Winding Down:
End of Service and Recycling for Wind Energy

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Photo by Werner Slocum. NREL 62957

NREL Transforming ENERGY

WINDExchange U.S. DEPARTMENT OF ENERGY

Webinar Logistics

Crews lower the nacelle as part of the decommissioning of a turbine at NREL.
Photo by Dennis Schroeder, NREL 51733

- This webinar will be recorded and posted to the National Renewable Energy Laboratory (NREL) YouTube channel (https://www.youtube.com/watch?v=58EYcYbRKqk&list=PLmIn8Hncs7bHwm27irhqb-iikRurVJ8YF&pp=iAQB) and the U.S. Department of Energy (DOE)'s WINDExchange website (WINDExchange.energy.gov)

- Pose questions using the Q&A function during and at the end of the presentation
    - Questions will be answered either during or after the webinar.

What Will We Cover?

- Introduction to wind energy end of service activities
- Recycling of wind energy components
- Overview of NREL and DOE efforts related to end of service and recycling
- Q&A.

Wind turbine blades being segmented for mechanical recycling at Veolia's blade recycling facility in Louisiana, Missouri.
Photo from Veolia

Speaker Bios

Chloe Constant is a Senior Project Leader at NREL where she oversees the Wind Energy Stakeholder Engagement and Outreach and Workforce Development programs. She worked on NREL's recent wind energy end of service community and stakeholder engagement project, engaging industry, community, and government stakeholders to better understand diverse perspectives and considerations for wind energy end of service activities. Prior to joining NREL at the end of 2019, she spent 10 years at E.ON (now RWE) where she worked in various positions for their renewables business, most recently as a director in mergers and acquisitions with a focus on land-based and offshore wind.

Derek Berry is a Senior Engineer at NREL and the Director of the Wind Turbine Technology Area within the Institute for Advanced Composites Manufacturing Innovation (IACMI), a Manufacturing USA Institute. He leads the NREL/IACMI team in the research of innovative composite materials and manufacturing for wind turbine blades and other components. Previously, he was the NREL Engineering Supervisor at the Wind Technology Testing Center in Boston, Massachusetts, where he was responsible for large-scale wind turbine blade test engineering operations. He also serves as the Operating Agent for the International Energy Agency (IEA) Wind TCP Task 45: Recycling Wind Turbine Blades. Prior to joining NREL, Derek spent 15 years as a wind blade design, manufacturing, and testing engineer at TPI Composites. Derek is a graduate of the U.S. Air Force Academy with a degree in aeronautical engineering.

End of Service Activities

Why Consider End of Service?

- Wind turbines have a typical lifetime of **25–30 years**, after which they are decommissioned or repowered
- More than **73,000 wind turbines** (consisting of **220,000 blades**) were deployed across the country as of 2023[1]
- A variety of important decisions must be made at different points in wind project lifetime, such as:
  - Should the project be decommissioned, or should it be repowered and continue to operate?
  - Will turbine blades be sent to a landfill or recycled?
  - What recycling method will be used to process blades?
- Decisions about end of service can affect landowners, host communities, the wind industry, state and local governments, sustainability goals, and more.

A legacy wind turbine in Iowa that was decommissioned in a full repower in 2001. Photo from Waverly Light and Power 11517

[1] Hoen, B.D., Diffendorfer, J.E., Rand, J.T., Kramer, L.A., Garrity, C.P., and Hunt, H.E. 2018. United States Wind Turbine Database v6.1 (November 28, 2023): U.S. Geological Survey, American Clean Power Association, and Lawrence Berkeley National Laboratory data release. https://doi.org/10.5066/F7TX3DN0.

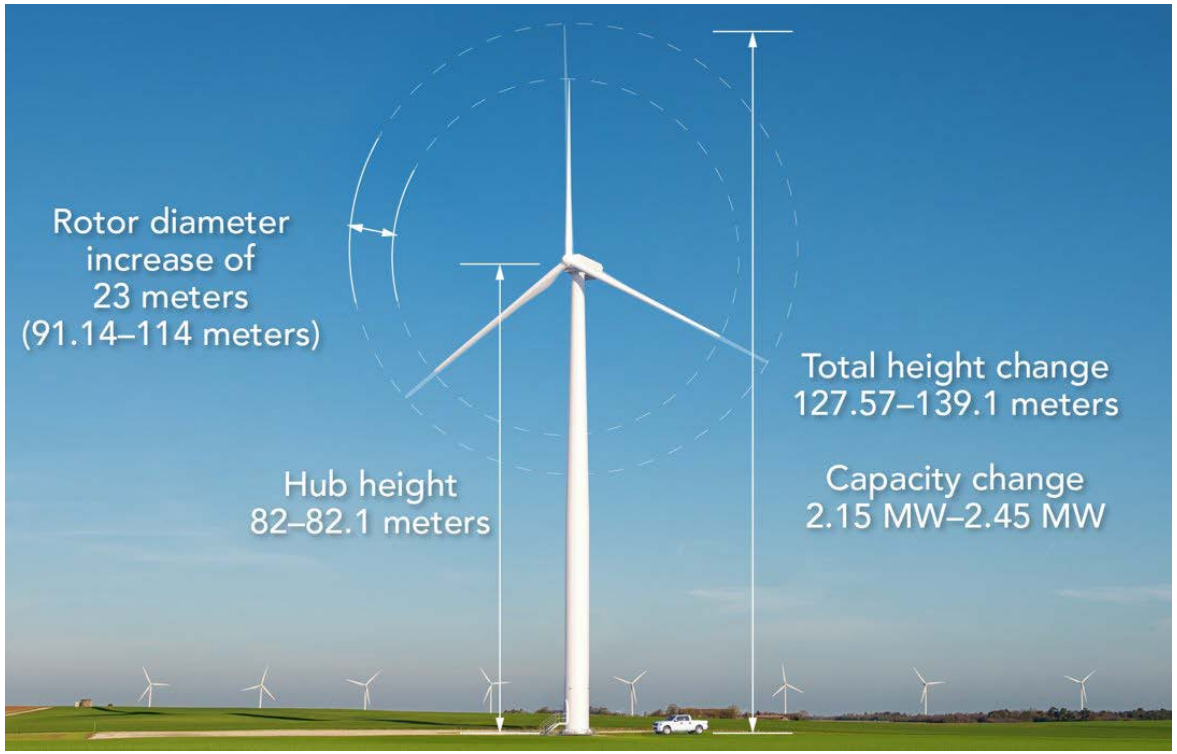
Repowering

- **Repowering** is the retrofitting or replacement of wind project components either in part or in full
- Different than repairing or replacing a single broken or worn component
- Extends life of existing wind farms and enables them to generate power more efficiently
  - New technology
  - Increased generating capacity per turbine
- Typically uses existing grid connections and transmission infrastructure.

Repowering underway at an RWE wind project near Cologne, Germany.
Photo from RWE

Partial Repowering

- **Partial repowering** replaces only certain turbine components, leaving turbines about the same size and typically not impacting project footprint
- Typically upgrades these components with new technology:
  - Blades
  - Gearboxes
  - Hubs
  - Main shafts
  - Main bearing assemblies
- Uses existing towers and foundations
- In most cases, hub heights for partially repowered turbines will not change.



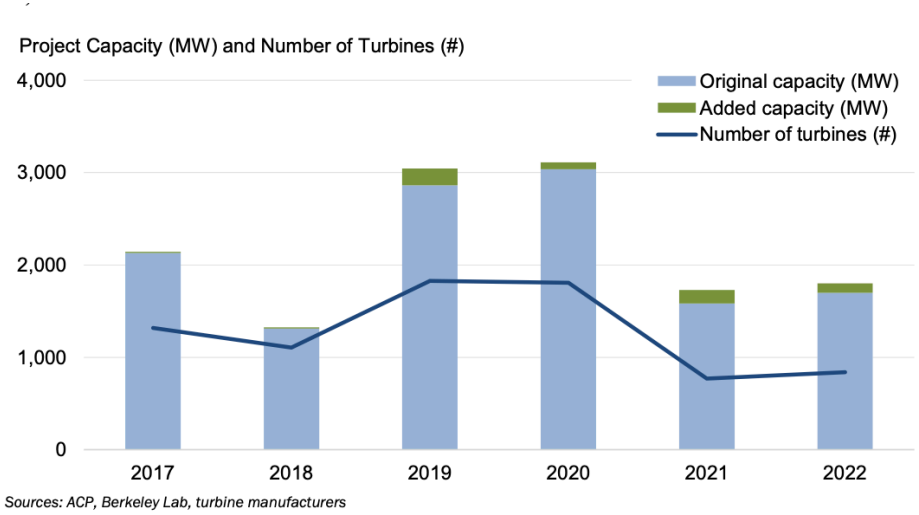
Based on statistics from the *Land Based Wind Market Report: 2022 Edition*, this image highlights the potential differences in total wind turbine height and rotor diameter that can occur after a partial repower. Image by Josh Bauer, NREL

Full Repowering

- **Full repowering** removes existing turbines and replaces them completely with new ones, increasing turbine size and changing the overall project footprint
- Older, smaller wind turbines can be replaced with fewer, newer, larger models
- Project could have the same total energy generation capacity from fewer turbines or could have increased capacity.

