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# Re-purposing Wind Turbine Blades: Matching Strategies and Innovation Governance Forms

**Majid Ali[a], Poul Houman Andersen[c*], Amjad Anvari-Moghaddam[a], Rudi P. Nielsen[b], Morten Enggrob Simonsen[b]**
a) Department of Energy, Aalborg University, Aalborg, Denmark
b) Department of Biology, Aalborg University, Esbjerg, Denmark
c) Aalborg University Business School, Aalborg, Denmark (corresponding author)

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**Abstract**: The decommissioning of wind turbine blades poses an escalating environmental and waste management challenge, as the composite materials found in these blades are difficult to recycle and often end up in landfills. With the projected growth in retired wind turbine blades, the waste burden is expected to reach 40–60 million tons by 2050. Traditional disposal methods, like mechanical and thermochemical recycling, are costly and result in low-value materials. Repurposing presents a sustainable alternative; however, matching decommissioned blades with appropriate industrial applications requires an innovative governance approach. This study leverages insights from innovation governance research and proposes a conceptual model for reusing decommissioned blades, focusing on bridging the gap between potential suppliers and users in various industries. By examining applications in construction, agriculture, and renewable energy systems, the study illustrates feasible repurposing strategies and explores the regulatory mechanisms needed to facilitate effective matching. Through expert interviews and case studies, the paper identifies barriers, such as logistical constraints and material degradation, and advocates for intermediate and third-party governance forms to support this marketization process. The findings highlight the importance of systematic matching mechanisms and regulatory frameworks in addressing the wind turbine blade disposal issue, underscoring the need for collaborative efforts in shaping sustainable solutions for end-of-life turbine materials.

## Introduction

In this conceptual paper, we suggest a novel way of matching potential users of waste materials with the providers of end-of-line wind turbine blades. In the wake of the renewable energy transition, the end-of-life disposal of blades from wind turbines presents a growing challenge. So far, the problem of decommissioning wind turbine blades (WTB) has been overshadowed by the urgency issues related to developing fossil-free energy sources. as a critical issue by industry actors. However, piles of turbine blades mount as increasingly larger wind power plants are being decommissioned (see Figure 1). The annual rate of decommissioned wind blade material is forecasted to reach 43.4 million tons by 2050 in Europe alone (Lichtenegger et al. 2020). Adding to the issue salience, waste management regulatory regimes tighten, creating new challenges for industry actors concerning handling this growing source of waste (Chioatto et al 2023). This is important not only from a commercial point of view since the disposal of blades represents a potential cost, but also from a sustainable image point of view, turbine producers find themselves increasingly criticized by salient stakeholders for not being a sufficiently green alternative (Fan & Zhang, 2024; Lichtenegger et al, 2020).

**Figure 1: EOL wind turbine blade depot**

WTBs are heavy and durable constructions, with a projected operational lifetime of 20-25 years and very little downtime. Blades primarily consist of glass fiber-reinforced polymer and in some constructions carbon fibers (Spini & Bettini, 2024). They are molded through a process known as resin infusion, creating a sturdy blade, which is also energy-consuming to break down into valuable primary components. Furthermore, the recycling economics is strained, since polymers become cross-linked in the curing process and their material quality and market value deter. Most often, they end up as a filler material, used in buildings, etc.

From a waste management hierarchy perspective, strategies for maintaining material value by keeping blades in their manufactured form are thus sought after (The European Waste Framework Directive, 2008/98/EC). Although there are examples of blade or blade segments being repurposed for instance as decorations in parks, they are few and far in between and do not address the volume and synchronicity issues related to managing waste stream operations (Drake & Spinier, 2013). At the same time, we suspect – given the recent salience of this problem – that the value-creating options related to matching the qualities of decommissioned blades with the potential material needs of manufacturers have not been adequately researched. Using insights from innovation governance research and recent research on reshaping industrial waste, we set out to conceptually explore how an alternative business model for matching possible users of decommissioned WTBs with potential users. The paper is structured as follows. First, we provide a background, outlining the magnitude of the problem related to decommissioning and the technique of blades and reviewing the existing literature. Next, we provide innovation governance as a theoretical lens, inspired by the literature on market shaping and the experiences from applying this perspective on a recent project on reshaping industrial waste (Laursen & Andersen, 2023). We provide a conceptual viable model for this initiative and corroborate it by using insights from expert interviews with industry actors. We end the paper by discussing possible avenues for new research and implementation roadblocks.

