the twenty-year life span.[5] Estimations have suggested that between 330,000 tons/year by 2028 and 418,000 tons/year by 2040 of composite material from blades will need to be disposed worldwide.[6] That would be equivalent to the amount of plastics waste generated by four million people in the United States in 2013.[7] This anticipated increase in blade manufacturing and disposal will likely lead to adverse environmental consequences, as well as potential occupational exposures, especially because available technologies and key economic constraints result in undesirable disposal methods as the only feasible options.

The material in the shells of the wind turbine blades is typically glass fiber-reinforced polymer (GFRP), a resin-matrix material reinforced with fiberglass. In particular, the shells are commonly made from a combination of epoxy resin and glass fiber reinforcement.[8] The blades also contain sandwiched core materials such as polyvinyl chloride foam, polyethylene terephthalate foam, or balsa wood, as well as bonded joints, coatings (polyurethane), and lightning conductors.[8] Conventional epoxy resins are thermosetting materials usually produced by a reaction of epichlorohydrin and bisphenol A in the presence of sodium hydroxide.[9] Both bisphenol A and epichlorohydrin are derived from petrochemicals. Contrary to other types, once cured, thermoset polymers cannot be melted and reshaped by applying heat at high temperatures. As a result, thermoset composites cannot be reformed by any means other than machining, which risks compromising the properties of the material through damage or destruction of the reinforcing fibers. Therefore, the GFRP found in the blades poses a challenge to find or develop more sustainable end-of-life alternatives.

The issue of wind turbine blade disposal had received little attention until recently when some of the oldest wind farms in the United States were in need of ways to dispose of blades that have reached the end of their usefulness. Currently, there are more than 100 wind farms in the United States that are fifteen years or older, with more than 2.38 GW of installed capacity.[10] Since the useful life of a blade is about fifteen to twenty years, these wind farms will likely need to replace a large number of blades in the near future. The United States' installed wind power capacity reached 74 GW at the end of 2015.[11] By using the

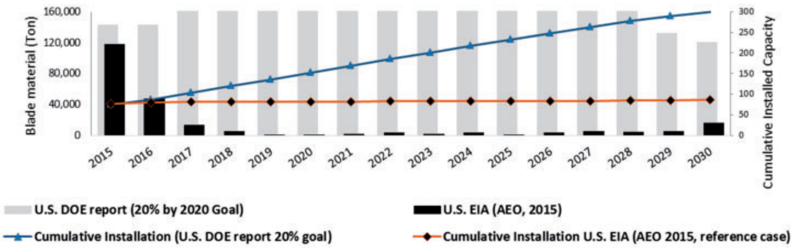

Figure 1. Estimated amount of blade material to be used per year (tons) and cumulative installed capacity (GW).
Source: U.S. Department of Energy,[3] American Wind Energy Association,[11] and U.S. Energy Information Administration.[13]

National Renewable Energy Laboratory 5-Megawatt reference wind turbine,[12] we estimate that about 10 kg of material is used per kilowatt of capacity, which means we will have about 728,000 tons of blade material to dispose of over the next twenty years. Disposing of this amount of material from existing capacity in a sustainable way will be challenging given the current technological and economic limits of available methods.

That amount of material does not include future wind power capacity installation, nor does it take into account blade replacement before the twenty-year life span. Both situations will serve to further increase the disposal challenge. Figure 1 shows projections of the estimated wind turbine blade material to be used in the United States wind industry annually over the next fifteen years. The same assumption of 10 kg of blade material per each kilowatt of installed capacity was used. Based on projections of wind installed capacity from the Annual Energy Outlook 2015,[13] we estimate that an average of approximately 15,000 tons of blade material will be used between 2015 and 2030 annually. The projection used is based on the reference case, which assumes that current laws and regulations remain unchanged and that about 35 GW of wind capacity would be added between 2015 and 2040. However, the U.S. Department of Energy's (DOE) projection suggests that the country will need to increase its wind energy installed capacity by an average of approximately 14 GW annually if it wants to meet the goal of 20% wind energy by 2030.[3] The projection was made in 2008 and no revision has been made since then, but a 2015 report by the U.S. DOE[14] suggests that with proper policy, the scenario of 20% by 2030 is feasible. In that case, we estimate that an average of about 165,000 tons of blade material would be produced annually.