These images highlight the potential changes that can occur during a full repower of a wind energy project. Older, smaller wind turbines (above) can be replaced with fewer, newer, larger models (below) that could have the same total capacity.
Images by Josh Bauer, NREL

Repowering Trends



Annual amount of partially repowered wind power; blue bars show the repowered projects' collective capacity prior to the repowering, while the green shows the amount of capacity added by repowering. The blue line shows the number of turbines that were partially repowered. This data does not include fully repowered projects.
Figure from *Land-Based Wind Market Report: 2023 Edition*

- Rates of repowering have some annual ebbs and flows, but repowering has become increasingly common in the last decade
  - Repowering could add 6.5–7.5 GW of energy to the grid in 2024, representing **nearly half of all new wind capacity added to the U.S. grid this year**[2]

- Repowering may be done for a variety of reasons:
  - May offer better return on investment, especially for older projects
  - Extends project's life
  - Technological advances during project's lifetime
  - Grid interconnection, siting and permitting approvals, and land lease agreements already in place
  - Reduced cost relative to new project
  - Replacing certain percentage of components allows project to requalify for the Production Tax Credit.

[2] Penrod, Emma. 2024. "Repowering will represent nearly half of all new wind capacity in 2024: Enverus." UtilityDive. https://www.utilitydive.com/news/wind-farm-repowering-outlook-enverus/707837/.

Decommissioning

Photo by Dennis Schroeder, NREL 20843

- **Decommissioning** is the removal of a wind energy project, which typically occurs at the end of the project's operational life or when it is being fully repowered

- Activities involved in decommissioning can include:
  - Felling turbines (i.e., controlled toppling of a whole turbine) or using cranes to disassemble turbines in sections
  - Partially or fully removing turbine foundations and below-ground cables
  - Removing substations, above-ground cables, buildings, fencing, and access roads
  - Restoring land to agreed-upon conditions

- Decommissioning entire wind energy projects is currently uncommon in the United States.

Decommissioning Regulations

- Local and state governments can set requirements or standards for decommissioning in their ordinances

- Project developers/owners typically submit a **decommissioning plan** that describes how they intend to remove infrastructure, restore the land, and process waste
    - Many local and state governments require these plans as part of siting and permitting processes

- Project owners may also be required to provide financial assurances like **decommissioning bonds** that guarantee there will be funds available to carry out decommissioning.

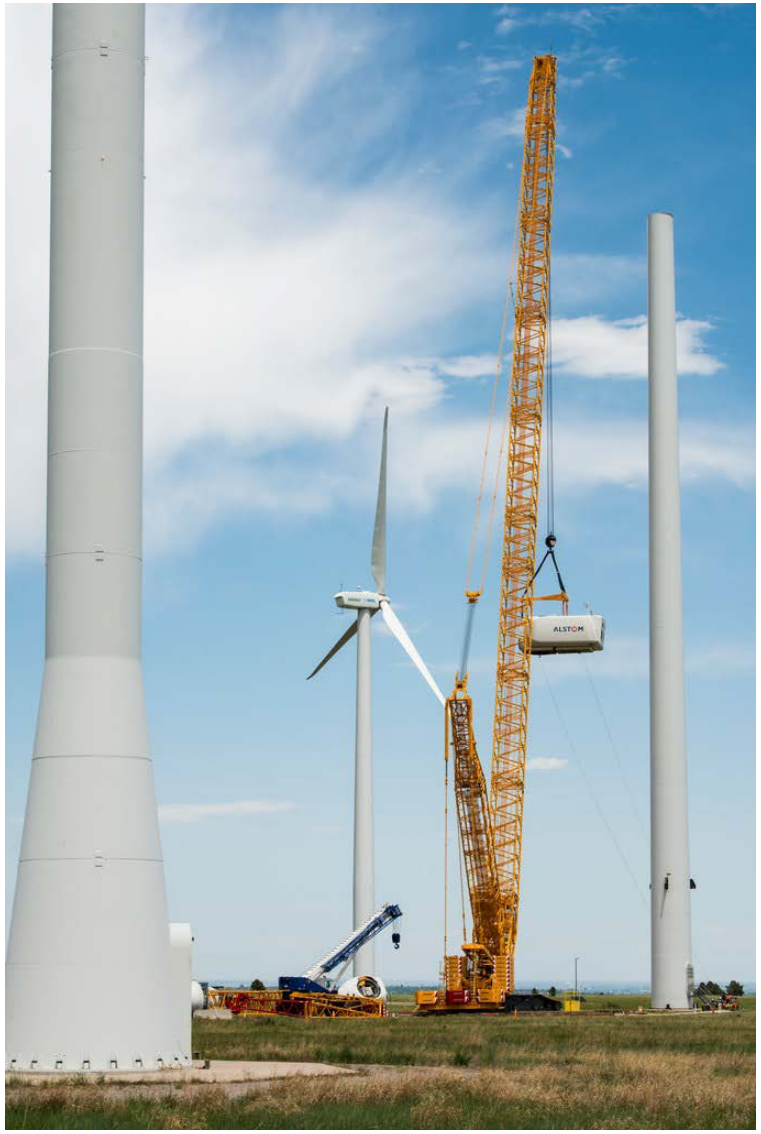


Photo by Dennis Schroeder, NREL 51735

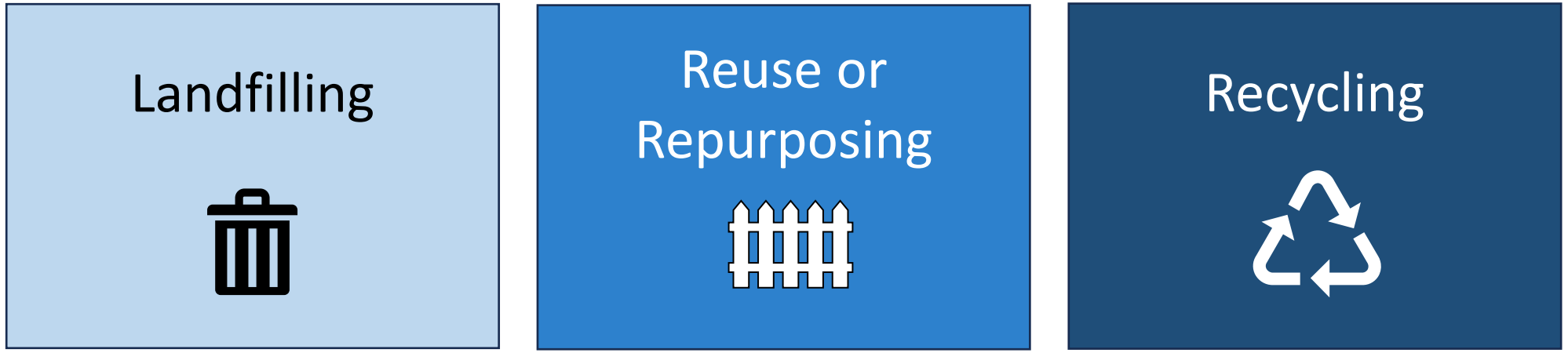
Land Restoration

- Land restoration is the process of restoring the land surrounding turbines to certain agreed-upon conditions following repowering or decommissioning
- Standards or requirements may be set in local ordinances, state laws, or landowner agreements
- Activities include:
  - Reseeding vegetation
  - Repairing damaged drainage tiles
  - Replacing soils
  - Decompacting land
  - Restoring the grade of the land.

