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RESEARCH ARTICLE

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Evaluating the environmental impacts of recycling wind turbines

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Abstract

Wind power is one of the fastest growing renewable energy sources. The wind turbines have an expected design lifetime in the range of 20 to 25 years after which decommissioning is expected. The trend in the wind turbine industry is that the turbines increase in size—especially when considering offshore wind turbines in the 7 to 8 MW size range. Life cycle assessments show that the materials used for manufacturing the turbines accounts for 70 to 80% of the environmental impact, so ensuring optimal recycling at the end-of-service-life is of economic and environmental interest and in line with the principles of transitioning towards a circular economy. The decommissioning and recycling process is analysed in this paper, with special considerations given to the environmental aspects of a theoretical 100% recyclability scenario. This includes cradle-to-gate life-cycle inventory analysis of the materials, embedded energy, and CO_2-equivalent emissions. The findings show that established recycling methods are present for most of the materials and that recycling of a 60 MW wind park at end-of-service-life provides environmental benefits as well as lowering the natural resource use and securing resources for use in the future. The saved energy is estimated to approximately 81 TJ. The reduction in emissions related to the recycling of wind turbine material totals approximately 7351 ton CO_2.

KEYWORDS

circular economy, end-of-service-life, life cycle assessment (LCA), recycling, waste management, wind turbines

1 | INTRODUCTION

Becoming a sustainable manufacturer extends to not only considering the manufacturing process and product but also the upstream and downstream activities across multiple product life cycles.[1] Several studies show that companies aiming for environmentally friendly products and operations will have a competitive advantage.[2,3] Companies missing this will more often be subject to higher waste costs and non-compliance with legislation.[4] The concept of sustainable manufacturing is broad in scope, includes all three elements of the triple bottom line and considers the entire life cycle of the product, from raw material extraction to end-of-service-life.[5] The research in this field often focuses on product development and how to keep the products or materials within a closed loop in the technosphere at the end-of-service life cycle stage.[6]

Wind turbines are considered an environmentally sound source of energy,[7] and life cycle assessments (LCAs) show that wind turbines pay back the energy used during their life cycle 23 to 57 times.[8] However, the end-of-service-life stage has been identified as a blind spot in LCAs of wind turbines, and little research has been conducted on this topic in relation to technological, economic, and environmental issues.[9] Limited practical experience exists on the decommissioning and recycling of wind turbines, especially related to offshore wind. It will likely be 20 years before substantial practical experience is gained in this specific field.[10] D'Souza, Gbegbaje-Das, and Shonfield call for an improved understanding of applicable recycling technologies and an improved recyclability of specific components to better assess the end-of-service-life stage of a wind turbine.[11]

In order to reduce the environmental impact of a product in a life cycle perspective, the aim is to extend the lifetime as long as possible, eg, through service, repair, reuse, and remanufacture.[12] Recycling is thus not a goal in itself but rather an essential tool in the toolbox of improved natural resource management. Closing the material loop is essential in the circular economy.[13] Worrell and Reuter argue that applying a product centric approach rather than a material centric approach is favourable in terms of environmental impact minimization.[14] However, material and component recycling is the ultimate end-of-service-life scenario. However, realizing this requires a complete awareness of the components, materials, and processes involved in the decommissioning phase. In the circular economy, the Ellen MacArthur Foundation highlights the power of the inner circle. The inner circle refers to establishing a product management hierarchy. The inner circles contain (a) extended lifetime through service and maintenance, (b) reuse or redistribution of products and components, (c) refurbish/remanufacture, whereas (d) material recycling is considered the outer circle.[15,16] However, this paper will have its focus on the recycling process (outer circle) and will not evaluate the impacts of service/maintenance, reuse/redistribution, and refurbishment/remanufacture.

1.1 | Research objectives

The purpose of this paper is to evaluate the recycling potential of wind turbines and the environmental benefits (energy and CO_{2}-equivalent savings) related to 'closing the material loop'. The study is based on literature review, manufacturer documentation, and interviews with experts from a wind turbine manufacturer and waste handling companies. The paper focuses on the impacts of recycling and as earlier mentioned, service, reuse, and remanufacture concepts are not further discussed in this paper even though highly relevant to the circular economy.

The paper seeks to answer the research questions:

> *How does the decommissioning process of wind turbines work? What is the environmental impact of recycling the materials at end-of-service-life?*

The remainder of this paper is structured as follows: Section 2 presents the methodology. Section 3 provides an overview of the decommissioning requirements and process of wind turbines. Section 4 analyses the lifecycle inventory of a 60 MW wind farm, and Section 5 discusses the impacts of closing the material loop. The paper concludes in Section 6.

2 | METHODOLOGY

The decommissioning process of wind turbines will vary due to differences in size, location, and other factors. However, some general process steps have been identified through literature reviews and informal interviews with employees in the wind turbine industry.

Data regarding materials needed for manufacturing of wind turbines have been obtained through a literature review and analysis of a turbine manufacturer's bill of material. A modern turbine requires large amounts of resources and high input of energy. In other industries, bringing these materials back into the material loop provides several benefits: it (a) reduces natural resource use, (b) lowers environmental impacts, (c) increases job opportunities, (d) increases resource and energy efficiency, and (e) stimulates the market for recycled materials.[17]

For this paper, a literature review on the topic of wind turbine recycling has been conducted to gain a conceptual understanding of the problem.[18] Both academic papers as well as manufacturer documentation have been reviewed. Further, the manufacturers bill of material has been analysed to quantify the material content of the wind turbine and cross-checked it with estimations from research. In addition, a literature review has been conducted to determine the energy demand and CO_2-equivalent emissions of the various material groups (both virgin and secondary). The aim has been reviewed "as new literature as possible." However, the literature has a time span of 12 years starting from 2003 until 2015, which causes uncertainty to the accuracy of the numbers compared with today's numbers. Literature with a certain age will have some uncertainty related to it as the processes and production might potentially have changed or been optimized since, which will impact the cradle-to-gate analysis. Further, the cradle-to-gate analysis of the materials can vary from material to material that might give some inconsistencies in the assessment method. However, the impression is that the overall result is not largely affected by this.

