# Status Overview

## Decom offshore wind farms, recycling, reusing and selling of components/materials

EUROPEAN UNION

Interreg
North Sea Region
Decom Tools

European Regional Development Fund

# Contents

# List of Abbreviations

**CE** Circular Economy. 12, 13

**EU** European Union. 5, 10, 11

**GFRP** Glass-Fiber-Reinforced Polymer. 5

**GHG** Green House Gas. 9, 10

**IRENA** International Renewable Energy Agency. 1

**LCA** Life Cycle Assessment. 3, 10

**OWF** Offshore Wind Farm. 1–9, 11–13

**REE** Rare Earth Elements. 5, 8, 11

# 1 INTRODUCTION

## 1.1. BACKGROUND

The world today is now facing the adverse effects of the unprecedented human influence on the climate system. Many countries are now transforming their electricity sector with a focus on wind power to meet their climate targets. The International Renewable Energy Agency (IRENA) predicts onshore and offshore wind combined, would generate 35% of the global electricity demand by 2050 [1]. To reach this target IRENA forecasts around 1000 GW of offshore capacity and 5044 GW of onshore capacity to be installed in the world by 2050 [1]. By 2019, 22.1 GW of offshore wind has been installed in Europe and the European Commission estimates installation of 450 GW of offshore wind capacity by 2050 in the European countries [2]. With this surge in installation of new Offshore Wind Farm (OWF) and due to the ageing fleet of currently operating OWF, the number of OWF required to be decommissioned will increase in the coming years. Figure 1.1 represents the number of offshore wind turbines that will reach the 20-year operational lifetime each year in Europe. 22 offshore turbines in 2020, 80 turbines in 2022 and 123 turbines in 2023 will reach the planned lifetime of 20 years and will require decommissioning [3]. Decommissioning can be defined as "*All the measures performed to return a site close to its original state as is reasonably practicable, after the projects lifecycle reaches to an end*" [4]. As the offshore wind industry is relatively young, there is only a limited amount of practical experiences in decommissioning and disposing the OWF.

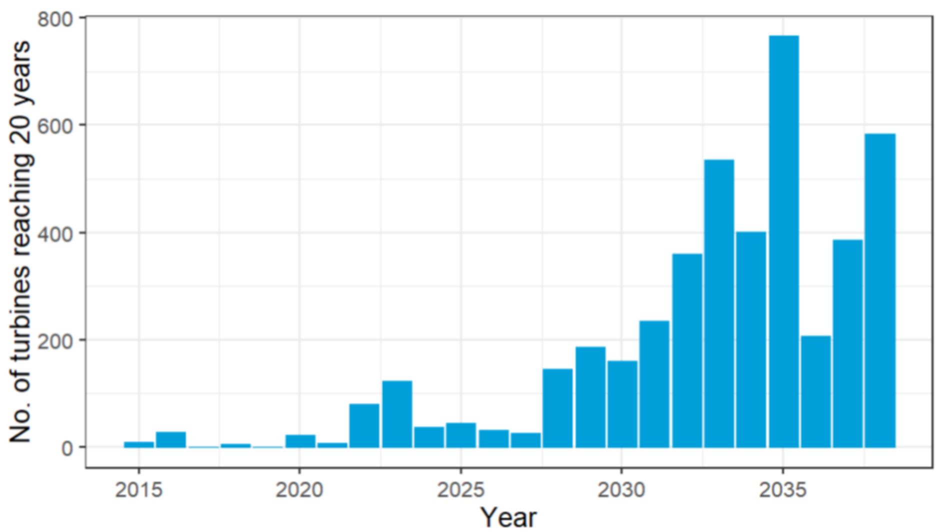


Figure 1.1: Number of offshore wind turbines reaching the 20-year lifetime annually in Europe [5]

The table 1.1 shows the list of decommissioned OWF in the world. Yttre Stengrund wind farm installed in Sweden was the first commercial offshore wind farm that was decommissioned in 2015. After 15 years of its operation, Vattenfall decommissioned the OWF. Vindeby (Denmark) was the world's first OWF installed back in 1991 and it was finally decommissioned in 2016 after 26 years of its operation. The decommissioning plan of the Beatrice Demo with Jacket foundations was approved in 2019 and it is expected that the turbines will be fully decommissioned between 2024 and 2027 [6].

Table 1.1: List of the decommissioned Offshore Wind Farms till date. Table based on the data from [5]. The OWF are arranged according to their year of decommissioning

| Wind farm | Country | Capacity and no. of WTs (MW) | Foundation type | Years of operation | Decommissioned year |
|---|---|---|---|---|---|
| Yttre Stengrund | Sweden | 10 (5 x 2MW) | Monopiles | 15 (2001-2015) | 2015 |
| Lely | Netherlands | 2 (4 x 0.5MW) | Monopiles | 20 (1994-2014) | 2016 |
| Vindeby | Denmark | 4.95 (11 x 0.45MW) | Gravity-Base | 26 (1991-2017) | 2017 |
| Utgrunden | Sweden | 10.5 (7 x 1.5MW) | Monopiles | 18 (2000-2018) | 2018 |
| Blyth | UK | 4 (2 x 2MW) | Monopiles | 13 (2000-2013) | 2019 |
| Beatrice Demo | UK | 10 (2 x 5MW) | Jacket | 8 (2007-2015) | 2024-2027 |

Decommissioning is the last phase in a projects lifecycle and it involves several steps. Initially, the **pre-decommissioning** preparations of submission of the decommissioning plan and getting the approval from the concerned authority is done. A detailed plan of the process with the availability of required equipment is made. Later the actual **decommissioning operations** involving the removal of structures is carried out. The wind farm is initially de-energised and isolated from the grid before the removal process. The structures are removed by carrying out processes reverse of installation. The process of turbine removal depends on the size of the turbine and vessel and crane being used to decommission. The foundations are either removed completely or are cut at seabed and the rest is left in situ depending on regulations and environmental impact. Different techniques to cut the structures that are implemented are diamond wire cutting, water jet cutting and use of controlled explosives. In the end, the **Post-decommissioning** stage corresponds to the disposal and maintenance of the decommissioned site. A survey after decommissioning is done to see the impact of the whole process and ensure that the site is brought close to its original condition.