Photo by Dennis Schroeder, NREL 20858

Component Processing

- Three major options for processing:



- Decisions are influenced by factors like:
  - Cost
  - Accessibility/transportation
  - Capacity of processing
  - Laws and regulations
  - Sustainability goals.

Landfilling

Wind turbine blades being buried at a landfill in Casper, Wyoming. Photos from Brendan Lachance, Oil City News

- Most wind turbine blades are currently disposed of in landfills
  - Landfilling is generally an easier option than recycling currently (e.g., lower cost, more proximate to project site, more processing capacity)
- In 2018, about 50,000 tons of blade waste were managed at U.S. landfills[3]
  - This was about 0.017% of combined municipal solid waste and construction and demolition waste managed by landfills that year (~291.1 million tons)[3]
- Landfilling blades can present challenges for landfill operators and communities, as they may **take up a large amount of landfill space** and can **require specialized equipment, capacity, and personnel**
  - Some communities have enacted landfill bans, and some landfill operators may not accept blades
  - Several countries have banned landfilling of blades (e.g., Austria, Germany, Finland, and the Netherlands).

[3] Oteri, Frank, Heidi Tinnesand, Chloe Constant, and Matilda Kreider. 2023. Wind Energy End-of-Service Guide. U.S. Department of Energy Office of Energy Efficiency and Renewable Energy. https://windexchange.energy.gov/end-of-service-guide.

Reuse or Repurposing

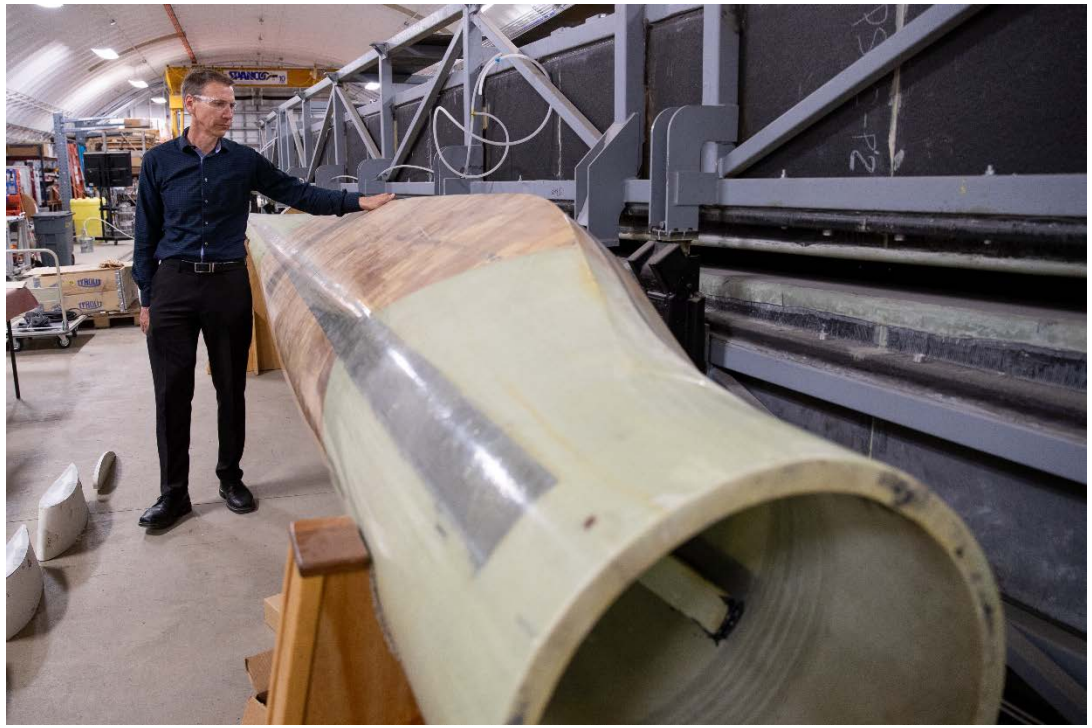
- **Reuse** of components as replacement parts in other wind turbines
    - It is relatively uncommon in the United States to sell components between project owners, but owners may move parts around within their portfolio of projects
- **Repurposing** involves the direct use of the decommissioned component to create new products like pedestrian bridges, playgrounds, benches, bike shelters, fences, and noise barriers.

Left: A repurposed blade that has been used to create outdoor seating. Photo from Anmet

Below: Construction workers install a footbridge across the Szprotawa River in Poland. Photo from Anmet

Recycling of Wind Energy Components

Component Recyclability



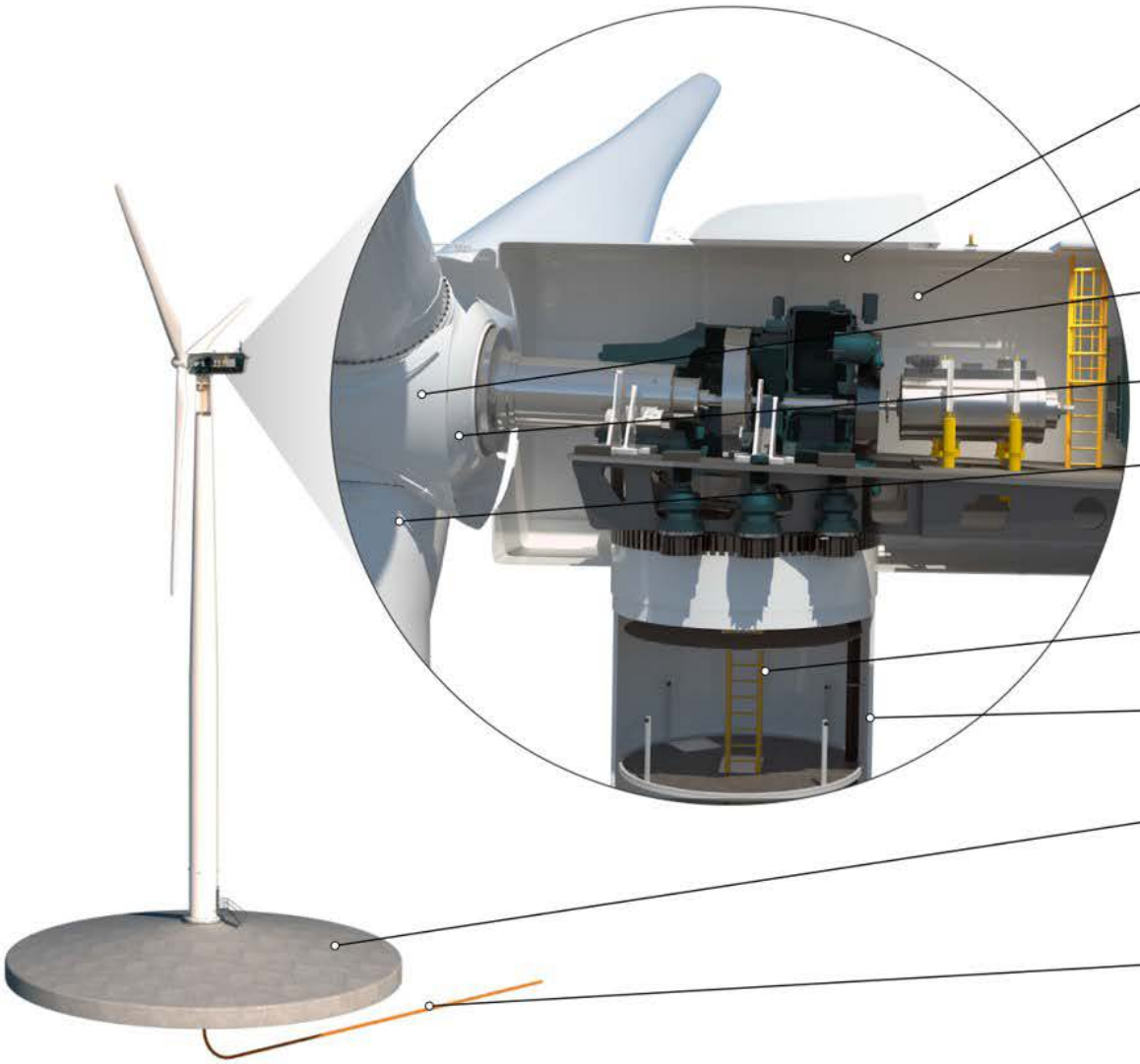
A recyclable blade prototype at the Composites Manufacturing Education and Technology (CoMET) Facility at the NREL Flatirons Campus.
Photo by Joe DelNero, NREL 81412

- **Towers, hubs, and some internal components** are made of **metal** materials that are easily recycled
  - 86%–94% of a wind turbine's mass (above ground)[4]
- **Blades and other components like nacelle covers** are made of **composite** materials that are more challenging to recycle
  - 6%–14% of a wind turbine's mass (above ground)[5]
- **Foundations and underground cables** are made of materials like **concrete, plastic, and metals,** and can often be recycled
  - However, they are often left at least partially in the ground
- **Rare earth elements** (used for **permanent magnets in wind turbine generators**) can be challenging to recycle.