To understand the decommissioning phase, several qualitative interviews have been conducted with experts from the field. The interviews were informal, face-to-face interviews, where open questions related to the topic were asked and the interviewee was able to direct the conversation into what was considered as important—in line with Bryman's recommendations for qualitative interviews.[19,20]

3 | DECOMMISSIONING OF WIND TURBINES

This section will introduce the general requirements for decommissioning of wind turbines and will provide an overview of the decommissioning process to support efficient recycling.

3.1 | Design life time and failures

Design life time is an expression of the time frame, where the wind turbine has calculated a small risk of failure. Empirical data show that the wind turbines often have a longer life time than the design life time as the design criterions historically has been conservative.[21] The design life of wind turbines is estimated to be 20 to 25 years. During its service life, different failures can occur. Luenga and Kolios have identified the main technological failure modes that might occur during service life that potentially can lead to the decommissioning of wind turbines.[22]

Repairs of failures and maintenance costs add up to 25% of the total levelized cost of energy. However, service/maintenance activities related to the inner circle are being made to avoid unexpected failures and decrease the cost of maintenance, eg, by integrating systems to monitor the condition of specific components and to control continuously the status of the turbine.[23] Supervisory control and data acquisition (SCADA) and remote diagnostics are part of new turbines. By understanding how fatigue is progressing for the different components within a turbine and for the specific turbines within a farm, the possibility of letting the turbines run the expected lifetime or even consider lifetime extension is higher.[24] Sensors on strategic parts can assist in providing data for calculating remaining loads and fatigue either through finite element method[25] or cycle count (during the whole lifetime of the turbine).[26] Keeping a turbine in prolonged lifetime operation equals increased revenue, but it also has higher operation and maintenance costs and a greater risk of structural failures. These failures are often costly, not to mention the corresponding safety risks. A low-risk alternative, the outer circle of the circular economy, is to decommission the turbine at the end of its design life. The downside is that this action delivers no additional financial returns aside from the salvage value.[26]

3.2 | The decommissioning process

More than 250 000 turbines are erected worldwide,[27] which means that a lot of material and energy is embedded in these products. The turbines are typically decommissioned at end-of-service-life either because of their salvage value or local legislative requirements. In the early start of the industry, there have been examples, where the turbines have been left behind. For example, some of the early Californian wind turbines remained after service life because of absence of local legislation requiring developers to cover the future tear down cost of a project.[28-30] The situation today has changed; often, an upfront bond is required by the wind park developers during the tender process. The payment terms can differ by country or project, but the end-of-service-life phase has increasingly become a part of the tendering and planning process.

Examples are following:

- The Netherlands Enterprise Agency has formulated the "Applicable Law for Offshore Energy," where regulation 6 requires the permit holder to "dismantle and remove all elements of the wind farm within 2 years at the latest after power generation operations have stopped."[30] Further, Regulation 7 requires that (a) "the permit holder will provide financial security of 120,000€ per installed MW planned before construction start," and (b) "the permit holder will increase the financial security by 2% per annum up to the time the wind farm stops operating and is due for decommissioning."[31]
- Similar rules are seen in, eg, Scotland, where section 75 specifies that the bond that must be put aside to insure sufficient funds for decommissioning.[32]
- In Denmark, the bond must be paid 12 years after the wind turbines begins to operate.[33]

The options to optimize environmental benefits from the end-of-service-life phase of a project is the focus of this paper.

The wind turbines will at some stage require decommissioning, when lifetime extension is no longer financially or technically viable. At this point, the turbine is disassembled and reduced to smaller pieces for recycling or disposal. It is estimated that almost all materials will be recycled according to Luenga and Kolios.[22]

Experience with onshore wind decommissioning is more advanced than offshore wind. The uncertainties, risks, and costs of offshore decommissioning are larger. Different attempts have been made to optimize the decommissioning process. The project ODIN-Wind sought to develop and demonstrate a management tool for decommissioning offshore wind turbines. The project sought to reduce the cost and time spent on decommissioning while minimizing the environmental impacts through component reuse and optimized waste management.[34] However, only few offshore farms have, to date, been decommissioned being: Yttre Stengrund (Sweden), Lely Wind Farm (Netherlands),[35] and Vindeby Offshore Wind Farm (Denmark).[36] However, these early offshore wind farms differ significantly from the wind farms being commissioned today in terms of, eg, turbine size, park size, foundation type, and distance to shore.

The decommissioning process for an offshore wind farm is shown in Figure 1 (excluding the risks related to changing weather conditions.) The bottom "values" indicates that there is a salvage value related to "circulating" the materials/components, whereas the materials that are not "circular" represent a cost at the end-of-service-life stage.

3.3 | Material recycling

The international standards for LCA allow for different ways of dealing with recycling. However, the inflows and outflows of recycled material should be consistent.[37] Many assessments credit the beneficial environmental impact of the lifecycle,[38] eg, as stated in relation to recycling of wind turbines.[39]

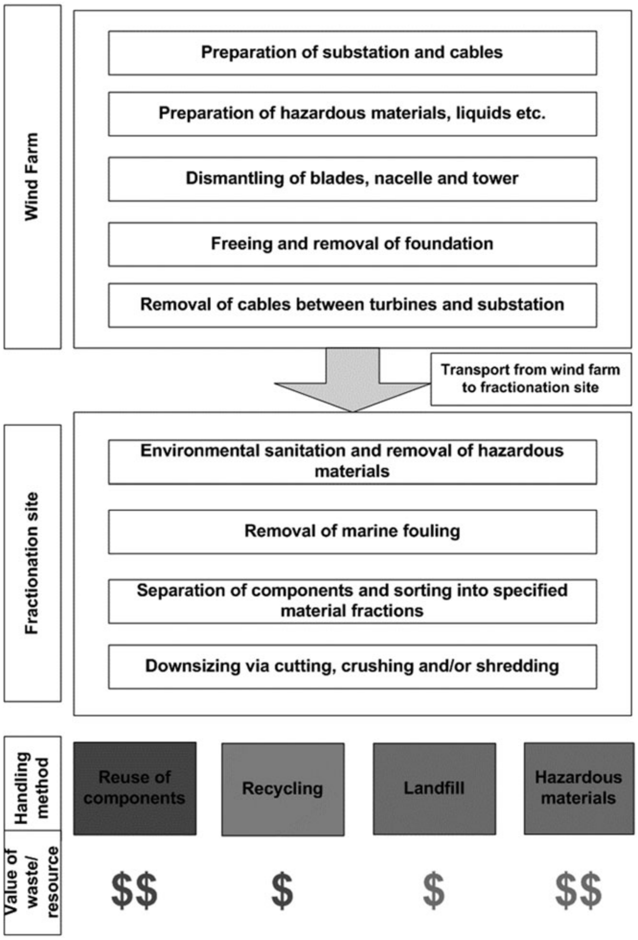


FIGURE 1 Decommissioning process for offshore wind turbines (adapted from ODIN-wind project [2014])[34]

