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Andersen, Per Dannemand; Bonou, Alexandra; Beauson, Justine; Brøndsted, Povl

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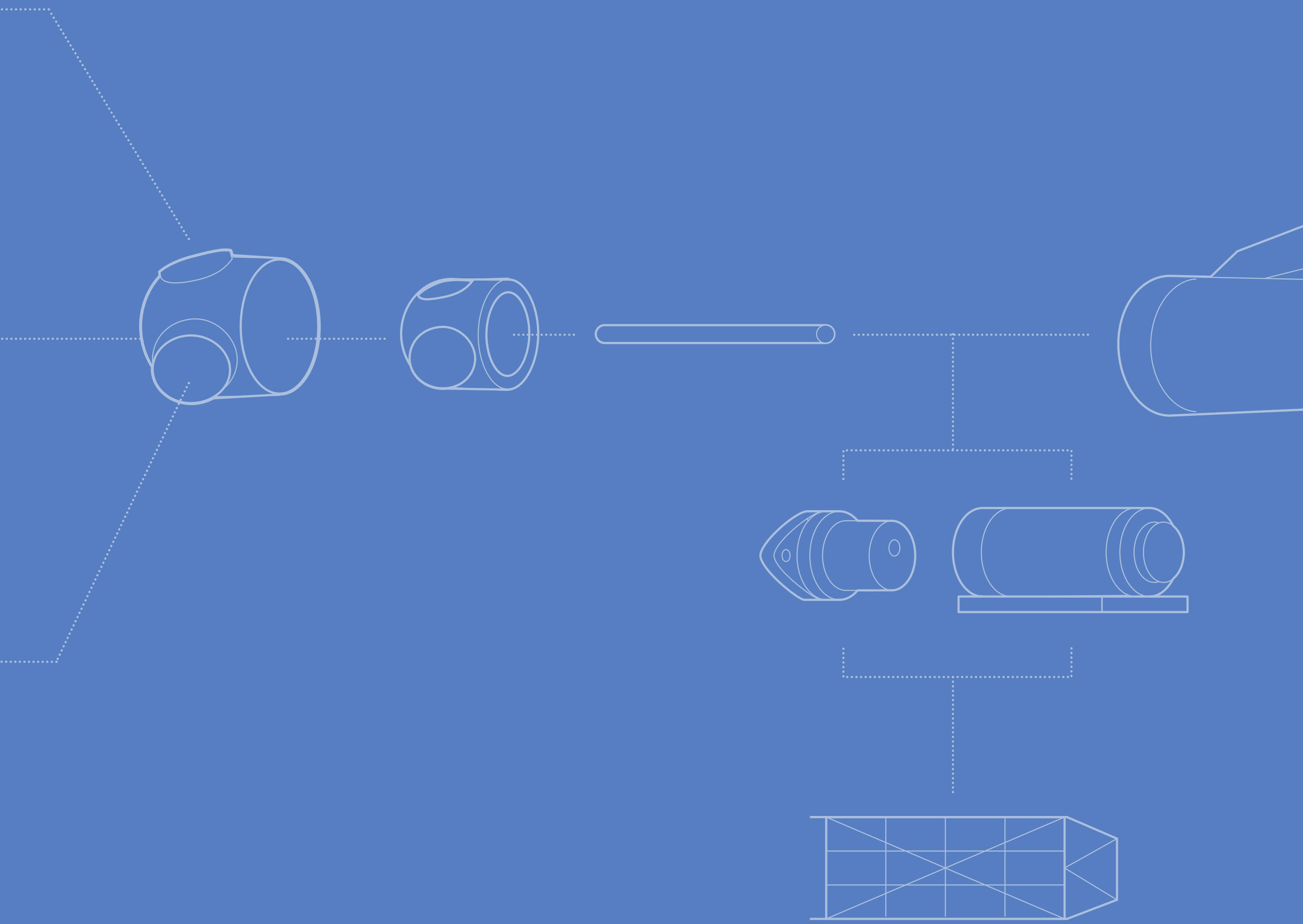
Chapter 13

Recycling of wind turbines

By **Per Dannemand Andersen** and **Alexandra Bonou**, DTU Management Engineering;
Justine Beauson and **Povl Brøndsted**, DTU Wind Energy



Wind turbines are one of the most environmentally sound technologies for producing electricity, and wind energy has very low environmental impacts. Within the life cycle of a wind turbine, however, the decommissioning phase has been identified as a blind spot when analysing the environmental impacts of wind power. Most previous impact analyses have focused primarily on the operational phase of the turbine's life cycle, and in some cases also on the manufacturing and installation phases.