## The magnitude and growth of the wind turbine blade disposal problem

As the global wind energy sector has expanded, a pressing environmental challenge has emerged concerning the disposal of WTBs at the end of their operational lifespan. Traditionally constructed from composite materials such as fiberglass and, in some cases, carbon fiber reinforced plastic, WTBs are built to withstand harsh weather conditions and deliver years of reliable energy production. However, these materials also make the blades difficult to recycle or repurpose, and thus they typically end up in landfills when retired. With the significant upscaling in wind energy deployment worldwide, particularly over the last two decades, the magnitude of blade disposal has reached concerning proportions, signaling an urgent need for sustainable waste management solutions.

The scale of the disposal problem is driven by several factors, with one of the most prominent being the rapid growth in wind turbine installations globally. According to recent industry reports, approximately 90 gigawatts (GW) of wind power capacity were installed annually from 2020 onward, translating into thousands of new turbines being erected each year (GWEC, 2021) Given that the typical operational lifespan of a turbine is about 20–25 years, the volume of blades entering the waste stream is set to grow significantly over the next decade, as early-generation turbines are gradually decommissioned. By 2050, it is estimated that between 40 and 60 million tons of composite material from blades will require disposal unless effective recycling or repurposing methods are implemented on a large scale.

A crucial aspect of the disposal problem is that current recycling methods for blade materials are either costly or technologically challenging, with only limited facilities worldwide capable of processing these materials. Present methods, such as mechanical shredding, thermal treatment, and chemical recycling, often struggle with the unique properties of blade composites. These materials are designed to resist breakdown, meaning that conventional recycling processes either yield low-value products or are prohibitively expensive. As a result, most decommissioned blades end up in landfills, with studies indicating that as much as 85–90% of blade waste has historically been disposed of this way.

Another contributor to the problem is the recent trend toward the production of larger blades as a means of improving turbine efficiency and output. Larger blades not only contain more composite material but also require more complex disposal or recycling processes due to their size. This trend amplifies the scale of the disposal problem, as each new generation of turbines is likely to produce more waste than the last, further straining existing waste management infrastructure.

## Repurposing strategies for sustainable development

As wind turbines reach the end of their operational lifespan, finding ways to repurpose their large, durable blades is essential. Innovative strategies to extend the life of these materials sustainably include repurposing as well as different degrees of disintegration for reuse:

***Existing Repurposing strategies***

1. Repurposing in Construction and Infrastructure
   - *Bridge and Pathway Construction:* Repurposed blades can be utilized as structural elements in pedestrian bridges, pathways, and other outdoor facilities. Their aerodynamic design, strength, and longevity make them suitable for such uses.
   - *Public Infrastructure*: Several cities have already adopted turbine blades in parks and public spaces as playground equipment, seating, and even bike shelters, turning these structures into functional, sustainable urban features.
   - *Emergency Housing and Modular Shelters*: Given the durability and lightweight nature of blades, they can serve as building components for emergency shelters or modular housing, providing a low-cost housing solution in remote or disaster-prone areas.
2. Agricultural and Industrial Applications
   - *Sound Barriers Along Highways*: Blades can be repurposed as sound barriers near highways and industrial zones. Their shape and material can help dampen noise pollution.
   - *Farm Infrastructure*: On farms, blades can be adapted for use as fencing, storage, and animal shelters, offering affordable and durable structures that withstand outdoor conditions.
3. Energy Systems and Renewable Integration
   - *Hybrid Energy Structures*: Repurposed blades could serve as support for hybrid renewable setups, such as solar canopies, allowing for the integration of solar panels to increase energy generation.
   - *Supports in Off-Grid Microgrid Systems*: Decommissioned blades can be reused in off-grid or microgrid systems, especially in remote or developing areas where additional materials may not be readily available.
   - *Battery Storage Facilities*: Repurposing blades as enclosures for battery energy storage systems (BESS) can add a sustainable touch to energy storage infrastructure.