Describing the scenario 20 years in advance is linked with some uncertainty.[38] However, some of the turbine components are relatively easy to recycle, with an established recycling process already established,[40] eg, tower, nacelle, and hub that are made of ferrous and non-ferrous metals. However, the economics of recycled materials are uncertain and changed over time.[38] Crawford emphasizes the difference between potential recyclability and actual recyclability, and some studies show the benefits of closed loop recycling,[41] whereas other argues that an ecosystem of businesses handling open-looped recycling is favourable.[42] In the transition to a circular economy, ensuring high quality recycling processes, to avoid downcycling where the materials end as by-products with reduced qualities, eg, filling material in concrete or asphalt should be the aim. However, the environmentally preferable solution is not necessarily the preferable economic solution.[10] An example is in a situation where the costs related to material separation exceed the virgin material costs, the recycler might favour mixing the materials, and thereby downgrading the quality. Ideally, turbine manufacturers, wind turbine owners, and waste management companies should collaborate to improve recycling efforts to ensure higher recycling rates and material qualities in the future.[43]

Studies assess the recyclability rate of wind turbines differently, which indicates a lack of consensus on the absolute numbers. However, most studies range between 80 and 90% recyclability.[44,45] Ortegon, Neis, and Sutherland estimate, based on three US cases, the salvage value of the turbines in the range of $39 677 to $45 463 MW^{-1} (which are heavily linked to the scrap material market). Some of the components are easy to disassembly and recycle.[9] For instance, the tower, hydraulics, generator, and gears are considered less problematic as the recycling industry is accustomed to handling these components and materials, while, eg, permanent NdFeb magnets, nacelle cover, and rotor blades are more challenging to recycle due to their structural size and composite structure.[46,47]

4 | ANALYSIS OF A TURBINES LIFE CYCLE INVENTORY

In this section, the material inventory of a 60 MW wind farm is compiled and the methods and associated environmental benefits of recycling the turbines are analysed. The complexity and uncertainty of waste handling methods for each turbine component differ. Often, the composite materials for making the blades is highlighted as the most difficult material to recycle,[48] and therefore, it will be given special attention in the following section.

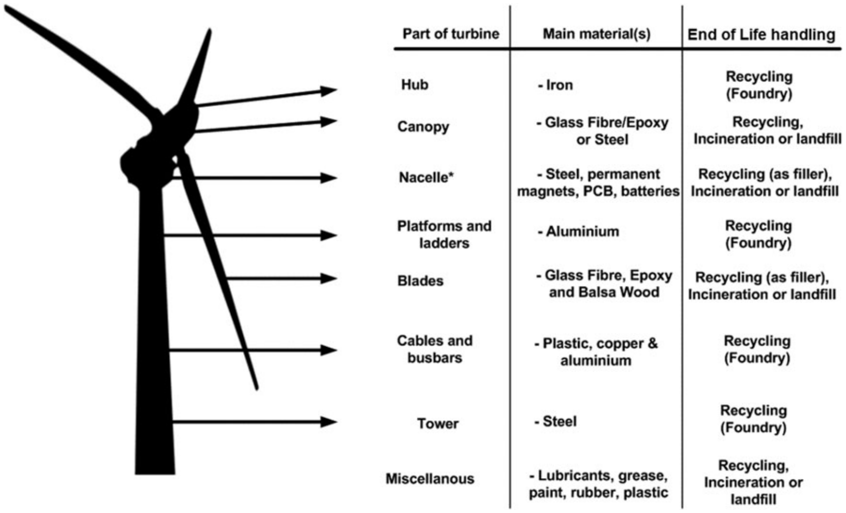
Turbine designs differ regarding wind class, manufacturer, technology choice, and other product parameters. Despite these differences, materials and most components in the wind turbine are like each other. The Figure 2 provides an overview of typical components within a direct drive turbine within the 3 MW class, the materials that they are composed of and their potential recycling route that will be explained in the following sections on material type.

Table 1 provides an overview of the aggregated material weights of the different materials from 60 MW capacity of wind turbines. When possible, materials are analyzed separately, but for lamps, batteries, NdFeB permanent magnets, and electronics, the objects are analyzed further in these sections (because of their integrated material structure).

4.1 | Cradle-to-gate inventory analysis

4.1.1 | Ferrous metals

As shown in Figure 2 and Table 1, ferrous metals are the most common material in wind turbines. There are four major modes for producing steel being blast furnace/basic oxygen furnace, electric arc furnace, direct reduction, and smelting reduction.[49] The energy required to produce 1 kg of steel varies between 14 MJ for the primary production/basic oxygen furnace route, 19.2 MJ for the primary production direct reduction/electric arc furnace route, and 11.7 MJ for the recycled production electric arc furnace route,[49] as shown in Table 2. The energy savings vary depending on the production and recycling methods. Steel can be recycled numerous times[17] and is the most common recycled metal with a well-functioning market for secondary market existing. However, steel is produced in a large number of different alloy compositions with different alloying ele-



Part of turbine	Main material(s)	End of Life handling
Hub	- Iron	Recycling (Foundry)
Canopy	- Glass Fibre/Epoxy or Steel	Recycling, Incineration or landfill
Nacelle*	- Steel, permanent magnets, PCB, batteries	Recycling (as filler), Incineration or landfill
Platforms and ladders	- Aluminium	Recycling (Foundry)
Blades	- Glass Fibre, Epoxy and Balsa Wood	Recycling (as filler), Incineration or landfill
Cables and busbars	- Plastic, copper & aluminium	Recycling (Foundry)
Tower	- Steel	Recycling (Foundry)
Miscellanous	- Lubricants, grease, paint, rubber, plastic	Recycling, Incineration or landfill

