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Evaluating Recyclability of wind turbine blades

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Evaluating Recyclability of wind turbine blades

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IEA Wind Task 45 Wind Turbine Blade Recycling
Deliverable 2.3

Evaluating Recyclability of wind turbine blades – Suggestion for an evaluation scheme

April 2024

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Background to the Document

This document has been prepared in support of IEA Wind Task 45, Subtask 2.1 “Prevention of waste”, Subtask 2.2 on the “Reuse and repurpose of end-of-life wind turbine blades” and Subtask 2.3 on “Recycling and recovery methods”. This document is the outcome of a workshop and a series of meetings gathering experts from academia and industry on the following topics: wind turbine blade materials and design, recycling of wind turbine blades and windfarm operation. The document provides a summary of considerations to evaluate the recyclability of blades and design aspects supporting blade recycling.

The intended audience consists of three main groups: first, project developers, owners, and operators, providing information on how to evaluate the recyclability of blade design alternatives (current blades, operational in the field, and new blades currently being developed). Second, designers, engineers, and manufacturers address how to anticipate recycling in the development of new blades and provide information to generate design solutions. Finally, decommissioners and recyclers, provide considerations to evaluate recovery pathways. This document provides a structured approach to different aspects to be considered.

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1 Introduction

This study focuses on the recycling of wind turbine blades after their functional use in a wind turbine system has ended. Hence, this study focuses on strategies to recycle components and materials, whereas lifetime prolongation and reuse strategies are excluded. Recycling of wind turbine blades can take place through repurposing, which involves whole or large pieces, through structural reuse of composite panels and beams, and the manufacturing of new materials with granulate or powder materials from wind turbine blades. This categorisation roughly follows the size of the material size used and a visual representation of this categorisation is suggested in Table 1.

Table 2: Categorisation of blade recycling strategies (adapted from Deliverable 2.2 of the IEA Wind Task 45)

Material description	Full blades	Large blade sections	Composite pieces	Ground / fine granulate	Milled / Powder
Length scale	> 10m	> 2 m	10 to 50 cm	< 40 mm	< 100 um
Repurpose					
Structural reuse					
Material recovery (pyrolysis, etc)					
Mechanical recycling					
Co-processing					

Much of the potential for end-of-life processing is determined by decisions at the design stage. Design for recycling guidelines is therefore being proposed for several products (Joustra et al., 2021a). For wind turbine blades, research is being done on how the design influences the possibilities for reuse (Beauson et al., 2022; Joustra et al., 2021b). Opportunities for wind turbine blade recycling will also, to a certain extent, depend on the decisions at end of service life. These influence the different options of waste management alternatives to landfill (e.g. reuse) (Laurentis and Windemer, 2024). While several studies have indicated factors that support the reuse and recycling of end-of-life wind turbine blades, there is still no comprehensive overview available.

This study aims to inventory the considerations to evaluate recyclability and to identify design aspects supporting the recycling of blades. In the following section, the method section describes the collection of insights on blade redesign and the analysis of the outcome of the workshop. The results section presents an overview of overarching design goals or design for recycling aims and supporting design aspects to facilitate recycling and repurposing of blades. The discussion section proposes a design for two approaches and combines proposals based on posters and guidelines. This document ends with a perspective of the current field and outlook.

2 Method

Insights and considerations to evaluate and design wind turbine blades for recycling were collected from the members of the IEA Wind Task 45 network. The collection of information took place through online discussions, which resulted in an overview document listing design aims and potential solutions. Building on these initial insights, a workshop was organized in November 2023 in Bristol at the National Composite Centre, to collect blade redesign proposals. The analysis of the collected insights and considerations distinguished between design for recycling aims and design aspects. The design for recycling aims to describe the rationale and the design aspects provide means to realize those in blade design. The design proposals were analysed using a provisional coding approach. The initial coding set was based on (Joustra et al., 2021a) and expanded with additional design aspects that emerged while analysing the proposals. This analysis enabled the creation of a comprehensive list of design aspects, also to relate those to the previously mentioned design aims.