Although the typical basic steps in the decommissioning process are same, the decommissioning plan changes with every OWF due to reasons like differences in governing regulations, locations of the site, type of structures and scale of decommissioning. Thus, the decommissioning process is found to be highly uncertain and is analyzed for each OWF in consideration.

After decommissioning, the components and different materials from an OWF need to be disposed of efficiently. Proper disposal of the components and the materials can generate monetary benefits and also reduce the overall environmental impact of the OWF. To harness this potential it is necessary to analyze the materials used in various components of an OWF. Different materials present their unique difficulties and key potentials when handled effectively. Furthermore, effective handling of the materials and components increases the overall sustainability image of wind turbines as a whole. The decommissioned turbine contains a mixture of various materials in its components that needs to be handled differently. Thus a study of the properties of these materials and the affecting parameters is necessary to optimally deal with the waste after decommissioning the OWF.


Hochschule Emden / Leer
+49 151 1527 0903
stephan.kotzur@hs-emden-leer.de
www.northsearegion.eu/decomtools

## 1.2. MATERIALS AND COMPONENTS USED IN OWF

The decommissioned turbine contains a mixture of various materials. The main materials used in an OWF are **cast iron, steel, copper, aluminium, fibreglass, epoxy and neodymium and dysprosium magnets**. These materials are further analyzed in the undertaken study. The required data for the analysis is gathered from various possible sources. Majority of the data was collected from the published articles, journals and websites. Qualitative validation of the collected data and more insights into the topic was done through correspondence with the people working in the wind industry. At present, there is no database specifying the mass of materials used in a wind farm according to wind turbine specifications. Thus, the data about the mass is gathered from several published studies. A total of 32 Life Cycle Assessment (LCA) studies were seen to be relevant with sufficient details in the data of mass of materials that could be used [7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23]. Out of these assessed studies, 15 Vestas published LCA were used [24]. These LCA studies specify the parameters of the wind farm into consideration and enlist the mass of materials present in the wind turbine as a bill of material. Data gathered from these studies was then modelled with curve fitting operations to give the aggregated value of mass of materials used in an OWF depending on its specifications. However, there are only a very few open source published studies specifying the mass of materials used in an offshore wind turbine. Hence an **important assumption was made in this analysis to consider the offshore wind turbine material content same as the onshore wind turbine.** Also, as the turbine components (Rotor, Tower, Nacelle) in both the turbine types onshore and offshore, have similar materials and quantities this further makes it a valid assumption. The construction of foundation which differs for an onshore and offshore turbine was specifically taken into account. Also, the difference in the cabling network of the wind farm which varies depending on onshore or offshore location was considered in this analysis. As generally there is a single offshore substation for an OWF, and the processes and materials of the offshore substation can be related to the structures of the wind turbine, modelling of the offshore substations was not considered in this analysis.

The materials used in a turbine were then split into different components namely **Rotor**, **Nacelle** and the **Tower** based on the LCA studies, as seen from table 1.2. A separate study for the **monopile foundations** for the turbines was considered to calculate the amount of steel used in the monopile foundations [25]. The materials used in inter-array and export cables were calculated based on the average turbine spacing and distance from the shore.

Table 1.2: Split of materials in a wind turbine into components obtained through the data from LCA studies. The percentage values of the materials highlighted in same colour add up to 100%

| Component | Materials | Split (%) |
|---|---|---|
| Rotor | Cast Iron | 31.3% |
| | Steel | 3.3% |
| | Fibre glass | 79.4% |
| | Epoxy | 100% |
| Tower | Steel | 76.6% |
| Nacelle | Aluminium | 100% |
| | Copper | 100% |
| | Magnet | 100% |
| | Steel | 20.0% |
| | Cast Iron | 68.7% |
| | Fibre glass | 20.6% |



Hochschule Emden / Leer
+49 151 1527 0903
stephan.kotzur@hs-emden-leer.de
www.northsearegion.eu/decomtools

The curve fit coefficients of the gathered data for the mass of materials are then used to predict the mass of materials in the considered OWF. As steel is predominantly found in the tower, the hub height of the turbine is chosen as a governing parameter for the mass of steel used. Cast iron, copper, magnet and aluminium as mainly used in the nacelle, the turbine capacity (MW) is the deciding factor while fibreglass and epoxy are used in the blades, thus rotor diameter is the governing factor to predict the mass of materials. This prediction model gives the mass of materials split into individual components depending on the specification of the OWF such as turbine capacity, rotor diameter hub height and distance from shore.

Similar to the mass of materials, other parameters of climate impact, recycling rate, monetary potential and criticality for the analyzed materials were found from various published studies.

