Belgium Offshore Wind Farms Decommissioning Costs Project

FPS Economy

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Executive Summary

Belgium offshore wind farms (OWFs) became operational from years 2009 till 2020. They are expected to be decommissioned from 2034 onwards. This report presents the results of the desktop study to predict the decommissioning costs and recycling revenues of all these assets. It has been predicted that decommissioning costs of existing OWFs in Belgium of 2.26GW capacity is about 952MEUR and offshore high voltage stations (OHVS) is about 215.7MEUR. Maximum possible revenues from materials resale is estimated at about 234.5MEUR.

OWF decommissioning cost has been estimated by estimating and adding up costs of wind turbine (WTG) removals, foundation removals, inner-array and export cable removals, scour protection removals, fuel used during major offshore works, pre-decommissioning and project management. In terms of WTG removal, reverse installation (i.e., first blades are removed one by one, then nacelle, and then the tower) and bunny ear configuration (i.e., one blade is removed first and then complete rotor with two blades are removed at once, followed by nacelle and tower removals) scenarios have been evaluated. For foundations, full extraction of the monopiles are considered and compared with the monopile internal cutting from under the seabed. All major works have been realized by jack-up vessels (JUV) supported by barge vessels (BV) and tug boats (TB). In case of gravity based foundation removal, de-ballasting, refloating and towing to the shore have been considered. Complete removal of all inner array and export cables and scour protections have been estimated. 9% of pre-decommissioning costs and 10% project management costs have been included in these numbers. Total of nine existing OWFs in Belgium have been modelled together with eight generic OWFs for the trend analysis. 150MW and 300MW OWFs with 3MW and 8MW WTGs and 700MW OWFs with 8MW, 12MW, 15MW and 22MW WTGs have been created and modelled for the trend analysis. Two scenarios using sheerleg or high lift vessels (HLV) have been used to predict OHVS removal costs. Experience and lessons learned from oil&gas platforms have been used for these predictions.

The study showed that WTG and foundation removals occupy 63% of the total decommissioning costs. Number of turbines, WTG capacity, vessel selection and offshore workability have the highest impact on the overall costs. Especially, higher WTG capacity has reduced the decommissioning costs for the same OWF capacity. It was predicted that a quarter of the decommissioning costs could be earned back with the material resale as maximum. When compared with the other studies from the literature, average cost of 421kEUR/MW calculated in this study is well in line with the average cost predictions from these studies. Nevertheless, more dedicated and detailed analysis should be performed, taking the actual state of the assets, workable weather windows and vessel availability into account, to accurately predict the actual decommissioning costs for every single OWF.

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Abbreviations

Abbreviation	Definition
BPNS	Belgian Part of the North Sea
BV	Barge vessels
COD	Commercial Operation Dates
EOL	End-Of-Life
GBF	Gravity based foundation
GFRPs	Glass-Fiber-Reinforced Polymers
JUV	Jack-up vessel
LCA	Life Cycle Assessment
MBD	Mechanical break down
MW	Megawatt
MEUR	Million Euro
NdFeB	Neodymium-iron-boron
OHVS	Offshore high voltage station
OWF	Offshore Wind Farm
PM	Project Management
REE	Rare Earth Element
TB	Tug boat
VLAREMA	VLAams REglement betreffende het duurzaam beheer van Materiaalkringlopen en Afvalstoffen
WDT	Weather downtime
WTG	Wind turbine generator

1 Introduction

1.1 The assignment

IMDC has been given the assignment by FPS Economy to perform a study on decommissioning cost estimations and revenues for the existing Belgium offshore wind farms (OWFs) and for the future potential wind farms in Princess Elisabeth Zone (PEZ).

Belgium OWFs became operational between 2009 and 2020 and they are expected to be decommissioned starting from 2034 till 2045. All wind farms should provide decommissioning provisions. This desktop study has been asked to provide detailed decommissioning cost estimations depending on the specific technology used in the wind farms and considering the Belgium context. These costs are estimated for wind turbines (WTGs), foundations, cables (both inner-array and export), OHVS (offshore high voltage stations). Furthermore, potential revenues via considering recycling or re-use options are required to be predicted.

1.2 Scope of the study

In total nine OWFs are located in the Belgium North Sea (Figure 1 1) which have in total of 2.26GW capacity. These OWFs consist of 399 units of WTGs with capacities ranging from 3MW to 9.5MW. Except C-Power, all OWFs have monopile foundations. C-Power contain six gravity based foundation (GBF) and 48 jacket foundations. Belwind has one demonstration wind turbine on a jacket foundation. Nine OHVS are used to collect and transport the generated electricity to the shore together with appx. 400km of inner-array cables and 320km of export cables.

The scope of this study is to predict:

- the costs of complete removal of all these assets,
- the costs of removal of generic wind farms of 150MW, 300MW and 700MW which contain 3MW (for 150MW and 300MW OWF case), 8MW, 12MW, 15MW and 22MW (12,15,22MW are only for 700MW OWF) WTGs as trend analysis,
- the mass and volume of all materials and recycling revenues of these assets.

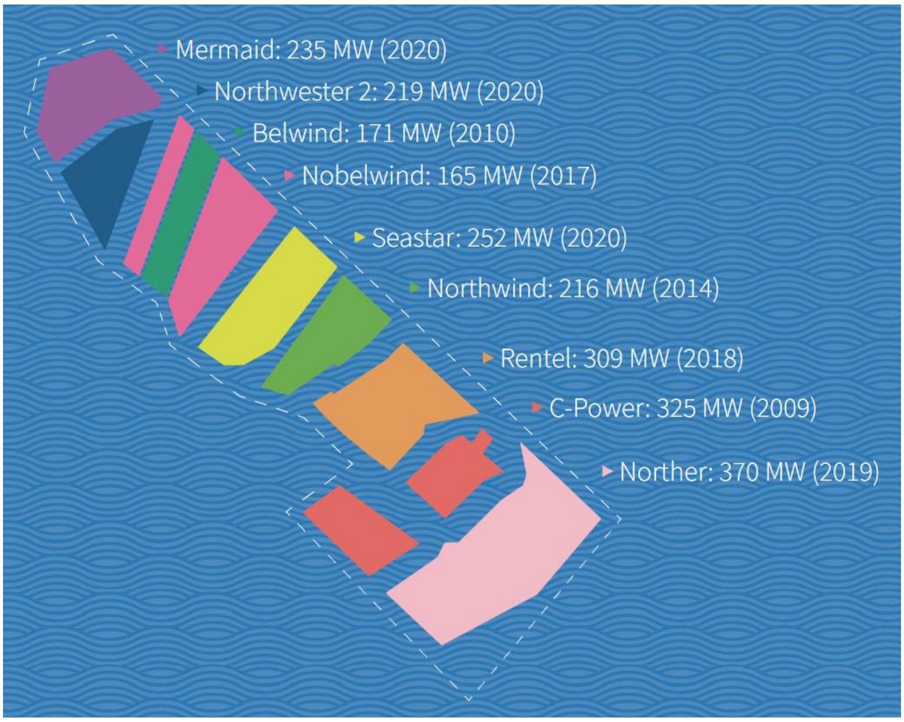

Figure 1-1 Existing OWFs in Belgium[1]

1.3 Approach

Cost predictions of OWF decommissioning varies significantly depending on the assets type, weight and dimensions, selected decommissioning techniques, vessels, equipment, etc. Experience and literature in this topic is still in development due to the increasing number of OWFs expected to be decommissioned in the next 10-15 years. Following steps have been followed in this project for the predictions:

- Nine Belgium OWF specifications are investigated in details: dimensions and material weights, locations, lengths; but also permit conditions of the concessions,
- Eight generic OWFs are generated and inputs are adapted from existing OWFs or other literature,
- Latest literature related to the decommissioning, recycling and end-of-life strategies of OWFs is analysed,
- Expert interviews are conducted about installations of Belgium OWFs, offshore oil-and-gas decommissioning activities, recycling methods specific to WTGs and blades,
- IMDC’s cost model is further expended,
- Removal and recycling scenarios are developed,
- All wind farms are modelled with the cost prediction model,
- All costs are predicted, several sensitivity studies are conducted, validations in the form of comparing with previous studies are performed,
- All material masses and volumes are predicted and revenues are estimated.

