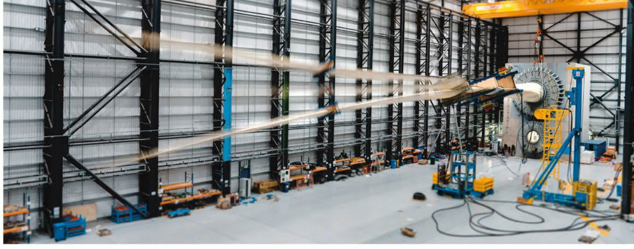


Angeliki Spyroudi

April 2021

Carbon footprint of offshore wind farm components

EXECUTIVE SUMMARY

Offshore wind is placed at the centre of global decarbonisation strategies and the UK leads the world in its offshore wind capacity with over 10GW installed and plans to reach 40GW by 2030. The need for decommissioning offshore wind turbines will become more prominent as the fleet ages. In the meantime, old or defective components continue to be replaced as part of ongoing Operations and Maintenance (O&M) activities, creating waste. End-of-use management of components and materials needs to be done with care under the current waste management guidelines and regulations. In principle, according to international agreements that the UK has signed, no parts, e.g. cables or foundations, may be left in the seabed (derogations may apply in some cases), which should be returned to its prior condition with minimal disruption to the marine environment. The challenge with these guidelines and regulations is that it is a very dynamic field, and there is a gap between the time any guidance is structured and the moment it reaches industry.

A life cycle assessment (LCA) is usually used to estimate the carbon footprint accounting for the total quantity of greenhouse gas emitted over the whole life cycle of a product or process as well as the environmental impact on abiotic factors, but a number of uncertainties can render this task quite complex. Wind power is one of the energy sources with the lowest carbon footprint, including construction and manufacturing activities, and it produces zero emission electricity. In our analysis, a brief estimation of the embodied carbon emissions and recycled content in an offshore wind farm operating 6MW and 10MW turbines showed that recycling them could save at least 35% of carbon emissions equivalent per kWh in the primary material of components. The turbine contributes 50% to the carbon emissions of primary materials used for the windfarm components, the analysis showed. Steel is used in more than 60% of the total mass of a wind turbine, and although recyclable, a large amount is directed to landfill. In terms of carbon emissions, steel has high embodied carbon content, although blades consisting of composite fiberglass materials are the most challenging to be

treated and recycled. A lot of research and innovation (R&D) activity is underway looking at processing methods and alternative materials. In the waste hierarchy Reuse, recycling and recovery are considered a reactive approach to waste management, so it is important to adopt a proactive approach and establish a sustainable framework in the offshore wind sector that will lead to a shift from linear to circular economy practices. In addition, such waste management policies should have longer-term perspectives so that companies avoid spending money on solutions that will only be of use for a very short while with no appropriate investment return.

ORE Catapult has developed the Circular Economy for Wind Sector Joint Industry Programme (CEWS JIP) which aims to bring together ideas and solutions from different research, operators, developers and policy makers on these end-of-life decisions and best sustainable practices, which should be adopted at the end of a wind farm's operating life. The JIP is planned to start in April 2021 for a duration of five years.

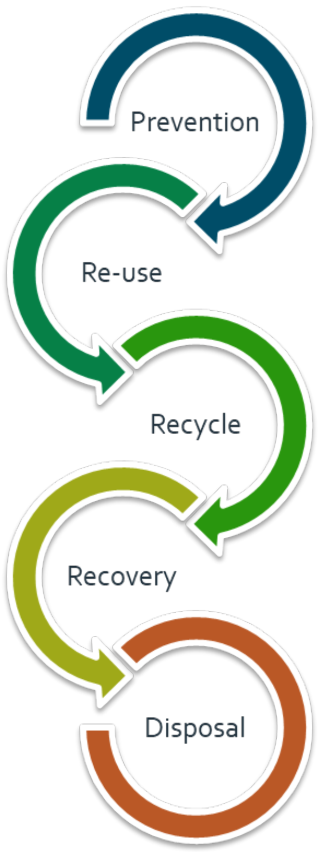
INTRODUCTION

In the last couple of years, the terms "green economy", "net zero" and "circular economy" have risen high up the UK governmental agenda following a global trend towards achieving sustainable economic growth. This has increased the level of attention on the environmental impact of the materials, production methods, maintenance and end-of-life practices for renewable energy generating assets. The Covid-19 crisis has put extra pressure on global economies to rethink the way they have structured their growth strategies. Production needs to recover after the economic slump and there are serious concerns that implementation of climate change policies and funding will be sacrificed on the way back to normality. However, the climate crisis will extend over decades and so what has been considered normality until now will not be enough to assist in meeting the ambitious targets of Net Zero by mid-century.