Overview of Concerns

The excellent stability of the GFRP material found in wind turbine blades has challenged the development of an optimal waste management method.

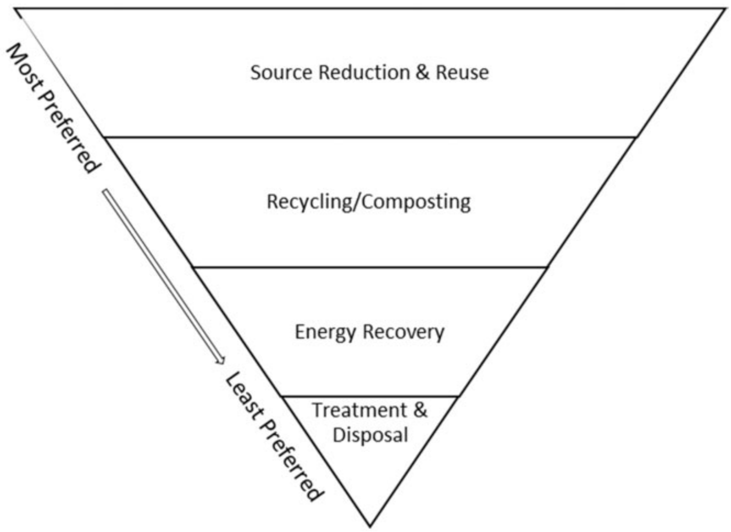

Figure 2. Non-hazardous waste management hierarchy.
Source: U.S. Environmental Protection Agency.[15]

According to the U.S. DOE's nonhazardous waste management hierarchy, source reduction and reuse, which refers to waste prevention and reutilization of items, is preferred to recycling (see Figure 2).[15] That is because recycling is a more energy-intensive process that entails collecting, sorting, processing, and remanufacturing what would otherwise be considered waste material.[15] Currently, there are different disposal methods for the GFRP found in the wind turbine blades, some of which are considered recycling methods whenever some recovery of energy and/or material is possible. Each method, however, carries negative environmental and economic implications, as well as potential occupational hazards.

Table 1 provides a summary of the existing disposal methods and their key concerns. Despite its negative consequences, landfilling has so far been the most commonly utilized wind turbine blade disposal method. Given that cured epoxy resin is present in the blades, landfilling is especially problematic because its high resistance to heat, sunlight, and moisture[16] means that it will take hundreds of years to degrade in a landfill environment. The wood and other organic material present in the blades would also end up in landfills, potentially releasing methane, a potent greenhouse gas, and other volatile organic compounds to the environment.[17] Even though gas collection systems that capture the methane released in landfills and use it as an energy source are common, a significant percent of the methane generated inevitably escapes depending on the overall efficiency of the system.[17] While methane emission from the balsa wood used in

Table 1. Existing disposal methods and some of their main concerns.

Disposal method	Economic	Environment and occupational exposure
Landfill	Opportunity cost of unrecovered material and concerns of long-term space availability	Release of methane and other volatile organic compounds from wood and other organics in the blades
Incineration with energy and/or material recovery	Significant energy and machinery requirements to cut and transport the blades to the incineration plant	Pollutant ash after the incineration process, possible emissions of hazardous flue gasses, and potential hazards from mechanical processing
Pyrolysis	Low economic viability because of degradation of resulting fibers	Emission of environmentally hazardous off-gasses and potential hazards from mechanical processing
Fluidized bed combustion	Low economic viability because of degradation of resulting fibers	Potential hazards from mechanical processing
Chemical	Economic viability dependent on chemical process used	Use of hazardous chemicals and dust from mechanical processing of the blades
Mechanical	Low market value of both the resulting fibers and substitute virgin material	Dust emission during the grinding process of glass fiber thermoset composites

Note. Courtesy of authors. See text for sources.

one blade would be insignificant compared with the alternative of burning fossil fuel to generate the same amount of electricity that a blade would generate,[a] other alternatives (e.g., composting) would be preferred from a long-term sustainability perspective. Likewise, landfilling creates issues of long-term space availability. Although landfill capacity appears adequate nationally, it is limited in some areas[19] and will likely be problematic in space-constrained states. It also carries an opportunity cost of unrecovered energy and material from the blades, some of which can be potentially recovered with other disposal technologies presented in Table 1.