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[1] https://www.belgianoffshoreplatform.be/en/projects/ accessed on 24/11/2023

For decommissioning cost modelling, parametrisation and decommissioning scenarios (Jalili *et al.*, 2022), (Shafiee and Adedipe, 2021), (Devoy McAuliffe *et al.*, 2018), (Nielsen, 2022) and (Eckardt *et al.*, 2022) have been used as main resources and they have been combined with the internal expertise within IMDC to further develop and adapt for the Belgium OWFs specific requirements. OHVS decommissioning costs have been estimated based on the experience coming from oil & gas platforms decommissioning. Recycling and end-of life scenarios for the OWF assets have been elaborated based on literature, interviews and internal expertise for Belgium context.

1.4 Reading guidance

This report consist of six chapters. First chapter summarizes the goal and scope of the project and describes the approach followed. Second chapter describes the decommissioning activities modelled in this project together with OWFs analysed and provides a summary of major technical assumptions. Third chapter focuses on the decommissioning cost prediction results as envisaged in chapter two. Chapter four describes the methodology of OHVS decommissioning and contains the decommissioning cost estimation results of different OHVSs with different dimensions. Chapter five explains recycling and end-of-life options for OWF assets, and provides revenue estimations for Belgium OWF assets. Chapter six is the last chapter and provides some discussion points.

2 Decommissioning works

2.1 Introduction

Decommissioning of offshore wind farms (OWF) projects consists of several offshore activities which can be divided as cost elements (Figure 2-1). This work-breakdown structure is used as baseline to calculate the decommissioning costs.

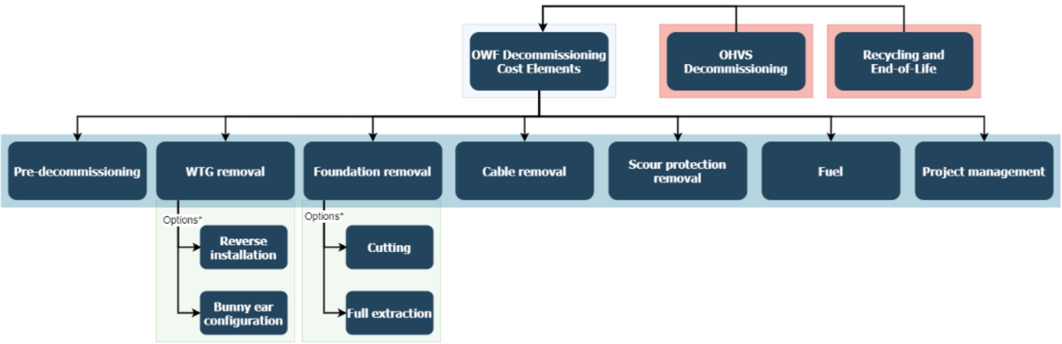

Figure 2-1 Activities and cost elements in OWF decommissioning

Decommissioning costs of the OWFs are modelled as follows:

$$c_{OWFdecom} = c_{pre} + c_{WTGr} + c_{FOUNr} + c_{CABLEr} + c_{SCOURr} + c_{fuel} + c_{PM}$$

Equation 2-1 Decommissioning costs work-breakdown

Where:

- $c_{OWFdecom}$: Total cost of offshore wind farm decommissioning,
- c_{pre}: cost of pre-decommissioning activities,
- c_{WTGr}: cost of WTG removal,
- c_{FOUNr}: cost of foundation removal,
- c_{CABLEr}: cost of inter-array and export cables removal,
- c_{SCOURr}: cost of scour protection removal,
- c_{fuel}: cost of fuel used during the decommissioning activities,
- c_{PM}: cost of project management of decommissioning project activities.

All costs are given in EURs and are using price sheets of 2023 (indexation calculated at the year of decommissioning is not included). These costs (chapter 3.1) are modelled using process based approach by estimating the duration of each activity, vessels and other equipment necessary for these activities and their rental prices and finally summing them up as shown in Equation 2-1.

Recycling and end-of-life related activities are covered in chapter 5. This means, the decommissioning works included in this chapter covers all activities until the offshore assets reach the port.

Decommissioning of OHVSs (chapter 4) are estimated separately by using lessons learnt and strategy from decommissioning of oil & gas platforms.

2.2 Removal scenarios

2.2.1 Vessel Selection

Major decommissioning activities are assumed to be carried out by large jack-up vessels (JUV) and the assets are transported to the shore using barge vessels (BV) towed by tug boats (TB). Alternatively, heavy lift vessels (HLV) could be used for these activities. HLVs have higher lifting capacity, and they can operate at higher water depths. On the other hand, they are more expensive than JUVs. Table 2-1 shows some example vessels used during the installation works in Belgium OWFs. Due to the relatively low water depths (20-25m in average), in principal, JUVs are suitable for the decommissioning works in Belgium OWFs. Rental price of JUVs also varies, for example, if they are used for transportation, in jack-ups mode or only in DP2 and lifting activities. Figure 2-2 shows typical day rates of vessels in function of their lifting capability. For this project daily rate of 200 kEUR is used which corresponds to about 2100 tons of lifting capacity according to Figure 2-2. This daily rate is taken as a representative price for the vessels to be used during the offshore decommissioning works.

Table 2-1 Some examples of installation vessels used in Belgium OWFs (Jalili *et al.*, 2022).

OWF	Foundation installation	WTG installation
C-power (Phase I)	Rambiz	Buzzard
Belwind	Svanen, JB114	JB114, JB115
C-Power (Phase II)	Buzzard, Rambiz	Neptune, Vagant
C-Power (Phase III)	Buzzard, Rambiz	Goliath, Vagant
Belwind (Prototype)	Pasific Osprey	Bold Tern
Northwind	Neptune	Resolution, Neptune
Nobelwind	Vole au Vent	Vole au Vent
Rentel	Innovation	Apollo

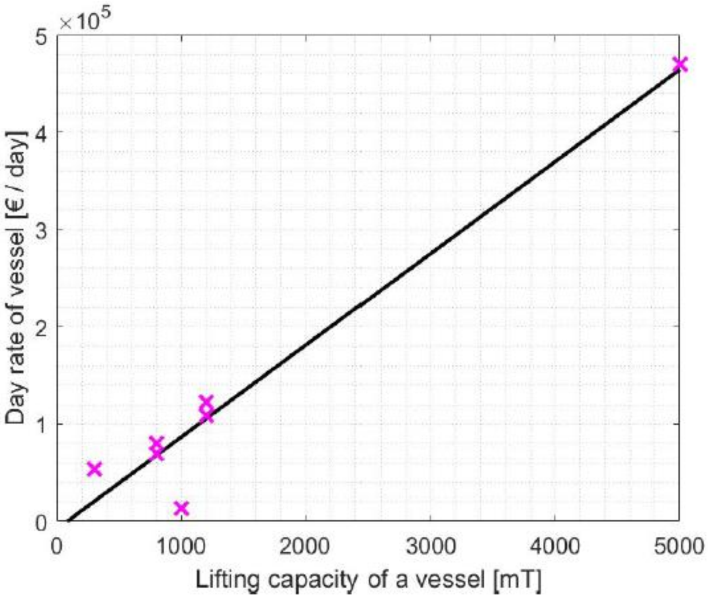

Figure 2-2 Vessel day rates shown for their lifting capacity (Nielsen, 2022)

2.2.2 WTG removal

WTG removal starts by parking the rotor, disconnecting and isolating it from the grid completely. Wind turbine removal preparation depends on the specific wind turbine and removal method selected. Nevertheless, it is important to make sure that all hazardous materials and fluids are removed from the nacelle and inspections are performed to assess the risks and plan safe removal operations. Moreover, it is important to remove the blades and the nacelle as fast as possible to mitigate the impact of parked condition loads that damage the wind turbine and create a safety concern. Normally, the order of removal is blades, hub and nacelle, and tower.

