IDENTIFICATION AND ENVIRONMENTAL ANALYSIS OF ECOSYSTEMS FOR DIFFERENT TYPES OF REPURPOSED APPLICATIONS OF DECOMMISSIONED LARGE-SCALE WIND TURBINE BLADES

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Keywords: Composite materials, End-of-life, Wind turbine blades, Repurpose, Life cycle analysis

ABSTRACT

The rapidly growing wind industry poses a fundamental problem for wind turbine blade (WTB) disposal in many areas of the world. WTBs are primarily manufactured from composites consisting of a thermoset matrix and reinforcing fibers. Currently, there are no economically viable recycling technologies available for such large-scale composite products. Thus, other treatment strategies for disposed WTBs have to be considered. This study explored the repurpose of WTBs as a promising alternative approach from a technological point of view. For this purpose, the study was guided by the categorization into four different types of repurposed applications: whole structure carrying moderate to high loads (type 1 (T1)), whole structure carrying low loads (T2), partial structure carrying moderate to high loads (T3), and partial structure carrying low loads (T4). A three-dimensional computer aided design model (CAD model) of an Enercon-40/500 WTB was derived in a reverse engineering procedure. Using the E40 WTB model, various ecosystems with different manufacturing technologies involved were investigated by the example of a climbing tower (T1), a playground (T2), a Photovoltaic (PV)-floating pontoon (T3), and a lounger (T4). A life cycle analysis (LCA) was conducted to evaluate the four repurposed applications according to environmental aspects. It was found, that the repurpose of E40 WTB composite material can reduce the environmental impact and lead to significant resource savings. In particular, end-of-life (EoL) WTBs have a high potential to substitute very emission-intensive structural materials.

1 INTRODUCTION

The goal of the European Union is a clean energy transition [1]. To enable the path towards decarbonisation of the European energy system, the use of wind energy has grown significantly in recent years, and it is expected to continue to increase in the upcoming years [2,3]. The wind industry uses wind turbines to generate clean energy. Among other components, a wind turbine consists of large-scale blades with a high proportion of composite materials [4,5]. In most cases, the WTBs are manufactured from a thermoset matrix, which is reinforced by glass fibers due to the advantage of combining high specific strengths and good adhesion properties between fibers and matrix, with very reasonable costs

[6–8]. A WTB made of glass fiber reinforced polymers (GFRP) has an expected operating time of approximately 20 years [2,6,9]. *Wind Europe* estimates that about 14.000 WTBs will be decommissioned by 2023 [4]. There are various predictions in the literature regarding the expected amount of WTB composite waste in the coming years. For example, Albers *et al.* [10] stated that the quantity of EoL WTBs in Europe will raise to 100.000 tons annually until 2034. It becomes evident that EoL WTB composite waste represents a rapidly growing global waste stream [9].

In 1994, Murphy [11] raised the topic of recycling composites. Still, the use of high-performance thermosets makes recycling fibers and matrix systems difficult, which is nowadays considered a major problem [2,6,12,13]. The irreversibly bonded structure of cured thermosets makes recycling composites a challenge [14], since they cannot be molten and reshaped after the curing process [15]. Sustainable and economically viable recycling solutions in industrial applications for GFRP are rare [13].

Given the aforementioned situation of a growing WTB composite waste stream and the difficulty of recycling these materials, new obstacles arise for the European composite waste industry to ensure the principles of the circular economy (CE) introduced by Pearce and Turner [16]. The CE focuses on the transition from a linear economy model based on take-make-waste principle to a circular model, in which, if composite waste is occurring, it becomes a valuable material resource [17]. The CE aims to maintain material resources by keeping them in the loop [18], allowing the development of new circular value chains by reusing materials from EoL composite products in high-value structural applications [19]. Various treatment strategies are conceivable to keep the integrity of composite products, reduce the consumption of natural resources, and minimize waste production [20].