Landfilling wind turbine blades at the end of their useful life is particularly appealing in the United States due to the amount of land available for disposal sites, which makes it the cheapest option. Unfortunately, the cost efficiency of landfill use also makes it very difficult for alternative disposal methods to compete. Conversely, many European countries have banned or reduced the landfilling of FRPs because of the high content of organic material, and as a result, alternative disposal methods are being explored.[20] Based on information obtained from phone interviews with eight U.S. landfill operators who are located near wind farms that are fifteen years of age or older, the estimated cost to put blade material in landfills, not including pretreatment and transportation costs, is approximately US$60 per ton. In the United Kingdom, where landfilling organics is not yet prohibited, the active waste disposal cost (which includes plastics) is approximately US$130 per ton.[21]

Incineration of blades is another disposal method with potential for energy and/or material recovery. Incineration of thermoset composites has some advantages, such as saving space and the economic value of utilizing the resin as a heat generator while recovering the fibers for different applications. Given that glass fiber is incombustible, the calorific value of GFRPs will depend on the proportion of polymer.[22] Despite these apparent advantages, there are important environmental issues with this disposal method. Combustion of GFRP is especially problematic because it can produce toxic gases, smoke, and soot that can harm the environment and humans.[23] Carbon monoxide and formaldehyde have been reported as residue from thermal degradation of epoxy resin.[24,25] Another residue is carbon dioxide,[24,25] which poses concerns regarding greenhouse gas emissions. In addition, about 60% of the scrap remains as pollutant ash after the incineration process, some of which is sent to landfills, potentially contaminating the sites. Possible emission of hazardous flue gasses is also among the issues with incinerating wind turbine blades. This is due to problems in the flue gas cleaning steps caused by the small fractions of glass fiber and pollutant byproducts.[8]

Other thermal processing methods include pyrolysis and fluidized bed combustion (FBC) and are aimed at recovering both the reinforcement fibers and the resin in the composite but can also recover combustion heat through a waste-heat recovery system.[26] The pyrolysis process decomposes the organic material into low molecular weight substances by applying heat in the absence of oxygen under controlled conditions.[27] The degraded polymer (in the form of smaller molecules such as oil, gas, or solid char) can be used as an energy source in other processes, while the glass fiber is left intact for recovery.[26,27] FBC is a similar method that consists of mixing fuel and air in a specific proportion for obtaining combustion.[28] Both processes recover glass and carbon fibers with some strength degradation that can be used for applications with lower mechanical demands, such as thermal resistance insulation material, although with limited economic viability.[26–28] The FBC for glass fiber composites seems to need a minimum production capacity of 10,000 tons/year to be economically feasible.[26] The pyrolysis process for carbon FRP seems to better retain the mechanical properties of the fiber and produce less fiber strength degradation compared with the FBC, but it also produces environmentally hazardous off-gases and residues, including carbon monoxide,[b] carbon dioxide, and methane.[29] A combined pyrolysis-gasification process for wind turbine blades developed in Denmark has not been commercialized because it is not cost-effective.[26] One key issue is that all these thermal processing techniques for wind turbine blades would also require fragmentation of the material into smaller pieces through mechanical processing before being fed into the reactors, increasing energy consumption and carbon dioxide emissions.