Two WTG removal methods are considered in this project.

- A reverse installation method, i.e. removing the blades one by one and then removing the nacelle, and removing the tower by cutting it into half is one of the most common technique used and considered as wind turbine removal method.
- The second method is called "bunny ear configuration" (Figure 2-3) where only one of the blades is removed and then the rest of the rotor is removed with two blades together in a single lift. Afterwards, nacelle and then tower are removed respectively. Alternatively, depending on the size of the rotor and the nacelle, it is also possible to remove the rotor with two blades, and nacelle completely in a single lift Figure 2-3. That alternative is not considered in this study which means we include the additional time to remove the nacelle[2]. Removal by bunny ear configuration is interesting because it can offer faster WTG removal possibility, so less offshore operations and lifting activities. It is highlighted that this method would require larger transportation vessels.

Figure 2-3 Wind turbine removal via bunny ear configuration and the vessels involved during Vindeby offshore wind farm decommissioning[3].

Implementation of these methods to the cost model is done by following the parametrisation suggested in (Jalili *et al.*, 2022).

$$c_{WTGr} = c_{mob/demob} + t_{WTGr}(c_{JUV} + 2c_{BV} + 3c_{TB})/24$$

Equation 2-2

Where;

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[2] Wind turbine shown in Figure 2-3 shows a bunny ear configuration WTG removal for a wind turbine of 450kW where rotor (hub and blades) are lifted together with the nacelle (rear part). In this project we assumed that first the rotor is lifted, and then nacelle is lifted afterwards which is a more conservative approach as this activity takes longer than the case rotor and nacelle lifted at once. In Belgium, smallest wind turbine is 3MW which is at least 3 times larger in size and more in weight compared to the one shown in the picture. These dimensions make lifting and transportation activities more complicated. That's why additional nacelle removal step is included to the bunny ear configuration in this project.

[3] Source: Orsted. Info: info@orsted.dk

$c_{mob/demob}$: combined mobilization and demobilization costs for all vessels,

c_{JUV}: day rate of JUV,

c_{BV}: day rate of BV,

c_{TB}: day rate of TB,

t_{WTGr}: total WTG removal time [h] and it is estimated as in Equation 2-3

$$t_{WTGr} = n\left(t_{JUVpos} + t_{JUVup} + bt_{bl} + t_{nr} + t_{tow} + t_{JUVdown}\right)$$

Equation 2-3

Where;

- n: number of WTGs,
- t_{JUVpos}: required time for positioning the JUV,
- t_{JUVup}: required time for jacking up the JUV,
- b: number of blades; 3 for the reverse installation, 1 for the bunny ear configuration,
- t_{bl}: required time for removing one blade,
- t_{nr}: required time to remove either the nacelle (reverse installation case) or the rotor with two remaining blades plus nacelle separately (bunny ear conf. case),
- t_{tow}: required time for removing the tower,

All times are in hours and costs are in EUR. In this parametrisation, operational windows required to remove each component are obtained from several other studies (Jalili *et al.*, 2022). Since these required operational windows depend on many factors including used equipment, experience of the personnel, weather downtime etc, a sensitivity study is carried out, to assess the impact of t_{bl}, t_{nr}, and t_{tow} to the overall costs. These results are presented in section3.1.2.1. Finally, once removed, all assets are transported back to the shore using two barge vessels towed by tugs.

2.2.3 Foundation removal

2.2.3.1 Monopiles

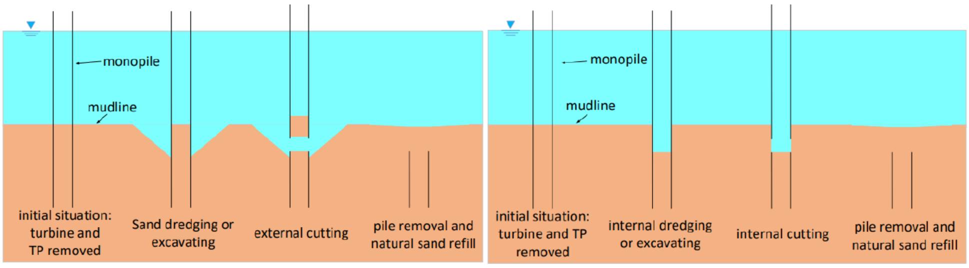
Two monopile removal scenarios are evaluated in the project:

- Underwater cutting of the monopile below the mobile seabed level.
- Complete removal of the monopiles. According to current project energy permits requirements, Belgium authorities require to completely remove the WTG foundations in Belgian OWFs.

Monopile cutting is a more common approach in offshore works due to its simplicity compared to complete removal. In this project, monopile cutting is taken into account to have another reference cost value for the monopile removal. In this scenario, TP is not removed from the monopile. Once the monopile is cut, it is lifted together with the TP.

Vibratory pile removal is one of the techniques which has already been used for full extraction of monopiles. In this method, a vibratory hammer is placed on top of the monopile and it loosens the monopile from the surrounding ground by applying vibrations at high frequency. Due to the large noise emissions of this operation, there must be a noise mitigation system foreseen during these operations. Moreover, in order to place the vibratory hammer, TP should be removed from the monopile. Depending on the TP-monopile connection method, TP is either cut (grout connected TPs) or unbolted (bolted TPs). In this exercise, cutting time and unbolting time of the TP is assumed to be the same for the same diameter.

Figure 2-4 Clamping of vibratory hammer on top of a monopile[4]



(a) External pile cutting

(b) Internal pile cutting

Figure 2-5 Monopile cutting; external and internal (Hinzmann *et al.*, 2018)

Abrasive Water Jet Cutters (AWJC) is selected as cutting method which reaches the cutting location from inside (Figure 2-5). For accessibility, the mud inside the monopile is removed first with pumps. In the literature, a cutting depth of 2m below sea bed is recommended(Jalili *et al.*, 2022). The seabed in Belgium North Sea is pretty dynamic; where the soft sand surface tends to transported around within years. Due to this reason, a deeper average cutting depth is considered.

Implementation of these methods to the cost model is done by modifying the parametrisation suggested in (Jalili *et al.*, 2022).

$$c_{FOUNr} = c_{mob/demob} + t_{FOUNr}(c_{JUV} + c_{BV} + 2c_{TB} + c_{equip})/24$$

Equation 2-4

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[4] https://offshore.pve-holland.com/content/987/669/The-Expert/Vibratory-pile-driving-%E2%80%93-a-serious-alternative-for-offshore-foundations.html, accessed on 27-11-2023.