## 1.3. DECOMMISSIONING ONSHORE AND OFFSHORE WIND FARM COMPARISON

There has been much more experience in decommissioning the onshore wind farms when compared to the offshore wind farms. There exist differences in the decommissioning operations of onshore and offshore wind farms. The governing regulations vary for onshore and offshore locations. Offshore decommissioning operations are dependent largely on the vessel and crane availability and are often difficult to perform due to harsh conditions at sea. The environmental impact is higher due to the need for foundation and cable removal for OWF. Additionally, the offshore substations need to be decommissioned as well in case of OWF. Compared to onshore sites, the risk of oil spillage, technical faults harm to the environment is larger while decommissioning the OWF. The decommissioned materials and components need to be transported through vessels to the ports and then disposed of respectively after OWF decommissioning.

Although the decommissioning operations of offshore sites differ and seem to be more difficult when compared to the onshore wind farms, the post disposal scenario is seen to be the same for onshore and offshore wind farms. As the materials and components are similar for onshore and offshore turbines, disposing of the components and materials is handled in a similar manner. The **only difference is in disposing of the different type of foundations and export cables** used in an OWF compared to the onshore wind farm which is considered in this analysis. But due to the similarities in the construction of turbines, **no prominent difference is observed in recycling, reusing and selling of the materials after decommissioning onshore and offshore wind turbines.** Thus the differences with regards to the disposing of the offshore foundations and cables are addressed in this analysis while disposing of the rest of the materials/components is similar in case of onshore and offshore wind farms.



Hochschule Emden / Leer
+49 151 1527 0903
stephan.kotzur@hs-emden-leer.de
www.northsearegion.eu/decomtools

# 2
# MATERIAL DISPOSAL STATUS

Different practices are undertaken to dispose of the materials and the components from the decommissioned OWF. Initially, the remaining life of the decommissioned components is estimated and if seen useful the components are reused for servicing of the wind turbines. However, predominantly the focus has been on recycling the materials from the components. A little thought on refurbishing and remanufacturing the materials and the components is giving by the industry. The main materials in an OWF are sold as a scrap material to gain monetary potential.

- **Steel, Cast iron, Copper, Aluminium :** Steel mainly used in the foundations and the tower sections of the wind turbine form the bulk of the material obtained. Steel and cast iron recycling industry has been established for many years thus these materials are easily recycled. Similarly, copper and aluminium is mainly recycled as they have a large monetary value.
- **Fibre glass, epoxy :** The fibreglass and epoxy resin used in the blades and the hub are of a primary discussion in the industry. Proper disposal of the fibreglass is one of the most challenging aspects due to the size of components, recycling complexity and low market value. The composites in the blades consist of various materials with different properties. The Glass-Fiber-Reinforced Polymer (GFRP) used is a thermoset composite and in a curing process, it undergoes an irreversible process which causes difficulty in recycling. Various European Union (EU) funded projects like ReFibre, Dreamwind, Genvind and LIFE BRIO focus on the investigation of new processes for proper disposal of blades [26].

  At present most of the blades are incinerated as an alternative to landfilling and the energy from combustion is used for other purposes. The blade sections are combusted at high temperatures up to 800 °C and the heat is used for energy recovery. However, the composites in blades have a low heating value thus limited energy recovery and around 60% of the scrap is left as ash which is harmful. Another common practice is to burn the reinforced plastic in cement kilns for cement production. About 10% of the input fuel is replaced with blades [27]. The fibreglass can also be treated with fluidised bed gasification operating at about 450 °C for better energy recovery. Or the pyrolysis technology of heating the blades in a reactor vessel under pressure in an inert environment can help recover the fibres for further low-level use. Solvolysis process is used to break the bonds of the carbon fibre usually at temperatures between 300 °C and 650 °C to recover the fibres with similar strength. Further research is carried out for viable commercial applications. Heating glass fibres above the temperature of 250 °C is shown to degrade their mechanical properties, thus the recovered fibres cannot be used in manufacturing wind turbine blades [28].
- **Magnets, Cables :** NdFeB (neodymium-iron-boron) magnets are most commonly used due to its superior performance. These magnets contain about 30% of Rare Earth Elements (REE) like Neodymium. At present, only a few companies deal with commercially recycling the magnets. Cables are initially separated into plastics and copper/aluminium, then the metals are recycled to gain high monetary value.

# 3
# Material Ranking

The importance of the main materials used in an Offshore Wind Farm (OWF) is assessed under various parameters like mass, recycling rate, monetary value, climate impact, complexity and criticality. Based on its relevance, ranks from 1 to 5 are given, where 1 signifies highly relevant or important while 5 indicates the material not so important under that parameter. The values of materials for the assessed parameters vary with respect to the OWF in consideration depending on the turbine capacity, number of turbines, type of foundations, etc. In the following section, the results of the Utgrunden wind farm located on the Swedish east coast are presented as a representative case study OWF. The Utgrunden OWF, owned by Vattenfall was decommissioned in 2018 by ZITON. The Utgrunden OWF had Enron Wind 70/1500 wind turbines with monopile foundations [29]. The OWF operated for 18 years before decommissioning. The figure 3.1 represents the specifications of the considered OWF. This dialogue box allows the user to model any OWF by changing these specifications.

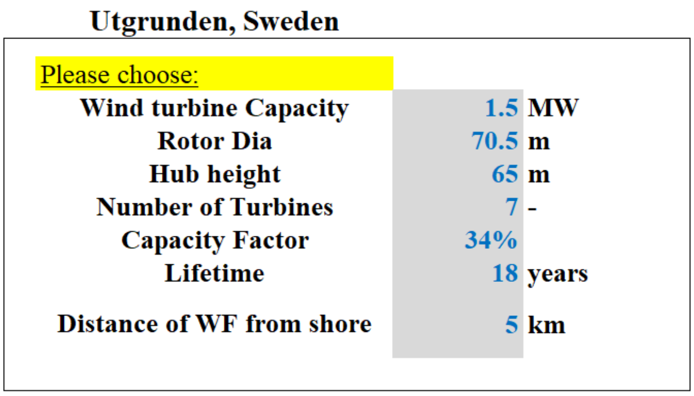


Figure 3.1: Dialogue box of the tool to choose the specification of the OWF in consideration. The values displayed are for Utgrunden OWF collected from [29].