Because the wind turbine industry is relatively young, there is only a limited amount of practical experience in the removal and recycling of wind turbines. This is particularly true of offshore wind turbines, which are a fairly recent phenomenon. However, wind turbine recycling is rising up the agendas of policymakers, researchers and industrialists. Several studies of the environmental impact of wind turbines have been carried out recently, along with technology development projects related to turbine recycling, especially for blades. Some manufacturers have also set targets for the recyclability of their wind turbines [1].

Deployment and decommissioning plans

How big is the problem? How many turbines do we need to decommission, and when?

The development phase of a new type of wind turbine might take five years. The planning of a large offshore wind farm might take 5–10 years. Most wind turbines have a design lifetime of 20–25 years. The decisions we take today on the design of wind turbines and wind farms will therefore affect decommissioning and recycling 30–40 years in the future – a rather distant point.

An older study identified a number of factors affecting the future market volume of wind turbines, and consequently the total amount of material used and ultimately to be recycled or disposed of [2]. The same study also identified factors affecting the design of future wind technology, and consequently the types of materials to be used (*Table 8*).

By the end of 2013 wind power had a total global installed capacity of 318 GW, a figure that had risen by approximately 40 GW annually from 2009 to 2013 [3]. Several organisations have developed scenarios for the future growth of the market. These include the International Energy Agency (IEA), which has published two such scenarios [4]. In the "2DS" scenario (an average global temperature rise of 2°C), 1,400 GW of wind power will be installed by 2030 and 2,300 GW by 2050. The more ambitious "hiRen" (high renewables) scenario envisages 1,600 GW of wind power by 2030 and 2,700 GW by 2050. Other organisations have suggested even higher future market volumes. The Global Wind Energy Council, the international trade association for the wind power industry, suggests 2,500 GW of installed wind power by 2030 and 4,800 GW by 2050. These figures do not distinguish between onshore and offshore sites.

By 2013 a typical offshore wind turbine had a capacity of approximately 4 MW and a rotor diameter of 120 m. The sizes of future turbines are more difficult to predict. The study mentioned above extrapolated

Table 8 – Factors determining the future amounts and types of wind turbine materials used and ultimately recycled or disposed [2].

Key factors affecting the future market development of wind turbines – determining the total **amount of material** used and ultimately recycled or disposed of:	Factors affecting the design of future wind technology – determining the **types of material** used and ultimately recycled or disposed of:
• National climate and energy policies • Future power market structures • R&D expenditure (public and industrial)	• New materials (replacement of steel, new composites, superconducting materials, etc.) • Design concepts and main components (power electronics, control strategies, superconducting materials, etc.) • Grid conditions (grid structure, power quality, etc.)

Table 9 – Masses of the major components of a 2 MW turbine [5].

Component	Mass (tonnes)
Tower	143.0
Nacelle	2.3
Hub	13.3
Blades	19.5
Nose cone	0.3
Transformer/converter	5.0
Generator	6.5
Gearbox	16.0
Bed frame	10.5
Main shaft	5.1

to suggest that the most common turbine size in the period 2020–2030 will be 10 MW [2]. A newer study has based its conclusion on an existing 2 MW turbine [5] (*Table 9*).

The 40 GW of turbines installed annually in the period 2009–2013 will reach the end of their operating lives during 2029–2033. Anticipating the IEA hiRen scenario, it is possible to make a rough estimate of the amount of material that will need to be recycled in the long term (*Table 10*). We assume that ½₀ of the capacity installed by 2030 will need to be decommissioned by 2050; the same estimate for blade material can be found in a recent German study [6].