Where

- c_{equip}: day rate of the additional equipment. For full extraction, vibratory removal system and noise mitigation system. For monopile cutting, it is the cutter and mud pump,
- t_{FOUNr}: total foundation removal time [h] and it is estimated by using Equation 2-5 when the monopile is removed by cutting or by using Equation 2-6 when the monopile if fully extracted.

$$t_{FOUNr} = n\left(t_{JUVpos} + t_{JUVup} + t_{cut} + t_{mud} + t_{lift} + t_{JUVdown}\right)$$

Equation 2-5

Where;

- t_{cut}: required time for cutting the monopile which depends on the monopile diameter and cutting speed.
- t_{mud}: required time to pump out the mud inside the monopile which depends on the pumping rate and the volume of mud that needs to be pumped.
- t_{lift}: required time to lift the monopile and place it on the BV.

$$t_{FOUNr} = n\left(t_{JUVpos} + t_{JUVup} + t_{ext} + t_{lift} + t_{JUVdown}\right)$$

Equation 2-6

Where;

- t_{ext}: required time to extract the monopile. This is calculated based on parametrical relation provided in (Nielsen, 2022): $t_{ext}: 0.0417D_0 + 0.3750$.

All parameters of the operational windows are in hours and costs are in EUR.

2.2.3.2 Gravity based foundations

Predictions for gravity based foundation (GBF) removal costs is provided for the C-Power OWF case. C-Power has 6 wind turbines using the GBF concept for the foundation (Figure 2-6) instead of the conventional monopile. These GBFs are made of stressed reinforced concrete and are installed on a prepared seabed with the help of water ballast, rock levelling layer and subsequent scour protection.

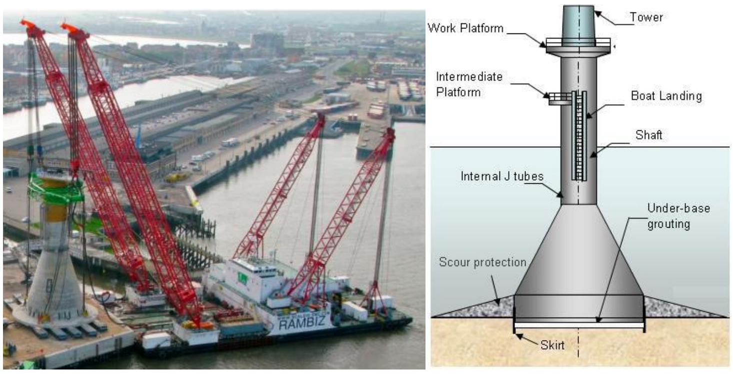

Figure 2-6 Left: Scaldis' Rambiz preparing the lift of a concrete GBF similar to the C-Power foundations(Alonso, 2013). Right: GBF concept[5]

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[5] https://www.wind-energy-the-facts.org/offshore-support-structures-7.html, accessed on 06-12-2023.

The structure of the GBF is designed to sustain temporary loads during the transport and installation, in particularly a certain amount of hydrostatic pressure from the outside. Depending on the installation concept, this hydrostatic pressure can be the total water head or less. This detail is important to plan the removal operations, in particularly the de-ballasting sequence for rising the structure from the seabed to a floating condition. The buoyancy needed it is not only dependent on the weight but also on the adhesive forces caused by the soil contact. Also important for the removal is a concept on how to remove the water from inside the structure. If the removal is considered to be achieved by lifting with a heavy lift vessel (HLV), the evacuation of the internal water is important to reduce the lifting weight. Furthermore, it has to be investigated if the scouring protection needs to be removed beforehand. This could be important in order to reduce the lifting weight. It needs to be verified if eventual open grout lines are available to be converted to jetting lines. If this is not the case, a concept for jetting high pressure water under the bottom slab shall be developed. Any activity requiring drilling of reinforced concrete or water evacuation needs to be paid specific attention in order not to damage or weaken the reinforcement in the concrete, otherwise the structure could collapse. Finally, once de-ballasted and refloated, the structures can be towed away to the dismantling location.

The estimation of the costs for such an operation is not simple without much review of the location, as designed/as build information, and some dedicated engineering. Part of the costs is not only the estimate of the operation timing, for the hiring cost of equipment, but also the preparatory work: on the structure, on the seabed and any additional dedicated special equipment (i.e. for de-ballasting) which need to be designed, manufactured and tested. Therefore, rough cost estimations provided here, based on predicted weight of 3600 t.

2.2.3.3 Jackets

Predictions of jacket foundation (JF) removal costs is done for C-Power wind farm for 48 wind turbine JFs and one from Belwind. A typical construction of JFs are shown in Figure 2-7. In this case, removal is only considered by cutting it from under seabed. Technical possibility of full removal of the jackets is possible but not considered in this study. This is mainly due to the lack of information obtained regarding the full extraction of the jacket structures. Cutting and the removal operations are adapted from the monopile removal case by replacing internal cutting with external one.

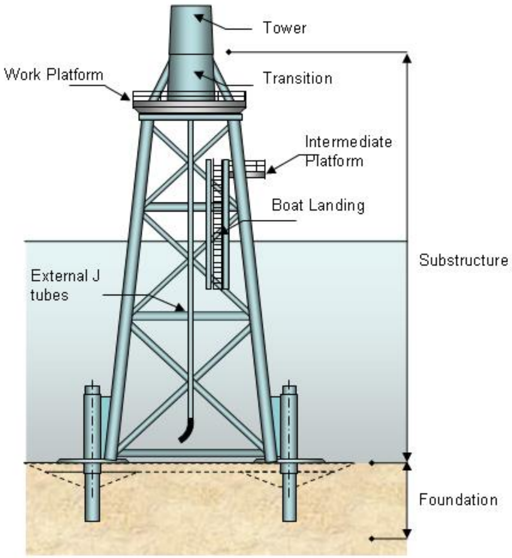

Figure 2-7 Jacket foundations used in offshore wind turbines.

2.2.4 Cable removal

In this study, the subsea power cables are assumed to be fully removed which means buried and protected cables in the seabed need to be unburied and then removed. Since these operations do not require JUVs, it is assumed that the removal is performed by one OSV (offshore support vessel) or a barge vessel (Open hatch bulk carrier) and one ROV (remotely operated vehicle) or Mass flow Excavators (MFE). ROV or MFE are needed to uncover the cables before they are pulled.

Cable removals costs are estimated by using Equation 2-7

$$c_{CABLEr} = c_{mob/demob} + t_{CABLEr}(c_{OSV} + c_{BV} + c_{ROV})/24$$

Equation 2-7

Where;

- c_{OSV}: day rate of OSV,
- c_{ROV}: day rate of ROV,
- t_{CABLEr}: total cable removal operational window and it is estimated by using Equation 2-8

$$t_{CABLEr} = t_{inner} + t_{export}$$

Equation 2-8

Where;

- t_{inner}: required operational window to remove inner-array cables,
- t_{export}: required operational window to remove export cables.

All operational window parameters are in hours and all cost parameters are in EUR. Removal operational windows are estimated based on the removal rates of 0.6 km/h for inner-array cables and 1.05 km/h for export cables as recommended in (Kaiser and Snyder, 2010).

Figure 2-8 Open hatch bulk carrier (Project Cargo Weekly, 2018)

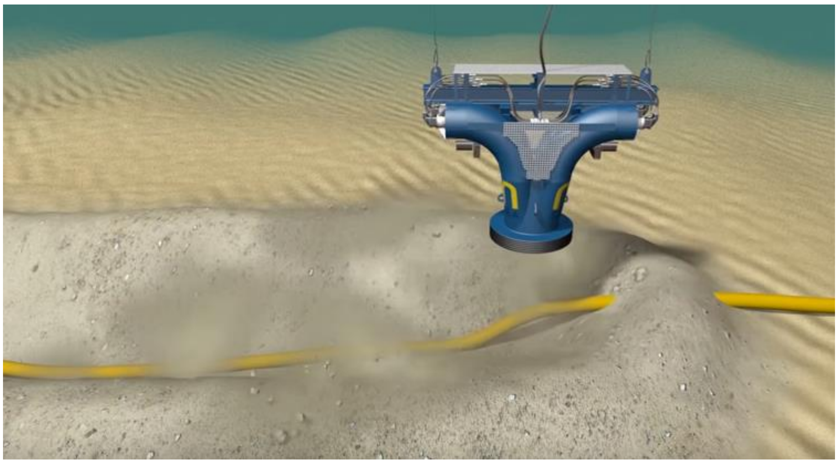

Figure 2-9 Visual impressions of the MFE blowing off the sand cover (N-SEA, 2018)

Figure 2-10 Cable grab (Pharos Offshore Group, 2017)

2.2.5 Scour Protection Removal

Scour protection removal predictions are based on the assumptions that all WTG foundations have riprap type scour protection (Figure 2-11), and the dimensions of the scour protection are estimated based on the monopile diameter as recommended by (Matutano *et al.*, 2013). For the gravity based foundation, scour protection removal is not included.