3 Results

The results section presents the outcome of the online preparatory discussion and the in-person workshop. 8 design for recycling aims and 14 design aspects were identified. Most design aspects apply to multiple recyclability considerations and could therefore be used in several design for recycling approaches. Therefore, design for recycling aims and overarching recyclability concerns are presented first, followed by the design aspects supporting those in more detail. The purpose and goals of each design for recycling are briefly summarized. The design aspects connected to the design for recycling aims are presented as well as examples to illustrate.

3.1 Design for recycling aims

3.1.1 Prevent contamination of materials in the recycling process

Some recycling routes are tailored for specific materials and the presence of other materials might be detrimental to the effectiveness of the process. To enable the recycling of any materials, a certain value and volume of recycled materials is also needed. Therefore, preventing contamination of materials during recycling may be required or may enable certain recycling strategies. However, separation processes during recycling are often some of the most limiting, difficult, and costly steps (e.g. solar and automotive industries). The goal of such design for recycling aims is to to sort out detrimental and toxic materials during recycling and increase the efficiency of recycling processes (availability, value and volume) thereby enabling a solid supply chain of recycled materials.

Preventing contamination may be addressed by design aspects related to material selection and connecting strategies between materials and components. A positive example in material selection: "if a thermoplastic resin system is used, it would be beneficial to ensure that core materials and bond line are also miscible thermoplastic with the resin and that the miscible mixture/solution has value in a second market application". The participants could not think of a negative example.

3.1.2 Supply chain criticality and environmental factors for sourcing

Supply chain criticality and environmental factors for sourcing in the design phase is connected to design aspects related to material selection, manufacturing, documentation and traceability. The goal of this design for recycling aim is to address supply chain concerns, such as the possibility of implementing reliable sourcing to source critical materials and resource-depleted materials. Providing a life cycle assessment (LCA) to the customer, including potential recycling routes is an example of the solution.

3.1.3 Facilitate data availability

Data availability at end-of-life during the design phase is connected to design aspects related to identification, traceability and documentation of materials. This could for example be performed with the preparation of material passports or environmental product declaration (LM Wind Power, 2022; Siemens Gamesa Renewable Energy, 2022; TPI Composites, 2019; Vestas, 2022). Participants commented that existing blade materials passports are incomplete, with materials missing. In general, blade materials need to be tested and the needs from recyclers resolved. This could be realized by improved communication between the different stakeholders involved in the recycling value chain, such as the OEMs and developers. Other solutions discussed by the participants are for example a central protected database to share at EoL for reuse/repurpose/recycle, or legal enforcement to disclose minimum info. A question pending is how to enable safe datasharing. Further solutions discussed are extended producer responsibility (EPR) which could be implemented by regulators.

3.1.4 Facilitate blade/material quality assessment

Facilitating quality assessments of end-of-life blades and materials during the design phase is connected to design aspects related to monitoring and documentation. Give access to blade data especially after the warranty periode to promote re-purpose when the blades reach end-of-life. Blade manufacturers should consider giving away more of the blade data information to facilitate the emergence of industries in the value chain able to re-purpose decommissioned blades. More information regarding the blade material composition and internal structure is needed for the design of products made of decommissioned blades.

Blade owners could also require access to these data during the procurement processes as they are ultimately responsible for the blade decommission management. This responsibility gives them leverage to shift from the current high blade data secrecy to a more reasonable one that also allows for an increase in the repurpose rate of decommissioned blades.

3.1.5 Lifecycle perspective on environmental and economic performance

This design for recycling aims to consider how to harmonise the economic and environmental performance throughout the life cycle of the product. In the design stage, one can anticipate successive stages in its life cycle. From production, through use, to maintenance and end of use. The goal is to achieve a global rather than a local optimum. So that lifetime, annual energy production, and reprocessability harmonise into an attractive business case.

3.1.6 Implement Recycling Programme

The implementation of a recycling programme during the design phase is connected to design aspects related to planning and documentation. When planning the wind turbine installation, the end of use should be included. "A recyclable blade without a concept/plan/pathway for a recycling method, including the required supply chain in place is not a blade that will be recycled." In addition to already existing legislation regarding the removal of installations at the end of life, an increasing number of tenders are imposing requirements on the substantiation of decommissioning activities. Thus requiring bidding consortia to anticipate decommissioning, reprocessing and defining an appropriate business case.