Mechanical processing is a relatively simpler disposal method that consists of cutting, shredding, and grinding the material to separate the fibers from resins, so it can be repurposed. This process is energy intensive and produces small fiber particles with poor mechanical properties that can only be used as filler reinforcement material in the cement or asphalt industries.[30] The low market prices for substitute materials, the cost of grinding machines, and the energy required to operate them limit the cost-effectiveness of using ground thermoset composite.[30] The dust emitted in the grinding process of FRP creates occupational health and safety risks for workers. Inhalation, as well as skin and eye contact can produce moderate irritation to mucous membranes, skin, eyes, and coughing.[31] Occupational exposure and prolonged inhalation of such particles have been found to produce alterations of the cellular and enzymatic components of the deep lung in humans, identified as acute alveolitis.[32] While exposure control technologies such as suction filtration, humidification of the cutting site, and encapsulation of the grinding process can minimize some of these negative impacts,[33] they can also further increase the cost and make mechanical processing even less cost-effective. More research is needed about the effectiveness of these technologies at minimizing impacts and about the respiratory disease hazards related to exposure to particles from FRP.

The last method is chemical degradation, which consists of first mechanically reducing the size of the blades, then degrading them using a chemical solution.[34] The organic portion can be used as a feedstock for other processes and the rest is reinforcement and filler material that can be repurposed. Some of the advantages of this approach are the potential for recovering the resin and the ability to preserve the mechanical properties of the reinforcing fiber. The chemicals are used to release the fiber from the resin and/or to eliminate damages from the fibers after recovery. Although no industrial-level chemical recycling of thermoset polymers has been done yet, some hazardous chemicals such as nitric acids and paraformaldehyde have been used in testing and development processes.[35,36] Occupational exposure to these chemicals can produce harmful respiratory diseases including potential nasal cancer, and dermal health effects.[37,38] Despite this approach's ability to maintain the mechanical property of materials, the use of these toxic and hazardous chemicals limits its attractiveness.

A more desirable situation for blade disposal would be to achieve the property of reworkability in thermoset composites. The property of reworkability mainly characterizes "the ability [of the thermoset material] to break down under controlled conditions [based on chemical and thermal techniques]."[39] The process reduces the mechanical strength, making it easier to reshape, recycle, and repair thermoset-based structures such as wind turbine blades.[39,40] A relatively new class of material called vitrimers can be thermally processed in a liquid state without losing network integrity, which means that upon heating, a rearrangement of the chemical bonds occurs that enable material deformation, processing, and recycling.[40] A reworkable thermoset means that the industry would have the ability to permanently deform the blade material without (or with minimal) loss in properties, as compared with what can be achieved at the moment. It would also avoid some of the negative environmental consequences and occupational exposure, while allowing for complete reuse of the material at the end of the blade's useful life. It would provide a wide number of options for blade treatment, such as easier repair without the need to replace the damaged blade, reutilization, or deformation to be used in other applications.

An Argument for More Research and Policy Intervention

There is a need to prioritize the safe and sustainable disposal of wind turbine blades before the anticipated influx of thermoset composite structures require dismantling. The current stock of blades and the actual manufacturing process use thermoset composites as the primary material, imposing constraints in both blade manufacturing and the disposal processes. If the goal is to increase the sustainability of the wind industry, we should find ways to encourage the development of better technologies in design, manufacturing, operations, and maintenance and disposal of the blades. Alternatives to the low-cost landfilling are needed as a disposal method due to its negative environmental impacts and the opportunity cost of recovered material. Given the current economic and regulatory climate, landfilling of blades will likely continue until another disposal method becomes as economically attractive. Consequently, discouraging the landfilling of blades will likely need effective policy intervention.

Besides economic obstacles, environmental issues and potential occupational exposures of combustion, pyrolysis, FBC, and chemical and mechanical processing must be addressed before any of these methods are widely applied in the industry. More research is needed to fully understand the health and environmental implications of some of these methods to workers, nearby communities, and overall population. Some of these technologies are relatively new or have had limited use in processing wind turbine blade material. As a result, there is considerable uncertainty about the feasibility of these technologies to function as a practical alternative for more sustainable wind turbine blade disposal. Because blades have to be cut on site before being transported to any processing plant or landfill, it is also important to understand workers' exposure to components of fiber-reinforced composites, as well as technologies and methods to minimize this potential hazard.