## 3.1. Mass

The mass of the materials used in Utgrunden OWF was predicted by the developed model. The total mass of the materials used in the OWF was 2969 tonne. The table 3.1 shows the materials ranked according to the quantity used in the Utgrunden OWF. Steel being used in the monopile foundations accounts for half of the whole wind farm mass. Steel is by far the most used material in the wind farm with 85% of the overall mass of the materials used in the OWF of which 34% steel is used in the turbine (Rotor, Nacelle, Tower). Thus, steel is highly relevant from the mass point of view. Cast iron followed by steel is ranked at number 2 and the cable weight with plastic and copper accounts for 3.4% of the total mass of the OWF. The lowest of the analyzed materials, with $5^{th}$ rank was magnets weighing 6.3 tonnes of the whole OWF mass.

Table 3.1: Mass distribution of the materials used in the Utgrunden OWF presented with ranks in increasing order. The amounts corresponds to Utgrunden OWF with 7, 1.5MW wind turbines and their foundations and cables (array and export cables combined)

| Materials | Mass | Rank |
|---|---|---|
| Foundation | 51.1% | 1 |
| Steel | 33.9% | 1 |
| Cast Iron | 6.0% | 2 |
| Cables | 3.4% | 3 |
| Fibre glass | 3.3% | 3 |
| Epoxy | 1.3% | 4 |
| Copper | 0.4% | 5 |
| Aluminium | 0.3% | 5 |
| Magnet | 0.2% | 5 |

## 3.2. RECYCLING RATE

The recycling rate of the materials varies according to the quality of the material, concentration in a component and available infrastructure. In the case of wind turbines, due to large quantities of materials in its components, the recycling rates are high compared to the global averages. The table 3.2 shows the recycling rates of materials in an OWF based on the analysis done in the report on recycling wind turbines [30]. Copper, Cast iron and aluminium are highly recycled as the recycling industries have been well established, securing the $1^{st}$ rank. Similarly, recycling rate of the steel used in turbines is 92%, however during decommissioning, the monopile foundation below the seabed is kept in situ, thus a 50% recycling rate of steel in foundations is assumed indicating partial removal. At present, most of the blades are disposed to cement kilns for incineration, **this approach is considered as a recovery and not included as recycling in this analysis**. Thus, 15% of fibreglass and epoxy is assumed to be recycled back into similar fibre material. The recycling of magnets back into its raw material is not yet well established thus they have the lowest rank with 5% recycling rate.

Table 3.2: Recycling rates of the materials used in an OWF. Data based on [30] report.

| Materials | Recycling rate | Rank |
|---|---|---|
| Copper | 98% | 1 |
| Cast Iron | 98% | 1 |
| Aluminium | 95% | 1 |
| Steel | 92% | 2 |
| Cables | 90% | 2 |
| Foundations | 50% | 3 |
| Fibre glass | 15% | 4 |
| Epoxy | 15% | 4 |
| Magnet | 5% | 5 |

The aggregated recycling rate for the whole turbine is calculated by the equation 3.1. This portrays what part of the wind turbine can be recycled.

$$Recycling\ potential = \frac{\sum (Recycling\ rate * mass\ of\ material)}{\sum mass\ of\ material} \tag{3.1}$$



Hochschule Emden / Leer
+49 151 1527 0903
stephan.kotzur@hs-emden-leer.de
www.northsearegion.eu/decomtools

**The recycling potential of the wind turbine is 84%**. This indicates the fraction of the wind turbine being recycled. With an increase in the recycling of fibreglass and epoxy, higher recyclability can be achieved, If the foundations and cables are included, **the recycling potential of the whole Utgrunden OWF is 67%**. This reduction in the percentage is mainly due to the foundation being left below the sea-bed.

## 3.3. MONETARY VALUE

The table 3.3 shows the monetary value that can be salvaged by the wind farm owner by selling these materials as scrap on the scrap market to recycling facilities. The values are based on the data of scrap values taken from the London Metal Exchange. The values of steel, copper and aluminium are taken from the London Metal Exchange. For fibreglass and epoxy mainly present in the blades, on average the wind farm owner needs to pay for the disposal of blades which is around 150 EUR/tonne. This amount primarily highlights the cost of transportation and gate fees if any [31] and varies depending on regulations of that country. The magnets have valuable Rare Earth Elements (REE) in them, and a large concentration in a wind turbine results in a monetary value of between 11-12 USD/kg for magnets [32]. Cable recycling is gaining attention in Europe, with the scrap value around 2464 EUR/Tonne [33]. This relatively high value is due to the presence of copper in the cables. The monetary value of the materials that can be salvaged depends on the percentage of material being collected for recycling. It is calculated as below.

$$Monetary\,Value\,(EUR) = Mass\,(ton) * Monetary\,value\,(EUR/ton) * Recycling\,rate\,(\%)$$

Table 3.3: Monetary value potential of materials that can be generated by the wind farm owner by selling the materials to recycling facilities.