3.1.7 Support decision-making

Supporting end-of-life decision-making during the design phase is connected to design aspects related to documentation. From a technological perspective, the likelihood of recycling is driven by four interacting factors; design, material selection, manufacturing technology and reprocessing technology.

These factors operate within a specific context were value chain considerations such as stakeholders, legislation, geographic considerations as well as operating conditions need to be addressed (Liu et al., 2022, 2019). Although these factors do not represent an exhaustive list, they can be considered driving factors for evaluating the process options at the end of use. As an example, there may be certain technologies that are ideal for specific blade materials, especially as new resin systems are introduced beyond epoxy and polyester, but those technologies and value chains of recycled material may not be readily available. At the same time, other compatible recycling technologies with less ideal pathway may be available.

Therefore, it is becomes important to evaluate the options available in a specific region, at a specific site, for a specific blade composition. An industry-wide harmonization of wind turbine blade design and materials would benefit and help streamline the recycling process.

3.1.8 Design for decommissioning and reprocessing.

Decommissioning and reprocessing during the design phase is connected to the design aspect related to Design for Disassembly and Embedded markings.

3.2 Design aspects

3.2.1 Dis-&reassembly

Joustra et al., (2021) define design for Dis- and reassembly as "*facilitating manual or mechanical disassembly and reassembly of the product to enable reuse of parts to improve the recovery rate".* In the case of wind turbine blades, design for Disassembly is to design the blades in a way that allows for easy disassembly, separating different materials for recycling. Designing for Dis-&reassembly could be facilitated with for example the use of a disassembly map (De Fazio et al., 2021).

3.2.2 Connection selection

Selecting connections during the design phase in the case of wind turbine blades could for example aim to ease the removal of root connectors and bolts, another strategy could be to use a glue connection system that allows easily separate parts (core, sandwich, labels) or avoid glue and epoxy-based glue. According to Joustra et al., (2021), the purpose of this strategy is "*selecting connections that can be accessed, opened, and reused where appropriate to facilitate use, rework, and recovery actions during product life".*

3.2.3 Material selection

By using a design allowing for high degree of recyclable materials that are easy to separate the recyclability of the wind turbine blade can be increased. In general, most recycling processes accept and make use of different materials, but it needs to work at scale. The easier the materials are to separate the more cost efficient the process can be.

Examples of materials are weldable resins, self-induced healing materials, epoxy and resins that are easy to depolymerise and reuse.

Based on the participants' experience, it is recommended to use less materials to have less risk of contamination when recycling. A more specific recommendation is to not use chlorine which is present in the PVC core materials. Instead, PET or balsa wood should be used. PUR used in coatings and in core materials is also to be avoided.

3.2.4 Manufacturing

Joustra et al., (2021) define design for manufacturing as "*selecting and optimising the process to minimise emissions and meet the material, functional, shape and recovery criteria".* This strategy could be implemented with supply chain management and logistics software. Such software tracks materials flows and a dedicated application programming interface (API) can be used to link software platforms.

3.2.5 Modularity

Joustra et al., (2021) define design for modularity as "*grouping features within the product to create sub-assemblies that are accessible, removable, and interchangeable".* This strategy could be implemented by *multiple-segment* production.

3.2.6 Structural design

Joustra et al., (2021) define design for structural reuse as *"optimising the material structure, shape, and product architecture to achieve the desired structural performance".* This strategy could be implemented with removable spar.

3.2.7 Surface treatment selection

Joustra et al., (2021) define design for surface treatment selection as *"selecting coatings and other surface treatments appropriate for the use, reuse and reprocessing of the product and its materials".* This strategy could be implemented by selecting coatings that comply with the requirements in the intial use phase (wind turbine) as well as anticipated secondary use cases or recycling processes.

3.2.8 Documentation

Joustra et al., (2021) define design for documentation *as "providing information about the product, components, and functions to stakeholders in the value chain and actors in the product and component lifecycle."* Participants emphasized the importance of data availability to enable efficient processing and preventing delays.

This strategy could be implemented for wind turbine blades through a pre-cutting plan and pre-plan for repurposing of components and parts. The end of use operators need info from all lifecycle stages which can be provided in a material/product passport, or a digital twin. These could be shared from a central protected database, where end-of-life information such as an LCA and more precise recycling information would be stored. Ultimately, such information could be included in the tender for decommissioning.

