The Landscapes of Wind Energy Waste

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Globally, wind energy is viewed as "carbon neutral", recognized for generating clean, greenhouse gas-free electricity without an ecological footprint. Considered to be one of the most environmentally promising and economically viable sources of renewable energy, its growth worldwide has rapidly accelerated, spawned by governmental climate emergency response targets like Net Zero Emissions by 2050. Incentivized by markets, developments in technology have followed, resulting in massive increases in turbine size and capacity, despite challenges of delivery and distribution; these trajectories are poised to continue.

With a lifespan of 20 to 25 years, a comprehensive life cycle analysis of wind turbine blades (WTBs) reveals a pressing environmental concern of their materials reuse (or disposal). Made of Glass/Carbon Fiber Reinforced Polymer, and fabricated to withstand immense wind force, both their material and assembly result in structural properties which currently preclude WTBs from being reused or recycled in a systemic, scalable way. Research and recent developments have resulted in targeted solutions which aim to change the stasis of key turbine component reuse. Challenging the perceptions of endlessly renewable energy and the fact that renewables are entirely carbon-neutral, this paper outlines factors that hinder large-scale reuse and recycling, touching on possibilities of the chemical and physical restructuring of the material; it focuses on possible upcycling options as a structural material in architecture and civil engineering, including large-scale use in the rewilding of waste landscapes.

INTRODUCTION

Wind energy has been growing at a record pace, fueled by the pressing mandate to decarbonize the world's economies through their associated energy industries, in order to mitigate the climate emergency. After the global covid pandemic, in 2022, wind electricity generation worldwide spiked, increasing by 14% to more than 2,100 TWh (Terawatt hour = 1,000 MWh). With China accounting for 40% of wind generation growth, the EU 14% and the United States 22%. The U.S. currently obtains 10.2% of its utility-scale electricity generation from wind (22% from renewables in general, 18% from nuclear energy and 60% from fossil fuels); this number is anticipated to be 18% in 2050 with renewables accounting for 44%.

As significant as those increases are, in order to meet Net Zero Emissions by 2050, wind electricity generation globally will need to increase at a much faster pace, by 17% annually to 7,400 TWh in 2030, with an immense growth in wind energy capacity, from 75 GW in 2022 to 350 GW in 2030. In order to achieve this, wind power component (nacelles, towers and blades) manufacturing capacity will need to considerably accelerate through an intensely coordinated effort of public and private sectors. Additionally, wind technology innovation will need to continue the current trend of focusing on increasing the productivity of turbines, especially in areas with low wind conditions, by developing turbines with longer WTBs and higher towers.

As the costs of the infrastructure and its energy produced have both fallen significantly over the past two decades, the number of installations and the efficiency of their operation have surged. Increased production and greater capacity have also caused wind turbine designs to dramatically increase in size. The hub height for utility-scale land-based wind turbines has increased 73% since 1999, to 98 meters (322 feet) in 2022. All of these directly affect both their environmental performance and environmental impact.

Ecologically, wind energy is often called one of the most promising and economically viable sources of renewable energy, recognized for generating clean, greenhouse gas-free electricity. It is advertised as being "carbon neutral" or able to provide clean energy without any emissions during operation. Although wind energy has numerous benefits in comparison to burning fossil fuels, a comprehensive life cycle analysis reveals that the environmental concern of its materials reuse (or disposal) persists across the globe.

WIND TURBINE BLADES (WTB)

While 85-90 percent of turbine component materials, measured by weight —such as steel, copper wire, electronics, and

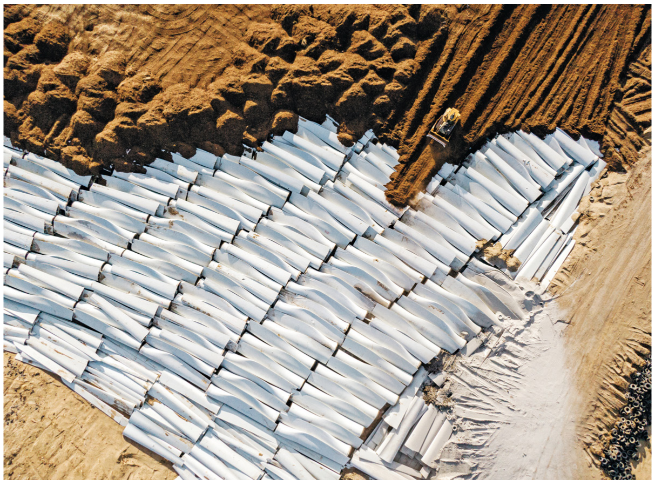

Figure 1.Wind Turbine Blades (WTBs) shown in the Casper, Wyoming landfill. . Image credit: Benjamin Rasmussen/Getty Images

gearing—can be recycled or reused, at this time the WTBs, made of fiberglass and resin, cannot be recycled easily and are generally considered waste. Rare Earth Elements (REEs), crucial raw materials in the manufacturing of permanent magnets used in turbine generators are similarly nearly impossible to recycle; toxic effluent emissions result from exhaustive mining activity required to extricate REEs; radioactive acid baths needed for REE separation from ores in the process of refinement generate radioactive waste. Although REE extraction is environmentally and geopolitically troublesome, this paper focuses on the problematic nature and potentials of WTB reuse and recycling, including: (1) the difficulty of estimating WTB mass, weight and therefore material end-of-life quantities; (2) current practices pertaining to WTB end-of-life disposal and recycling; and (3) reuse and upcycling through a series of proposed solutions converting WTBs into new construction products, as structural material in architecture and civil engineering, including a large-scale use in the rewilding of waste landscapes.