By comparison, vehicles reaching the end of their lives are estimated to reach a mass of 14 million tonnes per year by 2015 in Europe alone [7].

Future challenges for decommissioning and recycling

Early life-cycle assessment (LCA) studies of offshore wind farms have concluded that environmental impacts come from three main sources [8, 9]:

- bulk waste from the tower and foundations (e.g. from steel production), even though a high percentage of the steel is recycled;
- hazardous waste from components in the nacelle (e.g. from alloy steel);
- greenhouse gases (e.g. CO_2 from steel manufacturing and solvents from surface coatings).

These results indicated that further analysis should take into account changes in the materials used in the tower and the foundations, as well as changes in the design of components in the nacelle (e.g. direct-drive designs and greater use of power electronics).

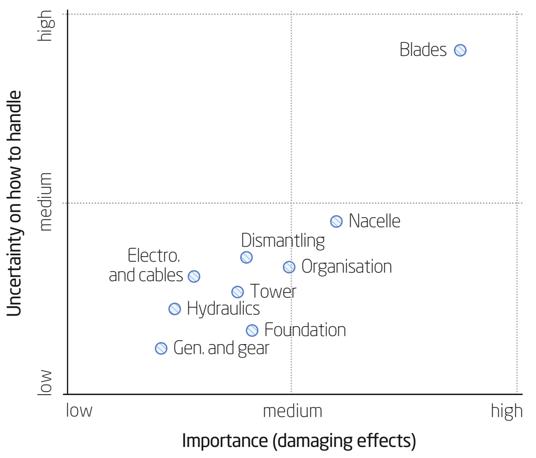
Cables play an important part in recycling plans for offshore wind farms [8]. Offshore sites require many kilometres of heavy cables of complex/composite construction to resist the harsh environment of the sea. There is a considerable environmental impact from the manufacture of the cables, and since they consist of many different materials, cables are also difficult to dismantle for recycling.

There are some uncertainties and limitations regarding LCA studies of offshore wind turbines. In particular, the specific processes needed for dismantling and recycling, which are crucial to the

Table 10 – Rough global estimates of recycled masses of key wind turbine components in the future.

	40 GW decommissioned annually by 2029-2033	80 GW decommissioned annually by 2050
Steel and cast iron (tower, hub, bed frame, main shaft) - 86t/MW	3,440,000 t	6,880,000 t
Alloys (generator, gearbox) - 11t/MW	440,000 t	880,000 t
Blades - 10t/MW	400,000 t	800,000 t

Figure 37 – Assessment of the environmental impact and uncertainties.



Assessment of the environmental impact and uncertainties involved in dismantling, recycling and disposing of wind turbines and their components [5]

environmental profile, are not known. Many material recovery processes were not included in these early analyses. Another example of the limitations of many environmental impact studies for wind turbines is that they tend to neglect land use, which is generally considered a critical point elsewhere. Newer LCA studies of wind turbines point to two uncertainties in assessing lifetime environmental impact [10]. The first relates to what will happen to materials and components, in particular the blades, at the end of their lives: will they be recycled, or dumped in landfills? The second area of uncertainty is about decisions taken on servicing and maintenance during the operating life of the turbines. Together, these two uncertainties create an uncertainty of 14–20% in the predicted life-cycle environmental impact of wind turbines [10].

As mentioned above, what happens at the end of a turbine's life has a considerable influence on its overall environmental impact. The options are: second-hand sales of complete turbines; refurbishment to extend the working lives of turbines in their original settings; remanufacturing and re-use of components; recycling; and landfill.

Some studies include only remanufacturing and recycling. Remanufacturing is the process of returning a used component to its original specifications, while recycling recovers the material value without concern for the functional value of the component [5]. However, there exists a second-hand market for used wind turbines. Turbines considered too old or too small for mature markets such as Denmark and Germany can be refurbished and sold in less mature markets such as Eastern Europe and Latin America, giving operators practical experience at low cost [11]. This second-hand market has recently surged.