3.2.9 Identification

Joustra et al., (2021) define identification as *"using labels, tags etc. to facilitate recognition of the product, parts, materials and/or its specifications."* This strategy could be implemented on wind turbine blades by labelling. A label stating the manufacturer, blade type, etc. would ease for the recycler knowing what product to enter its recycling process.

3.2.10 Monitoring

Joustra et al., (2021) define monitoring solutions as *"determining and logging of product properties and use conditions over the product lifetime."* This strategy could be implemented by logging operating conditions and maintenance history of the blade. Retrieving data from structural health monitoring systems during the use phase would help facilitate proper evaluation of the blade condition, for example on the accumulated fatigue damage, incidental repairs and residual strength. This is particularly important for repurposing strategies.

3.2.11 Standardisation

Joustra et al., (2021) define design for standardisation as *"using well-known, defined, and widely used components, processes, dimensions, materials etc. in the product design, or developing a standard layout for the product(range). This design aspect relates, but is not restricted to industry* *standardisation".* This strategy could be implemented through a percentage target of recovered materials reuse used in the wind turbine blade.

3.2.12 Embedded markings

Embedded markings and imprints from the mould are often used in manufacturing to assist assembly and connector placement. This strategy could be implemented through embedded markings/indicators on the blade surface detailing location of spar box and connectors, so one knows where to cut.

Embedded markings, such as imprints or prints on the blade facilitate decommissioning, transport (lifting and support points). As well as indicating position of materials (e.g. transition from solid GFRP to lightweight core material), structural parts (shear webs, spar caps, etc.) and facilitate setting out a segmentation pattern for down-sizing onsite and laying out predefined cutting patterns.

3.2.13 Traceability

Traceability and/or voluntary disclosure from OEM's (material passport development) is needed to understand the end-of-life value chain and ensure sustainable practise. The industry would need to reflect where to stop the traceability conversation (after the blade leaves the wind site and arrives at a recycling facility, its second life, etc.). An environmental product declaration coupled with a material passport would be a helpful pairing.

3.2.14 Timing & planning

In addition to already existing legislation regarding the removal of installations at the end of life an increasing number of tenders are imposing requirements on the substantiation of decommissioning. This timing and planning for decommissioning will support market development as it provides a forecast on material availability, which is a current challenge in developing reprocessing facilities (Gast et al., 2024; Liu et al., 2022).

3.3 Alternative solutions

In addition to adapting and optimising the current blade designs to facilitate recycling, in its broadest sense, alternative solutions are proposed. These include new blade concepts altogether:

- Robotised maintenance and repair
- Proposals for turbines with multiple rotors instead of one big one
- Combining airborne wind energy with conventional turbine
- Reshaping & reforming thermoplastics: make things that don't look like blades (but what about the foams?
- Material composition to enable repurposing
- New concepts: the Magnus blade

4 Discussion

Based on the collected design for recycling suggestions, we propose two recyclable blade design concepts. First, a blade design optimised for recycling, thus featuring design aspects that support separating and reprocessing materials. Second, a blade design optimized for repurposing, facilitating pre-processing of the blade into segments or reusable parts. These blade concepts are made to present and stimulate discussion on radical redesign proposals and their implications.

4.1 Concept 1: Design for recycling

The design proposal for recycling initially targeted pyrolysis. However, most of the design proposals are also applicable to other recycling processes, such as mechanical or chemical recycling. The main objective is to avoid contamination of materials in the recycling process, in addition to supporting dismantling and pre-processing.