Offshore wind is placed at the centre of global decarbonisation strategies and the UK leads the world in its offshore wind capacity, which has grown particularly fast in the last decade while costs have dropped rapidly. Current capacity is over 10GW in the UK with plans to reach 40GW by 2030. An increase in installations and higher wind speeds resulted in record UK electricity production from offshore wind (13.2 TWh) in the first three months of 2020, accounting for 47% of the UK's electricity.[1] Development will continue to increase in line with governmental ambitions and fuelled by innovation as the industry seeks new ways to reduce time and costs at different stages of construction and operation. However, the expected lifetime of a windfarm nowadays is at least 25 years and limited attention has been paid so far to the decommissioning phase and its potential environmental impact.

Vattenfall completed the first ever decommissioning of an offshore wind farm at the beginning of 2016 for the 10MW Yttre Stengrund Wind Farm in Sweden followed by Ørsted (previously named Dong Energy) which decommissioned Vindeby Offshore Wind Farm in Lolland a few months later. Only seven full-scale multiple turbine projects have been decommissioned globally. Practical experience of offshore wind decommissioning is minimal in the UK as the industry is still relatively young, so only one offshore wind farm decommissioning project has been completed to date: that was the two Vestas V66 2-megawatt turbines in Blyth, Northumberland. The oil and gas sector has a considerable experience in decommissioning offshore platforms where knowledge can be transferred to offshore wind.

Decommissioning of onshore wind turbines is still developing in the UK, and although the process offshore is more challenging, it is similar in terms of what happens to a wind turbine after useful life and waste treatment practices. Developers are not currently fully aware of the different options available for a) lifetime extension, repowering and decommissioning at the wind farm level, b) of reuse, repair, refurbish, remanufacture at the component level and c) of recycling at the materials level. Repowering and life extension need to be investigated in detail in terms of cost and environmental impact, but ultimately decommissioning is unavoidable. Disposal of components and materials to landfill is considered the last resort when all the other previous steps in the waste hierarchy are not possible (Figure 1), so there is a need for discussion and innovative thinking to find the best ways to minimise waste and then proactively re-design the future generation of wind turbines. Dismantling operations at sea will require extra care, time and money and the seabed should be left intact irrespective of the method selected.



Waste prevention and reduction in design and manufacture. Use of minimal hazardous material.

Repurposing items for use elsewhere

Conversion of waste to a new product or material.

Recovery of energy from materials (e.g. incineration, anaerobic digestion).

Landfill and incineration without energy recovery.

Figure 1 Waste hierarchy

This Analysis & Insights Paper will draw attention to the carbon implications of end-of-use management after decommissioning of offshore windfarms. It also investigates wind turbine components, especially blades, to address environmental concerns and flag the need for defined legislation on this often neglected but important issue. Note that this analysis is not a full life cycle assessment and the carbon footprint estimates refer to materials used for manufacturing of components.

THE CHALLENGE

The decommissioning of offshore wind turbines will become as issue of growing importance as the fleet is aging. ORE Catapult estimates that around 1.5GW of offshore wind will need to be decommissioned by 2030 globally and 13GW by 2040. The cost of decommissioning 37 offshore wind farms could be between £1.3 billion (€1.4 billion) and £3.6 billion (€4.1 billion).[2] In principal, 85% to 90% of materials used in wind turbines – the foundation, tower, components of the gear box and generator – may be recyclable. However actual recycling rates currently onshore are much lower despite recycling being the recommended option if reuse is not possible. For example, steel used to be exported for smelting in a blast furnace (a carbon intensive process) in locations halfway around the globe, so although recycling is generally considered a green option, this activity was associated with significant emissions. Blade recycling or disposal is highly challenging as they are manufactured from complex composite material and require logistical, technological as well as regulatory and economic solutions for the collection, transportation and waste management of the material. Around 15,000 wind turbine blades (onshore and offshore) will be decommissioned in Europe in the next five years so this will be an issue that needs to be addressed soon.[3]

In the UK, the end-of-use management of components and materials needs to be done with care under the current waste management guidelines and regulations. According to UK legislation, the Energy Act 2004, there should be a "*..provision about restoring the place to the condition that it was in prior to the construction of the object..*" and the international OSPAR Convention states that the structures should be removed using "*..techniques which minimise impacts on the environment..*" including re-suspension of the sediment .[4] Reuse and recycling of components and materials is not as established for the moment in offshore wind as in onshore. Oil and gas and offshore wind decommissioning will rise significantly in the coming years. The decision between component reuse, material recycling, energy recovery or disposal will be mostly determined by regulation based on the units available and able to handle this waste, energy requirements for treatment and economic benefit.