Another option is to extend the working life of turbines by updating them with newer or refurbished components. Some independent operators, like the DMP Group, specialise in refurbished components for wind turbines. "Repowering" a wind farm usually implies replacing old turbines with newer and larger ones. In that sense it is the site that gets repowered and not the individual turbines.

If old turbines cannot be re-used economically they must be dismantled, their components recycled wherever possible, and the remainder dumped or incinerated. Many components have a commercial value because they contain materials such as steel and copper, and most turbine components are well known to established recycling companies. However, the consequences of recycling increased numbers of generators containing rare-earth magnets are not well studied.

An older study assessed the environmental impact and uncertainties related to decommissioning wind turbines (*Figure 37*) [2]. The study found that blades constitute a major problem, and there is much uncertainty about how to get rid of them properly and safely. The problem lies in the fibreglass composite used for blades. Fibreglass is a low-value material and the dust produced when the blades are cut up creates a hazardous working environment. Empty nacelles are also hard to recycle because they contain many different types of materials, including composites and PVC foam. Electronics and cables are less problematic, since the recycling industry is used to handling these.

A newer study indicates that dismantling and "reverse logistics" might be more costly than the original installation phase [5].

Based on information from companies the authors of this chapter have assessed the recycling or disposal rate of wind turbines built using current technology (*Table 11*). Electronic components are notable for their low recycling rate, such that up to 50% needs to be treated as waste. Since most LCA and recycling studies of wind turbines focus on the blades, there seems to be a need for better knowledge of how to recycle electronics and other composite components like cables and hydraulic hoses.

Institutional issues

A recent British study of the incentives for recycling composite wind turbine blades in Europe analysed the legislative regime for the recycling of blades, and found it to be quite comprehensive. Blade recycling is subject to EU Directives on issues such as landfill, vehicles (the End of Life Vehicles Directive), waste incineration, waste electrical and electronic equipment (WEEE), and the Waste Framework [7].

Also important may be the EU rules on extended producer responsibility (EPR), which has been applied to a number of sectors such as vehicles and electronic and electrical equipment [7]. Under EPR, manufacturers are responsible for the life cycle impact of their products [12].

This complexity emphasises the importance of knowledge exchange and knowledge development in the interaction between the design, dismantling and recycling phases for wind turbines. Furthermore, the institutional and organisational structure required to dismantle and recycle offshore wind turbines was until recently quite uncertain [2, 5].

Who will actually dismantle and remove the turbines at the end of their lives? Three business models can be identified. In the first, this is the job of established independent operators in the removal and recovery sector. In the second model, which is a variation of the first, specialist independent operators will carry out most of the work, but the blade materials will be recycled by an emerging class of start-up firms set up to take advantage of this opportunity.

The third model involves collaboration and strategic alliances between wind turbine producers (Original Equipment Manufacturers) and the removal and recovery industry. Of the three, this model is the

Table 11 – Recycling rates and disposal routes for wind turbine components.

Material	Recycling/Disposal rate (%)	Disposal method
Ferrous high alloy	98	Recycling
Ferrous metal	95	Recycling
Steel		Recycling
Aluminium and aluminium alloys	95	Recycling
Copper, magnesium, nickel, zinc and their alloys	98	Recycling
Precious metals and other non-ferrous metals and alloys	98	Recycling
Plastics, rubber and other organic materials	100	Incineration with energy recovery
Electronics	50	Recycling with energy recovery
Batteries	100	Recycling
Concrete, bricks etc.	64	Landfill
Sand and gravel	0	Remains in the ground after wind farm is dismantled
Blades	95	Landfill or recycling
Remaining materials		Incineration or landfill

Source: Based on authors' analysis of information from companies.

best adapted to the expected regulatory changes towards extended product liability and increased producer responsibility. It might also be preferred by the wind turbine manufacturers (OEMs), since it will help them to feed knowledge back into their product development processes and so benefit from designing for recyclability [5].

However, there seems to be a need to further analyse the societal and environmental consequences of these business models and perhaps others. In particular, studies show the need for development policies to encourage recyclability and to stimulate markets for second-hand turbines and independent recycling operators [5].