| Materials | Monetary Value | Rank |
|---|---|---|
| Cables | 32.1% | 1 |
| Steel | 30.6% | 1 |
| Foundations | 25.1% | 1 |
| Copper | 8.5% | 2 |
| Cast iron | 4.4% | 3 |
| Aluminium | 1.7% | 4 |
| Magnet | 0.5% | 4 |
| Epoxy | -0.8% | 5 |
| Fibre glass | -2.1% | 5 |

A total of 704714 € can be recovered by selling the materials from Utgrunden OWF. Around 32% of this monetary potential can be gained by recycling cables, this provides an incentive to remove all the cables. However, cable recycling infrastructure and process vary depending on location, so the monetary value can vary. Steel, even with its low monetary value per ton, due to the large amount being used in a wind farm, can generate up to 55% of monetary value with 30.6% generated from steel used in a turbine and 25% from steel being used in the monopile foundations, thus it has a $1^{st}$ rank. Copper can generate 8.5% monetary value due to its high scrap value. At present, magnets are not recycled on a large extent, with the assumed 5% recycling rate for magnets, they generate 3225 € or 0.5%. However, with a more focus on recycling



Hochschule Emden / Leer
+49 151 1527 0903
stephan.kotzur@hs-emden-leer.de
www.northsearegion.eu/decomtools

magnets in the near future by assuming a 90% recycling rate, magnets can salvage 58055 € with just 6.3 tons being used in the OWF. Disposing of fibreglass and epoxy primarily in blades incur costs for the wind farm owner. These costs vary depending on the regulations of the countries, with a cost of 150 €/ton, disposing of the blade materials would cost a total of around 3% of the monetary value (fibreglass and epoxy combined). Thus they are the lowest ranked at $5^{th}$ as it costs the wind farm owner money to dispose of the blades at present. Thus new measures to effectively dispose of these materials should be investigated.

## 3.4. CLIMATE IMPACT

The different materials used in a wind turbine require energy to produce them. The UNEP study mentions the energy consumed by the metals in primary and secondary production (from scrap). Primary production of aluminium is intensive with 190-230 MJ/kg required for every kilogram of aluminium production. Energy consumption for copper is between 30-90 MJ/kg and for steel, it is 20-25 MJ/kg [34]. Average Green House Gas (GHG) emissions from the production of the materials in a wind turbine are based on the ecoinvent database of Idemat [35]. As production of recycled glassfibres and magnets from recycled materials are still not commercial processes, no data was available. Production of epoxy resin by recycling interestingly emits more greenhouse gasses in the process due to extra processes to convert it back compared to virgin production.

The table 3.4 shows the net emissions calculated based on the emissions from primary and secondary production of materials. The net emissions are calculated as the emissions from primary production of a material subtracted by the savings in emissions from secondary production (recycling) of the same material. Magnets have the highest $CO_2 - eq$ emission with 12.51 $ton\ CO_2 - eq/ton$. Production of fibre glass emits 5.8 $ton\ CO_2 - eq/ton$ as at present it is not recycled back into its raw material. Primary production of aluminium emits 7.3 $ton\ CO_2 - eq/ton$, however, producing aluminium from scrap (recycling aluminium) produces only 2.5 $ton\ CO_2 - eq/ton$, thus a higher recycling rate of aluminium reduces its net GHG emissions to 2.8 $ton\ CO_2 - eq/ton$ and is at a $3^{rd}$ rank. Similarly, steel and cast iron emit more GHG gasses for their primary production, however, recycling them substitutes the need of virgin (primary) production hence lowering the $CO_2 - eq$ emissions. Thus they are ranked at $5^{th}$ spot.

Table 3.4: Net GHG emissions considering the primary production and savings from recycling of the materials. Data based on the ecoinvent database of Idemat [35]

| **Materials** | **GHG emissions (ton CO2-eq / ton)** | **Rank** |
|---|---|---|
| Magnet | 12.51 | 1 |
| Fibre glass | 5.82 | 2 |
| Epoxy | 2.80 | 3 |
| Aluminium | 2.77 | 3 |
| Copper | 2.27 | 3 |
| Cables | 1.68 | 4 |
| Foundations | 1.42 | 4 |
| Steel | 0.67 | 5 |
| Cast Iron | 0.37 | 5 |


Hochschule Emden / Leer
+49 151 1527 0903
stephan.kotzur@hs-emden-leer.de
www.northsearegion.eu/decomtools

The average GHG emission intensity for the turbine is calculated by multiplying the mass and GHG intensity of that material and dividing by total mass of a turbine as 193 tons. Thus on average, 1kg of material used in a wind turbine emits 1.15 $kg\ CO_2 - eq/kg$ of GHG. The table 3.4 shows only the climate impact (GHG emissions) of the materials, detailed Life Cycle Assessment (LCA) analysis of the materials show that different materials have different intensity of environmental impact. The rankings of the materials change if the indicator is water use, toxicity or resource scarcity.

## 3.5. Complexity

The complexity refers to the difficulty of recycling the material. Thus rank 1 indicates a material difficult to recycle while $5^{th}$ rank signifies easy recycling of material. At present, there are only a very few companies who look into commercial scale recycling of magnets as the process of recycling magnets is still difficult, thus it ranks first in the complexity of recycling. Similarly, there is still research ongoing to develop a commercial process to recycle the glass fibres and epoxy back into the raw materials. Recycling the blades is the topic of discussion in the wind industry today and with no clear commercial solution in practice, it also ranks first in the complexity of material recycling. The cables due to the need for separation of plastic coating and copper is ranked $2^{nd}$. The steel in the monopile foundation as it is submerged under the sea, it first needs to be scraped of any deformities and then recycled, hence are ranked at a $3^{rd}$ spot. Recycling experience of aluminium, copper, steel and cast iron is transferable from other industries and have been developed since many years. Thus, they are not considered to be a complex process for recycling and have lower ranks.