REGULATIONS FOR WASTE MANAGEMENT

There is no statutory decommissioning scheme for onshore renewable energy infrastructure and decommissioning is based on agreements between the project developer, the local planning authority within whose jurisdiction the project in question is located and the landowner who has granted a lease for the project.[5] Planning conditions should be attached to the consents issued by the local planning authorities in England and Wales including requirements on decommissioning. From 1 January 2015, UK waste regulations require businesses to separate recyclable material from other waste (e.g. the Waste (England and Wales) Regulations 2011 as amended in 2015).[6] However, there is currently no specified waste legislation for the wind sector although general waste regulations do apply, including an obligation to recycle where possible. The Environment Agency has a range of responsibilities, including regulating waste management facilities, monitoring and enforcement issues, and licensing and monitoring waste movement (including exports).[7]

In Scotland, the Scottish Environment Protection Agency (SEPA) is responsible for regulating the activities which take place at onshore wind farm sites. The Local Planning Authority (LPA) is responsible for enforcing planning conditions, and SEPA looks at Duty of Care as part of waste regulations, but an established refurb/recovery market is also needed to allow better planning of waste produced. In offshore wind, Marine Scotland manages execution of decommissioning programmes (SEPA acts as a designated regulation authority) and the moment that end-of-use components and materials are shipped onshore, supervision becomes SEPA's remit. In general, all wind farms until now had to make complex arrangements to comply with the EU directives below.

- Landfill
- Waste Framework
- Industrial Emissions
- Chemicals and their storage

The relevant Local Planning Authority (LPA) controls an individual development's decommissioning as a condition of planning or energy consenting. The Scottish Government's energy consents team covers >50 MW wind farms that fall under Section 36 of the Electricity Act and is directly answerable to Scottish Government ministers, but the decommissioning conditions still defer to the LPA, which is responsible for enforcing planning permissions. Conditions are focussed on removal of all infrastructure down to 1m and often refers to wind turbines, ancillary equipment and buildings being dismantled and removed from the site and the land being restored and subject to aftercare, in accordance with the restoration and aftercare scheme. In addition, planning applications can also require an Environmental Impact Assessment, compliance with Controlled Activities Regulations, Waste Regulations and protected species licensing.[8] In particular, Scottish Natural Heritage (SNH) has an advisory role on potential impacts on habitats and environmental impacts and has written some guidance around onshore decommissioning, but there is still a fair amount of variation at the regional level and there are ongoing discussions to standardise LPAs. SNH, Scottish Water and Historic Environment Scotland are statutory consultees in any planning application. Similar guidance and consultees exist in England, Wales and Northern Ireland.

On international regulations, OSPAR, the multi-governmental forum which cooperates to protect the marine environment of the North-East Atlantic, has developed guidance on environmental considerations for the development of offshore wind farms and recommends best practices to assess, minimise and manage their potential impacts. The UK now insists on increasingly precise decommissioning plans for new offshore renewable energy infrastructures having long-term environmental impact as a priority and following the legislation of waste management above. Developers are obliged to decommission installations at the end of life; however, some exceptions can also be applied where removal is not considered the best practice.[9]

COMPONENTS

According to Wind Europe's annual statistics report, 174MW of onshore wind were decommissioned in 2019 in Europe, mainly in Germany, while only 185MW were repowered from the 11.7GW of new installations.[10] The United States has decommissioned about 195MW of capacity.[11] In offshore wind, approximately 40MW have been decommissioned globally with repowering and life extension strategies starting to attract the attention of the industry as the oldest assets approach their end of life.[12]

Looking at offshore wind, there is a range of turbine models currently operating in the market, mostly produced by a small number of large original equipment manufacturers (OEMs). Siemens has manufactured over 3,700 offshore wind turbines obtaining 60% of the market. In general, a wind turbine is mainly composed of blades, nacelle and tower, and depending on whether it is installed onshore or offshore, it will require appropriate foundation configuration to maintain its stability. For onshore turbines, gravity-based foundation is the usual choice while, for offshore, monopiles dominate the market followed by jacket and gravity-based. The rapid development of offshore wind is now leading developers into deeper waters and further distances from shore where floating wind foundations will be a large part of the market in the coming decades.