The treatment strategy of repurposing is a promising approach for EoL WTB from an environmental, economic and social point of view [12,21,22]. The repurpose of an EoL WTB is defined as the reuse of composite structures from the WTB in a new product with a different function [20]. The repurposed product is designed to fulfill the requirements of a structural or semi-structural application [13]. Often, it presents lower structural value than the original WTB [4]. Several approaches for repurposing WTBs were proposed by the *Rewind-Network* [23,24]. Some examples were explored more in detail, e.g., a *transmission pole* [25], *affordable housing elements* [26,27], and *bridges* [22,28–30]. Other projects have also investigated the use of WTBs for urban furniture and playgrounds [28,31]. The benefits of repurposed applications are as follows: first, reusing the structure and quality of composites without resource-intensive reprocessing [13] instead of downsizing WTBs to low-value structural components, such as fillers [32], secondly, extending the operating time of the composite materials, and thirdly, decreasing impacts along the product life cycle [13] by keeping large quantities of composites out of unsustainable routes, such as landfill. Therefore, considering repurposed applications forms an essential part of the CE [33].

The primary focus of this investigation is the reuse of WTB composites utilizing repurposing options. Summarizing repurposing as a single manufacturing step, however, does not consider the complexity of this treatment strategy. Different actors and technologies are involved in each of the process steps, and there exist dependencies between the different processes and stakeholders. The constellation of actors, technologies and institutions that are interdependently connected is referred to as an *ecosystem* [34,35]. Within this study the focus lies on the technological dimension of the ecosystem to manufacture a repurposed application made of EoL WTB material. The Enercon-40/500 WTB [36] serves as base material to classify, and quantitatively characterize different types of repurposed applications. These are classified into various types based on the current damage state of the WTB, and its measured geometry. For each type, the technological aspects of the ecosystem are characterized and the repurposed applications are evaluated according to environmental aspects using the LCA method according to DIN EN ISO 14040 [13,37,38].

2 MATERIALS AND METHODS

2.1 Types of repurposed applications

After disassembly of the WTBs, inspection of the EoL composite structures is required to decide, which repurpose application is appropriate. Therefore, non-destructive testing (NDT) applied to WTBs based on visual or ultrasonic inspection, thermography, radiography, electromagnetic analyses, acoustic emission technique, acoustic-ultrasonic testing or shearography, among others, enable detection as well as diagnosis of damages to the blade's outer shell [39,40]. In addition to damage detection, other evaluation criteria such as the geographic location of the WTBs must also be taken into account. Another important aspect of the decommissioned WTBs reuse is the knowledge of the actual geometry.

Based on the information collected about the current damage state of the WTB, its disassembly location, and its geometry, reuse by repurposing can be classified into four different types:

T1 - *whole structure carrying moderate to high loads*,

T2 - *whole structure carrying low loads*,

T3 - *partial structure carrying moderate to high loads*,

T4 - *partial structure carrying low loads*.

The repurpose of the whole structure for T1 and T2 applications is suitable for small WTBs with a length of less than 30 m [28], preventing manufacturing costs of segmentation. Partially repurposed applications according to T3 and T4 can be implemented by cutting segments from the EoL WTB (cf. 2.3).

2.2 EoL E40 WTB as base material – Geometric characterization and material composition

The CAD software CATIA V5-6R2018 (Dassault Systemes, Velizy-Villacoublay, France) was used to reconstruct the 3D model of an E40 WTB in a reverse engineering process. For this purpose, the blade was cut into seven segments with a wire saw (see Figure 1a) for further closer examination. In order to characterize the geometry of the E40 WTB, manual measurements were performed on the cross sections (see Figure 1b). In addition, 3D LiDAR (3D Laserscanner Leica BLK360, Leica Geosystems, Heerbrugg, Switzerland) scanning was carried out to provide an overall scan of the outer shell of a segment (see Figure 1c).