WTBs, components precisely engineered out of Glass/Carbon Fiber Reinforced Polymer composites bound by thermosetting resins, have an average lifecycle of 20-25 years after which they must be replaced. It is projected that WTBs will produce 43.4 million tons of waste worldwide by 2050. The amount of WTB material that will need to be recycled annually is 400,000 tons between 2029 and 2033. It will increase to 800,000 tons per year by 2050 a figure that doesn't include newer, taller higher-capacity versions, which have yet to be installed.

WTBs are usually replaced in kind, swapped for longer WTB or installed on new larger turbines when wind farms are upgraded. For example, every 18 to 24 months, an onshore wind turbine suffers a major failure, requiring either a gearbox change or a blade replacement. Currently, decommissioned WTBs have no commercial value. Because there are so few options for recycling WTBs presently, the vast majority of WTBs that reach end-of-use are either being stored onsite or taken to landfills. WTBs are commonly cut into several pieces onsite, a process requiring large equipment such as a vehicle mounted diamond-encrusted industrial saw, similar to what is used in quarries. The process emitting a great deal of carbon-dioxide on its own.

In evaluating future WTB reuse potentials, it is important to point out engrained obstacles which make evaluation of WTB end-of-life quantity estimates inconsistent and imprecise. Much of the research asserts the inaccurate estimation and methodology regarding how much blade waste there will ultimately be because: (a) the first cycle of installations has not all reached decommissioning and data on the actual number of WTBs decommissioned is scarce. An approximation that could be used is that each WTB at current size (Each WTB is 120 feet long and cut into 40-foot pieces before being buried) will need between 30 and 44.8 cubic yards of landfill space; (b) the exact mass of a WTB is not a standard and varies widely; and (c) turbine capacity has increased six-fold since 1995 largely due to turbine size increases. Future increases are unknown – turbines have the potential to get substantially bigger than those in use today. There also isn't any agreement on what is included in the "mass" or "tonnage", when considering waste. WTBs have approximately 10% material by mass that is metal (steel bushings and bolts used to connect the blade to the hub, metal in the blade tip and vortex generators), sometimes included in weight estimates. Based on those imprecisions, it is difficult to predict the financial feasibility of any future process of recycling currently being developed.

CURRENT PRACTICE

At present, in practice, there are two leading end-of-life solutions for WTBs: landfill and incineration.

As there are so few options for recycling WTBs currently, and because the U. S. wind energy industry is still young, the vast majority of the WTBs that reach end-of-use are either being stored in select places close to places of deployment, or taken to landfills. WTBs are landfill-safe at the end of their commercial life. Buried in stacks that reach 30 feet underground, WTBs will ultimately be left in landfills forever unless there is a value to the recycled product. Small utility or municipality landfills are an added expense costing up to $600,000 per year (Casper, WY).

Disposal is more regulated in countries that have had wind energy for longer. The European Union has waste management rules, and regulations do not allow landfill disposal due to pollution and other ecological impacts. Often WTBs in member countries are burned in kilns. Energy recovery or gasification, although productive, is generally considered to be environmentally harmful, but is the current preferred method due to its low cost.

Transporting the WTBs is an enormous challenge. Old WTBs must be cut by diamond-wire saws into sections small enough to fit on a flatbed truck in order to be transported. WTBs average around 50 meters in length in the United States (164 feet), the