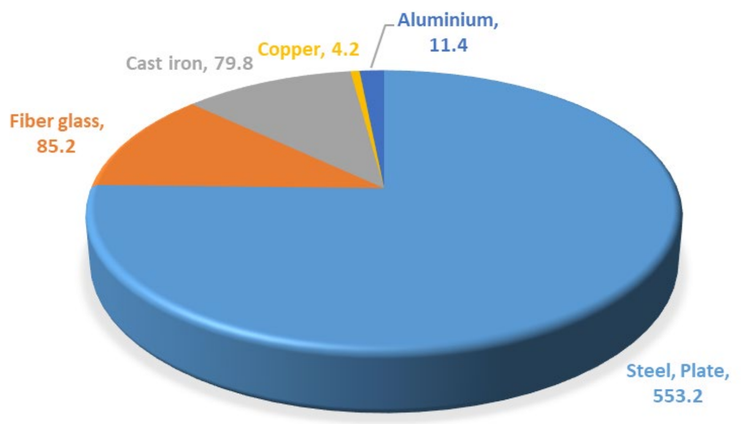


Figure 2 Offshore wind turbine 6MW material mass breakdown (tonnes)[13], [14]

According to the National Renewable Energy Laboratory, wind turbines are predominantly made of steel (71-79% of total turbine mass), fiberglass, resin, or plastic (11-16%), iron or cast iron (5- 17%), copper (1%), and aluminium (0-2%).14[14] The rapid increase of turbine and blade size has shifted the interest from glass to carbon fibres, a newer alternative material, lightweight and with high stiffness which has been adapted to the industry some years ago for larger turbines although its cost is still high. The size and the distinction between onshore and offshore affect the design and materials used. Topham, *et al.* analysis concluded that manufacturing two smaller turbines is more environmentally friendly (in terms of the material use requirements) compared to a single larger turbine. The need for good recycling measures becomes even more important as larger amounts of resources will be required as the industry and turbine sizes grow. The typical masses by material of a large offshore wind turbine with a 6MW rating are shown below (excluding the foundation).

Finally, transition pieces, subsea cables, meteorological masts and offshore/onshore substations should also be removed when a wind farm ceases operation under current UK regulations, although there is a growing consensus in the Oil & Gas sector that this may not always be best practice, e.g., rigs to reefs or reuse in CCUS. Copper is used for the manufacturing of cables and coils. The transition piece, tower, gearbox and nacelle are all made of steel of various configurations based on the thickness and durability required for each part. Nacelles can also contain composites and PVC foam, and the gearbox also includes a small amount of cast iron, copper and aluminium. Main shafts, generator and the blade hub also include cast iron. If the turbine has no gearbox, a direct drive magnet generator can include copper and rare earth materials such as neodymium and dysprosium.

For foundations, the materials used can vary a lot depending upon the design. Monopiles currently dominate the market but as industry is moving to deeper water sites other designs are gaining ground. Figure 3 presents estimates on the number of foundations globally by type up to 2050. Approximately 12,000 units will be installed globally by 2025 representing a mass of 3.5 million tonnes of steel in foundations.