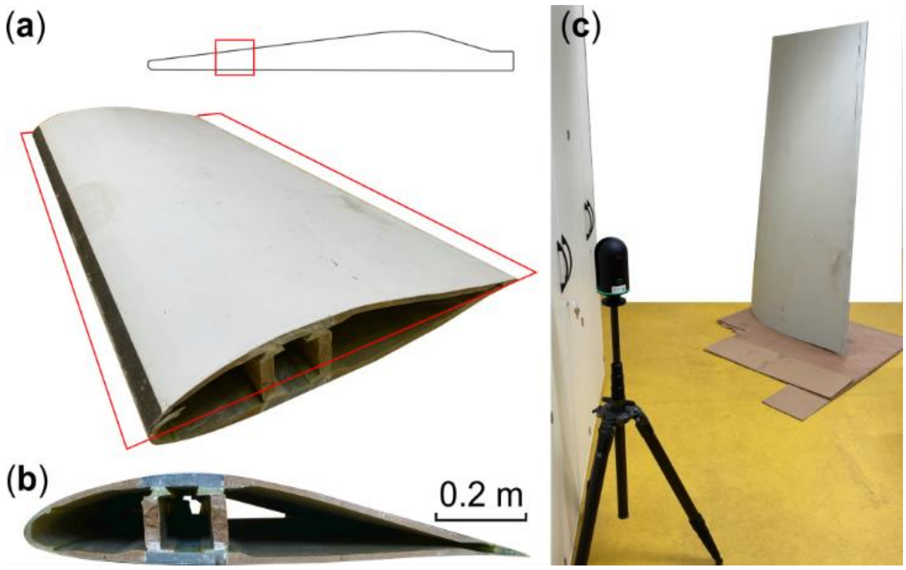

Figure 1: (a) Segment E40 WTB, (b) Cross section E40 WTB, (c) LiDAR scanning of segment.

The geometry of the E40 WTB (see Figure 2a) was designed by cross sections and quantitative data from technical data sheets [36]. The overall scan was used to check the consistency of the designed outer geometry, where a good fit was observed between the CAD model and the scan.

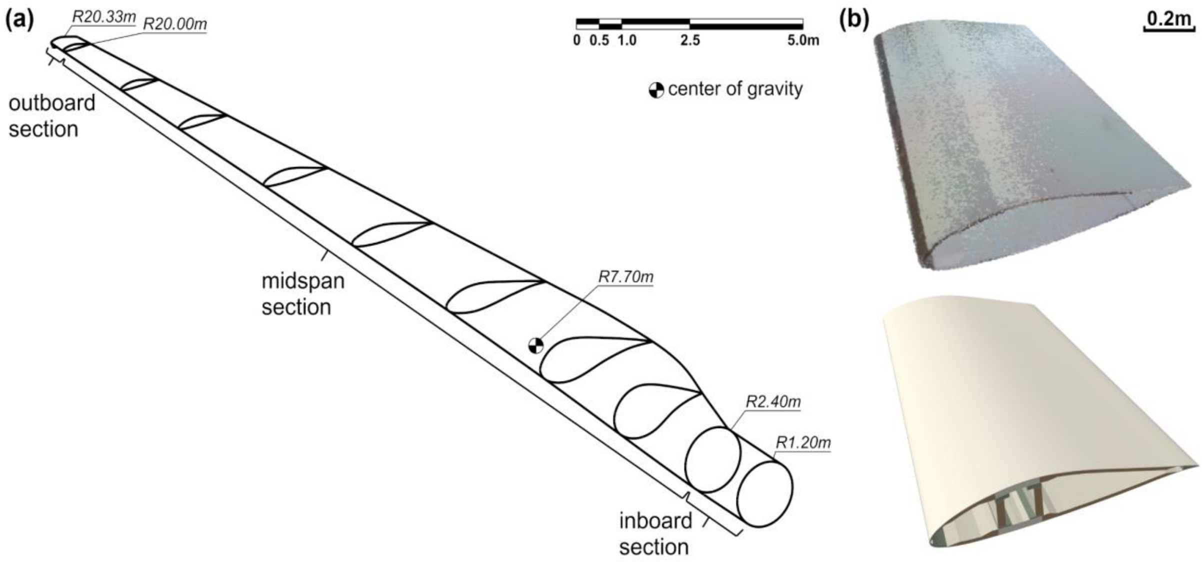

Figure 2: (a) E40 WTB geometry, (b) CAD model and scan.