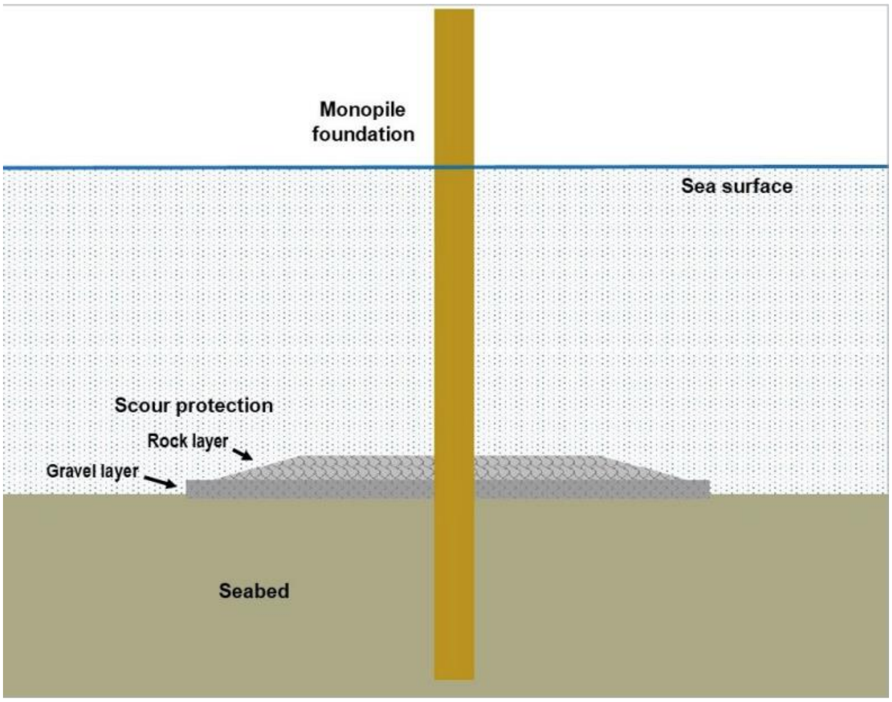

Figure 2-11 Riprap type scour protection around a monopile foundation (Turbine Reefs: Nature-Based Designs for Augmenting Offshore Wind Structures in the United States, 2021)

Removal operations are performed by a Derrick Crane Barge Vessel (DCBV) with a clamshell bucket following the recommendation from (Jalili *et al.*, 2022), a BV by using Equation 2-9

$$c_{SCOURr} = c_{mob/demob} + t_{SCOURr}(c_{DCBV} + c_{BV} + c_{ROV})/24$$

Equation 2-9

Where;

- c_{DCBV}: day rate of DCBV,
- t_{SCOURr}: total scour removal operational window and it is estimated by using Equation 2-10.

$$t_{SCOURr} = n(\frac{V_s}{r_s})$$

Equation 2-10

Where;

- V_s: scour protection volume [m^3] predicted relative to the monopile diameter,
- r_s: rate of scour protection removal [m^3/h] taken as 144 m^3/h for this study.

Figure 2-12 Scancrawler (Scanmudring, 2018)

Figure 2-13 Cable grab (Scanmudring, 2018)

2.2.6 Other costs

Three additional costs elements are included in the decommissioning cost calculations in this study which are

- fuel costs,
- pre-decommissioning costs and,
- project management (PM) costs.

Both pre-decommissioning and PM costs are added as percentage on top of the overall costs as 9% and 10% respectively, following the recommendations in (Jalili *et al.*, 2022). Fuel costs are estimated only for the JUVs since these vessels have the highest consumption rates and therefore are responsible from the major part of the fuel costs. Fuels consumption rate of 50t/day from Figure 2-14 is assumed for all JUV operations. And 806 [EUR/tons] is used as fuel cost[6].

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[6] Obtained from https://shipandbunker.com/prices#MGO, accessed on 29-11-2023.

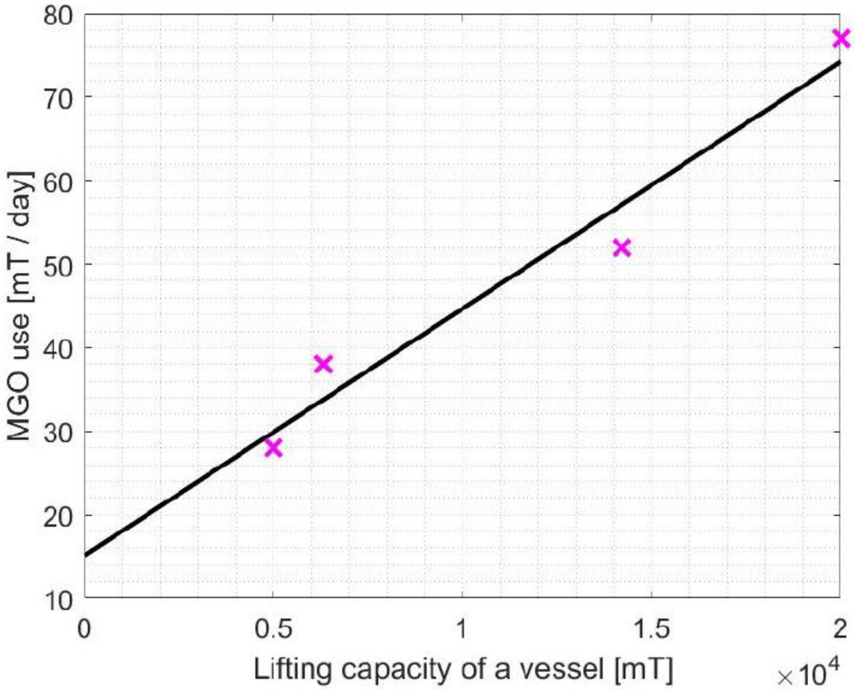

Figure 2-14 Fuel (Marine Gas Oil -MGO) consumption wrt lifting capacity of the vessels (Nielsen, 2022).

It should be noted that normally, additional 20-25% contingencies and 10-20% risks are included on top of the total costs in the decommissioning projects. Furthermore, contractors normally also add some profit margins on top as well. However, these costs are not included in the total decommissioning costs as they vary greatly from project to project and depend highly on the selected contractors, shared responsibilities between the contractors and the asset owners in terms of risk sharing, etc.

2.3 OWF Scenarios Evaluated

In total of seventeen different OWFs are modelled for this study; nine of them are corresponding to the existing Belgium OWFs and eight of them are generic OWFs modelled for the trend analysis and with the goal to investigate how decommissioning costs might impact the Princess Elizabeth Zone (PEZ) offshore wind concessions.