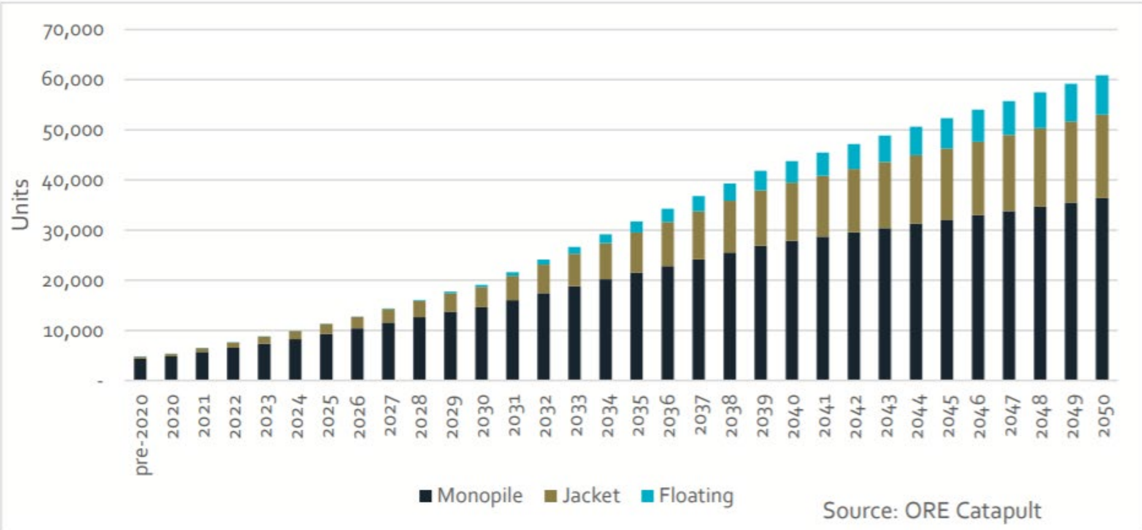


Figure 3 Global deployment (number of units) by foundation type

Monopile foundations are made of steel plates which form steel tubes and are the dominant choice to date for water depths of up to 40m. They are installed into the semi-hard seabed by either large impact or vibratory hydraulic hammers or the piles are grouted into sockets drilled into rock.[15] After monopiles, jackets are the most common foundations, also widely used in oil and gas, consisting of corner piles interconnected with slender steel bracings to form a lattice tower. Another type of foundation, the Gravity Based Foundation (GBF), comprises a steel or concrete "pillar" mounted on a base heavy enough to resist wind and wave loads and removing the need for any seabed piling. Less widespread types in offshore wind but with considerably less steel material needs are also suction bucket, tripod and twisted jacket foundations. Finally, floating substructures are coming to the fore thanks to their ability to unlock high resource potential in deep waters. The most common typologies of semi-submersible, spar and tension leg platform (TLP) have been made of steel to date, but there are also existing and planned concrete designs. Steel and synthetic fibres (nylon, polyester) are used for moorings, anchors and other auxiliary equipment.

Blades

From all the parts described above, blades have attracted the highest interest in terms of their disposal treatment. They are built from a composite material which is constituted of metallic, organic or inorganic base structural components that are able to minimise material fatigue at low cost. Today 2.5 million tonnes of composite material are in use in the wind energy sector globally.[3] Large offshore wind blades are generally made from glass fibre-reinforced plastics (GFRP) or polyester resin reinforced with glass, which is lightweight while offering high performance and reliability. Other materials included in blades are epoxies, polyesters, vinyl esters, polyurethane, or thermoplastics, balsa wood or foams such as polyvinyl PVC, PET, PE, PUR for coatings and metals such as copper wiring, steel bolts, etc. Carbon fibre has been introduced in the last five years as blades have grown longer and it has been incorporated into load critical areas at the blade root and internal stiffeners. However, blades are large and can create a great amount of waste if not treated properly. Recycling could be the best option, but the complex nature of composite materials makes this process extremely challenging and costly accompanied with high safety risks. In particular, a blade yields about 15,000 pounds (6.8 tonnes) of fibreglass waste and breaking it down into smaller parts creates hazardous dust.[16]

LINEAR TO CIRCULAR ECONOMY

Although 85-90% of a wind turbine can be recycled, there is still a large amount of material that is directed to landfills. This "linear" approach to product development has been the norm for decades, however, increase in demand and the scarcity of natural resources leads to a more "circular" model where reuse and recycling minimises waste of valuable materials (Figure 4). This circular economic model can minimise the amount of resources taken from the natural environment, maximise the prevention of waste, and optimise their economic, social, technical and environmental values throughout consecutive lifecycles.[17] Preventing waste by planning ahead of the wind turbine's end of life is considered the first step in the waste hierarchy pyramid (Figure 1). Maintenance and repair can also reduce waste before reuse or recycling decisions should legally be taken. An EPSRC project, co-funded by the Offshore Renewable Energy (ORE) Catapult, the Department for International Trade and the University of Leeds proposes a Circular Economy Framework focussing on offshore wind challenges.[18]

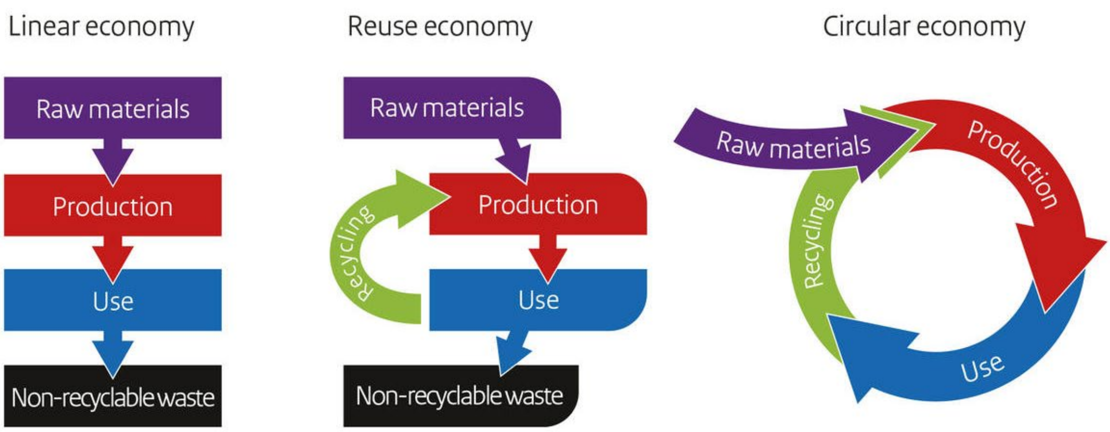


Figure 4 Linear, transitional and circular economic models[19]