According to Figure 2a, the E40 WTB consists of three different sections: the *inboard*, the *midspan*, and the *outboard section* [41]. The largest bending moment is exerted on the *inboard section*, where the WTB is connected to the turbine axis [12]. This section starts at rotor radius R = 1.2 m. It is tubular with a circular shape and a wall thickness of 55 mm [42]. The *midspan* section extends from rotor radius R = 2.4 m and ends at rotor radius R = 20 m. The section includes several airfoil profiles, and it seems to offer the best opportunity to provide structurally continuous component geometries. The *outboard section* ranges from rotor radius R = 20 m and R = 20.33 m. It has a winglet at the tip to meet aerodynamic and structural requirements. The section has a relatively flat airfoil profile because it has to resist high air speeds [12].

Following Fingersh *et al.* [5] the mass m [kg] of a WTB is a direct function of the rotor radius R [m],

$$m = 0.1452 * R^{2.9158}. \quad (1)$$

With R = 20.33 m, the mass of an E40 WTB is calculated to 947 kg. This is also in accordance with data sheets [43, 44]. Furthermore, the material composition of a WTB by weight is given by approximately: 60 % glass fiber, 23 % thermoset resin and adhesive, 9 % core material, and 8 % metal [5]. The mass of the individual material components of the E40 WTB is listed in Table 1.

Material Component	Weight [wt. %]	Mass [kg]
Glass fiber	60	568
Thermoset resin and adhesive	23	218
Core material	9	85
Metal	8	76
Total	100	947

Table 1: Estimated material composition of an E40 WTB by weight percentage and mass.

The mass distribution of the material components of the E40 WTB is in line with the created CAD model. The center of gravity given in the data sheet [36] could be confirmed in the digitized model (see Figure 2a).

2.3 Segmentation of EoL WTBs

For repurposed applications that require only a partial structure (T3 and T4) of the WTB, these components have to be cut out of the structure. Therefore, heavier processing is required, with additional cost due to the fiber content of the WTB [42]. During sectioning, the orientation of the fibers in the WTB has to be considered. A high fiber content requires additional coating of the cutting equipment (e.g. diamond-like carbon coating). Health and safety precautions are necessary when processing large-scale composite structures and handling micro glass particles [28]. It can be difficult to section the WTB due to thick and tough GFRP walls [12]. Various technologies are available to cut the WTBs, including *wire saw* cutting, *circular saw* cutting or *waterjet cutting*.

The *wire saw* is a water-cooled wire made of steel with diamond teeth, which is positioned around the outer shell of the WTB. It is possible to cut all material components, including the core material and metal. The sectioning method is not limited to the dimensions of the WTBs outer shell, as the length of the wire can be varied. The cutting process is fairly environmentally friendly, since the cooling water can be recycled, and it results in smooth and well-defined cuts. However, the *wire saw* cutting process is very time consuming [28,45].

There are different sizes of *circular saws*, which range from manually operated to hydraulically driven saws with blade sizes up to 2 m diameter. Depending on the blade size, the circular saws can cut all dimensions of the WTB. Although, depending on the structure, multiple cuts may be required to section the overall WTB. The main advantage of this method is that independent cuts can be conducted in all directions. Therefore, it is possible to extract selected material components from the WTB, such as the main laminates of the spar caps. The disadvantage is that operators are exposed to possible safety hazards like abrasive dust [28].