***Thermochemical recycling of turbine blades***

When looking further than mechanical recycling of End-of-Life turbine blades, thermochemical methods are the next step in the recovery of components from the blades. Typically, these methods are divided into thermal and chemical methods, with several technologies under each category such as pyrolysis, fluidized beds, solvolysis, etc. (Ge 2024). Compared to mechanical recycling approaches none of the thermochemical processes are currently operational at industrial scale but are at lab and pilot scales.

When applying both thermal and chemical there is a loss of mechanical properties of the fiber reinforcement, be it glass or carbon fibers. This can be losses of more than 50% of the tensile strength of the fibers, but some methods have proven to provide high-strength fibers with retained tensile strength in the range of approx. 90% (Liu 2019, Sokoli 2017). To increase the value of the recovered products from the turbine blades it is important that the fiber component can be recovered with a high retained strength, as this allows for a wider range of secondary applications of the fibers. The thermal methods cover pyrolytic methods (conventional and microwave-assisted) as well as fluidized bed recovery of composites. In pyrolysis, the composite is subjected to high temperatures in the range of 400-700oC in the absence of oxygen to produce oil from the resin as well as some non-condensable gas from the resin and a solid fraction including the fiber material (Gopalraj 2020). However, during pyrolysis, the fibers generally deteriorate and lose much of their tensile strength, normally ending in the range of 50% of the original strength in the case of conventional pyrolysis and 75% for microwave-assisted pyrolysis (Leon, 2023). This leads to the need for further treatment of the fibers using various surface treatments to minimize defects (Spini 2024). In fluidized beds, a high airflow at elevated temperatures (400+oC) allows for the recovery of fibers when treated, however, due to the heat the fibers are significantly decreased in mechanical properties (Spini 2024), as was seen with pyrolysis.

Solvolysis covers methods where solvents are used at moderate to high temperatures and pressures to degrade the resin of the composite and leave the exposed fibers. However, temperature also negatively affects the properties of the fibers, leading to a high degree of focus on low-temperature solvolysis approaches, which at the same time provide a more sustainable energy use.

Finally, a method for deconstructing epoxy composites into bisphenol-A and clean fibers using a ruthenium-catalyzed process has been demonstrated (Ahrens 2023). Although a promising step for recycling epoxies, this is reported as a slow process with the deconstruction of a 5g turbine blade taking 6 days to complete (Ahrens 2023).

## Designing for recycling

As turbine blades will be needed in the future as well an approach of designing for recycling is also gaining traction. Several approaches are pursued in this regard, with examples such as alternative formulations compared to traditional epoxies and polyesters. In 2021 an alternative thermoset formulation was used by Siemens Gamesa to produce their Recyclable Blade which is tested under operational off-shore conditions (Spini 2024). This blade is reported to be recyclable using low-temperature solvolysis (Leon 2023). Likewise, LM Windpower is testing a thermoplastic resin (Elium® by Arkema) for producing recyclable blades (Spini 2024). The use of thermoplastics compared to thermosets can potentially highly influence the difficulties normally observed with the recycling of thermosets.

In summary, current strategies for re-purposing and various forms of recycling are less than optimal or under-used and only partly match the magnitude of the problem and the management of the growing WTB flows. Finding the right users of the waste material is a central challenge in waste management symbiosis (Angelis-Diakis et al, 2021). In the next section, we therefore seek ways to extend the existing use or dissemination of use strategies.

## Re-use as an innovation-matching problem

The different re-uses (repurposing, recycling) of WTBs present technical opportunities, but current models for creating symbiosis effects are inadequate. Viewing the problem as one of innovation matching has so far been ignored. In the following, we apply an innovation-matching perspective, as we believe the application of market governance principle is a viable way forward in solving the waste problem. To become innovations, the WTB waste output needs to be marketized, which requires a viable and ongoing exchange between users and providers of material flows, rather than one-time solutions.