Demand for used onshore wind turbines and components is high in developing countries offering fast delivery and cost saving of up to 40% compared to new ones. As offshore wind cost drops and new markets emerge, a market for second-hand turbines could open up as well. However, turbine components can also be repurposed in other forms and not for their original function, e.g. as for creating playgrounds for children, building benches, bus stop and bicycle parking shelters. If component reuse is not possible then the developer should think what options are available for recycling materials. The above are good examples of wind turbine reuse and recycling but are currently occurring as one-offs at a small scale. What is needed is to employ large-scale, cost effective solutions which will be widely implemented and create an established market for recycled materials.

Our best current estimates put the cumulative mass of steel in foundations (monopiles and jackets of offshore wind turbines only) at 3.5 million tonnes by 2025.[20] Steel, which is the material used in more than 60% of the total mass of a wind turbine, is the top recycled material (in terms of volume) as it maintains its quality and value when scrapped. However, steel is usually found in the form of alloys with other materials which makes the process of residual separation complex and quite expensive. Scrap steel can be traded in the market and saves up to 56% energy in comparison with making metal from ore.[21] Recycling one tonne of steel conserves one tonne of iron ore, 635kg of coal and 54kg of limestone compared to primary production.[21] Cast iron is totally recyclable and can be recovered fully to meet its primary purpose. Copper in turbine components can also be recycled easily and is worth up to 90% of the cost of the original material depending on its purity.[22] As dangerous gases are emitted during copper extraction, recycling is the preferable treatment from both an economic and environmental perspective. Cables consist of different materials including copper which is challenging to dismantle. Also, the common industry practice for subsea cables is burial, again being preferred in terms of cost and environmental impact. Steel is also present as nuts and bolts throughout the turbine and is a key material for the nacelle (drivetrain and generators) and towers (which can weigh approximately 600 tonnes for a 10MW turbine).

Approximately 2.5 million tonnes of turbine blade composite material exist in offshore wind turbines installed globally. Around 60,000 tonnes of it is expected to be decommissioned within the next two years. The high durability of fiberglass composite material used in blades becomes a negative when it needs to be treated as it is currently extremely difficult to degrade. It is a cheap material being manufactured using high temperature furnaces run from fossil fuels, so the environmental impact of this process is high. Siemens Gamesa states that blades made of epoxy and fiberglass may be shredded and incinerated where the burning of epoxy generates energy, which can be recovered. The residues from fibreglass incineration can be used in other secondary applications (e.g. for cement production). Current recycling methods consume high amounts of energy and can be hazardous, which increases the cost and makes them unfeasible at the present time. So far, there is little evidence of the emergence of sustainable blade recycling on an industrial scale, although blade waste is expected to increase rapidly.

Existing direct drive permanent magnets (DD-PMGs) for wind turbine drivetrains rely on large volumes of rare-earth magnets to produce electricity, estimated at 650kg per MW. Magnets from the direct drive turbines can be demagnetised, remagnetised and used or reused for new magnet production. Neodymium alloy magnets (NdFeB) are the most common rare-earth magnets using Neodymium and usually Dysprosium to increase magnetic performance at high temperatures. Rare earth elements (REE), as their name indicates, are scarce, expensive and sourced almost exclusively from China (>80%) which only in the last decade has started looking at more sustainable manufacturing procedures. As a dominant supplier, China is able to control supply prices. The environmental impact is high at the point of extraction, a process that is intensive in its use of energy and chemicals.[23] Although recycling processes exist for smaller objects like batteries, there is no certain process for wind turbine recovery, so these REE are currently disposed of, worsening the imbalance in supply and demand. Recycling aims to extract the rare earth elements from the magnets again, which is an extremely labourious and expensive process and combined with the loss of quality during this process makes recycled material less attractive for new magnets.