To address the safety hazards for operators, *waterjet cutting* could be a good alternative. The dust generated is collected in the water filtration system. The abrasiveness of this method can be increased by adding high hardness sand-like grains, increasing its effectiveness. Furthermore, when compared to wire or circular saws that rely on friction between the part and the cutting tool, there is no risk of tooling degradation [12] as well as no heat-affected zones in the part, increasing the quality of the surface finish [46].

2.4 LCA of repurposed application types

For the estimation of the potential environmental impact reduction through repurpose of E40 WTBs, the screening LCA method is used. The goal is to compare the resource consumption and emissions through substitution of structural materials by discarded WTBs [37,47]. In particular, the substitution of materials with a high carbon footprint offers potentially major environmental benefits. The scope of the LCA in this study is the assessment of the process routes as well as the comparison between the repurpose and the reference application concerning the associated environmental impact. The product sustainability software LCA for Experts (GaBi) (Version 10.7.0.183, Sphera Solutions Inc., Chicago, USA) with the environmental footprint 2.0 data base are used. The LCA data refer to the reference years 2021-2022. A process analysis of the four introduced repurpose application types (T1, T2, T3, and T4) is conducted for specific examples. An associated reference application is specified for each repurpose application based on its dimensions and function. The functional unit is defined as one product for T1 and T2 (e.g. one climbing tower for T1), and as 100 products for T3 and T4 (e.g. 100 Loungers for T4). The system boundary reaches from material sourcing to the manufacturing of the applications (cradle to gate). The subsequent use phases are not considered as they are seen as equivalent.

The material of the EoL WTBs is considered using the cut-off approach. Since the processing operations during the setup of the four considered applications are mainly manual, they are assumed to be equivalent. Also the electrical power of the cutting equipment is considered to be equivalent, independently from the specific segmentation machinery used for each repurpose application (cf. 2.3). An average representative transport distance of 500 km is assumed to relocate the WTB to the repurpose application site. For this study, only the share of the E40 WTB which is used for the repurpose application is considered. Neither the environmental impact of tool wear nor the utilization of the NDT technologies is taken into account due to the expected low influence on the total emissions.

3 RESULTS AND DISCUSSION

3.1 Ecosystems of T1, T2, T3, and T4 based on specific applications

A possible application for the repurposed type T1 - *whole structure carrying moderate to high loads* - is a climbing tower. It is expected that two entire EoL E40 WTBs can be set up for this application (see Figure 4a). Thus, the climbing tower would have a total mass of 1.894 kg, consisting of 1.136 kg of glass fiber material as well as 436 kg of thermoset resin and adhesives material. The dimensions of the application are approximately 19.13 m × 3.95 m × 0.96 m. No segmentation technology is involved for the manufacturing of the climbing tower, as two entire EoL E40 WTBs are repurposed. Due to expected high loads, e.g. wind loads, the structural integrity of the WTB material must be ensured. Therefore, NDT technology is needed within the ecosystem of the WTB climbing tower manufacturing processes. The reference application is a 20 m high steel lattice tower (foundations 2x2 m, tapering design, L steel profiles), covered with texture coated boards on two sides. The wood is not produced sustainably. The manufacturing process is defined as the same process between repurpose and reference application. The foundation, the attachment part as well as the effort required for set up are assumed to be the same between the both applications.

The investigated application for T2 - *whole structure carrying low loads* - is a playground. In accordance with the climbing tower, it is assumed that two entire EoL E40 WTBs will be repurposed for manufacturing the playground (see Figure 4b). Therefore, T2 has the same total mass and dimensions as the climbing tower. It is not required to use NDT technology in this application, since it is assumed that only low loads are expected. However, cutting technologies are needed to cut the holes in the WTB structure. The reference application consists of a pine wood construction (length 15 m, height 2 m, and wood impregnated), and a 12 m long crawling tunnel made of polyethylene (PE). A wood waste of 5 % is assumed. The wood is not produced sustainably. The manufacturing process is defined as the same process between repurpose and reference application.