Innovation can broadly be understood as the process of creating and implementing new and valuable ideas that successfully meet market needs in new ways. New ideas can be manifest in products and services, but also new ways of organizing work, etc. (Nelson, 1991; Metcalfe et al, 2024). Innovation processes are however not randomly appearing and there are systematic differences concerning whether various levels of social systems are capable of being innovative (Porter, 1990; Chesborough, 2024). This has turned the focus to the processes governing innovation. Innovation governance is here defined as an institutional actor’s attempt to establish frameworks, processes and practices that support innovation activities. Innovation governance is increasingly seen by policymakers and other stakeholders as a central means for solving the systemic problems related to the looming climate crisis.

A key issue in innovation governance is how to match resources— like physical items, knowledge, and skills— with problem owners. This process involves setting up regulatory conditions that help businesses find ways to create value together. In environments where businesses interact, such as markets or industries, this matching process is crucial because there aren't established systems to connect resource providers with those who hold complementary resources.

From an innovation governance perspective, the challenge of matching potential users with providers of waste streams differs depending on the waste hierarchy level. Two different concerns are at stake: one concern pertains to the potential loss of value involved in the handover of waste from end-of-life WTBs to an alternative use and the other pertains to the cost of searching and matching waste with potential alternative beneficial uses. As the material moves up (or down) in the waste hierarchy parameters relating to these issues change. Breaking down the waste into its primary components is costly in terms of energy use and loss of potential features in the material. At the same time, the more generic the material is, the easier it is to find alternative users of that material. This allows for innovation governance regulatory mechanisms that are close to if not the same as regular market mechanisms, such as auctions. Maintaining the blade material in its present state for as long time as possible preserves the value and character of the material, but the matching costs related to searching for and possibly contracting with users are high and correspondingly require capable governance mechanisms. Below, we conceptually match the different states of blades in the waste hierarchy with adequate governance mechanisms.

The way resources are paired with potential users involves two main steps: potential suppliers search for relevant resources while buyers look for resources with potential usefulness. This exchange transforms random offerings into valuable matches. Information plays a vital role in this process, helping to connect different market players.

The interactions between suppliers are not random; they depend on relationships between them and the available resources. Suppliers influence one another indirectly, and their interactions with buyers and other market players also shape their decisions.

## Matching providers of end-of-use turbine blades with potential users

The generic governance forms suggested in Figure 2 show a hierarchy matching the re-used forms of waste from WTBs. It includes (simple) market governance, intermediate governance forms and third-party governance forms. At the base of the waste hierarchy, we find market governance for reuse. In this form, potential us-