Considering that carbon emissions are produced during the lifecycle of the windfarm and during the manufacturing stage, disposal of components at the decommissioning phase not only produce a high amount of additional waste but also represent a loss of valuable materials able to be repurposed. Different materials have different emission factors and recyclability levels but as mentioned, almost 90% of a wind turbine can technically be recycled. The method of life cycle assessment (LCA) is used to estimate the carbon footprint accounting for the total quantity of greenhouse gas emitted over the whole life cycle of a product or process. In practice, a complete LCA is a difficult task that carries uncertainty at some stages, especially at end-of-life management. This analysis gives a brief estimation of the embodied carbon emissions and recycled content in materials using conversion factors relevant to each component. For a complete life cycle assessment, more detailed data is needed (transport for construction, O&M, decommissioning and components/equipment during repairs). The results of this analysis reflect specific scenarios and should be seen as indicative, not as a source of definitive answers.

Figure 5 shows the carbon emissions and savings from recycling materials from a 6MW and 10MW wind turbine. On average this analysis found that recycling can save at least 35% of embodied carbon emissions equivalent per kWh compared to new manufacturing. Based on this analysis, the turbine contributes 50% to the total carbon footprint of materials used in wind farm components. Our estimation showed that carbon savings from offshore wind electricity generation compared to the same electricity produced from natural gas is on average 143 ktCO_2e per unit. Embodied carbon emissions in primary materials used to manufacture wind farm components are estimated at 5.5 ktCO_2e per unit on average, which can reduce only by up to 4% the carbon saving from replacing natural gas.

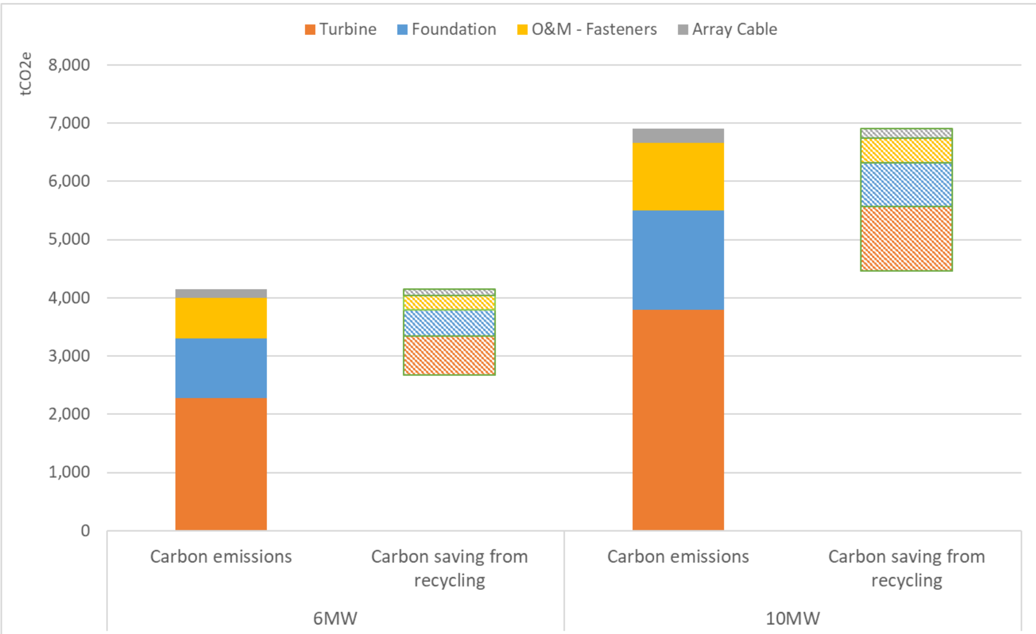


Figure 5 Carbon emissions and carbon saving from recycling of windfarm components

NEW TECHNOLOGIES AND INNOVATION

As national governments across the world are committing to net-zero targets there is an urgent need to find effective innovative solutions to minimise waste and recover components and materials. The EU has recently announced its Green New Deal which includes a 50-55% emissions reduction target for 2030; a climate law to reach net-zero emissions by 2050; a transition fund worth €100bn and a series of new sector policies to ensure all industries are able to decarbonise.[24] In particular, the UK has committed to a net-zero target by 2050 and follows similar strategies, setting a budget of £350 million to cut emissions in heavy industry and drive economic recovery from coronavirus.[25]

When it comes to blades, there is currently a lot of R&D activity focussed upon reclamation (mechanical, thermal, chemical) including gasification, solvolysis, high voltage pulse fragmentation, pyrolysis, mechanical grinding as well as co-processing. Alternative materials such as carbon fibre, or blades that combine high-tech textiles into an internal composite structure, such as those developed by UK SME ACT Blade, have also a high potential to improve the performance and recyclability of blades.