Table 3.5: Ranking of materials based on complexity (difficulty of recycling) the materials. Ranks given based on author's analysis

| **Materials** | **Complexity Rank** |
|---|---|
| Magnet | 1 |
| Fibre glass | 1 |
| Epoxy | 1 |
| Cables | 2 |
| Foundations | 3 |
| Aluminium | 4 |
| Copper | 4 |
| Steel | 5 |
| Cast Iron | 5 |

## 3.6. Criticality

The criticality of various materials has been analyzed by the EU. The criticality is a measure of how a certain material is economically and strategically crucial for the European economy. Raw materials with high importance to the EU economy and with high risk associated with their supply are addressed as critical materials. The economic importance is calculated based on the importance of a given material in the EU economy in terms of end-use applications and the value added in various sectors. The supply risk represents the disruption of the supply chain of the materials to EU. It is based on the concentration of the primary supply from countries and their governance. Availability of substitute materials that can be feasibly replaced for the same



Hochschule Emden / Leer
+49 151 1527 0903
stephan.kotzur@hs-emden-leer.de
www.northsearegion.eu/decomtools

purposes, and secondary production of raw materials by recycling reduces the criticality of the material.

Table 3.6: Ranking of criticality of materials with 1 as highly critical and 5 as least critical material. Ranking is based on the author's analysis of EU Critical raw materials report [36].

| **Materials** | **Criticality Rank** |
|---|---|
| Magnet | 1 |
| Steel | 2 |
| Cast Iron | 2 |
| Aluminium | 3 |
| Fibre glass | 4 |
| Epoxy | 4 |
| Cables | 4 |
| Copper | 5 |

The table 3.6 shows the rank of the criticality of materials used in an OWF. The EU report on critical materials does not rank the critical materials, thus the ranks in the table are author's analysis based on the values of supply risk and economic importance in the report [36]. The NdFeB magnets are the most critical material used in an OWF. China produces almost 95% of the global REE required for the magnets, thus it poses a huge supply risk. Also, low recycling of REE at present further adds to the criticality. Extensive use of cast iron and steel in all the sectors in EU makes them the $2^{nd}$ critical material. The synthetically produced fibres and resins can be produced anywhere, thus they are at a lower $4^{th}$ rank. Whereas, a low supply risk in manufacturing copper makes it the last ranked critical material under consideration.

This chapter shows how the prominence of materials change under different comparing parameters. This analysis depicts the need to focus on multiple materials and continue the research to increase the usability, monetary value and sustainability of the materials used in an OWF. The next chapter highlights the important conclusions and recommendations for better handling of the materials from decommissioned OWF.



Hochschule Emden / Leer
+49 151 1527 0903
stephan.kotzur@hs-emden-leer.de
www.northsearegion.eu/decomtools

# 4
# Conclusion and Recommendations

As seen from the previous discussion, different materials were highly ranked under different parameters like mass, recycling rate, monetary value, climate impact, complexity and criticality. Steel is important due to the quantity used and monetary potential. Cables are important from monetary perspective. Magnets are highly critical and have high climate impact. Blades are crucial due to their volume and complexity in effective disposal. These important materials should be on focus to maximize the benefits. Also, further research on finding substitutes of these materials to limit the dependency should be carried out. **Hence a wind farm owner should have special attention on steel, cables, magnets and wind turbine blades.**

At present the main focus is on finding ways to recycle the material, however there is an opportunity to apply the principles of Circular Economy (CE) in disposing of the materials/components from the decommissioned OWF. The goal of the CE principle is to make sure that the products or materials re-enter the system at the highest possible quality. The figure 4.1 shows the preferred approach according to the CE principles in disposing of the components. The prevention of resources from being consumed is the most preferred option compared to disposing of the waste.

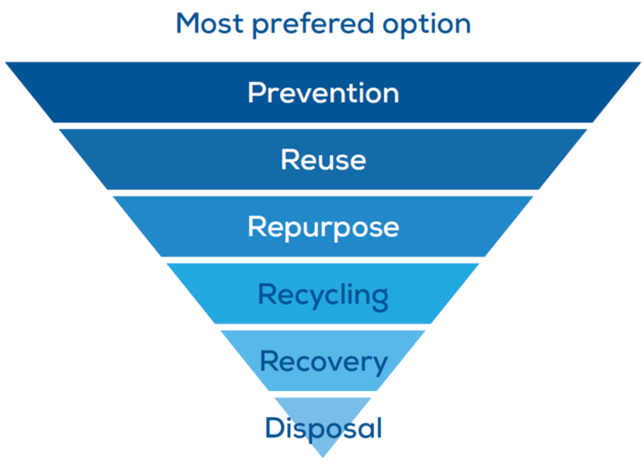


Figure 4.1: Waste hierarchy according to CE principles for sustainable waste management. Source: image taken from [37]

In the case of wind turbines, the primary focus should be on to reduce the amount of waste being generated, this can be achieved by a mass reduction in the components and minimize the waste during production. During the operation phase, the wind turbine should be duly maintained and required repairs should be done to increase its lifetime. When further repair work turns unfeasible, the working components can be reused directly for other wind turbines. Remanufacturing should be done if some major components need replacements, functional parts from other turbines can be used to rebuild a working wind turbine. Also, the components after some processes can even be repurposed for applications other than a wind turbine. If the component as a whole cannot have a functional use, the materials in it are recycled to obtain raw material. If the recycling is not feasible, the energy from the component can be harnessed to utilize for other processes by incinerating the material. Lastly, landfilling of the material or incinerating without any recovery is least favoured when disposing of waste.