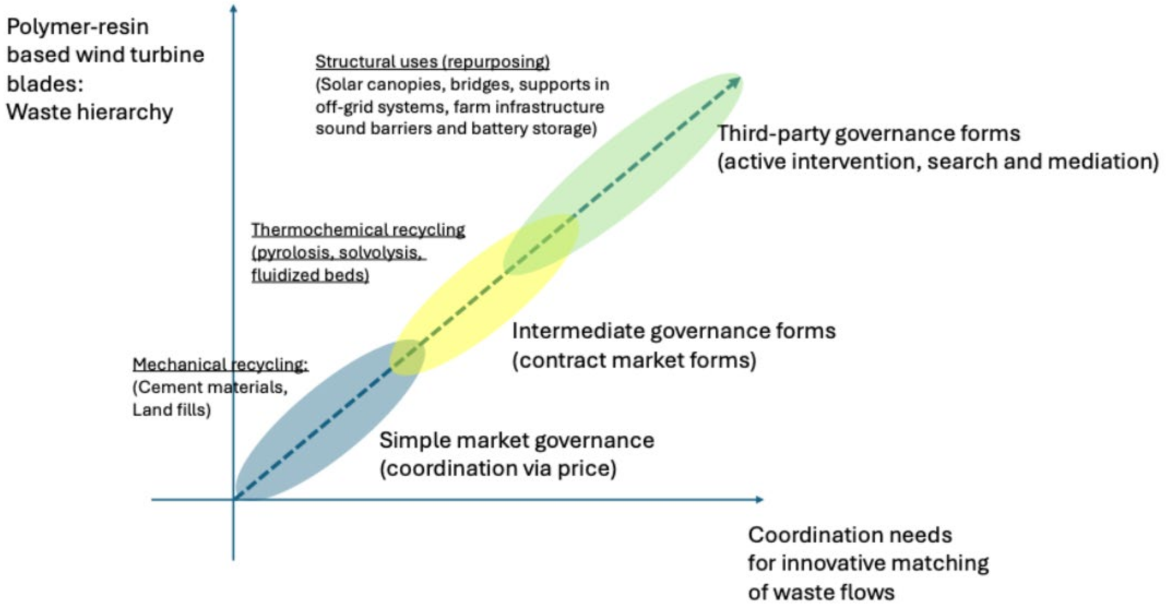


**Figure 2. Matching waste hierarchies with waste management forms © own work.**

ers are only limited by market size and coordination between users and providers is regulated by price signals. This form requires developing a reusable material out of end-of-life turbines, which can be valorised and used like other materials. For instance, US cement producers buy EOL blades on market terms and use them as filler materials (Jacoby, 2022). The corresponding market governance mechanism can ensure the absorption of waste flows to an almost unlimited extent, but it does little to levitate the environmental impact of the waste material. For instance, using turbine blade material in cement simply delays the problem related to releasing the material as epoxy is re-released when buildings are demolished.

Matching potential users with the advantages related to thermochemical recycling as a process for managing waste flows calls for exchanging much more information than in the case of material, corresponding to a governance form which can deal with more complex matching of users and producers. In the intermediate governance form, systematic scrutiny of existing industry uses and accessible descriptions of material characteristics and timing of production processes. This is needed for potential users can deploy cost-benefit perspectives and determine whether adaption to this waste material as a resource provides a reasonable business case. Also, this governance form opens for the formation of and commitment to buyer-supplier relationships where mutual negotiations can lead to the development of joint solutions. Problems with some innovation matching similarities to the one suggested here, are found in waste management treatment, where specification and scrutiny of available wastewater qualities are critical for matching potential users and providers (Duong & Saphores, 2015).

At the top of the waste hierarchy, we find strategies for matching users who benefit from maintaining most of the priorities of the material with providers of WTBs. This requires not only coordination of material properties but also of logistical flows and clock speed, given the physical properties of the blade that make them difficult to store and handle. The experiences from "Reshape Waste" - a recent project at Aalborg University, show that third-party innovation governance, where re-purposing of materials is used to develop new products and solutions valuable to markets, rather than replace existing materials would be a relevant option to explore further (Feast & Laursen, 2023).

## Conclusions

In summary, innovative ways of solving how waste material can be reused require both technological and commercial solutions. So far, however, little focus has been given to the matching of innovation governance forms and the challenges of matching users and providers. Effective matching happens when suppliers understand their own goals and relationships, allowing them to collaboratively create valuable exchanges. Parallel to developing new ways of repurposing and recycling the material, we suggest a stronger focus on designing processes for systematically scrutinizing and developing new matches.

## References

Ahrens, A., Bonde, A., Sun, H. et al. (2023) Catalytic disconnection of C–O bonds in epoxy resins and composites. Nature 617, 730–737. https://doi.org/10.1038/s41586-023-05944-6

Alderson, W. (1957): *Market behaviour and executive action*, Richard D. Irwin

Angelis-Dimakis, A., Arampatzis, G., Pieri, T., Solomou, K., Dedousis, P., & Apostolopoulos, G. (2021). SWAN platform: A web-based tool to support the development of industrial solid waste reuse business models. *Waste Management & Research*, *39*(3), 489-498. https://doi.org/10.1177/0734242X21989413.

Chesbrough, H. (2024). Twenty years of open innovation. *MIT Sloan Management Review*, *65*(2), 1-3.

Chioatto, E., & Sospiro, P. (2023). Transition from waste management to circular economy: the European Union roadmap. *Environment, Development and Sustainability*, *25*(1), 249-276 https://doi.org/10.1007/s10668-021-02050-3.