FIGURE 2 Illustration of turbine parts, main materials, and potential disposal methods (own illustration)

TABLE 1 Total potential recyclable materials from 60 MW wind turbines

Materials used in the Wind Turbine	Approximate Material (kg)
1. Ferrous metal	6 560 000
2. Aluminium	104 000
3. Composite materials	660 000
4. Lubricating oil	30 000
5. Electronics	124 000
6. Batteries	36 000
7. Fluorescent lamps	3800
8. NdFeB magnet	40 000
9. Copper	292 000
10. Balsa wood	29 000
11. Polyethylene	32 000
12. Polypropylene	6600
13. Polyvinylchloride	6000
14. Miscellaneous (less than 1% of total weight)	
Total	**7 923 400**

TABLE 2 Potential recycling routes for wind turbine blades. Adapted from Cherrington et al[7]

Process	Description
Mechanical	Through shredding, crushing, milling, and similar downsizing processes, the composite material is broken down into smaller pieces. Separation of the resulting material into resin and fibrous products is possible afterwards. Between 2003 and 2005, the ReACT project (funded by the European Commission) tested mechanical recycling of composite material. The project found that it could shred the blades down to 15-25 mm fibres, but these were difficult to reuse due to their small size and due to the resin residue that was often attached to the fibres. Also, the project found that the grinding process used a lot of energy because of the hardness of the glass, and the value of the material (eg, as a filler) was quite low. Another downside was that the process gave impure end materials.
Pyrolysis	Composites are heated to high temperatures (450-700°C) in absence of oxygen. The resin is converted into a gas or vapour. The fibres remain inert and can be recovered. The Danish company ReFiber was known for this method, which included a process where a blade was cut into container pieces on site and then shredded to hand-sized pieces. They were continually fed into an oxygen-free rotating oven with a temperature of 500°C. The by-product resin gas would be used for electricity production or heating of the ovens, while in a second rotating oven, the glass fibres would be "cleaned" in the presence of atmospheric air. Potential metals would be removed for recycling by use of magnets and dust would be removed to clean the glass fibres. In the case of ReFiber, the glass fibres were mixed with a small amount of polypropylene and passed through an oven to make insulation slab.
Oxidation in fluidized bed	Combustion of the composite material in a hot and oxygen-rich air flow with temperatures between 450 and 550°C to separate the resin from the fibres.
Chemical	In a chemical solution, the resin is decomposed into oils, which free the fibres. A recycling possibility is chemical recovering through solvolysis. However, the use of aggressive and hazardous chemicals as well as the high cost is often highlighted as a potential downside of this.

ments such as Cr, Mn, Nb, B, etc, which increase the complexity of the steel and make recycling more difficult. Accumulation of tramp elements can be a future problem if the main source for steel production is scrapped steel instead of ore.[14]

4.1.2 | Aluminium

Part of the turbine is aluminium mainly in cables, ladders, or material for platforms. Recycling of aluminium is considered an important part of the aluminium industry because of its significant reduced environmental impact compared with primary production. Aluminium can be recycled repeatedly without significant loss of properties. However, impurities will most likely be picked up and dissolved during its cycles. The average recycling rate of aluminium is 27%.[50] Virgin aluminium is one of the most energy intensive materials, and the benefits of aluminium recycling are well-documented.[17] BIR estimates the energy requirement of primary aluminium production is 47 MJ kg^{-1} including mining, production via Bayer process, Hall-Herout process, electrolysis, and casting. The energy requirement for recycled aluminium production is estimated to be 2.4 MJ kg^{-1}, which is a saving of almost 95%.[49]

4.1.3 | Composites

Composite material is the main material in the blades and often the nacelle. The wind turbine blades typically consist of glass fibre as a reinforcement fibre, epoxy as a plastic polymer, balsa wood as a core material, and a polyurethane coating and lightning conductors with glass fibres, epoxy, and balsa wood being the main materials.[51] The use of composite materials is increasing. The thermoset matrix-based composites are used in other industries as well such as aerospace, automotive, or even for building playgrounds.[52]

Recycling of composite material is not as straight forward as steel because of the complicated composite construction.[51] The challenges of today do only include blades of 15 to 20 m of length,[53] whereas the future will include the blades with lengths of 75 to 80 m.[7] Perry, Bernard, Laroche, and Pompidou suggest that three parameters are to consider: (a) Having the recycling technology available, (b) finding a dismantling solution and an access to a market for the recyclate, and (c) material identification and selection for recycling.[52]

In regard to available technologies, three main routes have been identified: landfill, incineration, or recycling to which recycling has a number of possible routes, eg, mechanical, pyrolysis, or chemical recycling. Landfill is highlighted as the least preferred option according to the waste hierarchy, and landfilling of blades in Germany has been banned. The most common route is incineration. A downside of this is that up to 60% is left behind as ash after incineration, which will be either landfilled or used in building materials. This might be affected by local factors such as legislation prohibiting the use of waste as filler material. Recycling is the alternative option. Several research projects have looked or are currently looking into recycling of wind turbine blades, eg, ReACT, GENVIND as well as the company ReFiber, which have developed a process for recycling blades. Today, a few established methods for recycling the blades are available,[51] and an overview of the recycling routes is provided in Table 2.

Common to all of the processes is lack of a business case. The cost of recycling operations and the lack of a market for the recirculated material have been identified as the two main barriers towards actual recycling.[7]

The energy required to produce 1 kg of composite material is estimated to 111.88 MJ kg^{-1} including fibre production, fabric production, resin production, and the pultrusion process as well as additives in the material. The estimated recycled composite cannot directly be used for same high quality purposes, but estimations indicate that the filler material saves 19 MJ/kg of the materials that it substitutes.[54]

4.1.4 | Lubricating oil

Lubricating oil can, when properly drained, be of value. Oil can be re-refined into a base stock for lubricating oil, in a process similar to refining crude oil. Oil can be recycled indefinitely because the lubricant does not wear out. Recycled oil is cleaned of contaminants such as dirt, water, used additives, and fuel. The result is a refined oil of as high quality as a virgin oil product.[55] The primary energy needed for oil production is estimated 10 MJ kg, whereas the re-refined oil requires 3.4 MJ/kg of energy.[17]

4.1.5 | Electronics

Electrical and electronic equipment (EEE) are in the end-of-service-life stage often complex scraps that are difficult to recycle due to their complex material composition. Waste of electrical and electronic equipment (WEEE) is commercially integrated in adapted conventional smelter-refinery processes that often focus on extracting copper concentrates and recovery of some precious metals as a by-product.[56] All WEEE should be recycled as many of the materials that are of high value and contain a certain amount of embodied energy.[17] As wind turbines become more sophisticated, increasingly and more complex EEE are added, so proper reuse or recycling should be ensured. Determining the energy demand, recycling rates, and carbon emissions of the electronics will not be accounted for in this study because of the varying degree of composition. However, often, valuable materials are present within the EEE in the wind turbine.