Thus, the decommissioned components should be assessed for other operations than directly recycling, to increase monetary benefits and sustainability and adhere to the CE principles. The following are the recommendations that can be implemented while disposing the components from the decommissioned OWF.

Tower : The tower sections should be checked for any cracks and the sections can be used in remanufacturing a wind turbine tower or can be used as a supporting structure for other applications. Also, substituting the steel with other sustainable materials is also gaining traction. Recently in May 2020, Modvion a Swedish company installed a 30m wooden tower [38].

Nacelle : The Nacelle of a wind turbine contains several materials, thus it is difficult to dismantle and segregate. The electronic components should be tested and if possible repaired or refurbished to use for other applications. The permanent magnets from the generator should be separated and the usable magnets can be reused after the magnetization process.

Blades : Reusing the blades for wind turbines is limited due to the deterioration in the quality after their lifetime. However, the blades present ways to remanufacture and re-purpose for other applications. The blades can be used to build bridges, public benches, house roofs, playgrounds, noise insulation barriers, precast concrete material and bike sheds.

Foundation : The whole foundation if possible can be reused as a base for upcoming technologies like Airborne Wind energy systems which are lighter in weight hence the reuse of foundations could be feasible for these technologies.

Cables : If repowering is considered, the same cables might be used due to their long lifetime, however technical feasibility should be assessed. Further research into increasing the recycling efficiency of cables should be done.

Overall there is still limited experience in decommissioning of the OWF. There is an urgent need to introduce improvements in handling the decommissioned OWF to further increase the sustainability and monetary gains from the wind farms. This offers opportunities for applying new concepts like CE for effective decommissioning and disposal of materials. To implement this, analysis of the materials used in the OWF is crucial and to find the prominence of materials under different parameters.

# Bibliography


[1] IRENA. *Future of wind - deployment, investment, technology, grid integration and socio-economic aspects*. 2019, pp. 1–88. ISBN: 9789292601553. URL: https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2019/Oct/IRENA_Future_of_wind_2019.pdf.

[2] Wind Europe. “Our Energy Our Future”. In: (2019).

[3] “Market Analysis DECOM Tools”. In: *Interreg North Sea Region* (2019), pp. 1–9. URL: https://periscope-network.eu/analyst/market-analysis-decom-tools-2019.

[4] Eva Topham and David Mcmillan. “Sustainable decommissioning of an offshore wind farm”. In: *Renewable Energy* 102 (2017), pp. 470–480. ISSN: 0960-1481. DOI: 10.1016/j.renene.2016.10.066. URL: http://dx.doi.org/10.1016/j.renene.2016.10.066.

[5] Eva Topham et al. “Challenges of decommissioning offshore wind farms : Overview of the European experience”. In: *J. Phys.: Conf. Ser.* (2019). DOI: 10.1088/1742-6596/1222/1/012035.

[6] ReNEWS.BIZ. *UK approves Beatrice demo decommissioning*. URL: https://renews.biz/51147/uk-approves-beatrice-demo-decommissioning-plan/.

[7] Fulvio Ardente et al. “Energy performances and life cycle assessment of an Italian wind farm”. In: *Renewable and Sustainable Energy Reviews* 12.1 (2008), pp. 200–217. ISSN: 13640321. DOI: 10.1016/j.rser.2006.05.013.

[8] Begoña Guezuraga, Rudolf Zauner, and Werner Pölz. “Life cycle assessment of two different 2 MW class wind turbines”. In: *Renewable Energy* 37.1 (2012), pp. 37–44. ISSN: 09601481. DOI: 10.1016/j.renene.2011.05.008.

[9] Mohamed R. Gomaa et al. “Evaluating the environmental impacts and energy performance of a wind farm system utilizing the life-cycle assessment method: A practical case study”. In: *Energies* 12.17 (2019). ISSN: 19961073. DOI: 10.3390/en12173263.

[10] Hermann Josef Wagner and Jyotirmay Mathur. “Life Cycle Assessment of a Wind Farm”. In: *Green Energy and Technology* 20.9783642329753 (2013), pp. 85–92. ISSN: 18653537. DOI: 10.1007/978-3-642-32976-0{_}8.

[11] Nesrin Demir and Akif Takin. “Life cycle assessment of wind turbines in PInarbaI-Kayseri”. In: *Journal of Cleaner Production* 54 (2013), pp. 253–263. ISSN: 09596526. DOI: 10.1016/j.jclepro.2013.04.016.

[12] Alexandra Bonou, Alexis Laurent, and Stig I. Olsen. “Life cycle assessment of onshore and offshore wind energy-from theory to application”. In: *Applied Energy* 180 (2016), pp. 327–337. ISSN: 03062619. DOI: 10.1016/j.apenergy.2016.07.058.

[13] Elsam Engineering A/S. “Life Cycle Assessment of offshore and onshore sited wind farms”. In: *Engineering* October (2004), p. 54. ISSN: Doc. no. 200128. URL: http://www.apere.org/manager/docnum/doc/doc1252_LCA_V80_2004_uk[1].fiche%2042.pdf.

[14] Jan Weinzettel et al. “Life cycle assessment of a floating offshore wind turbine”. In: *Renewable Energy* 34.3 (2009), pp. 742–747. ISSN: 09601481. DOI: 10.1016/j.renene.2008.04.004. URL: http://dx.doi.org/10.1016/j.renene.2008.04.004.