Cooperman, A., Eberle, A., & Lantz, E. (2021). WTB material in the United States: Quantities, costs, and end-of-life options. *Resources, Conservation and Recycling*, *168*, 105439. https://doi.org/10.1016/j.resconrec.2021.105439

Drake, D. F., & Spinler, S. (2013). OM forum—Sustainable operations management: An enduring stream or a passing fancy? *Manufacturing & Service Operations Management*, *15*(4), 689-700. https://doi.org/10.1287/msom.2013.0456

Duong, K., & Saphores, J. D. M. (2015). Obstacles to wastewater reuse: an overview. *Wiley Interdisciplinary Reviews: Water*, *2*(3), 199-214. https://doi.org/10.1002/wat2.1074.

Fan, W., & Zhang, C. (2024). Does Green Finance Affect Economic Performance? Growth and Crowding-Out Consequences. *Emerging Markets Finance and Trade*, 1-21. 10.1080/1540496X.2024.2345186

Feast, L., & Laursen, L. (2023). Design from Waste Materials: Situation, Problem, and Solution. *Learn X Design Conference Series*. https://dl.designresearchsociety.org/learnxdesign/learnxdesign2023/fullpaper/16

Gharde, S., Kandasubramanian, B. (2019) Mechanothermal and chemical recycling methodologies for the Fibre Reinforced Plastic (FRP), Environmental Technology & Innovation, 14, 100311, https://doi.org/10.1016/j.eti.2019.01.005.

Ge, Z., Wu, Y., Zeng, M., Zhang, H. (2024) A Critical Review on the Structure and Recovery Technologies of End-of-Life Wind Turbine Blades. Energy & Fuels, 38 (20), 19393-19413. DOI: 10.1021/acs.energyfuels.4c03648

Global Wind Report 2021, available online: https://gwec.net/wp-content/uploads/2021/03/GWEC-Global-Wind-Report-2021.pdf (accessed on Nov 8, 2024)).

Laursen, L. N., & Andersen, P. H. (2023). Resource and supplier interaction in network innovation governance: the case of innovating at Unilever. *Journal of Business Research*, *156*, 113465. https://doi.org/10.1016/j.jbusres.2022.113465

Gopalraj, S.K., Kärki, T. (2020) A review on the recycling of waste carbon fibre/glass fibre-reinforced composites: fibre recovery, properties and life-cycle analysis. SN Appl. Sci. 2, 433. https://doi.org/10.1007/s42452-020-2195-4

Leon, M. J. (2023). Recycling of wind turbine blades: Recent developments. Current Opinion in Green and Sustainable Chemistry, 39, Article 100746. https://doi.org/10.1016/j.cogsc.2022.100746

Liu, P., Meng, F., Barlow, C.Y. (2019) Wind turbine blade end-of-life options: An eco-audit comparison, Journal of Cleaner Production 212, 1268-1281, https://doi.org/10.1016/j.jclepro.2018.12.043.

Nelson, R. R. (1991). Why do firms differ, and how does it matter? *Strategic Management Journal*, *12*(S2), 61-74. https://doi.org/10.1002/smj.4250121006

Metcalfe, S., Broström, A., & McKelvey, M. (2024). On knowledge and economic transformation: Joseph Schumpeter and Alfred Marshall on the theory of restless capitalism. *Industry and Innovation*, 1-14. https://doi.org/10.1080/13662716.2024.2376318

Sokoli, H.U., Beauson, J., Simonsen, M.E., Fraisse, A., Brøndsted, P., Søgaard, E.G. Søgaard (2017) Optimized process for recovery of glass- and carbon fibers with retained mechanical properties by means of near- and supercritical fluids, The Journal of Supercritical Fluids 124, 80-89, https://doi.org/10.1016/j.supflu.2017.01.013.

Spini, F., & Bettini, P. (2024). End-of-Life wind turbine blades: Review on recycling strategies. *Composites Part B: Engineering*, 111290. https://doi.org/10.1016/j.compositesb.2024.111290

Waste Framework Directive." Accessed: Nov. 7, 2024. [Online]. Available: https://environment.ec.europa.eu/topics/waste-and-recycling/waste-framework-directive_en.