2.3.1 Belgium OWFs

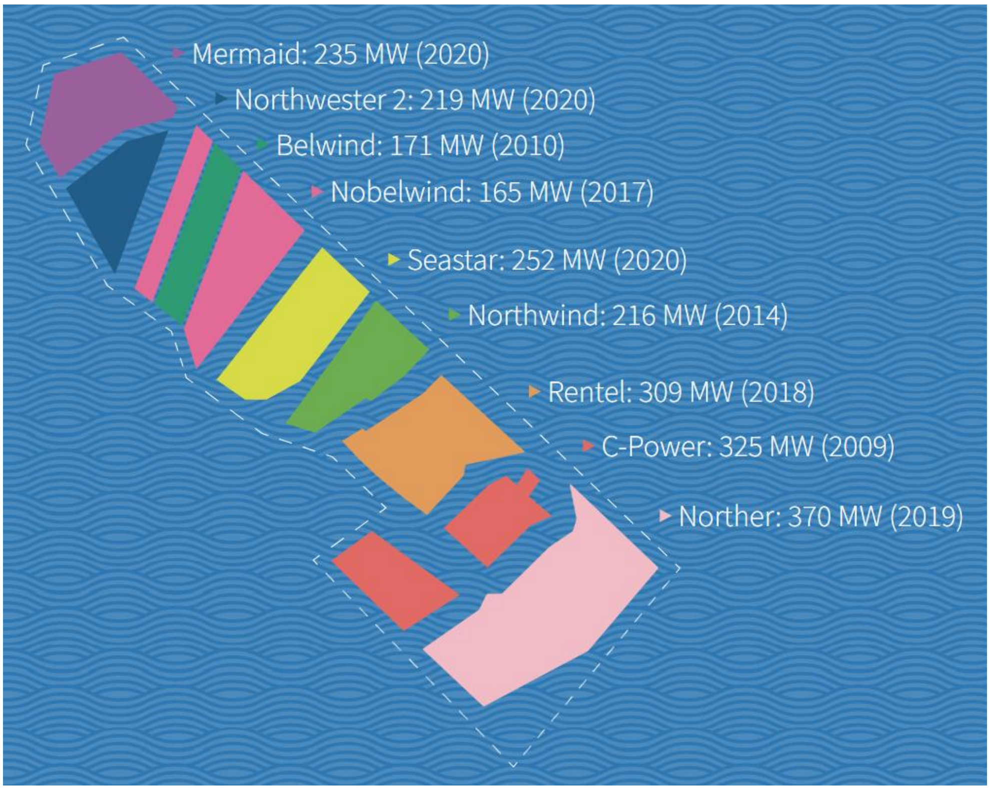

Figure 2-15 operational OWFs in Belgium[7]

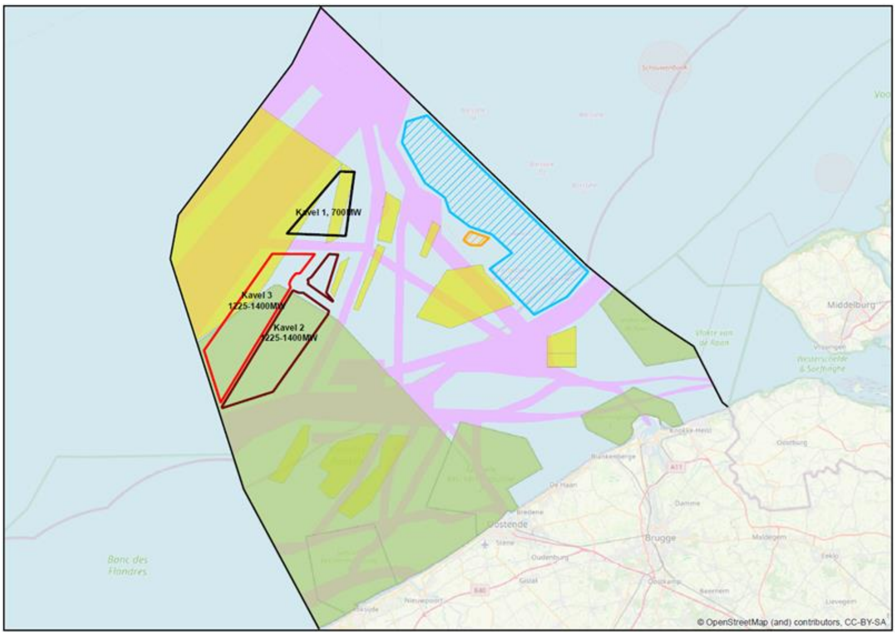

Figure 2-16 Princess Elisabeth Zone for new OWFs indicated with black, 25ummary25 and red inside the Belgian North Sea zone.[8]

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[7] https://www.belgianoffshoreplatform.be/en/projects/ accessed on 24/11/2023

[8] https://economie.fgov.be/en/themes/energy/belgian-offshore-wind-energy accessed on 24-11-2023

Table 2-2 Overview of Belgium offshore wind farms

Wind farm	Capacity [MW]	WTG type	No. WTG	Expected year of decom.	Foundation Type	Dist. to shore [km]	Ave. depth [m]
C-Power	325.5	Senvion 5MW, 6.2MW	54	2034	6 x GBFs, 48 x Jacket	30	12-27
Belwind	165	Vestas 3.3MW	55	2038	Monopile	49	20-35
	6	Haliade 6MW	1		Jacket		
Northwind	216	Vestas 3MW	72	2034	Monopile	37	16-29
Nobelwind	165	Vestas 3.3MW	50	2037	Monopile	47	26-38
Rentel	309	Siemens 7.4MW	42	2040	Monopile	34	22-36
Norther	370	Vestas 8.4MW	44	2041	Monopile	23	20-35
Northwester2	219	Vestas 9.5MW	23	2045	Monopile	51	34
Seastar	252	Siemens 8.4MW	30	2045	Monopile	40	22-38
Mermaid	235.2	Siemens 8.4MW	28	2045	Monopile	54	22-40

From the existing offshore wind farms (Figure 2-15 and Table 2-2), C-Power and Northwind are expected to be decommissioned in the next 10-11 years. Decommissioning activities in the future PEZ wind farms (Figure 2-16) are not expected before 2055.

2.3.2 Generic OWFs for Trend Analysis

150MW, 300MW and 700MW OWF are modelled and investigated with WTGs ranging from 3MW to 22MW in the scenario matrix in Table 2-3. All wind turbines use monopiles. Wind turbine and monopile properties are approximated from the Belgium OWFs of the same sizes for 3MW and 8MW versions. For 12, 15 and 22MW, reference wind turbines from IEA Task 37[9] are used. Cable lengths of 700MW OWFs are used from the PEZ environmental impact assessment study.

Table 2-3 Wind farms used in trend analysis

	150MW	300MW	700MW
3MW	☑	☑	
8MW	☑	☑	☑
12MW			☑
15MW			☑
22MW			☑

2.4 Technical assumptions overview

Main technical assumptions used in decommissioning cost predictions are collected in Table 2-4.

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[9] https://github.com/IEAWindTask37, accessed on 06-12-2023

Table 2-4 Main technical assumptions used in decommissioning cost calculations.

#	Assumption	Motivation
1	JUVs, supported by BVs and TBs are used for the major offshore works.	Suitable for Belgium offshore conditions, cheaper price compared to HLVs.
2	Weather or sea state related delays are not included.	Depends on historical weather data, not integrated into the models available.
3	Mechanical breakdowns related works are not included.	Depends on the current state of each and every asset; no information is available.
4	12h/12h shifts are used for the continuation of offshore works.	Experience from OWF installations, reduces the impact of weather related delays.
5	Vibratory pile removal devices are available for monopile diameters of more than 6m.	Growing interest in full monopile extraction, developments in industry to reduce costs and increase reliability.
6	Cutting time and unbolting time of TPs are equal for the same diameter.	No information regarding unbolting times of TPs.
7	GBFs de-ballasted and refloated and towed to the shore as decommissioning strategy.	Used experience from installation.
8	All wind turbine foundations have scour protection and volumes are predicted based on monopile diameter according to guidelines from literature.	Lack of specific information related to the actual volumes of protection.
9	Specs of 12MW, 15MW and 22MW wind turbines are obtained from reference WTGs used in the scientific literature.	Not much data is available about these wind turbines as many of them are not in the market yet.
10	Cable lengths of 700MW OWF case is obtained from PEZ EIA studies.	This data was already available to IMDC.
11	Costs related to contingencies and risks are not included.	Highly uncertain parameters. Depend on contractor and specific agreements.
12	In-land transportation or storage costs either at the port or in warehouses are not included in the decommissioning costs.	Part of the waste treatment and recycling strategy.
13	All cost items are applicable for 2023 indexation. Costs do not consider indexation at the year of decommissioning works are expected. EUR is used as currency, VAT or other taxations are not included.	Needed for up-to-date and realistic predictions.