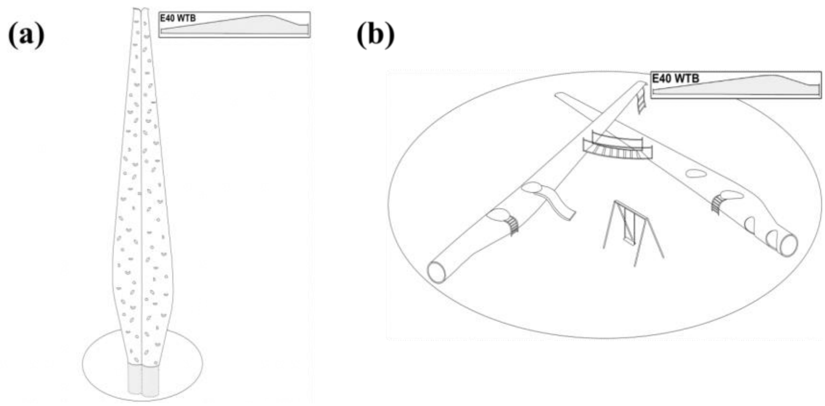

Figure 4: (a) Climbing tower (T1), (b) Playground (T2).

For T3 – *partial structure carrying moderate to high loads* – a photovoltaic (PV)-floating pontoon is under examination. The end of the midspan section of the EoL E40 WTB could be used for the pontoon (see Figure 5a). Based on the information from the designed CAD model, the repurposed WTB segment would have a total mass of 52.2 kg, consisting of 31.3 kg of glass fibers as well as 12 kg of thermoset resin and adhesive material. The dimensions are approximately 1.92 m × 1.1 m × 0.19 m. For manufacturing the pontoon, the EoL E40 WTB initially has to be cut in two positions, e.g. by a wire saw or a circular saw. Afterwards, the state of sectioned segment must be checked by NDT to ensure that no damage is present, and the composite structure can resist expected loads. After cutting and NDT, the remaining openings are sealed with a 2 mm thick GFRP raw material laminate. A PE pontoon is chosen as the reference application, which is manufactured by blow moulding. It is assumed, that the attachment parts (coupling parts) are the same between repurpose and reference application.

A lounger was chosen for T4 – *partial structure carrying low loads*. The highest part of the EoL E40 WTB could be suitable for a relaxing lounger (see Figure 5b). In addition, two areas of the midspan section of the E40 WTB serve as feet. According to the designed CAD model, the repurposed lounger has a total mass of 40.2 kg including 24 kg glass fibers as well as 9.25 kg thermoset resin and adhesive material. The dimensions of the lounger are around 1 m × 1.98 m × 0.63 m. To manufacture the repurposed lounger, several cuts must be performed on the EoL E40 WTB. A circular saw is considered for the construction of the feet, because independent cuts must be made in different directions. Since low loads are expected for the lounger, no NDT is planned during the manufacturing process. A lounger made of a steel frame with PE rattan covering (weight around 20 kg) is chosen as reference application. The paint finish is not taken into account.

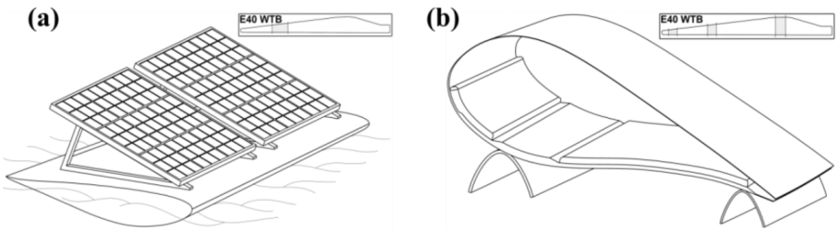

Figure 5: (a) PV-floating pontoon (T3), (b) Lounger (T4).