[4] Vestas. 2020. *The Vestas Sustainability Report 2019*. Aarhus N., Denmark: Vestas Wind Systems A/S. https://www.vestas.com/en/sustainability/reports-and-ratings#lcadownload.

[5] Tota-Maharaj, K. and A. McMahon. 2021. Resource and Waste Quantification Scenarios for Wind Turbine Decommissioning in the United Kingdom. *Waste Disposal and Sustainable Energy* 3: 117–144. https://doi.org/10.1007/s42768-020-00057-6.

Component Recyclability



Nacelle Cover
- Fiberglass Composites–Landfill, Recycle

Nacelle Internals
- Gearbox, Generator, Main Bearing, Etc.
- Aluminum, Iron, Copper, Permanent Magnets, Lubricants–Recycle

Hub
- Iron–Recycle

Rotor Cover
- Fiberglass Composites–Recycle, Landfill

Blades
- Fiberglass Composites, Carbon Fiber Composites, Balsa Wood–Recycle, Repurpose, Landfill

Tower Internals (Ladders, Platforms)
- Aluminum–Recycle

Tower
- Steel–Recycle

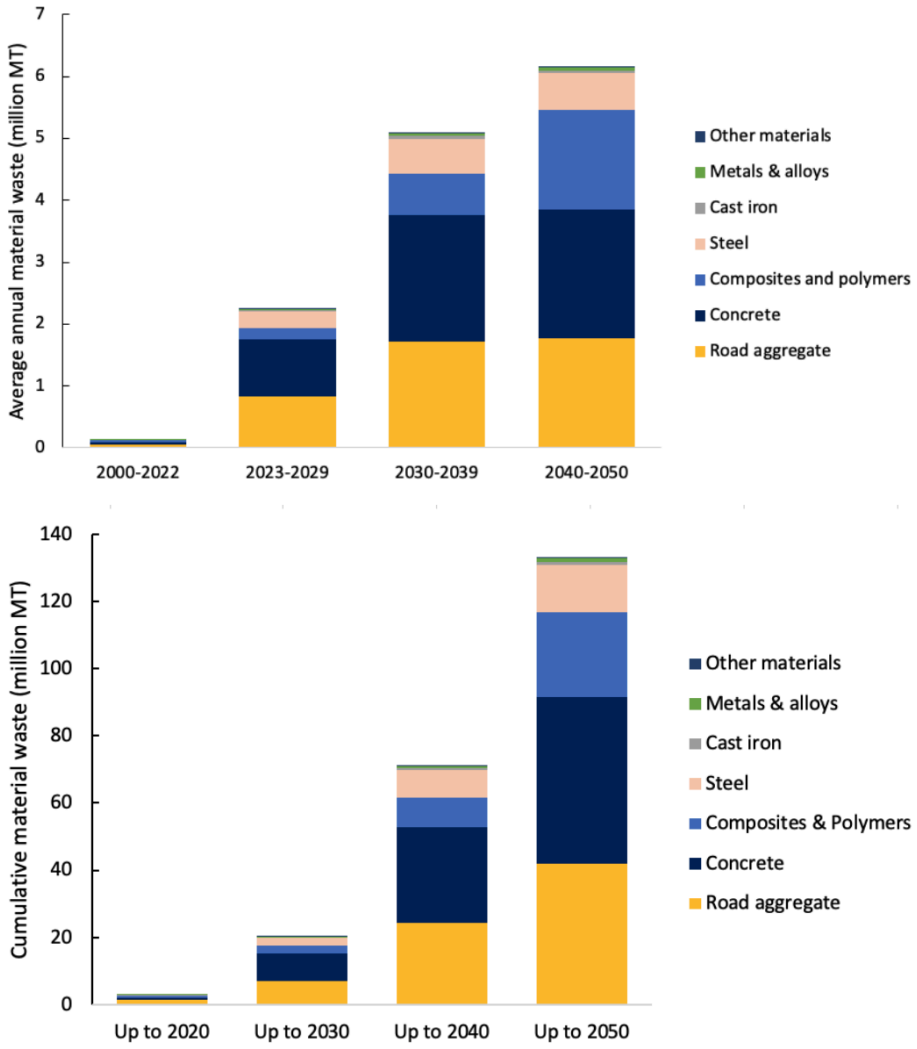
Foundation
- Concrete–Repurpose, Recycle, Landfill, In–Place Disposal
- Steel–Recycle, In–Place Disposal

Below ground cables
- Copper, Aluminum–Recycle, In–Place Disposal
- Plastic–Landfill, In–Place Disposal

This diagram identifies different wind turbine components and project-related infrastructure, the materials they are made from, and how they are typically processed when a wind energy project reaches its end of service.
Image by Josh Bauer, NREL

Volume of Waste Materials

- Under a high wind energy deployment scenario, we will see significant growth in the volume of waste from wind energy
  - Cumulative decommissioned material could reach up to 133 million metric tonnes by 2050, without considering partial repowers[6]
- Road aggregate, concrete, and a growing volume of composite and polymer materials are projected to represent the largest portions of wind energy waste materials over the next few decades
  - Materials are decommissioned at different rates and at different times.