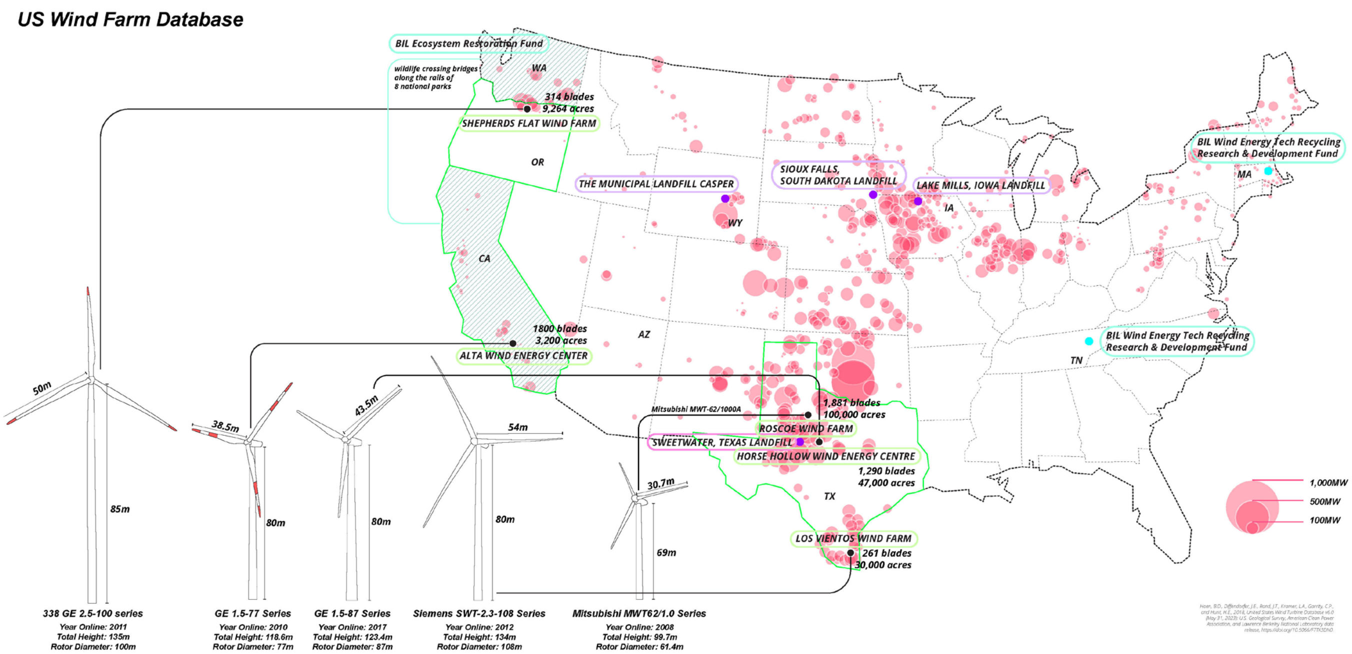

Figure 2. Map of the United States showing distribution of wind farms, sorted by capcity Image credit Lia Lee / Dragana Zorić

dimension of an Olympic sized swimming pool. As designs trend towards bigger turbines and taller towers, WTBs produced today can reach 60-80 meters in length, making transport exceedingly difficult. Moreover, wind farms are generally located in sites that are distant from main roads, dismantling or recycling facilities, which makes logistics and dismantling costs higher. In fact, early research and development focused on breaking down a WTB. A process that used to take 4-6 workers about 90 minutes to cut a 120-foot WTB in two now takes 2-3 workers 10-15 minutes to cut and load.

WTB RECYCLING

The relatively short history of the wind turbine industry and low production volumes have led to there being no successful industrial scale WTBs recycling processes thus far that have yet been well-defined, established and found to be economically feasible.

The most pressing problem in fiberglass recycling is how to create resins that, when a WTB has outlived its usefulness, can be returned to a liquid state. Current resins, called thermosets, react under heat during production and become solid, but the process can't be reversed. In the past four or five years, researchers have studied new material systems — thermoplastic resins — that could be recovered under high heat, while also recovering the WTBs' fiberglass and core, usually balsa or foam.

Due to the complexity of this composite material which requires specific processes for recycling, today, the main technology for recycling composite waste is through co-processing (cement kiln), mechanical recycling, pyrolysis, solvolysis, high voltage pulse fragmentation and gasification (fluidized bed).

Cement kiln is a procedure of crushing and burning WTBs, breaking up the composite fibers in ovens in order to reclaim the fiber to be used as replacement for virgin, mined materials such as sand, clay and limestone in the production of the cement clinker. For end products, fibers are mixed with fillers and reused in concrete, paint and glue. Mechanical Recycling entails shredding parts into raw fiberglass material that produces fine and course particulates that can be mixed with rock, plastic or other fillers. The mixture is then turned into thermoplastic fiberglass pellets to be used in injection molding and extrusion manufacturing processes; or panels decking boards, warehouse pallets, various building infrastructural uses and weather-resistant siding. Both processes involve carbon emissions, and arguably, chopping up WTBs into smaller pieces will eventually introduce another kind of long-life, indestructible micro-material into the environment.

Pyrolysis (thermal recycling) converts the polymer to gas, oil and char, while the fibers remain inert while; solvolysis (chemical decomposition) uses reactive solvents (nitric acid, ammonia or glycol) in order to extricate pure fibers without resin. Aside from greenhouse gas emissions, and component toxicity, neither have been shown to be effective at enough of a large scale to address anticipated waste quantities nor are they cost effective.

Recycling technologies are all accompanied with significant material losses. Increasing the purity of recovered materials and improving energy consumption related to this recovery are key areas for improvement in coming years.