4.1.6 | Batteries

Batteries are present in various parts of the turbine, eg, the SCADA system. Sullivan and Gaines researched the cradle-to-gate life cycle energy requirements of various types of batteries.[57] The materials contained in the battery differ as well as the production steps. Rydh and Sandén researched the energy requirements for recycling of batteries.[58] The CO_2 emissions generated from battery production are quite high, and recycling of these significantly reduces the emissions.[17]

4.1.7 | Lamps

Recycling of complex, multi-material products such as lamps requires a balanced network of different types of processes in order to recover most of the material and capture potentially harmful materials such as mercury. Recovering the phosphors from fluorescent light can be done relatively easy from the inside of the tubing, where the powder can be separated using hydrometallurgical processing methods. Potential mercury content can be kept within a closed loop.[50] According to Osram, the energy needed to produce one fluorescent lamp is 14.7 MJ, and the energy needed to produce a LED lamp is 35.64 MJ kg.[59] However, data for recycled lamps are not obtainable, and these have been left out of the assessment.

4.1.8 | NdFeB rare earth permanent magnets

The main components in NdFeB rare earth permanent magnets are iron, boron, neodymium, and dysprosium. Neodymium and dysprosium are part of the rare earth elements, which despite their name, are not rare. Recycling of rare earth elements has historically been low (less than 1%).[60] However, reuse and recycling of NdFeB rare earth permanent magnets for wind turbines are more straightforward as they are relatively large, accessible, and demountable. In regard to recycling, several options exist. The magnets are processed into powder/alloy by using downsizing in hydrogen atmosphere,[61] through dissolution of the NdFeB rare earth permanent magnet followed by a purification process,[62] or by melting the magnet into a master alloy.[62] Sprecher, Xiao, Walton et al estimate that the energy use for primary production of NdFeB rare earth permanent magnets is 330 MJ kg and the energy use for recycled magnets is 191.4 MJ kg.[63] Possible recycling methods for end-of-service-life NdFeB rare earth permanent magnets are under development to improve the economic feasibility and lower the environmental impact.[56]

4.1.9 | Copper

Copper is a widely used metal in many applications because of its properties. Copper can be used in pure form or be alloyed with, eg, Zinc or Nickel, which forms brasses and bronzes.[64] In general, copper is produced by pyrometallurgical and hydrometallurgical processes. The pyrometallurgical process starts with ore concentrate, while the hydrometallurgical process starts with soluble copper ions in a copper solution.[49] Energy savings related to the recycling of copper vary depending on the different production methods, but ranges, according to BIR, between 10.6 MJ kg^{-1} (pyrometallurgical) and 19.2 MJ kg^{-1} (hydrometallurgical) as production of recycled material only require 6.3 MJ/kg.[49] In principle, copper can be recycled endlessly without loss of quality. However, some elements integrated in the products along with copper can cause problems, eg, aluminium.[64]

4.1.10 | Balsa wood

Wood is produced through a natural biological process unlike steel and concrete that are produced through technological processes in factories. Dry weight wood has a composition of 50% carbon, 44% oxygen, 6% hydrogen, and traces of several minerals. Relatively, little energy is needed for the manufacturing and processing of wood compared with other materials. End-of-service-life is the single most variable for the energy and carbon profile of wood products, when considering the life cycle. Wood products are well-suited for material cascading to improve the resource efficiency and can be reused or recycled before ultimately recovering the energy or putting into landfill. To close the material loop, nutrients from the ashes can be returned to the forests to ensure closed nutrient cycles.[65] The cradle-to-gate energy needed to produce wood varies depending on the regions. Harvesting, manufacturing, and transporting the logs are common steps. Puetmann and Wilson estimate the energy required for lumber is 8.97 MJ/kg and plywood is 7.57 MJ kg^{-1} and balsa are within this range.[66] Recycled wood will save approximately 6.4 MJ/kg.[17] No data on CO_2-eq have been found for this study.

4.1.11 | Plastics (polyethylene [PE], polypropylene [PP], and polyvinylchloride [PVC])

Plastics are synthetic organic polymers, mainly made from petrochemical feedstocks. Plastics is known to have properties that (a) make them easy to shape, (b) resist them from corroding, and (c) have specific characteristics that can be promoted based on layer structure or additives. However, additives can later on be a barrier to recycling. PE, PP, and PVC are all part of the thermoplastics that do not undergo chemical changes when heated, so they can be moulded again. In a recycling process, plastics are typically mechanically recycled, which includes four steps: (a) sorting, (b) shredding, (c) washing and drying, and (d), melting and reprocessing for pellets or final product. The essence is to know the composition of the plastic material and secure clean waste streams.[67] According to Hopewell, Dvorak, and Kosior, the energy requirements for PE is 76.7 MJ kg^{-1}, PP is 73.4 MJ kg^{-1}, and PVC is 56.7 MJ kg^{-1}. Recycled material varies between 8 and 55 MJ kg^{-1} depending on the recycling process (55 MJ kg^{-1} is chosen as reference point in this analyse for PE and PP and 40 MJ kg^{-1} for PVC).[68]

Table 3 provides a summary of the life cycle inventory analysis of Section 4.1.1 to Section 4.1.11.