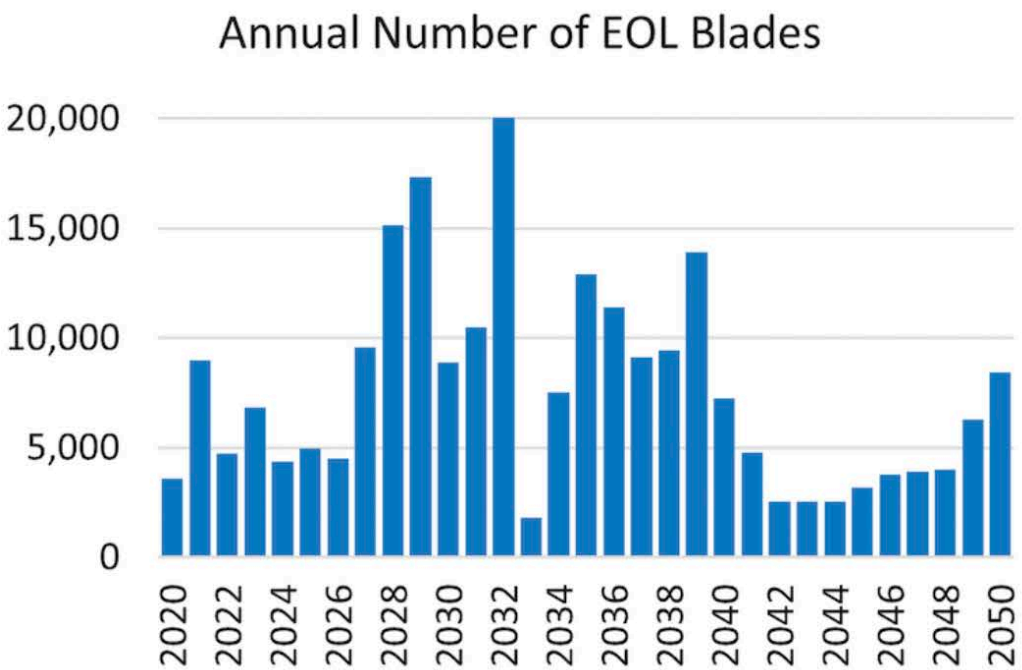


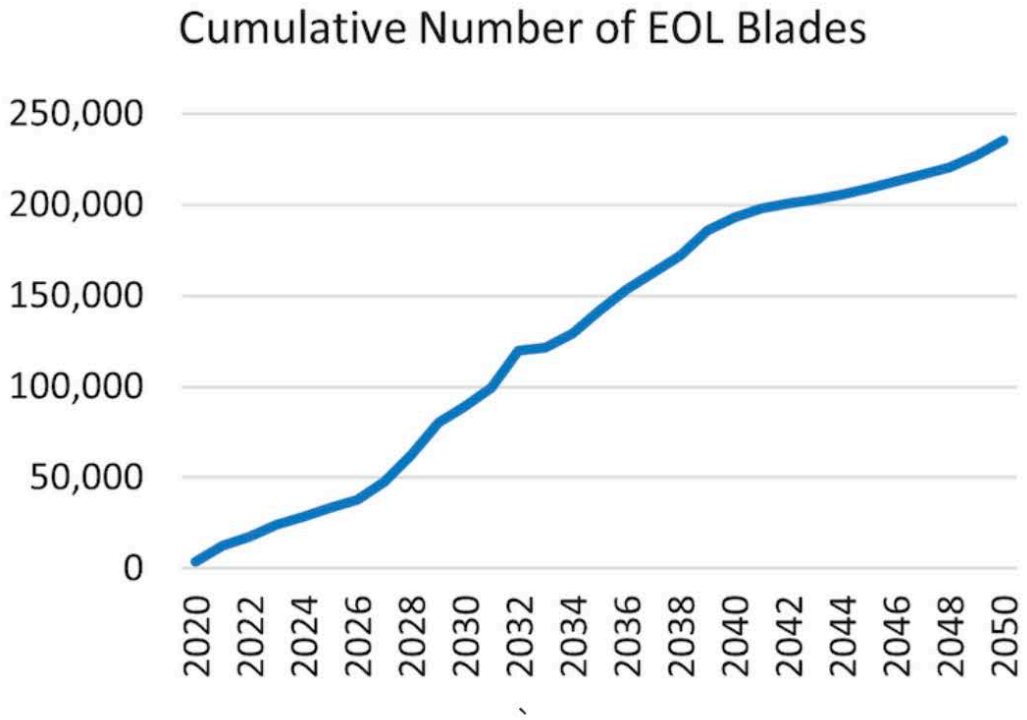
Annual (top) and cumulative (bottom) waste projections for wind energy materials under the high-deployment scenario by 2050. Note MT = metric tonnes
Figure from U.S. Department of Energy *Road Map for Recycling Energy Systems in the United States*

[6] Christoffel, Tyler et al. Forthcoming. *Road Map for Recycling Wind Energy Systems in the United States Part 1: Providing a Baseline for America's Wind Energy Recycling Infrastructure for Wind Turbines and Systems.* U.S. Department of Energy.

Blade Waste Estimates

- On average, **3,000–9,000 blades are being taken out of service per year in the United States** and that number is expected to increase to 10,000–20,000 blades per year by 2040.[7]





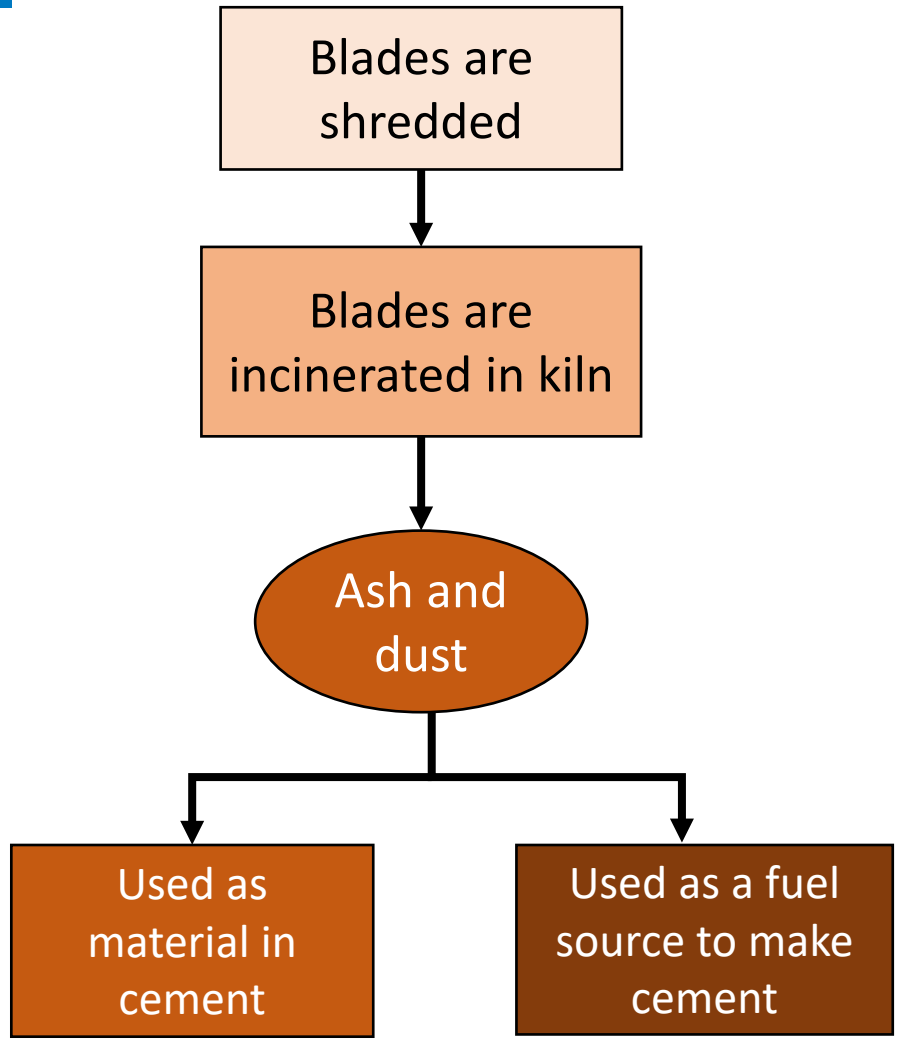
Estimates of end-of-life wind turbine blades projected to be taken out of service each year (left) and total (right).
Figures from Cooperman, Eberle, and Lantz (2021)

[7] Cooperman, A., A. Eberle, and E. Lantz. 2021. Wind Turbine Blade Material in the United States: Quantities, Costs, and End-of-Life Options. *Resources, Conservation and Recycling* 18: 105439. https://doi.org/10.1016/j.resconrec.2021.105439.

Recycling Blades: Mechanical Recycling

- **Mechanical recycling** grinds or shreds blades into materials that are repurposed for use in other manufacturing processes
  - May be used as replacement material within a product or replacement fuel to make a product