3 Cost estimation

3.1 OWF Decommissioning Cost Estimations

3.1.1 Introduction

Decommissioning cost estimations of the OWF assets are provided in this chapter for WTGs and for foundations, before overall costs are presented. Sensitivity analysis results are directly integrated into these sections instead of presenting them in a dedicated section for the coherence.

3.1.2 WTG removal costs

WTG removal costs are estimated for reverse installation method; where first the blades are removed, and then the rotor and the nacelle and the tower. Bunny ear removal configuration is added for comparison in Figure 3-1. Northwester, Seastar and Mermaid OWFs have shown relatively lower costs compared to the rest of the OWFs, mainly related with the number of turbines they have are less than the rest of the OWFs. This also is visible in Figure 3-2 where the decommissioning duration[10] is compared; the less number of turbines, shorter the offshore operations. When generic OWFs are investigated in Figure 3-3, especially for the 700MW OWF configurations, total cost reduces with the increase in WTGs size. In reality, this reduction will be less due to the differences in lifting capacity and size of the vessels selected for the operations which is elaborated in section 2.2.3.1 and shown in Figure 3-9. Nevertheless, a decreasing trend is captured.

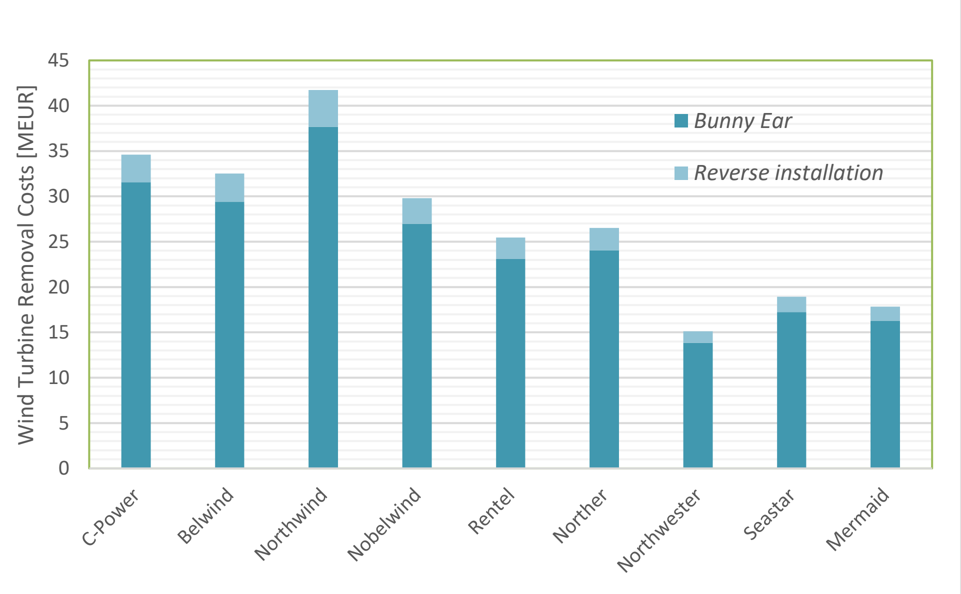

Figure 3-1 WTG decommissioning costs [10] estimated for Belgium OWFs (bunny ear configuration and reverse installation decommissioning method)

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[10] The effective decommissioning duration is estimated by summing the duration for jacking up and positioning operations of the JUV, removing all components, and jacking down and travelling to the next WTG. Weather downtime (WDT), mechanical breakdown (MBD), delays due to (un)availability of vessels, or any other waiting times are not included.

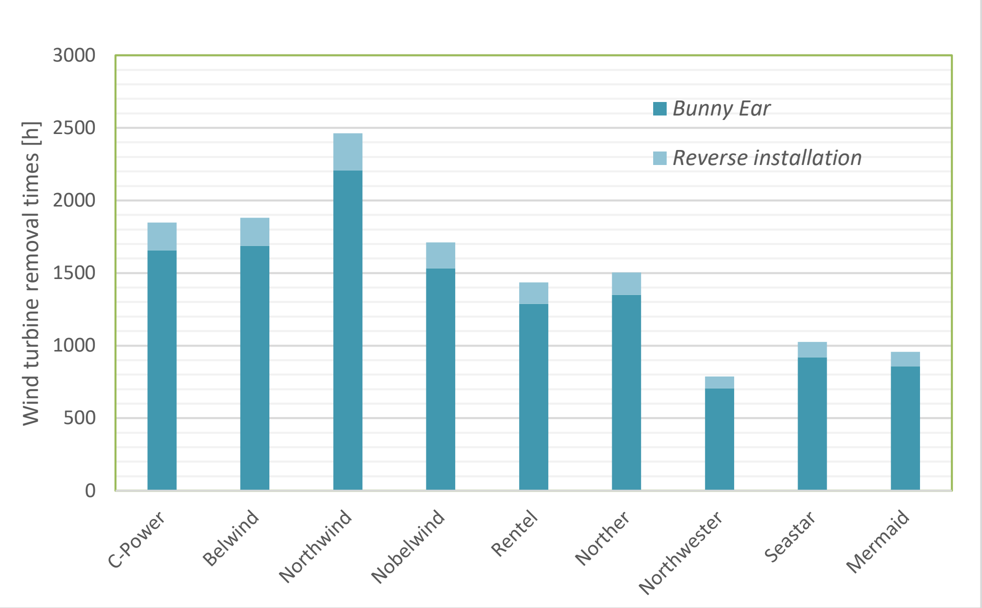


Figure 3-2 WTG effective offshore decommissioning duration[10]

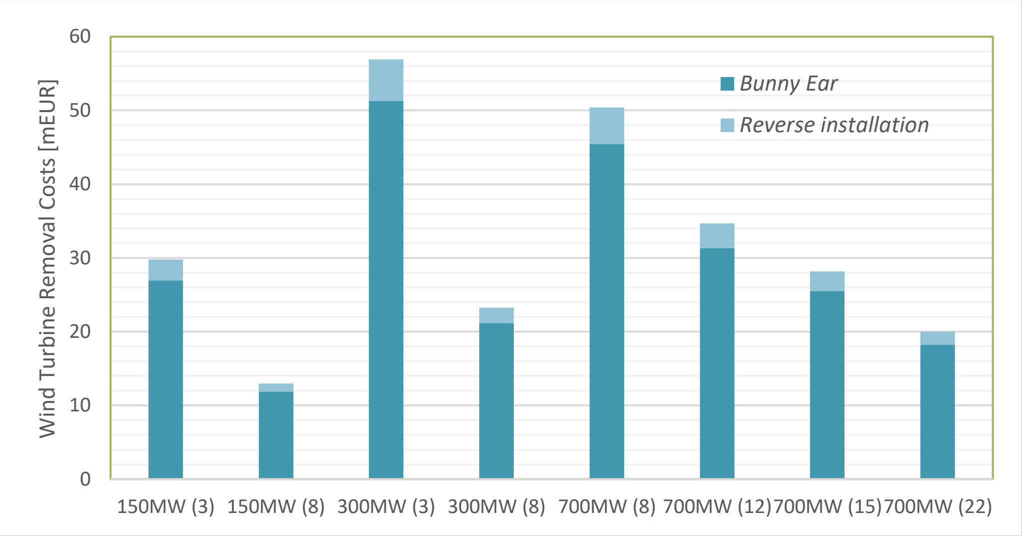


Figure 3-3 WTG removal costs estimated for the generic OWFs. Number in the parentheses represents the WTG size (i.e. 700MW (12) refers to the 700MW OWF consisting of 12MW wind turbines)

Similar analysis are shown by looking at cost per MW values in Figure 3-4. In this case, OWFs with 3MW WTGs, which is the smallest WTG size installed offshore in Belgium, end up with the highest costs per MW. A decreasing trend is associated with the larger turbine capacity.