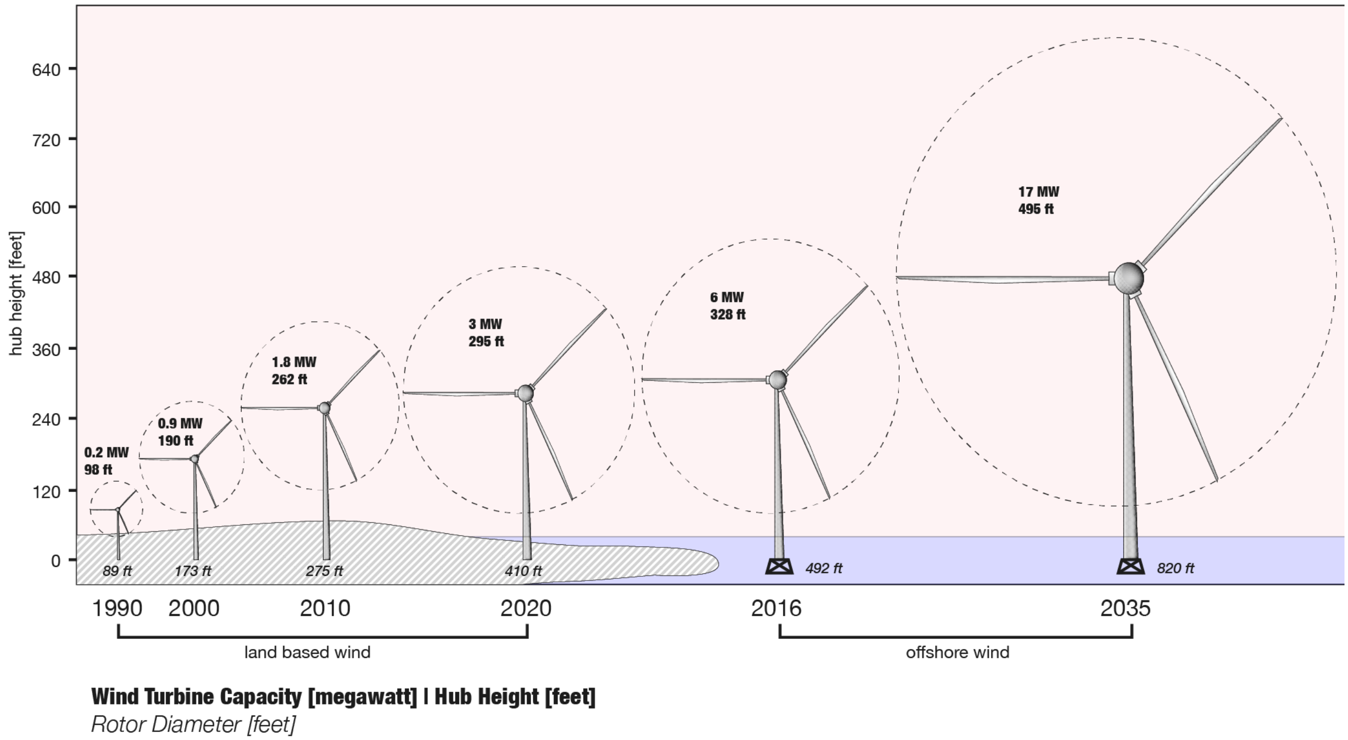

Figure 3. WTB Size Increase. Image credit Andrew Dionne / Dragana Zorić

WTB REUSE

New studies are exploring possibilities of "full recycling", or upcycling – structurally reusing the composite WTBs including as structural components in buildings, architectural products, bridges or artificial reefs. These use WTB's unique structural and architectural properties. WTBs are lightweight, flexible when force is applied on the flat side, and stiff and sturdy when force is applied on the leading edge, allowing 100% of the composite materials (fiber and polymer materials) to be recycled. Some studies have revealed that directly reusing blades in bridge fabrication or furniture making, for example is the most sustainable alternative with furniture making in second place. Taking into account key properties and dimensions of the blades, and evaluating each specific section of a particular blade type, architects and engineers can define feasible uses.

Re-Wind, a collaborative network established between University College Cork, Queens University Belfast and Georgia Institute of Technology have done extensive research, testing and design on how WTBs can be reutilized into alternative structures upon end-of-life.

Re-Wind's designs for low-profile pedestrian and vehicular bridges demonstrate the exceptional strength of the WTB material, utilized as primary load-carrying structural members. For bridges, WTBs are sliced horizontally and placed side by side with their trailing edges abutting each other. To achieve the needed structural strength for this configuration, the WTB may need to be used as a load-carrying permanent non-removable concrete form and filled with lightweight filler and concrete. The concrete may be reinforced and acts as a structural composite with the WTB which serves as the tension member of the composite system. A concrete deck, or other decking materials, can be used together with the low-profile assembly to act as part of the assembly composite. Concrete abutments with specially designed cavities are used to support the bridge ends.

A full-scale bridge prototype in Cork, Ireland, constructed in 2022 by Re-Wind demonstrated the ease of in difficult site access conditions requiring structures to clear riparian buffer of river and protect existing trees. For pathways, WTBs are similarly installed; additional support is needed since the blade is not filled with concrete. These can be used in a variety of park locations, wetlands and nature preserves where pedestrian access must be separated from the park's surface, protecting the flora and fauna. This application replaces the commonly found timber boardwalk.

Given how costly and complicated it is to transport WTBs, converting WTBs to utility poles for electric power transmissions lines, from remote rural wind farm locations to urban centers – is another prototype that Re-Wind has pursued. Aside from transmission line towers, standing the blades up vertically makes them useful for short-range cell towers, shade structures, or wind barriers. The asymmetrical nature of the WTB section requires a special hardware necessary for WTB retrofit; in many instances, it is crucial to its reuse - a key part which must itself be developed. Vertical uses of WTBs also requires a foundation at the base of the pole, commonly constructed out of concrete.