Recycling fibreglass

As indicated above, it is well known that fibreglass blades can create recycling problems. Several decades of research have now resulted in practical methods for recovering and recycling glass fibre and other materials from composites. [13, 14, 14A] Unfortunately, high investment and processing costs mean that the recovered glass fibres are more expensive than pristine ones, so commercial applications have therefore been limited. The Danish company ReFiber used pyrolysis to recover glass fibres from wind turbine blades for re-use in thermal insulation, but after five years of operation the company ceased trading in 2007 for economic reasons.

The recovery processes are primarily chemical and thermal in nature, with processing temperatures in the range 300–700°C. [15, 16] The most-studied techniques are the fluidised bed, a thermal oxidation process operating at around 450°C; [17] pyrolysis, which decomposes organic molecules into smaller ones in an inert atmosphere at temperature of 300–700°C;[18–21] and supercritical fluids (see below).[22–24]

Heating glass fibres to temperatures above 250°C has been shown to degrade their mechanical properties. [14, 23, 25–28] This limits the use of recovered glass fibres in high-performance composite. One of the challenges is therefore to reduce the operating temperature of the recycling processes. Supercritical fluids are promising in this respect. Many fluids at temperatures and pressures just above their critical points have interesting properties, including high solvent power and liquid-like density combined with gas-like diffusivity and viscosity.

The European project EURECOMP (2009–2012) investigated the use of water to dissolve the matrix material in glass fibre reinforced polyester, but the results were unpromising at temperatures below 300°C. [22–24]

Another project, Genvind (2012–2016), is now running in Denmark with the aim of finding recycling and re-use solutions for wind turbine blade materials. Because the reasons for decommissioning blades are diverse (most often they are still intact), the project is considering several scenarios and process steps, from dismantling to re-use of complete blades. The project's many partners, from both industry and universities, are working to develop suitable technologies and future industrial applications.

Another route might be to produce cement by using decommissioned turbine blades and other waste composites as both a fuel and a raw material. The polymer component of the composite acts as a fuel, while the glass leaves a silica-rich ash that can substitute for some of the sand normally required to make cement. The Lägerdorf cement plant in Germany, operated by Holcim, is already doing this, incorporating up to 50% of fibreglass ash into the clinker. The company claims that the resulting cement is no different from normal in terms of quality and applications. [28]

Perspectives

Based on the above, we can make some recommendations for research, industry and policy.

First, there is a general need for more accurate data to improve LCA calculations relating to wind turbines. This may be especially important for decisions concerned with service and maintenance. These are considered key issues in driving down the cost of electricity produced by wind power, yet they have environmental consequences that may not yet be fully understood. Better data is also needed for the recycling of wind turbine components and materials, especially blades. Since materials are responsible for the largest fraction of the total life-cycle emissions from wind turbines, uncertainties in data on recycling have a big influence on the LCA of the turbines as a whole.

Second, design for recyclability is high on the agenda in many industries, including wind power. However, there is a need for better understanding of likely material substitution in future turbine designs. There may also be a need for more knowledge on how to dismantle turbines and break down complex components into recyclable materials.

Third, there is a need to know more about the potential markets for products made from recycled materials. There are established markets for scrap steel and alloys, but there is limited knowledge about the market for secondary products from wind turbine recycling, such as composite matrix materials derived from blades.

Fourth, as wind turbines become more technologically advanced, the use of rare earth materials is increasing, especially in magnets. We need to know more about how to recycle or recover magnets and rare earths.

Fifth, we need policies to stimulate OEMs to design for recyclability, for example through extended producer responsibility within a product service system framework. Valuable experience could be learned from other industries.

Sixth, the current rapid rise in wind power projects in the longer term is creating new business opportunities for second-hand turbines, refurbished components, turbine dismantling services, and recycling of materials. Further into the future, policies to stimulate such markets and entrepreneurial activities might be needed.

As the global installations of wind turbines increase to develop issues related to the decommissioning of wind turbines becomes increasingly higher on the agenda – both in policy making, among researchers and in industry. This chapter has touched upon the most important of aspects related to this issue. However, in a longer perspective much knowledge is still needed.