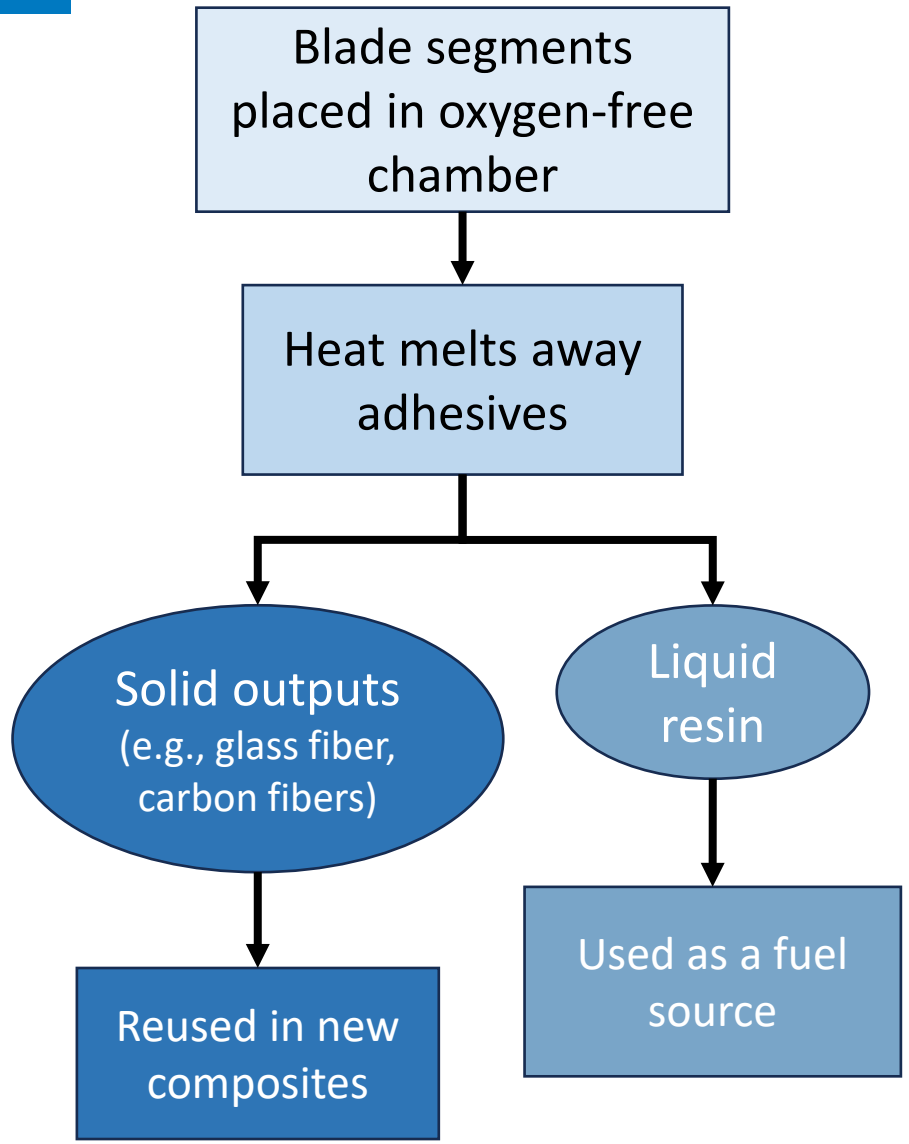
- **Cement coprocessing** is a common mechanical recycling method.



The process described in this graphic is specific to cement coprocessing; other mechanical recycling processes involve different steps and outputs.

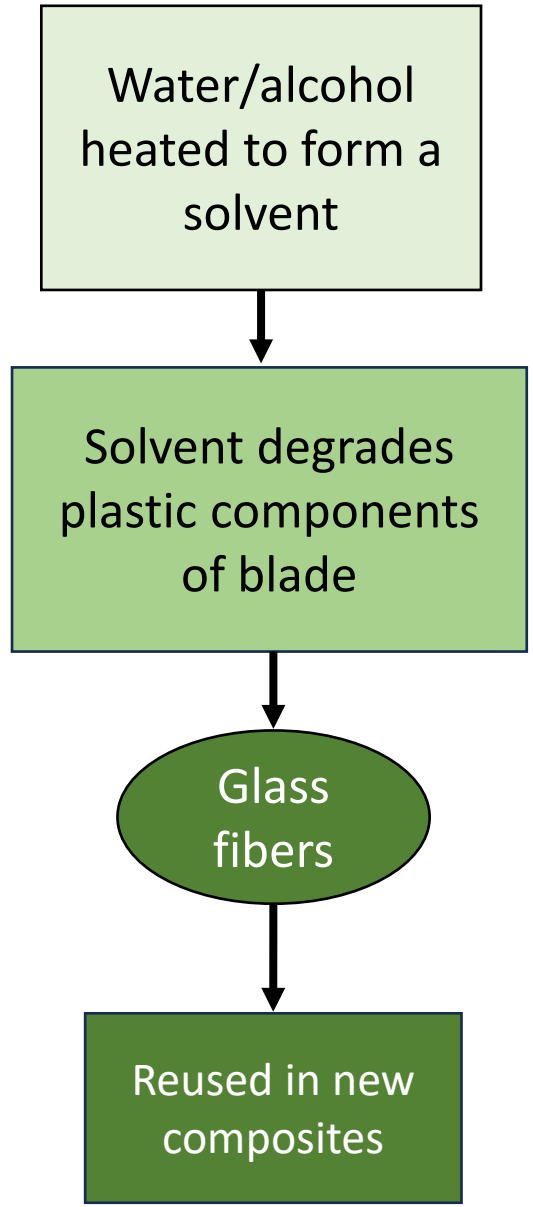
Recycling Blades: Thermal Decomposition

- **Pyrolysis or thermal decomposition recycling** uses heat to recover glass fibers that can then be upcycled into new composite-based materials
  - Blades are segmented and placed into an oxygen-free chamber where heat is used to melt away adhesives
  - One output is liquid resin that can be used as a fuel source
  - Solid outputs are glass fibers, carbon fibers, and ash, which can be reused (such as creating new glass fibers).



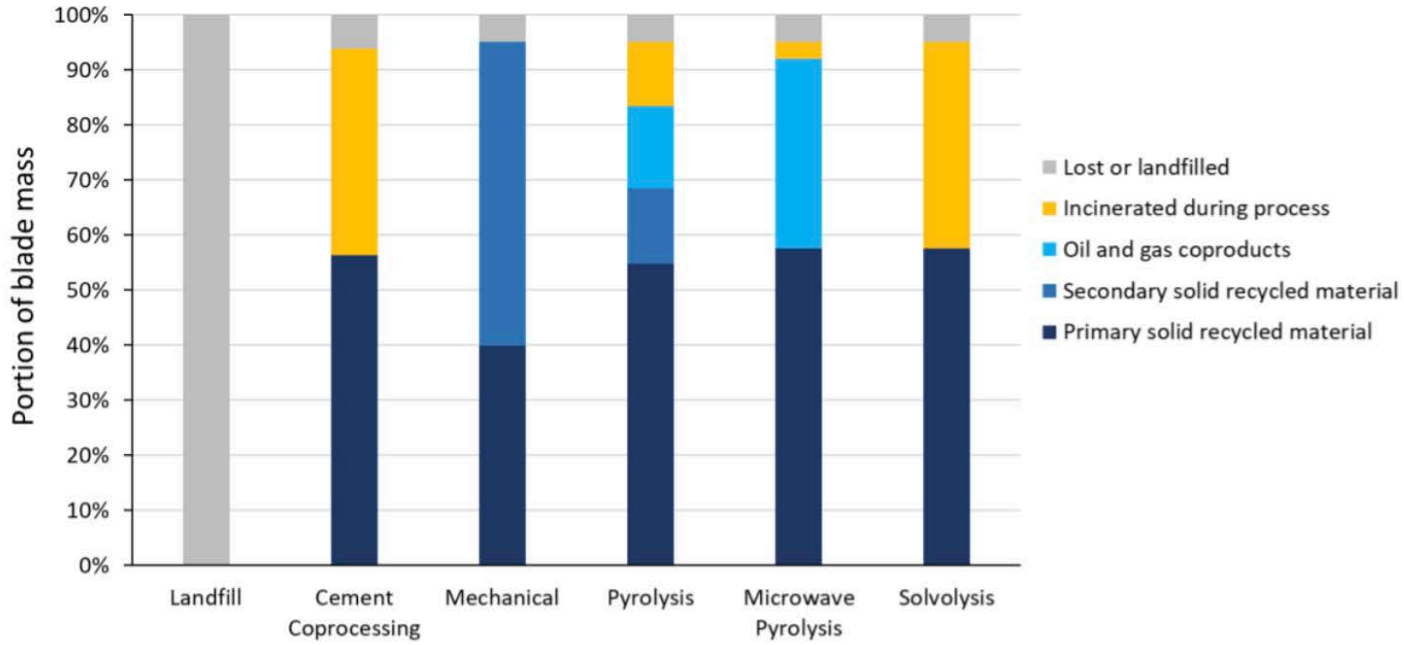
Recycling Blades: Chemical Decomposition

- **Solvolysis or chemical decomposition recycling** separates glass fiber from other components through dissolution
  - Water and/or alcohol are heated to form a solvent that degrades plastic components of the blade into smaller parts and releases glass fibers
  - Glass fibers can be reused.