5 | IMPACTS OF "CLOSING THE MATERIAL LOOP"

The evaluation shows that closing the material loop has a positive impact on the use of natural resources, emissions, and energy use. As shown in Table 3, the energy requirements for secondary materials are (not surprisingly) in general lower than for virgin materials. However, the analysis also showed that some materials or structures, such as the blade, will face a loss in quality after recycling. Table 3 shows that ensuring recycling of the materials from a 60-MW wind farm the energy savings is equal to approximately 81TJ that is equivalent to the energy consumption of approximately 14 400 persons in Denmark in a year (1568 kW h^{-1} per person). Further, Table 3 shows that approximately 7351 ton of CO_2 emissions can be saved, which equals to approximately 52.5 million km of car driving (average emission of 0.17 kg CO_2 km^{-1}). The analysis assumes a recycling rate of 100% of the identified materials that can be questioned; eg, balsa wood is intertwined in fibres and epoxy, so this is the theoretical maximum. However, models to reflect real-life scenarios can easily be made from this transparent overview.

Recycling of wind turbines makes good sense from an environmental point of view. However, to maximize the benefits of the recycling process, several conditions can be analysed further and improved. This analysis evaluates the potential of materials recycling, but some components in the wind turbine like the electrical and electronic components have a complex and unknown material composition that can hinder the possibility of recycling efficiently and economically. In these structures, valuable materials like, eg, gold, platinum, and alike might occur and will potentially be lost in the recycling process. Documentation and information of the material composition of the different components like, eg, carried out in other industries ranging from fully voluntary (aviation industry) to semi-regulated (shipping industry) to fully regulated (automotive industry), which can be relevant to analyse in relation to this case.[69]

To achieve recycling figures close to this optimistic scenario will depend on the technical and logistic competences near the wind farm. The legal bonds secure that the funding needed for decommissioning and recycling of the components, but it does not ensure that the competences needed for handling the components in an efficient way is present. Logistics and access to technical recycling solutions will play an important role

TABLE 3 Theoretical energy and CO_2 savings from 100% recycling of wind turbines

Materials used in the Wind Turbine	Amount of Material (kg)	Energy Saved (MJ kg^{-1})	Total Energy Savings (GJ)	CO_2 Saved (kg)	Total $CO_{2\ \mathrm{Savings}}$ (ton)
1. Ferrous metal (steel and iron)	6 560 000	7.5	**49 200**	0.84	**5510**
2. Aluminum	104 000	44.6	**4638**	3.54	**368**
3. Composite material	660 000	19	**12 540**	N/A	**N/A**
4. Lubricating oil	30 000	6.6	**198**	N/A	**N/A**
5. Electronics	124 000	N/A	**N/A**	N/A	**N/A**
6. Batteries	36 000	140	**5040**	13.62	**490**
7. Fluorescent lamps	3800	N/A	**N/A**	N/A	**N/A**
8. NdFeB magnet	40 000	138.6	**5544**	17	**680**
9. Copper	292 000	10.6	**3095**	0.88	**257**
10. Balsa wood	29 000	6.53	**189**	0.77	**22**
11. Polyethylene	32 000	21.7	**694**	0.5	**16**
12. Polypropylene	6600	18.4	**121**	0.6	**4**
13. Polyvinylchloride	6000	16.7	**100**	0.5	**3**
Total			**81 361**		**7351**

in ensuring high-recycling rates as these will be closely connected to the economics of this process. For decommissioning, a lot of the infrastructure and equipment for commissioning the wind farms can be reused, but developing the recycling management practices and competencies will play a role in the viability of ensuring proper end-of-life management.

Another relevant point is the reuse of components. The wind turbine is designed to a lifetime of 20 to 25 years, but some components might have been exchanged during the lifetime or not been utilized to its full capacity. Smart monitoring could support the potential for reusing these as spare parts for similar turbines. Ultimately, documentation, monitoring, and appropriate design principles can help increase the recycling rates to avoid components being sent to a shredder, where the quality, value, and environmental benefit are reduced. Further research and practical examples on the economics of recycling of turbines might have the potential to improve the efficiency of the recycling process and thereby the business case.

A large and crucial topic not addressed in this study is the economic impact of recycling of turbines. As shown, it makes sense to optimize the end-of-life phase from an environmental point of view, so how to combine that with economic sustainable practices would be an interesting study to complement this.

6 | CONCLUSION

The purpose of this study was to analyse the decommissioning process of a wind farm and evaluate the environmental impacts of recycling the wind turbines. The outcome indicates that the decommissioning phase can be a complex process with some risks and uncertainties included, where thorough planning is crucial for an optimised outcome. Legislation sets requirements for the decommissioning phase. The salvage value is fluctuating due to the scrap value of the materials, but earlier projects have indicated the salvage value per MW. However, an optimization potential that is related to documentation of the contained materials prior to decommissioning as well as thorough established processes for decommissioning can help the business case as well as the environmental benefits of recycling the wind turbines.

Recycling of wind turbines at end-of-service-life provides significant environmental benefits as well as lowering the natural resource use and securing resources for future use. The energy savings of approximately 81 TJ from recycling 60 MW of wind turbines is equal to annual electricity use of approximately 14 400 Danish persons. The reduction in emissions related to the recycling of wind turbine material of approximately 7351 ton CO_2 that is equivalent to approximately 52.5 million km of car driving. The comparisons show how much benefit can be gained from recycling wind turbines whilst preserving resources for future generations. Further, 60 MW capacity only constitute approximately one thousandth of the yearly installed wind turbine capacity worldwide.

This study has focused on evaluating the potential benefits of material recycling of wind turbines based on data from literature, experts, and manufacturer documentation. Practical experiences—and thereby data—on decommissioning and recycling wind turbines will improve the accuracy and the estimation of the actual recycling benefits and impacts. To be able to fully recycle wind turbines, an exchange of information between manufacturers and end-of-service-life handlers may be beneficial (similar to what has been done in the automotive industry) to secure "closed material streams" that are easy recyclable. This can help increase the recycling rate and thereby give benefits to both manufacturers, wind turbine owners, and end-of-service-life handlers. Further, expanding the knowledge-based management practices and competencies within this field is needed to achieve the higher recycling rates. To support this, the effects on economic impacts of the end-of-life stage would constitute a good complement to this study.