[15] E. Martínez et al. “Life cycle assessment of a multi-megawatt wind turbine”. In: *Renewable Energy* 34.3 (2009), pp. 667–673. ISSN: 09601481. DOI: 10.1016/j.renene.2008.05.020.

[16] Manfred Lenzen and Jesper Munksgaard. “Energy and CO 2 life-cycle analyses of wind turbines review and applications”. In: 26.2002 (2002), pp. 339–362. URL: https://www.journals.elsevier.com/renewable-energy.

[17] Yuh Ming Lee and Yun Ern Tzeng. “Development and life-cycle inventory analysis of wind energy in Taiwan”. In: *Journal of Energy Engineering* 134.2 (2008), pp. 53–57. ISSN: 07339402. DOI: 10.1061/(ASCE)0733-9402(2008)134:2(53).

[18] Karl R. Haapala and Preedanood Prempreeda. “Comparative life cycle assessment of 2.0 MW wind turbines”. In: *International Journal of Sustainable Manufacturing* 3.2 (2014), pp. 170–185. ISSN: 17427231. DOI: 10.1504/IJSM.2014.062496.

[19] Jian bo Xie et al. “Assessments of carbon footprint and energy analysis of three wind farms”. In: *Journal of Cleaner Production* 254 (2020). ISSN: 09596526. DOI: 10.1016/j.jclepro.2020.120159.

[20] Roberto Dones et al. “Life Cycle Inventories of Energy Systems : Results for Current Systems in Switzerland and other UCTE Countries. Ecoinvent report No. 5. Paul Scherrer Institut Villigen, Swiss Centre for Life Cycle Inventories”. In: *Ecoinvent report* 5 (2007).

[21] P. Koltun and A. Tharumarajah. “Life Cycle Impact of Rare Earth Elements”. In: *ISRN Metallurgy* 2014 (2014), pp. 1–10. ISSN: 2090-8717. DOI: 10.1155/2014/907536.

[22] Jesuina Chipindula et al. “Life cycle environmental impact of onshore and offshore wind farms in Texas”. In: *Sustainability (Switzerland)* 10.6 (2018), pp. 1–18. ISSN: 20711050. DOI: 10.3390/su10062022.

[23] R. H. Crawford. “Life cycle energy and greenhouse emissions analysis of wind turbines and the effect of size on energy yield”. In: *Renewable and Sustainable Energy Reviews* 13.9 (2009), pp. 2653–2660. ISSN: 13640321. DOI: 10.1016/j.rser.2009.07.008.

[24] Vestas. *Vestas Life Cycle Assessments*. URL: https://www.vestas.com/en/about/sustainability#!lcareports.

[25] Vicente Negro et al. “Monopiles in offshore wind: Preliminary estimate of main dimensions”. In: *Ocean Engineering* 133 (2017), pp. 253–261. ISSN: 00298018. DOI: 10.1016/j.oceaneng.2017.02.011.

[26] Wind Europe. “Discussion paper on managing composite blade waste”. In: (). URL: https://windeurope.org/wp-content/uploads/files/policy/topics/sustainability/Discussion-paper-on-blade-waste-treatment-20170418.pdf.

[27] Spyridoula Karavida and Reet Nõmmik. “Waste Management of End-of-Service Wind Turbines”. PhD thesis. URL: https://projekter.aau.dk/projekter/en/studentthesis/waste-management-of-endofservice-wind-turbines(c318ea18-6b67-491c-9258-f58233e3796f).html.

[28] ETIP Wind. “How wind is going circular - Blade recycling”. In: 826042 (2019).

[29] *4COffshore Utrunden 1Offshore Wind Farm*. URL: https://www.4coffshore.com/windfarms/sweden/utgrunden-i-sweden-se03.html.

[30] Per Dannemand Andersen et al. “Recycling of wind turbines”. In: *DTU International Energy Report 2014* July (2014), pp. 91–98. URL: http://www.natlab.dtu.dk/english/Energy_Reports/DIER_2014.

[31] *END OF LIFE OPTIONS FOR COMPOSITE MATERIALS*. URL: https://compositesuk.co.uk/composite-materials/properties/end-life-options.




Hochschule Emden / Leer
+49 151 1527 0903
stephan.kotzur@hs-emden-leer.de
www.northsearegion.eu/decomtools

[32] Jonas Pagh Jensen. “Narrowing , Slowing and Closing the resource Loops - Circular economy in the wind industry”. PhD thesis. 2018. ISBN: 9788772101569.

[33] *Rockaway Recycling*. URL: https://rockawayrecycling.com/metal/insulated-cable/.

[34] UNEP. *Environmental Risks and Challenges of Anthropogenic Metals Flows and Cycles*. Tech. rep. 10. 2013, pp. 769–770. DOI: 10.1227/01.NEU.0000108643.94730.21.

[35] *IDEMAT eco costs*. URL: https://www.ecocostsvalue.com/EVR/model/theory/subject/5-data.html.

[36] EUROPEAN COMMISSION. *Study on the review of the list of critical raw materials - Publications Office of the EU*. Tech. rep. 2017. DOI: 10.2873/876644. URL: https://op.europa.eu/en/publication-detail/-/publication/08fdab5f-9766-11e7-b92d-01aa75ed71a1#.

[37] “Accelerating Wind Turbine Blade Circularity”. In: May (2020).

[38] *Modvion-Swidish company developing wooden modular towers*. URL: http://www.modvion.com/.




Hochschule Emden / Leer
+49 151 1527 0903
stephan.kotzur@hs-emden-leer.de
www.northsearegion.eu/decomtools