It can be stated that, depending on the repurposed type, different technologies are required to manufacture the application. Accordingly, the ecosystems are different in terms of the technological dimension.

3.2 LCA of T1, T2, T3, and T4 based on specific applications

Figure 6 shows the resulting data in the six environmental impact categories: Global warming potential (GWP), acidification (AP), ozone depletion (ODP), land use, eutrophication (EP), and photochemical ozone formation (POCP). The categories are not weighted. For a better comparability and presentation of the results, the applications PV-floating pontoon (T3) and lounger (T4) are calculated for an amount of 100 units.

The LCA study indicates that using repurposed E40 WTBs can reduce the environmental impact of the applications considered in this study. Since the proposed applications require only few additional processes for repurposing, the largest environmental impact arises from the transport process. It can be seen that in particular the substitution of energy intensive material such as steel seems to be suitable to reduce overall emissions. In general, applications should be selected for repurposing that require only low processing effort. However, this analysis examines a relatively light E40 WTB with a component mass of about 1000 kg. Therefore, the results are not directly transferable to larger WTBs, as the emissions of the transport processes are highly mass-dependent. Since the analyses of the reference applications are estimations based on literature and web research, they should not be seen as representative for all possible designs. In the following, the results of the four different repurpose applications are discussed briefly.

T1 - Climbing tower: It is proposed to repurpose two entire E40 WTBs as a single climbing tower after disassembly. For this reason, emissions are mainly driven by the transport process. This results in high reduction potentials, especially for GWP and land use with saving potentials of 94 % and 99 %. The overall savings potential ranges between 68 % and 99 % compared to the reference application.

T2 – Playground: It is proposed to repurpose the whole structure of two E40 WTBs as a playground after dismantling. Compared to the climbing tower, additional cutting operations are required. Emissions regarding land use and ODP could be largely avoided through the repurpose of WTB. The high potential is due to the non-sustainable production of the wood, the lower durability despite repeated surface treatment, as well as using petroleum-based plastic for the crawl tunnel. The savings potential ranges between 51 % and almost 100 % compared to the reference application.

T3 – PV-floating pontoon: Two segmentation cuts are needed to realize the repurpose of an E40 WTB as a PV-floating pontoon, as well as additional material to close the resulting openings. In comparison to the reference application, the highest savings potential is reached for GWP and ODP with around 69 % and 62 %. Among the four repurpose types examined, T3 exhibited the lowest savings potential for EP of approximately 22 %, compared to the reference application. This is mainly due to the additionally required virgin material.

T4 – Lounger: An important contributor to the environmental impacts of the repurposed lounger are the cutting processes, because several cuts (in total the application has the largest cutting length) are needed during manufacturing. Nevertheless, T4 shows lower impacts across all impact categories compared to the reference case, with the highest savings potential achieved in the category GWP with 94 %. In total, the reductions of the environmental impact range between 59 % and 94 %.