Addressing these issues is particularly important for the disposal of the already-installed wind turbine blades. Nevertheless, because more blades are being manufactured and installed every year, the urgency to design blades that are economically and environmentally sustainable will create greater opportunities for new solutions and technology to emerge. However, these technology developments will depend on the extent to which they are prioritized in the future. In contrast, as a near-term solution, mechanical recycling with material reutilization in cement production may become more attractive if occupational safety can be ensured by developing the necessary standards and technologies. There are inhalable dust control standards for particulates exposure regulated by the U.S. Occupational Safety and Health Administration.[41] Implementing the aforementioned technologies (suction filtration and humidification) can help the potential industry comply with such standards and make mechanical recycling a more preferable option. However, more research is needed to ensure that those safety measures are adequate and that they will not further increase costs. As mentioned earlier, however, the property of reworkability would represent the gold standard in blade disposal as it implies complete reutilization of the materials without the need to use hazardous chemicals or to destroy/degrade the fibers. More research is still needed, but efforts are being made in that direction, as some research projects are funded by the National Science Foundation and the U.S. DOE.[42,43] Increasing budgets of research centers and laboratories to support research on alternative disposal methods would be one form of policy intervention.

In the short term, for thermal, chemical, or mechanical processing to become more appealing to the plastics recycling industry in the United States it must become a more economically competitive option. The capital investment and labor requirements make recycling too costly compared with the end market values of repurposed composite materials without some form of government intervention. Furthermore, it can be argued that landfill operators are being subsidized as they do not internalize the negative environmental externalities generated by landfilling waste. Therefore, tax breaks and subsidies are one method to reduce the cost for emerging and existing recycling companies compared with landfilling. For instance, policy intervention to prohibit or to impose a tax on the landfilling of wind turbine blades could encourage the industry to look for alternative disposal methods. In the current U.S. political environment, however, it will be challenging for such laws to pass at the federal level. Another possibility would be individual states banning the landfilling of composites thermoset. However, it would only be effective if enough states do it so as to make it economically unfeasible for wind farms to transport the blades at the end of life from one state to another state where it is not banned. A more effective scenario could be a regional approach in which groups of states pursue common strategies that establish disincentives on the landfilling of composites thermoset.

Few individuals and organizations recognize the problems inherently related to blade recyclability. This situation creates an obstacle for promoting policy interventions to solve these problems. As a result, manufacturers, wind farm operators, and advocates have largely ignored the issue, focusing efforts on promoting wind energy and addressing other issues such as negative impacts on wildlife and noise generation. The wind energy industry would likely be reluctant to support such regulations unless it was part of a broader initiative that expands wind energy incentives to offset potential negative economic consequences. For policy interventions to succeed at the federal level, a major public awareness campaign is needed to raise consciousness levels about the current blade manufacturing and disposal practices. However, a public awareness approach should be carefully framed to include the true costs and benefits of wind energy as compared with fossil fuel alternatives. Over time, these issues will get attention in the media and will join the existing list of public environmental and ecological concerns, which the industry has been constantly looking for ways to address.[44] To address existing concerns, the wind energy industry has begun siting power plants in areas with lower bird and bat population densities, placing turbines in areas with low prey density, and using different numbers, types, and sizes of turbines to reduce bird and bat fatalities. Others actions include reducing aeroacoustic noise from the turbines, and technologies such as bubble curtains, cushion blocks, temporary noise attenuation pile design, vibratory pile drivers, and/or press-in pile drivers.[44]

Directives regarding producer responsibility can also be an effective policy tool. The *Extended Producer Responsibility* within the European *End of Life Vehicle Directive* establishes, among other things, that producers should manufacture vehicles that allow reusing and recycling the materials (e.g., automotive vehicles disposed after 2015 should allow 95% recovery with minimum 85% recycling), as well as be responsible for the disposal of the vehicles.[45] In the United States there is no federal legislation governing extended producer responsibilities, and End of Life Vehicle directives have been limited to voluntary programs.[46] Cherrington et al.[20] discuss how introducing the directive to the wind energy sector and developing strategies for blade disposal at an early stage would enable sustainable recovering and recycling methods to be in place when needed. Tojo[47] argues that, at least in theory, requiring producers to assume the management costs of disposal should incentivize them to improve environmental performance of the product and encourage innovative solutions.