Mass Yield Analysis

- Processing methods have different outputs in terms of what happens to the materials when they are processed; they may be:
  - "Lost" or landfilled
  - Incinerated during process
  - Made into oil and gas coproducts
  - Made into primary or secondary solid recycled material
- Mechanical recycling and microwave pyrolysis (a form of thermal decomposition recycling) produce the most solid recycled material.[8]

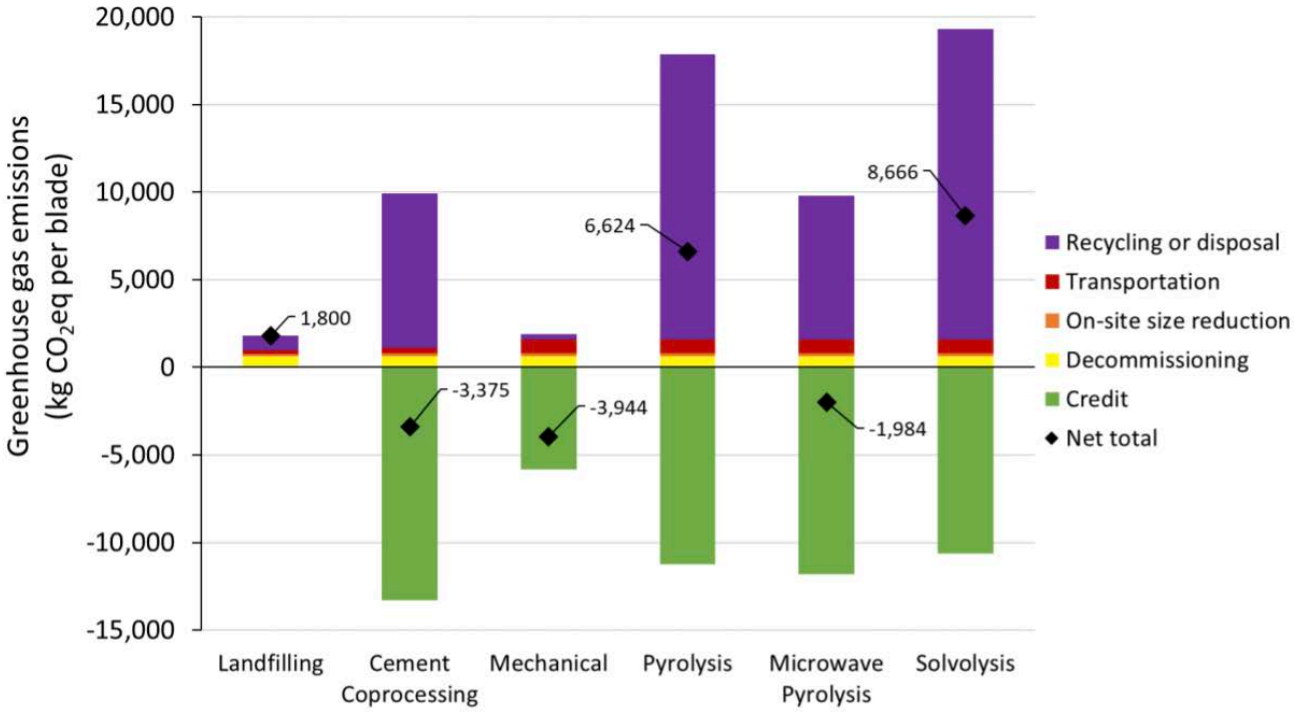


Wind turbine blade mass yields through different processing methods.
Figure from U.S. Department of Energy *Road Map for Recycling Energy Systems in the United States*

[8] Christoffel, Tyler et al. Forthcoming. *Road Map for Recycling Wind Energy Systems in the United States Part 1: Providing a Baseline for America's Wind Energy Recycling Infrastructure for Wind Turbines and Systems.* U.S. Department of Energy.

Life Cycle Analysis for Blade Processing Options

- Recycling processes tend to be energy intensive and produce greenhouse gas emissions
    - For some processes, these emissions may outweigh the benefits of the recycled product they create
- Emissions of all recycling approaches are many times less than the total blade manufacturing emissions[9]
    - Blade recycling is thus an opportunity to **reduce life cycle emissions of blade materials** if it becomes technically and economically feasible to reuse materials to make new blades or other products.[9]



Life cycle greenhouse gas emissions of recycling approaches compared with landfilling.
Figure from U.S. Department of Energy *Road Map for Recycling Energy Systems in the United States*

[9] Christoffel, Tyler et al. Forthcoming. *Road Map for Recycling Wind Energy Systems in the United States Part 1: Providing a Baseline for America's Wind Energy Recycling Infrastructure for Wind Turbines and Systems.* U.S. Department of Energy.

Blade Design

- Research is being conducted to develop wind turbine **blades that are specifically designed to be recycled**
  - Several blade manufacturers, as well as NREL, have developed prototypes
  - One manufacturer, Siemens Gamesa, has set goals of producing fully recyclable blades by 2030 and fully recyclable turbines by 2040[9]
- Replacing traditional thermoset epoxy resin, which is currently used in most blades, with either **thermoplastic resin** or **reversable thermoset resin** could enable more complete recycling.

Construction of a revolutionary 13-meter thermoplastic blade at NREL. A vacuum bag covers the laminate and mold, which is infused with resin.
Photo by Ryan Beach, NREL 62034

[9] State of Green. 2023. "The world's first recyclable offshore wind turbine blades." https://stateofgreen.com/en/solutions/the-worlds-first-recyclable-offshore-wind-turbine-blades/.

State of the Blade Recycling Industry

- There is **no standardized process** or commercial application for recycling blades
- The blade recycling industry, while increasing in size, still has a limited capacity
- As of 2022, blade recyclers in the United States had the **capacity to recycle more than 3,000 blades per year**[10]
  - 3,000-9,000 blades being taken out of service per year currently and 10,000-20,000 per year by 2040[11]
- As new processing methods mature and secondary supply chains are developed, opportunities for blade recycling and repurposing are expected to become more widely available.

Final product that is realized when the mechanical recycling process is complete in Veolia's blade recycling process.
Photo from Veolia

[10] Farzan, S. 2022. "How to Recycle a 150-Foot Wind Turbine Blade? Haul It to Louisiana, MO." *St. Louis Public Radio*. May 27, 2022. https://news.stlpublicradio.org/health-science-environment/2022-05-27/how-to-recycle-a-150-foot-wind-turbine-blade-haul-it-to-louisiana-mo.

[11] Cooperman, A., A. Eberle, and E. Lantz. 2021. Wind Turbine Blade Material in the United States: Quantities, Costs, and End-of-Life Options. *Resources, Conservation and Recycling* 18: 105439. https://doi.org/10.1016/j.resconrec.2021.105439.

Challenges in Expanding Blade Recycling

After optimizing it in the lab, the NREL team used their new PECAN resin to glue together a 9-meter wind turbine blade made with fiberglass composites and a balsawood core in NREL's Composites Manufacturing Education and Technology Facility.
Photo by Troy Boro, NREL

- Recycling is more expensive than landfilling and is not yet up to scale
- Recycling facilities likely to be farther away from wind project sites resulting in higher transportation costs for project owners compared to using local or regional landfills
- Inconsistent flow of blade waste means recyclers do not have a steady supply of waste to process, making it difficult to scale up their businesses.

NREL and DOE Efforts

Scaling Up Blade Recycling: Carbon Rivers

Recycled glass fibers at different stages of Carbon Rivers' process.
Photos from Carbon Rivers