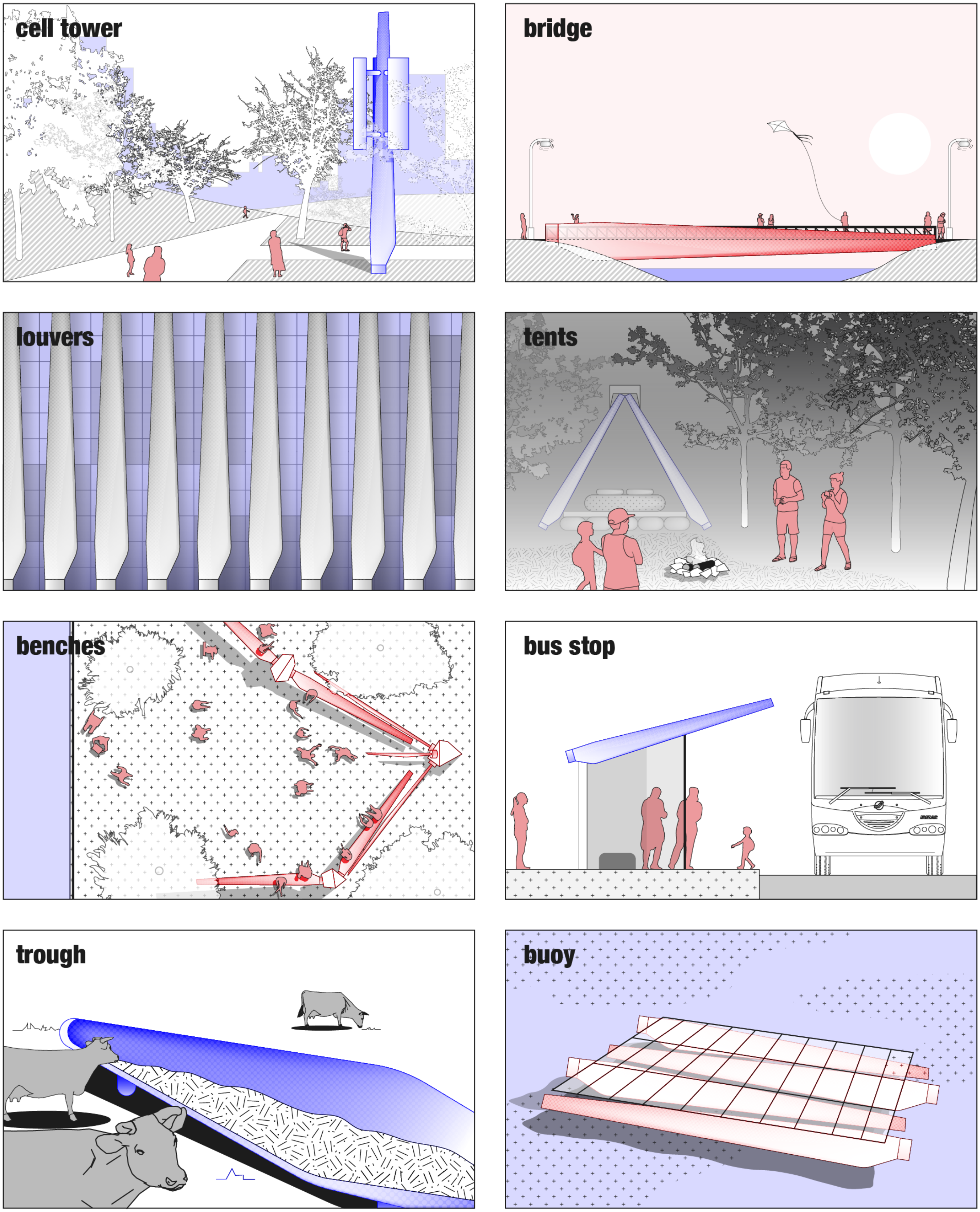

Figure 4. Proposed WTB Uses, as inspired by Re-Wind. Image credit Andrew Dionne / Dragana Zorić

Researchers have proposed retrofitting existing CMU dwellings in places of high heat and humidity. Large scale WTB pieces are broken down into parts, making it possible to reuse different WTB segments for specific housing applications. From a 100-meter WTB, a circular segment can be extracted from the section closest to the hub, becoming a platform which elevates the dwelling out of a flood plain. Additionally, discrete segments of a WTB can be used as door or window covers, as well as large scale roof frame and interlocking roof panel systems. Although the proposal addresses WTB geometry and material tapering necessitating fillers and similar joint sealers, the research circumvents the necessity of fasteners, their material, manufacture and geometrically complex design. “The resilient design of WTBs to withstand harsh conditions makes the flatter panel section suitable for house siding, roof shingles, highway sound barriers, bridge parts, street furniture, or road signage.”

It is especially feasible to use WTBs in marine environments because they do not corrode nor degrade, and the hollow body allows them to float. The root end can be sealed to use in floating applications such as buoys or floats on water storage ponds for shade to prevent evaporation. Structures can be constructed near off-shore wind farms, requiring little transport. WTBs can be used to build a range of floating or standing marine structures such as platforms, docks, piers, jetties and buoys. WTBs can be oriented horizontally or vertically, where they can either float in deep waters or be fixed to the sea bed in shallow waters. Re-Wind shows the floating platforms carrying very large photovoltaic solar arrays. WTBs reused this way can also be a low-cost method of water storage for communities requiring it.

The example of Wikado playground in Rotterdam, designed by Superuse Studios demonstrates that reusing segmented parts of end-of-life products as construction elements can provide a promising alternative to current disposal methods. Five decommissioned WTBs are placed around an existing open area, their bases used as towers, creating a maze-like space. The WTBs are used for climbing, burrowing, and playing in other ways while simultaneously providing structural support.

A variety of urban furniture, shelters, canopies and roofing elements can be made from blade parts. These include bus-stop shelters, bicycle storage shelters, building entry canopies and parking-lot canopies, large roofing systems much like long span truss-joists.

Many types of barrier structures can be designed from WTBs. Sections of the blade spar-cap (the arc-shaped segment) can be extracted to make stiff vertical posts to replace timber or steel posts and used to make construction and highway barriers – walls for noise mitigation, erosion control, wind protection, and sediment erosion. Acting as seawalls, they may also serve as protective barriers against future sea-level rise.

Lendager Group has been working on a scalable solution where sections of WTBs can be reused as sun shading devices in on high-rise buildings. Building codes, and the associated lack of materials testing, currently do not allow for the installation of WTB segments on the façade. A series of fire tests, conducted in order to establish a fire rating for WTBs, have revealed that a WTB section with fire-retardant expanding paint is not a better solution than an untreated WTB section.

It is important to note that the most successful construction elements created out of WTBs considered the original blade design process and were connected to decisions made in the original product design. This results in identification of design opportunities and aspects that enable multiple lifecycles of the composite material. Current designs of WTBs, however, do not take structural reuse into account. Possible ways to achieve this are through segmentation patterns, modularity etc.

If left in situ near decommissioned sites, a scenario not requiring transport nor cutting, WTBs can be used in a process of rewilding at different scales. They can be filled with on-site fill material to create a ballast and rotated on the short end to be retaining walls. In this case, with the WTB resting on the ground, stresses would not an issue as long as a majority of the WTB length is supported . WTBs can be laid out in patterns or paired up along roads, filled with clean soil and planted with native vegetation and carbon sequestering trees. The WTB material, extremely weather resistant, is long performing and would be a part of a permanent solution.