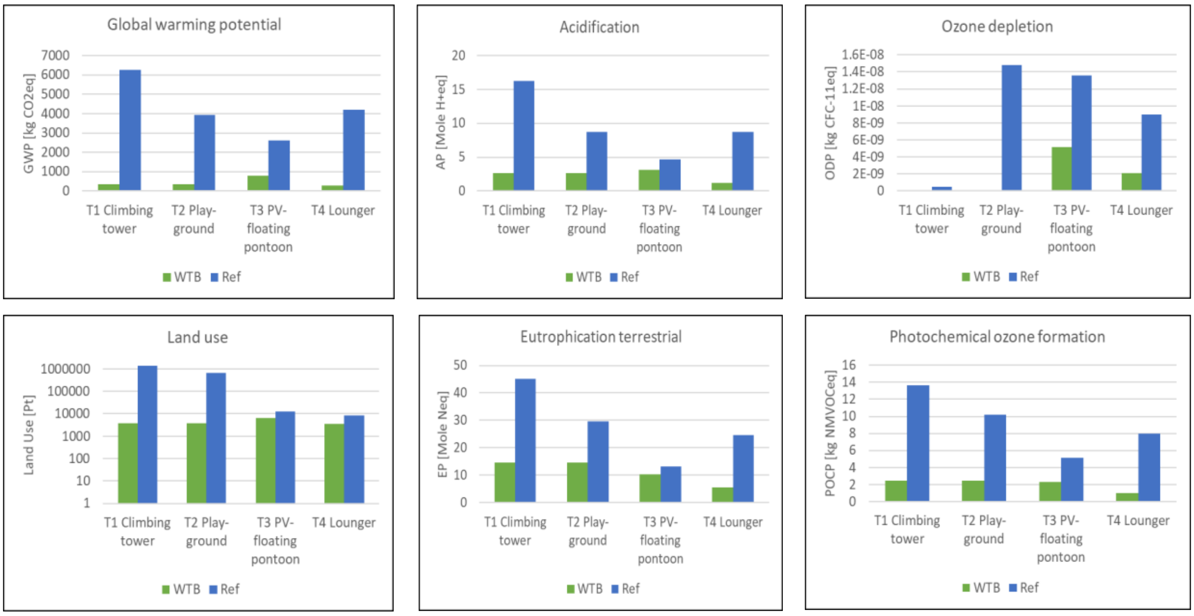

Figure 6: Results of the LCA in the considered impact categories. Repurposed WTB applications are colored green and the reference applications blue. For a better visualization, the results for T3 (PV-floating pontoon) and T4 (lounger) are calculated for 100 units.

4 CONCLUSIONS

The presented repurposed applications of an E40 WTB support a new perspective for repurposing large-scale composites. This investigation demonstrates, that according to the type of repurposed application, different technologies (regarding segmentation and testing) are required for the manufacturing process. Thus, the ecosystems differ in the technological dimension.

Using EoL E40 WTBs as structural material potentially reduces the environmental impact for the examined applications. This is due to the displacement of impacts from energy intensive virgin raw-material production avoided by the repurposed materials. In addition to the reduction of environmental impact, the manufacturing of a climbing tower (T1), a playground (T2), a PV-floating pontoon (T3), and a lounger (T4) keeps composite material after the first life cycle out of unsustainable routes, such as landfill or incineration. The LCA results show, that repurposed applications with low process expense should be preferred. If additional virgin raw-material is required to manufacture the repurposed application, the savings potential is reduced even for small quantities.

For the E40 WTB repurpose, the transport to the locations for application has a major impact. However, the substitution of energy intensive raw material offers a clearly greater advantage. The influence of transportation will increase with larger and thus heavier WTBs, and needs to be further investigated.

The repurposing strategy may become a promising alternative if recycling is still not economical, and incineration is not possible due to CE efforts. However, the challenge to upscale a repurposed application to mass production is still unsolved. Consequently, further research is needed to transfer repurposed ecosystems to the relevant industries.

ACKNOWLEDGEMENTS

Funded by the European Union, within the HORIZON-CL4-2021-RESILIENCE-01 project "European recycling and circularity in large composite components (EuReComp)", call "A Digitized, Resource-Efficient and Resilient Industry 2021", HORIZON Research and Innovation Actions, Contract Number 101058089. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or HADEA. Neither the European Union nor HADEA can be held responsible for them.

We acknowledge support of the Faculty of Civil Engineering of Leipzig University of Applied Sciences for the provision of the LiDAR scanning devices. We thank Anika Schreyer (Leipzig University of Applied Sciences) for the conceptual design of Fig. 4 – Fig. 5 and Pamela Voigt (Leipzig University of Applied Sciences) for administrative support in carrying out the reverse engineering process. Also, special thanks go to Levin Schilling (TU Dresden) for providing support performing the LCA. Last, for proof reading we are thanking Chiara Enderle (Leipzig University).

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