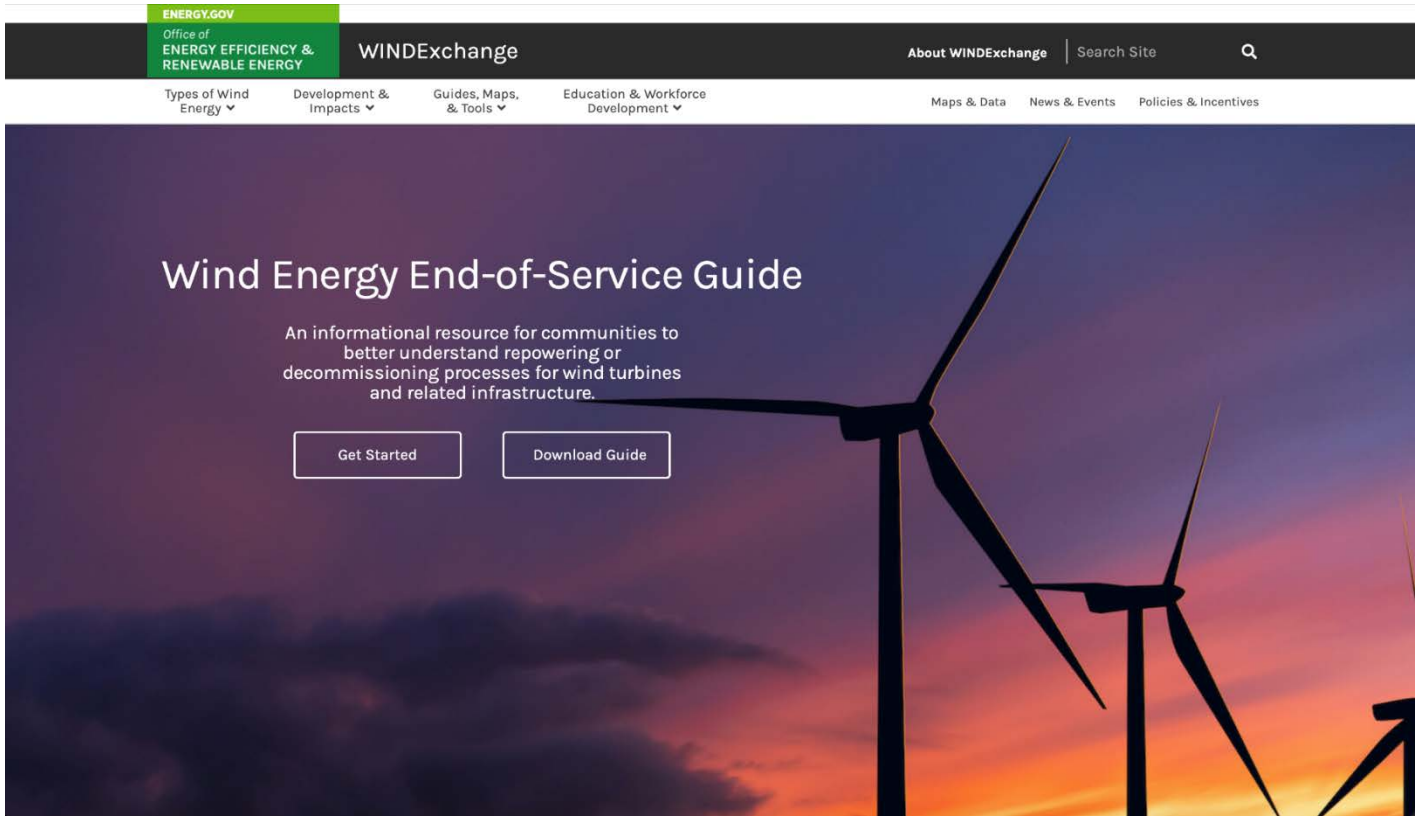
- Funded by the DOE Wind Energy Technologies Office, Carbon Rivers and the University of Tennessee Knoxville scaled up a process to recover clean, mechanically intact glass fiber from blades
- Carbon Rivers uses a **pyrolysis** process to separate organic components of the blade (e.g., resins, polymers) from inorganic fiberglass material
  - Organic products are converted back into raw hydrocarbon products which can be used for energy production
  - **Net positive energy output**
  - Recycled glass fiber can be used in place of virgin fiberglass in different composite applications or even incorporated into virgin fiberglass, creating a **circular economy**
- Carbon Rivers has commercialized this process and operates a recycling facility in Tennessee.

NREL End of Service and Recycling Projects

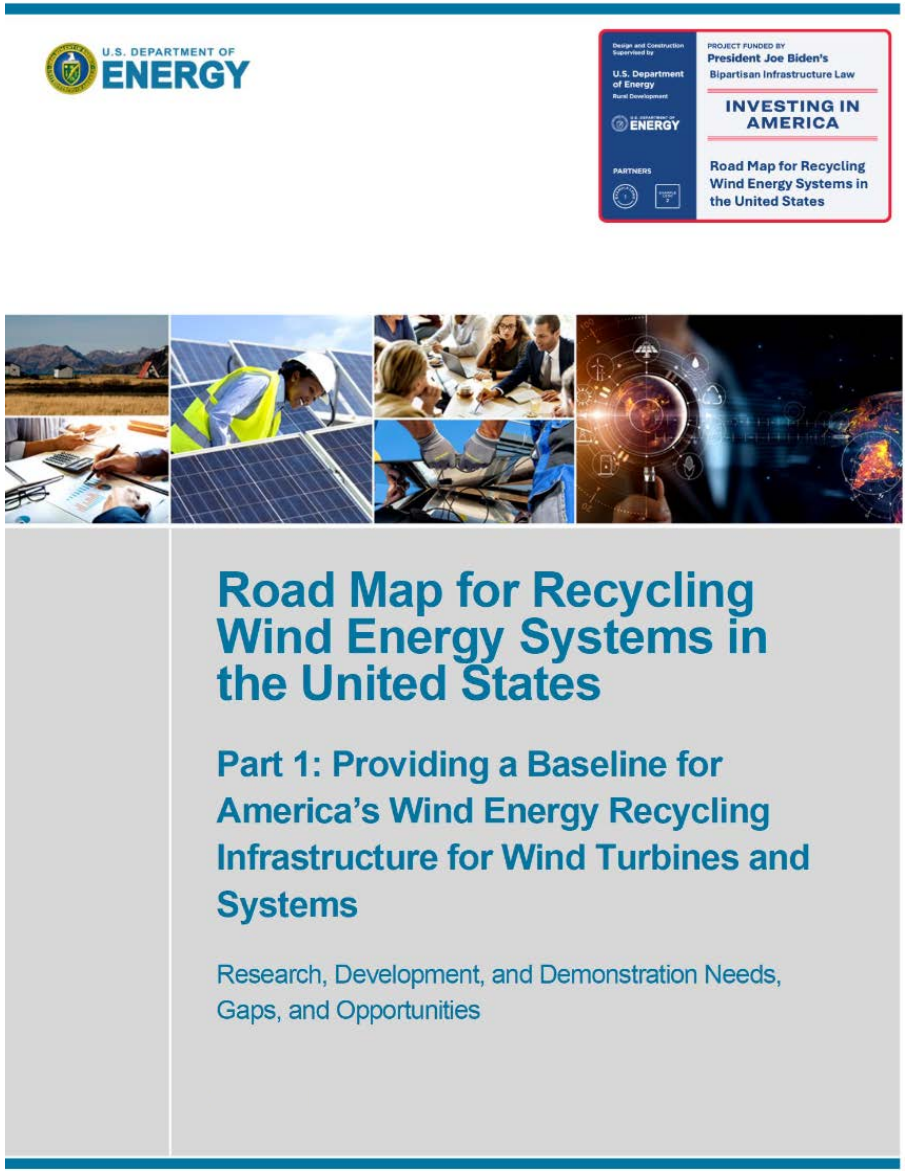
- Funded by the Bipartisan Infrastructure Law (BIL), NREL is involved in multiple projects related to wind energy end of service and recycling:
  - **Wind Energy End of Service Community and Stakeholder Engagement Project**
    - Engaging industry, community, and government stakeholders to better understand diverse perspectives on wind energy end of service
  - **Wind Technology Recycling Assessment**
    - Researching and assessing innovative approaches to increasing the reuse and recycling of wind turbine components
    - Collaboration between NREL, Sandia National Laboratories, and Oak Ridge National Laboratory
  - **Distributed Wind Recycling Roadmap**
    - Creating a roadmap to proactively enabling recyclability for distributed wind energy before the expected growth of the industry
    - Collaboration between Oak Ridge National Laboratory and NREL.

Photo by Dennis Schroeder, NREL 20866

Publications



https://windexchange.energy.gov/end-of-service-guide



Report is forthcoming

U.S. Department of Energy Wind Turbine Materials Recycling Prize

- In 2023, DOE's Wind Energy Technologies Office launched the **Wind Turbine Materials Recycling Prize**, funded by BIL
  - $5.1 million competition to help the U.S. develop a cost-effective, sustainable recycling industry for two key materials used in wind turbines:
    - Fiber-reinforced composites
    - Rare earth elements
  - Part of the American-Made Challenges series of competitions.

Top: Timeline and details for the Wind Turbine Materials Recycling Prize. Bottom: Map of phase 1 winners.
Graphics from U.S. Department of Energy

Thanks and Q&A!

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NREL/PR-5000-89658

Photo from Michael Okoniewski, Iberdrola Renewables 15244

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