Repurposing WTBs to rewild landscapes presents an additional strategy to tackle waste issues and foster environmental sustainability. Potential approaches include: creating artificial wildlife habitats where discarded WTBs can aid in providing shelter for a variety of wildlife species while engendering biodiversity; placing disused WTBs as barriers in areas prone to erosion caused by dynamic processes of wind and water, thus preserving soil fertility and preventing degradation; supporting plant growth and rewilding efforts as structures that assist plants in growth, including climbing plants, where the understory layer in a forested site needs establishment; incorporating WTBs into green infrastructure projects by create structures that aid in water movement and/or retention; arranging WTBs strategically to create wildlife corridors or connect existing natural habitats, facilitating the movement of wildlife between different areas, promoting genetic diversity and enhancing ecosystem resilience; integrating WTBs into land art installations can serve both aesthetic and ecological purposes, drawing attention to rewilding initiatives and raising awareness about the importance of restoring natural habitats. All of these strategies are large in scale and can successfully support the goals and ambitions of a rewilding agenda.

Lastly, while stringently considering the specific needs and characteristics of an ecosystem, rewilding can be coupled with policy at decommissioning sites or targeted landfills, so that WTB removal, disuse and discard automatically trigger a wholesale rewilding effort involving environmental experts, conservationists, and community stakeholders. Whereas previously WTBs

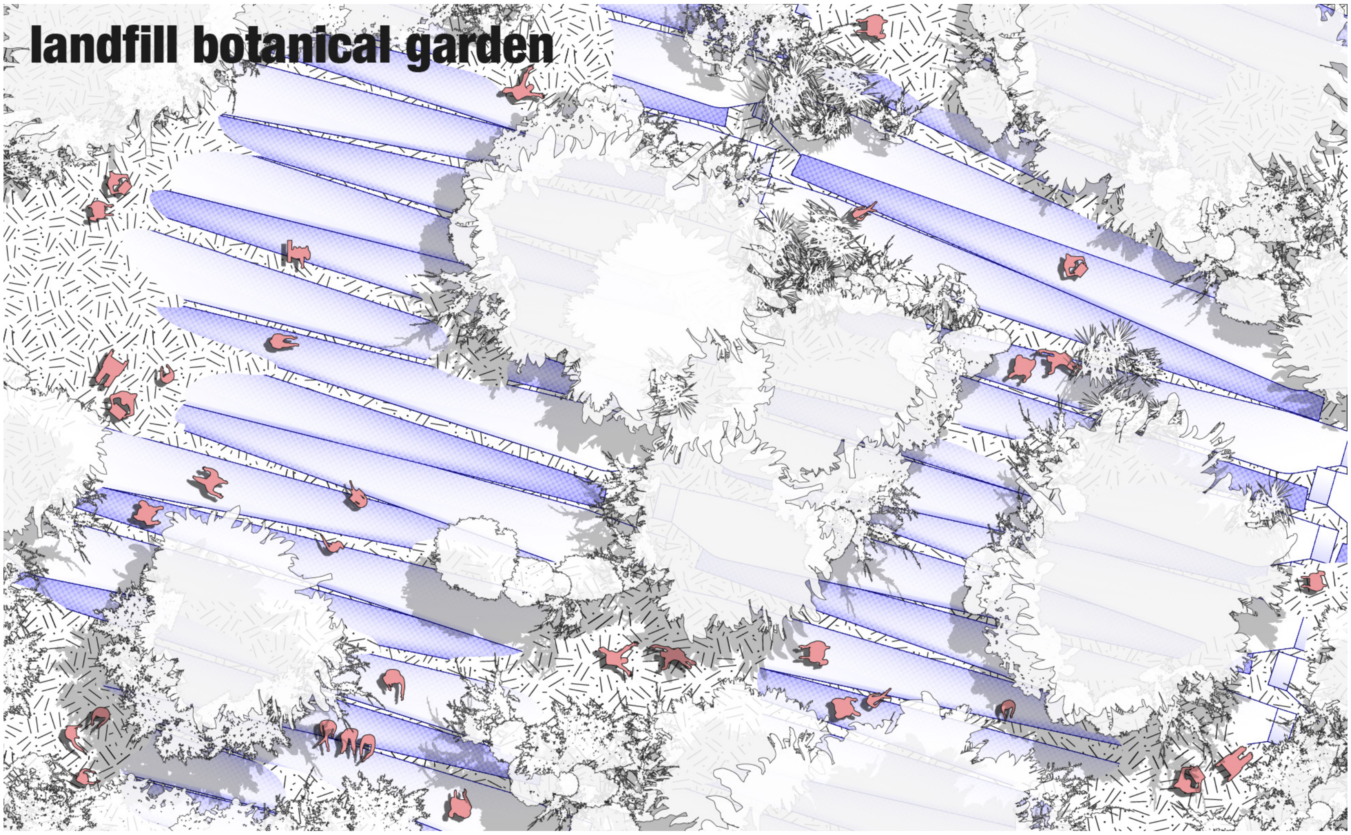

Figure 5. Landfill Botanical Garden. Image credit A. Dionne / D. Zorić

would be considered waste, and the site a "dump", the recipient landscape can be turned into a native ecosystem, an inspired environment, a tourist destination, a botanical garden - a beautiful place replacing blight.