At the same time, a transition to new manufacturing processes is needed to allow harvesting of wind energy in a more sustainable manner. A 2014 report by Global Wind Network[48] about the competitiveness of the wind energy sector concluded that to enhance blade manufacturing competitiveness in the United

States, research and development initiatives to optimize materials, designs, and processes are needed. For example, enhancements can be made by utilizing less material and more environmentally sustainable resources, such as less toxic and nonfossil fuel-dependent chemicals, by increasing blade life through better design, and by applying technologies such as condition monitoring methods and remaining useful life prediction techniques. Improvements could also involve developing materials that allow recyclability and blade designs that maximize power output and minimize impacts on the ecosystem. Such manufacturing innovations will contribute to the long-term sustainability of the wind energy industry. Policy interventions would significantly aid this effort and could include encouraging global collaboration that increases knowledge transfer from learning-by-doing and learning-by-searching processes, increasing the budget allocated to wind energy research for the DOE, National Science Foundation, and other publicly funded departments and laboratories, as well as providing subsidies or tax credits to companies allocating a percentage of their revenue toward research and development.

Technological Innovation

Researchers have been investigating some technological innovations. One potential development would be the manufacturing of blades using thermoplastics composites instead of thermosets. Contrary to thermosets, thermoplastic materials soften when heated and do not cure or set, making them easier to recycle. Some effort is being made to substitute thermoset composites with thermoplastic composites in some components of offshore wind turbine blades,[49,50] but technical limitations exist. The higher viscosity of the melted thermoplastic means slower flow of material, which makes it difficult to manufacture large, utility-scale blades.[50] The thermoplastic has higher viscosity than the thermoset, but a special reactive thermoplastic that processes like a thermoset, and that can be used to prepare thermoplastics composite, will flow into the mold and solidify faster, reducing the processing time.[50] Manufacturing blades with thermoplastic can be faster with the injection molding process, which consists of injecting the thermoplastic with pressure to fill a mold. However, vacuum infusion, instead of injection molding, is used in blade manufacturing because it reduces the formation of voids in laminates of large areas. Another drawback of using thermoplastic is that, it requires higher processing temperature, increasing the manufacturing costs. In addition, mechanical properties such as static and fatigue strength of thermoplastic are less suitable for manufacturing wind turbine blades,[49] which are subjected to many different environments at the wind farms. While there are technical limitations, the use of thermoplastic composites is becoming attractive for blade manufacturers due to ease of repair, recyclability of the material, and the short mold-cycle times in manufacturing.[49,50] While those limitations prevent it from being the solution in the near future, the use of thermoplastics would nevertheless constitute an important contribution to the recyclability of the blades.

While the use of thermoplastic would allow for blades recycling, it is not entirely environmentally sustainable because it may involve a petroleum-based resin. Therefore, another potential development in the manufacturing process of wind turbine blades is the substitution of petroleum-based thermosets with bio-based thermosets.[51,52] In particular, one novel research approach is focused on the use of thermoset epoxies that are easily produced from a vegetable oil, minimizing energy intensity and costs.[43] Some research indicates that epoxidized linseed oil can be the basis for a thermoset whose mechanical properties are comparable to petroleum-based epoxy resins.[51,52] Ongoing work aims to optimize the epoxidized linseed oil system for use in wind turbine blade manufacturing. In addition, current research suggests that another advantage to the use of epoxidized linseed oil is that it is much safer for workers than conventional epoxy resins based on bisphenol A and epichlorohydrin.[43] The production of epoxidized linseed oil is a relatively clean, efficient process, without toxic reagents or byproducts involved. It is also less reactive and more stable at room temperature, making it safer to use than conventional epoxies,[43] where the curing process is often so exothermic that it can actually cause fires if not properly managed.