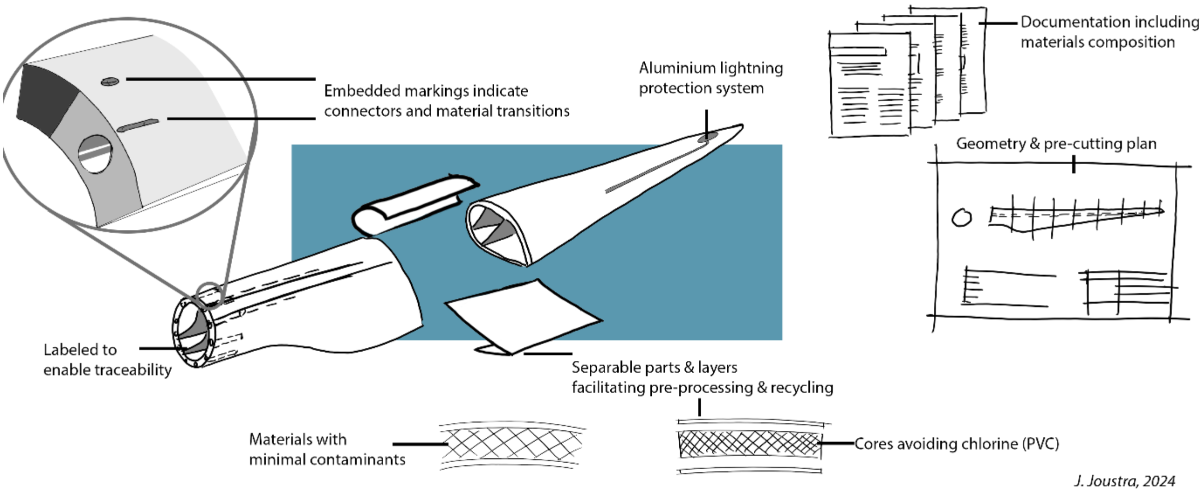

Figure 2 Concept of wind turbine blade designed for recycling (image by J. Joustra, 2024)

Contamination is addressed by ensuring proper separation of the materials. In pre-processing, this is done by cutting apart the embedded connectors and spar caps. This is facilitated by indicating the location of these elements by embedded markings. Subsequently, the materials of the parts obtained are easy to separate. The material selection takes into account preventing the presence of contaminants, such as chlorine in the core materials.

Dismantling, pre-processing and recycling are supported by making the data of the blade traceable. The blade is physically marked for this purpose, possibly with a direct reference to a repository with data. The data on material composition and geometry are available and used for dismantling (e.g. lifting and transport), pre-processing and recycling.

4.2 Concept 2: Design for repurposing

Repurposing and structural reuse both aim to reuse parts of the sheet as-is. For this, it is important to assess the condition of the material. The design therefore takes into account disassembly of structural parts and data availability to supports quality assessment. Together, this enables assessment and design for potential reuse applications.

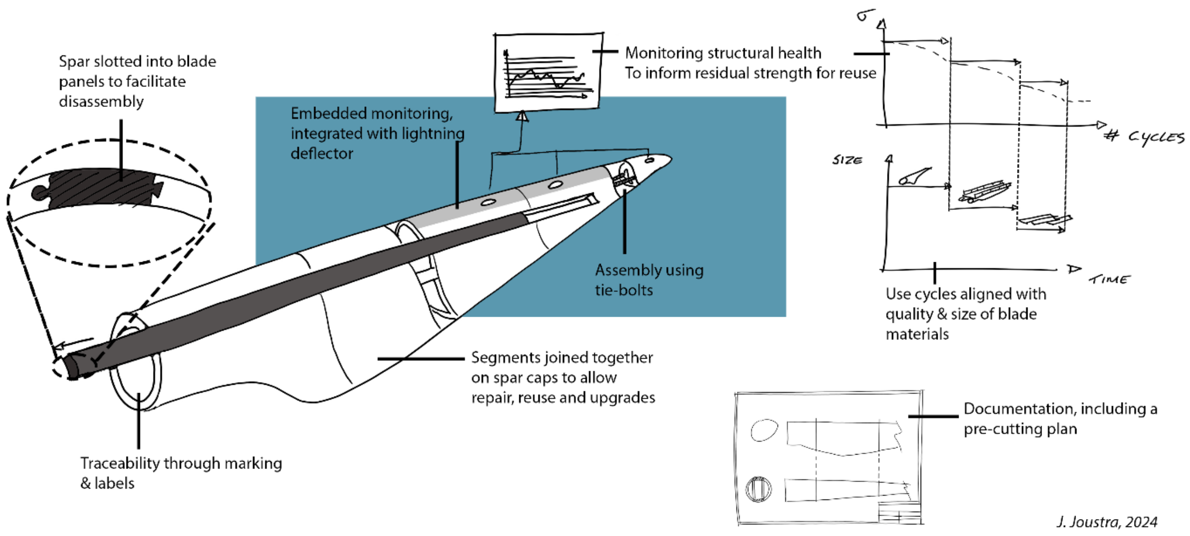

Figure 3 Concept of wind turbine blade designed for repurposing (image by J. Joustra, 2024)

To facilitate harvesting of construction elements, the blade is composed of a series of individual segments. These are joined together with the sparcap and connected by tie-bolts. The sparcap slots into the blade panels, to enable reuse as a whole as well as separate parts. This construction supports not only reuse of blade parts but also exchange of segments in case of repairs and upgrades.