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REFERENCES

1. Jayal A, Badurdeen F, Dillon O Jr, Jawahir I. Sustainable manufacturing: modeling and optimization challenges at the product, process and system levels. *CIRP J Manufact Sci Technol*. 2010;2(3):144-152.
2. Yang C, Lin S, Chan Y, Sheu C. Mediated effect of environmental management of manufacturing competitiveness: an empirical study of manufacturing firms. *Int J Prod Econ*. 2010;123(1):210-220.
3. Menzel V, Smagin J, David F. Can companies profit from greener manufacturing? *Meas Bus Excell*. 2010;2:22-31.
4. Ball P, Evans S, Levers A, Ellison D. Zero carbon manufacturing facility—towards integrating material, energy and waste process flows. *J Eng Manuf*. 2008;223(9):1085-1096.
5. Allwood J, "What is sustainable manufacturing?," Sustainable Manufacturing Seminar Series, 16th February 2005. Institute for Manufacturing, Cambridge, UK
6. Smith L, Ball P. Steps towards sustainable manufacturing through modelling material, energy and waste flows. *Int J Prod Econ*. 2012;140(1):227-238.
7. Cherrington R, Goodship V, Meredith J, et al. Producer responsibility: defining the incentive for recycling composite wind turbine blades in Europe. *Energy Policy*. 2012;47:13-21.
8. Siemens Wind Power. *Environmental Product Declaration*. Siemens AG; 2014.
9. Ortegon K, Nies LF, Sutherland JW. Preparing for end of service life of wind turbines. *J Clean Prod*. 2012;39:191-199.

10. Borup M, Dannemand Andersen P. Recycling and removal of offshore wind turbines—an interactive method for reduction of negative environmental effects. Risoe National Laboratory, Risø, 2014.
11. D'Souza N, Gbegbaje-Das E, Shonfield DP. *Life Cycle Assessment of Electricity Production from a Vestas V112 Turbine Wind Plant*. Copenhagen: PE North West Europe ApS; 2011.
12. Prendeville S, Jensen JP, Bocken N, Peck D. Creating sustainable value through remanufacturing: three industry cases. *J Clean Prod*. Under Review
13. Ellen MacArthur Foundation. *Towards a Circular Economy, Vol 2: Opportunities for the Consumer Good Sector*. Ellen MacArthur Foundation; 2013.
14. Worrell E, Reuter MA. Definitions and Terminology. In: Worrell E, Reuter MA, eds. *Handbook of Recycling*. Oxford: Elsevier; 2014:9-16.
15. Ellen MacArthur Foundation. *Towards the Circular Economy Vol 1: An Economic and Business Rationale for an Accelerated Transition*. Ellen MacArthur Foundation; 2012.
16. Jensen J, Skelton K. Wind turbine blade recycling: experiences, challenges and possibilities in a circular economy. *Renew Sust Energ Rev*. 2018;97:165-176.
17. Asmatulu E, Overcash M, Twomey J. Evaluation of recycling efforts of aircraft companies in Wichita. *Resour Conserv Recycl*. 2013;80:36-45.
18. Rienecker L, Jørgensen P. *Den Gode Opgave*. Samfundslitteratur, 2010.
19. Bryman A. *Social Research Methods*. Oxford: Oxford University Press; 2012.
20. Kvale S. *InterView: introduktion til et håndværk*. Copenhagen, 2009.
21. Stage M. Ingeniøren. 2015. [Online]. Available: http://ing.dk/artikel/spoerg-scientariet-hvad-sker-der-med-de-udtjente-vindmoeller-180203. [Accessed 23 December 2015].
22. Luenga MM, Kolios A. Failure mode identification and end of life scenarios of offshore wind turbines: a review. *Energies*. 2015;8(8):8339-8354.
23. Puglia G. *Life Cycle Cost analysis on Wind Turbines*. Gothenburg: Chalmers University; 2013.
24. Weijtjens W, Iliopoulos A, Helsen J, Devriendt C. Monitoring the consumed fatigue life of wind turbines on monopile foundations. Conference Prooceedings of EWEA Offshore 2015. 2015, Copenhagen
25. Tenguria N, Mittal N, Ahmed S. Design and finite element analysis of horizontal Axis wind turbine blade. *Int J Appl Eng Res*. 2010;1(3):500-507.
26. Sharpley N. Windpower engineering & Development. 2013. [Online]. Available: http://www.windpowerengineering.com/featured/evaluating-ways-to-extend-turbine-life-past-20-years/. [Accessed 23 December 2015].
27. Global Wind Energy Council. Global wind energy council. 2014. [Online]. Available: www.gwec.net/global-figures/wind-in-numbers. [Accessed 29 July 2015].
28. Barnard M. Reneweconomy. 2012. [Online]. Available: http://reneweconomy.com.au/2012/more-wind-energy-myths-debunked-madigan-claims-put-to-the-test-19963. [Accessed 29 July 2015].
29. Fugleberg J. Atlas Obscura. 2014. [Online]. Available: http://www.atlasobscura.com/articles/abandoned-dreams-of-wind-and-light. [Accessed 29 July 2015].
30. Gipe P. Wind-works. 2013. [Online]. Available: http://www.wind-works.org/cms/index.php?id=43&tx_ttnews%5Btt_news%5D=2804&cHash=ceac96f5cb7597fd41366e9b4ceeca04. [Accessed 29 July 2015].
31. Netherlands Enterprise Agency. *Applicable Law for Offshore Wind Energy*. Netherlands Enterprise Agency; 2015.
32. The Scottish Government. Scottish planning series: olanning circular 1/2010: annex to circular 1/2010: planning agreements. Planning obligations and ogod neighbour agreements. The Scottish Government, 2006.
33. Wittrup S. Ingeniøren. 2016. [Online]. Available: http://ing.dk/artikel/aldrende-havmolleparker-abner-marked-klog-nedrivning-182308. [Accessed 07 March 2016].
34. Energiforskning.dk. Energiforskning.dk. 2014. [Online]. Available: http://energiforskning.dk/en/node/7664. [Accessed 23 December 2015].
35. offshoreWIND. OffshoreWIND.biz. 2015. [Online]. Available: http://www.offshorewind.biz/2015/12/04/vattenfall-starts-first-ever-offshore-wind-farm-dismantling/?utm_source=emark&utm_medium=email&utm_campaign=daily-update-offshore-wind-2015-12-07&uid=4506. [Accessed 28 December 2015].
36. WindPowerOffshore. WindPowerOffshore. 2016. [Online]. Available: http://www.windpoweroffshore.com/article/1382887/dong-announces-vindeby-decommissioning. [Accessed 07 March 2016].
37. Ekvall T, Weidema B. System boundaries and input data in consequential life cycle inventory analysis. *Int J Life Cycle Assess*. 2004;9(3):161-171.
38. Davidsson S, Höök M, Wall G. A review of life cycle assessments on wind energy systems. *Int J Life Cycle Assess*. 2012;17(6):729-742.
39. Martínez E, Sanz F, Pellegrini S, Jiménez E, Blanco J. Life-cycle assessment of a 2-MW rated power wind turbine: CML method. *Int J Life Cycle Assess*. 2008;14(1):52-63.
40. Sørensen MG. Interviewee, general manager H.J. Hansen (waste handling company). *Wind Turbine Recycl*. [Interview]. April. 2015.
41. Huysman S, Debaveye S, Schaubroeck T, et al. The recyclability benefit rate of closed-loop and open-loop systems: a case study on plastic recycling in Flanders. *Resour Conserv Recycl*. 2015;101:53-60.
42. Webster K. Circulate. Circulate, 03 June 2016. [Online]. Available: circulatenews.org/2016/03/how-closes-the-loop-my-good-fellow/. [Accessed 03 June 2016].
43. Tse T, Esposito M, Soufani K. How businesses can support a circular economy. *Harv Bus Rev*. 2016.
44. Guezuraga B, Zauner R, Pölz W. Life cycle assessment of two different 2 MW class wind turbines. *Renew Energy*. 2012;37(1):37-44.
45. Gamesa. *Environmental Product Declaration on 5MW turbine*. Gamesa; 2015.
46. Dannemand Andersen P, Bonou A, Beauson J, Brøndsted P. Recycling of wind turbines. In: Hvidtfeldt Larsen H, Sønderberg Petersen L, eds. *Wind Energy—Drivers and Barriers for Higher Shares of Wind in the Global Power Generation Mix*. Risø: Danish Technical University; 2014:91-97.
47. Atherton J. Declaration by the metals industry on recycling principles. *Int J Life Cycle Assess*. 2007;12(1):59-60.