CONCLUSION

Although WTBs are not toxic in landfill deposits, future increases in recycling and reuse of WTBs at decommissioning will provide significant environmental benefits as well as lowering the use of natural resources. The rate and amount of landfill that WTBs are projected to consume, is a fraction of that of other landfill items such as thermoplastics from everyday household use. Regardless, the full, circular end-of-life recycling and reuse processes will necessitate an exchange of information between manufacturers and wind farm owners/operators. Governments will need to adopt ambitious standards and financial incentives, invest in infrastructure required to recycle and reuse at this massive scale, develop new business models and potentially engage legislation that will make manufacturers liable for what ultimately happens to their WTBs.

Ultimately, upcycling, the process of repurposing WTB parts holds the most promise, but must be further researched with regards to mechanical systems, structural analysis, logistics, and detailing. Architectural and infrastructural applications must become cost effective with an ease of dis- and re-assembly, coupled with social accessibility and acceptability". Certification and standardization will be crucial, with new standards of quality control. Lastly, facilitating new materials research and innovation into bio-based composites, natural fiber composites, wood based and bamboo composites with mycelium where the material can more easily be reused or recycled.

In some circles, renewable energy is still seen as a disrupter of the status quo, a host of new technologies that displace current entrenched mainstay industries, with their clearly defined hierarchies. As wind energy approaches its fourth decade, embedded in the literal powering of U.S. and beyond, as its socially and economically disruptive function wanes, and as it becomes mainstream, it is important to understand it for what it is in totality. Acknowledging the nuanced nature of wind power not being as clean as its image purports, is yet another disruptive action. Opening up avenues of discourse regarding how the detritus of energy production can transition to productive large-scale infrastructures, designed within our own field of architecture has the potential to be empowering, both to the discipline, but also to individuals and communities who were once targeted as depositories of WTB waste; they can be benefactors of new infrastructures, but also of jobs and knowledge, having had inclusion in the process.