To properly evaluate the quality of the blade, a monitoring system is integrated with the lightning deflection system. This structural health monitoring provides an indication of the residual material quality and the design limits for next lifecycle applications. CAD drawings of the blade and suggested cutting patterns are available to support pre-procesing and developing secondary designs. As such, the subsequent uses can be chosen to best match the available materials in terms of properties & geometry.

4.3 Opportunities & barriers

Opportunities and barriers reported by the participants are Regulation, Data sharing, Materials & process development and the most desirable Recycling routes at the end of use are unclear. The unclarity is due to a combination of possibility & developments in market & research projects. There is a need to create economies of scale in recycling facilities.

5 Conclusion

In this report, we provide guidance on evaluating the recyclability of wind turbine blades. Consultation with participants in the IEA WindTask 45 project led to 8 aims considered to support blade recyclability. The recyclability aims are linked to 14 aspects in the design of a blade. As such, the report also offers starting points to take recycling into account already in the design stage.

Recycling is addressed in this report in the broadest sense of the word. From repurposing large parts to reprocessing granulated materials. As a result, a number of the report's recommendations are at a high level of abstraction. Currently, several of these processes are under development, and there is no clear preferred solution on the market yet. These processes are expected to continue being materialised in research projects. Following, there will be a push to market through industry action & regulations.

6 References

Beauson, J., Laurent, A., Rudolph, D.P., Pagh Jensen, J., 2022. The complex end-of-life of wind turbine blades: A review of the European context. Renew. Sustain. Energy Rev. 155, 111847. https://doi.org/10.1016/j.rser.2021.111847

De Fazio, F., Bakker, C., Flipsen, B., Balkenende, R., 2021. The Disassembly Map: A new method to enhance design for product repairability. J. Clean. Prod. 320, 128552. https://doi.org/10.1016/j.jclepro.2021.128552

Gast, L., Meng, F., Morgan, D., 2024. Assessing the circularity of onshore wind turbines: Using material flow analysis for improving end-of-life resource management. Resour. Conserv. Recycl. 204, 107468. https://doi.org/10.1016/j.resconrec.2024.107468

Joustra, J., Flipsen, B., Balkenende, R., 2021a. Circular Design of Composite Products : A Framework Based on Insights from Literature and Industry. Sustainability 13, 7223. https://doi.org/10.3390/su13137223

Joustra, J., Flipsen, B., Balkenende, R., 2021b. Structural Reuse of High End Composite Products: a Design Case Study on Wind Turbine Blades. Resour. Conserv. Recycl. https://doi.org/10.1016/j.resconrec.2020.105393

Laurentis, C. De, Windemer, R., 2024. When the turbines stop: Unveiling the factors shaping end-of-life decisions of ageing wind infrastructure in Italy. Energy Res. Soc. Sci. 113. https://doi.org/10.1016/j.erss.2024.103536

Liu, P., Meng, F., Barlow, C.Y., 2022. Wind turbine blade end-of-life options: An economic comparison. Resour. Conserv. Recycl. 180, 106202. https://doi.org/10.1016/j.resconrec.2022.106202

Liu, P., Meng, F., Barlow, C.Y., 2019. Wind turbine blade end-of-life options: An eco-audit comparison. J. Clean. Prod. 212, 1268–1281. https://doi.org/10.1016/J.JCLEPRO.2018.12.043

LM Wind Power, 2022. Blade Material Passport - LM 37.2 P2.

Siemens Gamesa Renewable Energy, 2022. Blade Material Passport Wind Turbine Blade B45.

TPI Composites, G.G., 2019. Environmental Product Declaration.

Vestas, 2022. Material Passport Wind turbine blade V47.