The other part of the research is focused on achieving the property of reworkability in both bio-based and conventional epoxies,[43] which would represent another medium- to long-term solution for optimal disposal. An optimal disposal method for wind turbine blades would overcome some of the issues with current practices and would require the least amount of effort and energy to implement while maintaining most of the value of the material. Unlike thermoplastics, current thermoset-based composites are by definition not reworkable once their curing is complete. As noted earlier, the reworkability of thermoplastics makes them attractive for effective blade recycling due to the reduced economic, occupational health and environmental consequences versus current disposal methods of thermoset. Being able to induce some measure of thermoplastic-like reworkability in thermoset-based composites would enable the bending, warping, or reshaping of (segments of) used blades into other shapes for different purposes without a significant loss in properties.[43] In addition, it might help to improve the efficiency of the manufacturing process and reduce variability, defect concentrations, and the need to overdesign structures by enabling the automated production of highly uniform flat plates that could be shaped after the fact into more complex geometries.[43]

Conclusion

Finding better ways to manage the expected high number of blades in need of disposal is important in order to harvest wind energy in a truly sustainable manner. Better management would mean that economic and societal needs for clean energy are fulfilled without compromising the environment. None of the current methods allow for optimal wind turbine blade disposal. All of them carry potential economic, environmental, and occupational health concerns. Policy interventions such as allocation of more research funding to blade manufacturing and disposal, the provision of incentive mechanisms to recycling, and directives of producer responsibility could help overcome or minimize some of the challenges associated with disposing of wind turbine blades. However, some of these policies are likely to be implemented only when environmentalists and the general public become aware of and understand the real extent of such challenges. We believe that the best option is to move toward a different, more sustainable manufacturing process in material and design that also allows for optimal disposal. That result could be achieved through greater government funding for research and development, as well as tax credits for companies which invest resources in research and development.

Some potential technological innovations include the use of thermoplastics instead of thermosets and the use of bio-derived resins instead of conventional, petroleum-based epoxy resins, in the manufacturing process of the blades. The former could have important implications for blade recyclability and costs. The latter promises a more sustainable manufacturing process using bio-based feedstocks such as vegetable oil. They both demonstrate considerable potential as more sustainable blade manufacturing and disposal processes. These initiatives, however, still must address important technical issues before they can be applied in utility-scale blade manufacturing. Realizing the property of reworkability in thermoset-based composites would allow for optimal disposal since it would allow for complete reutilization of all the materials in the blade.

If the industry cannot come up with more sustainable manufacturing and disposal processes, public acceptance of wind energy would decline if the public becomes aware of these issues, inhibiting its growth as one of the main sources of electricity generation in the United States. There is great potential in wind energy because it is economically viable and much more environmentally friendly than fossil fuel-based electricity generation. It has become cost-effective for the electricity generation industry and is cheaper than other renewables, such as solar. However, the inability to overcome the barriers to wind turbine blade manufacturing and the continued landfilling of blades will represent a real challenge for wind energy expansion within the U.S. energy portfolio in the future.

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Notes

a. A 20-meter blade would use 41.2 kg of balsa wood and would produce about 876,000 kWh per year.[18] That amount of wood would generate 0.0000534 tons of CO2-e in a landfill environment. In contrast, the amount of natural gas that would have to be burnt to produce the same amount of energy (876,000 kWh/year) would generate 0.3261 tons of CO2-e. This would be an underestimated difference given that bigger blades are more energy efficient (for details on the formula used, see http://www.environment.gov.au/system/files/resources/b24f8db4-e55a-4deb-a0b3-32cf763a5dab/files/national-greenhouse-accounts-factors-2014.pdf).
b. Carbon monoxide is not a greenhouse gas, but it should be considered environmentally harmful because it is "a pollutant that affects methane, carbon dioxide, and tropospheric (lower atmospheric) ozone," which "plays a role in both air pollution and climate change..." (see http://www.giss.nasa.gov/research/briefs/shindell_09/).

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