ENDNOTES

1. Pu Liu, Claire Y. Barlow. “Wind turbine blade waste in 2050”. Waste Management, Volume 62. 2017. Pages 229-240.
2. IEA (2023), Tracking Clean Energy Progress 2023, IEA, Paris https://www.iea.org/reports/tracking-clean-energy-progress-2023, License: CC BY 4.0
3. “U.S. Energy Information Administration - EIA - Independent Statistics and Analysis. What is U.S. electricity generation by energy source? https://www.eia.gov/tools/faqs/faq.php?id=427&t=3.
4. EIA
5. IEA
6. Ibid
7. “Wind Turbines: The Bigger, the Better,” Energy.gov, n.d., https://www.energy.gov/eere/articles/wind-turbines-bigger-better.
8. Ibid
9. Liu and Barlow
10. “Advantages and Challenges of Wind Energy.” Energy.gov. https://www.energy.gov/eere/wind/advantages-and-challenges-wind-energy.
11. Abidur Rahman, Omar Farrok, and M. Mejbaul Haque. 2022. “Environmental Impact of Renewable Energy Source Based Electrical Power Plants: Solar, Wind, Hydroelectric, Biomass, Geothermal, Tidal, Ocean, and Osmotic.” Renewable & Sustainable Energy Reviews 161 (June): 112279. https://doi.org/10.1016/j.rser.2022.112279.
12. Rare Earth Elements (REE) are a group of seventeen chemical elements that occur together in the periodic table. The metals, relatively abundant despite the name, all share specific characteristics, including heat resistance and high electrical conductivity. These unique properties make REEs indispensable to many products, from smartphones to more advanced technologies. Key elements, components in generators for wind turbines are neodymium, praseodymium, dysprosium and terbium, which are used to manufacture neodymium–iron–boron (NdFeB) permanent magnets.
13. Dias Patricia Alves, “The Role of Rare Earth Elements in Wind Energy and Electric Mobility,” JRC Publications Repository, n.d., https://doi.org/10.2760/303258.
14. Helene Gaudin, “Implications of the Use of Rare-Earth Elements in the Wind Energy Market,” sustainalytics.com, n.d., https://www.sustainalytics.com/esg-research/resource/investors-esg-blog/implications-of-the-use-of-rare-earth-elements-in-the-wind-energy-market.
15. W. J. Zhang et al., “Sustainable Transformation of End-of-Life Wind Turbine Blades: Advancing Clean Energy Solutions in Civil Engineering through Recycling and Upcycling,” Journal of Cleaner Production 426 (November 1, 2023): 139184, https://doi.org/10.1016/j.jclepro.2023.139184.
16. Liu and Barlow
17. Chris Martin. “Can’t Be Recycled, So They’re Piling Up in Landfills.” Bloomberg Green. 5 February 2020.
18. For purposes of calculation, one can assume a conservative estimate of one blade being replaced on each turbine every 48 months. It is projected that a wind farm producing 1.0 GW of electricity with typical 8 MW wind turbines consisting of three blades, each with a mass of about 35 tons, will produce 13,000 tons of landfill in 20-25 years.
19. Ibid
20. “Circular Economy: Blade Recycling Is a Top Priority for the Wind Industry.” WindEurope, 12 Mar. 2020, windeurope.org/newsroom/news/blade-recycling-a-top-priority-for-the-wind-industry/
21. There does not seem to be a standard on how to convert blade or turbine type designation (e.g., LM 13.4, Vestas V52, GE 1.5 MW) to either mass or volume, so as to be able to figure out the amount of waste that the particular blade will become.
22. Bank and Delaney
23. Peter Deeney et al., “End-of-Life Alternatives for Wind Turbine Blades: Sustainability Indices Based on the UN Sustainable Development Goals,” Resources, Conservation and Recycling 171 (August 1, 2021): 105642, https://doi.org/10.1016/j.resconrec.2021.105642.
24. Christina Stella. “Unfurling The Waste Problem Caused By Wind Energy.” National Public Radio, Sept. 10, 2019, npr.org/2019/09/10/759376113/unfurling-the-waste-problem-caused-by-wind-energy
25. Martin
26. Stella
27. Martin
28. Bank and Delaney
29. Nacef Tazi, Junbeum Kim, Youcef Bouzidi, Eric Chatelet, Gang Liu. “Waste and material flow analysis in the end-of-life wind energy system, Resources, Conservation and Recycling”.
30. Kevin Simpson. “Most Used Wind Turbine Blades End up in Landfills. Colorado Is Part of the Push to Make the Industry Greener.” The Colorado Sun, 26 Feb. 2020, coloradosun.com/2020/02/26/wind-turbine-blades-colorado-landfills/.
31. Liu and Barlow
32. Simpson
33. Fritz
34. Bank and Delaney
35. Leon Mishnaevsky Jr. “Sustainable End-of-Life Management of Wind Turbine Blades: Overview of Current and Coming Solutions”. Materials 2021. https://doi.org/10.3390/ma14051124 https://www.mdpi.com/journal/materials
36. Mishnaevsky
37. “High Voltage Pulse Power Technology, Mineral Processing Plants, Selective Crushing.” Selfrag, 2 Dec. 2020, www.selfrag.com/about/.
38. “Fluidized Bed Combustion.” Wikipedia, Wikimedia Foundation, 3 Apr. 2021, https://shorturl.at/sHLMR
39. Fritz
40. WindEurope
41. Fritz
42. Ibid
43. S. A. Shelley, “Wind Waste“. 3 March 2020, OWOE – Blog. www.ourworldofenergy.com/blog.php?bid=2406.
44. Mishnaevsky
45. Van Exter, Pieter. Bosch, Sybren. Schipper, Branco. Sprecher, Benjamin. Kleijn, René. 2018. “Critical Metals for Renewable Energy: Mapping Supply and Growing Demand.” Metabolic, www.metabolic.nl/publication/metal-demand-for-renewable-electricity-generation-in-the-netherlands/
46. Ibid
47. Ryan Martini and George Xydis, “Repurposing and Recycling Wind Turbine Blades in the United States,” Environmental Progress & Sustainable Energy 42, no. 1 (June 22, 2022), https://doi.org/10.1002/ep.13932.
48. Bank and Delaney
49. Peter Deeney et al., “End-of-Life Alternatives for Wind Turbine Blades: Sustainability Indices Based on the UN Sustainable Development Goals,” Resources, Conservation and Recycling 171 (August 1, 2021): 105642, https://doi.org/10.1016/j.resconrec.2021.105642.
50. Re-Wind Design Catalog 2022 2nd Edition. https://shorturl.at/giCFZ
51. “Four Smart Ideas for Keeping Wind Turbine Blades out of Landfills,” Canary Media, June 14, 2022, https://www.canarymedia.com/articles/wind/four-smart-ideas-for-keeping-wind-turbine-blades-out-of-landfills.
52. Yulizza Henao-Barragan et al., “Infrastructure Application of Decommissioned Wind Turbine Blades as Energy Transmission Pole”. Re-Wind Network.
53. Lawrence C. Bank et al., “Concepts for Reusing Composite Materials from Decommissioned Wind Turbine Blades in Affordable Housing,” Recycling 3, no. 1 (January 17, 2018): 3, https://doi.org/10.3390/recycling3010003.
54. Martini and Xydis
55. ibid
56. Re-Wind Design Catalog 2022
57. Tslil Strauss, “Blade Made Playgrounds - Superuse Studios,” Superuse Studios, February 1, 2023, https://www.superuse-studios.com/projectplus/blade-made/.
58. Re-Wind Design Catalog
59. Strauss
60. Reconstructing The World, “Reusing Old Wind Turbine Blades on a Wooden High-Rise: Cutting down Windmills and Fire Testing,” Video, YouTube, September 28, 2023, https://www.youtube.com/watch?v=jRIKmZRxVWM.
61. “Demonstration Project on Recycling Wind Turbine Blades for Sunshades on Future High-Rise Buildings,” n.d., https://brandogsikring.dk/en/research-and-development/development-of-fire-safe-bio-based-and-circular-construction-products/demonstration-project-on-recycling-wind-turbine-blades-for-sunshades-on-future-high-rise-buildings/.
62. Jelle Joustra, Bas Flipsen, Ruud Balkenende. “Structural reuse of high end composite products: A design case study on wind turbine blades, Resources, Conservation and Recycling”. Volume 167. 2021, https://doi.org/10.1016/j.resconrec.2020.105393
63. Martini and Xydis
64. Jensen JP. Evaluating the environmental impacts of recycling wind turbines. Wind Energy. : 29 September 2018. https://www.eenews.net/assets/2020/02/26/document_ew_02.pdfhttps://doi.org/10.1002/we.2287
65. Belton, Padraig. “What Happens to All the Old Wind Turbines?”
66. Canary Media. “Four Smart Ideas for Keeping Wind Turbine Blades out of Landfills.” June 14, 2022. https://www.canarymedia.com/articles/wind/four-smart-ideas-for-keeping-wind-turbine-blades-out-of-landfills.
67. Bank et al.
68. “‘This Project Is Mushrooming,’” College of Engineering, November 18, 2022, https://engineering.ucdavis.edu/news/project-mushrooming.
69. Mishnaevsky