In addition, there is a small number of SMEs who are starting to refurbish rotor and nacelle items, notably Renewable Parts Ltd who are currently able to refurbish small mechanical components such as brake callipers and yaw gears (and looking at new products in partnership with University of Strathclyde). They are mainly focussed onshore at the moment but looking to offer similar services to offshore operators. Renewable Advice is pioneering recycling of wind farm turbine blades, while Renewable Oil Services is another entity who have ambitions to recover high-value additives from gearbox oils.

Regarding rare earth materials, there are a number of end-of-life options available including direct reuse in their current form or shape, reprocessing of alloys to magnets after hydrogen decrepitation, pyrometallurgical methods, gas-phase extraction and hydrometallurgical methods.[26] A further initiative exploring this issue is the EU-funded project SUSMAGPRO (Sustainable Recovery, Reprocessing and Reuse of Rare Earth Magnets in a European Circular Economy). This project aims to develop a pilot supply chain for recycled neodymium magnets in Europe.[27] In the UK, the RaRE (Rare-earth Recycling for E-machines) project has secured £1.9m of funding from Innovate UK to develop technologies for recovering rare earth materials from old equipment and recycle them for use in new electric motors.[28] These are only some of the projects and research underway in this area. There is also a clear opportunity to substitute the rare earth magnets used in DD-PMGs with ferrite, an innovative design developed by the SME GreenSpur.

There are also a number of programmes and initiatives currently ongoing or ready to start globally. The most recent examples supported by the Offshore Renewable Energy (ORE) Catapult supports are SusWIND and the Circular Economy for Wind Sector Joint Industry Programme (CEWS JIP).

SusWIND has been launched by the National Composites Centre (NCC) in partnership with the ORE Catapult and is supported by the Crown Estate and RenewableUK. The aim of this initiative is to accelerate the development of technology, processes and materials that address the recyclability and future development of composite wind turbine blades. ORE Catapult collaborates closely with academia, such as our work with Dr Anne Velenturf of the University of Leeds who is leading research into a sustainable circular economy for wind energy infrastructure co-funded by EPSRC, ORE Catapult and the Department for International Trade. In parallel, ORE Catapult is developing an industry-wide five-year programme named Circular Economy for the Wind Sector (CEWS), which is open to both onshore and offshore wind farms in the UK and around the world that want to gain a detailed understanding of the cost implications for decommissioning and the end of life of monopiles, blades and key components with recycling/reuse and repowering potential.

CONCLUSIONS

- There is currently no specified waste legislation for the wind sector and although there is a legal requirement for recycling in the UK this is not tailored to the wind sector.
- Steel is the main material found in turbine structures, with fibreglass (and carbon fibre), resin or plastic, iron or cast iron, copper, and aluminium also comprising a significant share.
- Approximately 12,000 offshore wind units will be installed globally by 2025 representing 3.5 million tonnes of steel in foundations.
- 85-90% of a wind turbine's materials are technically recyclable but there are still difficulties with implementation due to lack of highly effective and feasible technologies, absence of provision in business models and gaps in regulatory framework.
- Blades are the most challenging part as these are usually made from GFRP which is a complex material and difficult to treat due to high costs, energy use and safety risks.
- A lot of R&D activity is underway for end-of-life treatment where carbon fibre is already used in larger blades and for manufacturing of blades combining an internal composite structure with high-tech textiles. Further improvements in design, reliability and reduction of material used for other components like the nacelle, tower, foundations and cables are also needed.
- On average recycling can save at least 35% of carbon emissions equivalent per kWh from assets in an offshore wind farm operating 6MW and 10MW turbines as opposed to new manufacturing of components.
- Early planning and a shift to a circular economic model will limit the disposal of scarce raw materials.
- Adapting a proactive approach to end of life in offshore wind as early as the design phase and establishing a sustainable framework can minimise the environmental impact of these assets and lead to a shift from linear to circular economic practices.

Appendices

RECOMMENDED READING

Circular Economy in Offshore Wind
Circular economy strategies for more sustainable wind energy
The wind industry's opportunity to lead the circular economy of the future
Sustainable Decommissioning: Wind Turbine Blade Recycling

AUTHOR PROFILE

Angeliki Spyroudi is Senior Strategy Analyst at the Offshore Renewable Energy (ORE) Catapult. She has a background in economics, regional development, environmental management and renewable energy technology. She investigates and analyses industry trends to give strategic insights of the offshore renewable energy market. In addition to this work, she conducts financial modelling on a variety of renewable energy projects, identifying cost reduction potential and the commercial viability of innovative technologies to support SMEs.

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