48. Andersen P, Bonou A, Beauson J, Brøndsted P. Recycling of Wind Turbines. In: *DTU International Energy Report 2014: Wind Energy—Drivers And Barriers For Higher Shares Of Wind In The Global Power Generation Mix*. Risø: Technical University of Denmark; 2014:91-97.

49. BIR, "*Report on the Environmental Benefits of Recycling*," Bureau of Recycling (BIR), London, 2008. http://www.bir.org/assets/Documents/publications/brochures/BIR_CO2_report.pdf

50. van Schaik A, Reuter MA. Material-centric and product-centric recycling and dfr rules. In: Worrell E, Reuter MA, eds. *Handbook of Recycling*. Oxford: Elsevier; 2014:307-378.

51. Larsen K. Recycling wind. *REINFORCEDplastics*, pp. 20–25, January/February 2009, 53, 1, 20, 25.

52. Perry N, Bernard A, Laroche F, Pompidou S. Improving design for recycling - application to composites. *CIRP Ann Manuf Technol*. 2012;61(1):151-154.

53. Brøndsted P, Lilholt H, Lystrup A. Composite materials for wind power turbine blades. *Annu Rev Mater Res*. 2005;35(1):505-538.

54. Song YS, Youn JR, Gutowski TG. Life cycle energy analysis of fiber-reinforced composites. *Compos Part A*. 2009;40(8):1257-1265.

55. Swain L. *Used oil recycling*. Environmental Encyclopedia; 2003.

56. Rombach E, Friedrich B. Recycling of rare metals. In: Worrell E, Reuter MA, eds. *Handbook of Recycling*. Oxford: Elsevier; 2014:125-150.

57. Sullivan J, Gaines L. *A review of battery life-cycle analysis: state of knowledge and critical needs*. Chicago: Argonne National Laboratory; 2010.

58. Rydh CJ, Sandén BA. Energy analysis of batteries in photovoltaic systems. Part I: performance and energy requirements. *Energy Convers Manag*. 2005;46(11-12):1957-1979.

59. OSRAM. OSRAM. 2012. [Online]. Available: http://www.osram.com/osram_com/sustainability/environmental/product-lifecycle-management/lca-of-a-compact-fluorescent-lamp/index.jsp. [Accessed 05 August 2015].

60. Graedel T, Allwood J, Birat J, Reck B, Sibley SG, Buchert M, Hagelücken C. Recycling Rates of Metals - A Status Report, A Report of the Working Group on Global Metal Flows to the International Resource Panel. UNEP, 2011.

61. Harris IR, Williams A, Walton A, Speight J. United States of America Patent 20120137829, 2012.

62. Binnemanns K, Jones PT, Blanpain B, et al. Recycling of rare earths: a critical review. *J Clean Prod*. 2013;51:1-22.

63. Sprecher B, Xiao Y, Walton A, et al. Life cycle inventory of the production of rare earth elements and the subsequent production of NdFeB rare earth permanent magnets. *Environ Sci Technol*. 2014;48(7):3951-3958.

64. Samuelson C, Björkman B. Copper recycling. In: Worrell E, Reuter MA, eds. *Handbook of Recycling*. Oxford: Elsevier; 2014:85-94.

65. Dodoo A, Gustavsson L, Sathre R. Recycling of Lumber. In: Worrell E, Reuter MA, eds. *Handbook of Recycling*. Oxford: Elsevier; 2014:151-164.

66. Puetmann ME, Wilson J. Life-cycle analysis of wood products: cradle-to-gate LCI of residential wood building materials. *Wood Fiber Sci*. 2005;38:2018-2029.

67. Shen L, Worrell E. Plastic recycling. In: Worrell E, Reuter MA, eds. *Handbook of Recycling*. Oxford: Elsevier; 2014:179-190.

68. Hopewell J, Dvorak R, Kosior E. Plastics recycling: challenges and opportunities. *Philos Trans R Soc B*. 2009;364(1526):2115-2126.

69. Jensen J. Product Passport as a tool for sustainable resource use. in *Global Cleaner Production and Sustainable Consumption*, Sitges, 2015.

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