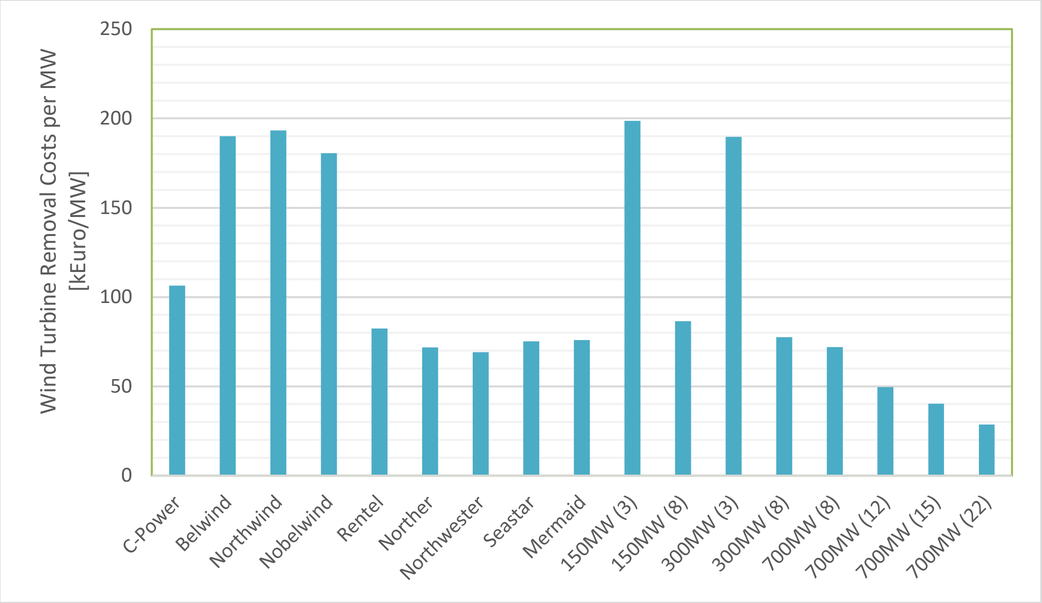


Figure 3-4 WTG removal costs per MW compared between Belgium OWFs and generic OWFs.

3.1.2.1 Impact of removal duration

In Figure 3-5, the impact on cost of 50% longer duration for the WTG decommissioning works (i.e. sensitivity wrt duration of offshore works) is shown. 50% longer operations are only assumed for WTG removal related operations, such as 50% longer duration of one blade removal, or 50% longer duration of tower removal activities. This is done to assess the impact of offshore works duration assumptions on the overall costs. Both for reverse installation and for bunny ear configuration, 50% increase in decommissioning works durations are found responsible from average of 20% increase of the costs.

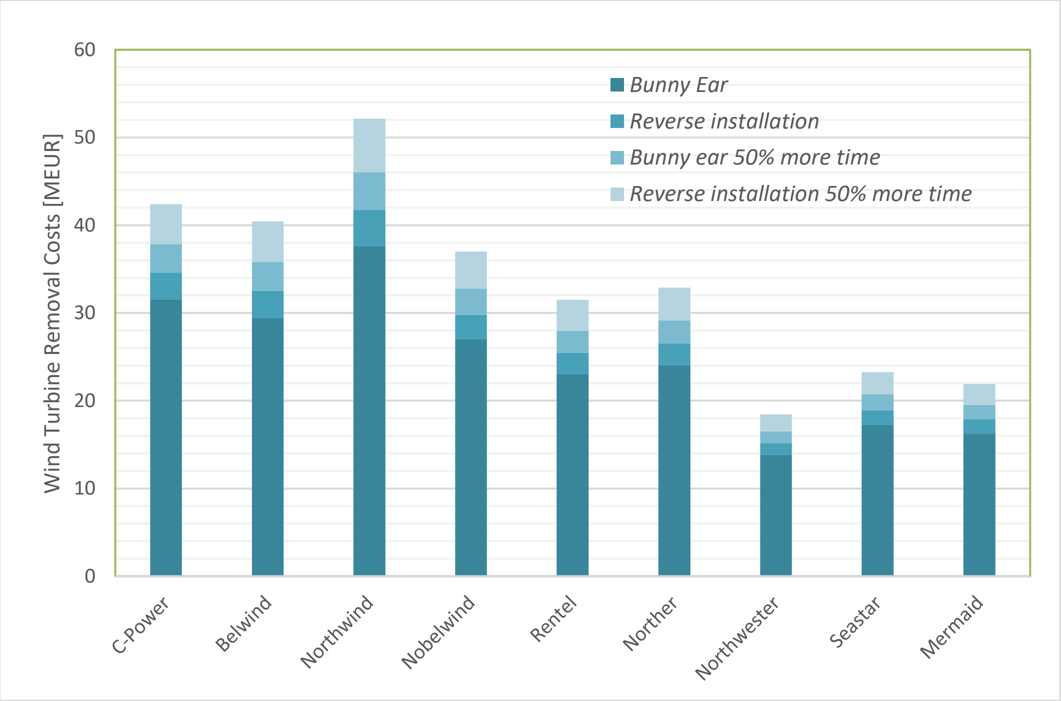


Figure 3-5 Comparison of the impact of 50% more time assumption for the duration of WTG removal activities on the WTG removal costs.

3.1.3 Foundation removal costs

Foundation removal costs for full extraction method is compared with cutting approach in Figure 3-6 for all Belgium OWFs. Except for C-Power, which has gravity based (GBF) and jacket foundation, all other OWFs have monopile foundations; therefore the costs are comparable with each other. As explained in the section 2.2.3, the GBFs requires different operations due to its complexity and for jacket based foundations, the predictions are performed with additional assumptions due to lack of information. These results are included in Figure 3-6 and Figure 3-7 for the completeness. Furthermore, monopile cutting is also included to have another reference as a removal method besides full extraction. Both total foundation removal costs in Figure 3-6 and effective foundation removal times in Figure 3-7 show the highest estimates result for Northwind OWF which has the highest number of foundations. On the other hand, C-Power's GBFs have the highest removal costs per foundation as there are only 6 foundations and due to the complexity of the removal. Another observation is about how monopile diameter impacts the difference between cutting and full extraction costs: the larger the monopile diameter gets, the smaller the difference between the cutting and full extraction costs becomes. Following this trend, it can be expected that for larger diameters, full extraction can be even cheaper than cutting. This result is consistent with the results of (Nielsen, 2022), even though the cost calculation methods, especially for cutting, used in this study and in available research (Nielsen, 2022) are slightly different. On the other hand, the reader should be aware that the equipment to remove monopiles larger than 6m diameters are still in development phase and not yet available in the market. Monopile removal costs per MW of capacity in Figure 3-8 indicates a clear reduction in cost per MW going from 3 to 7-9 MW wind turbines.

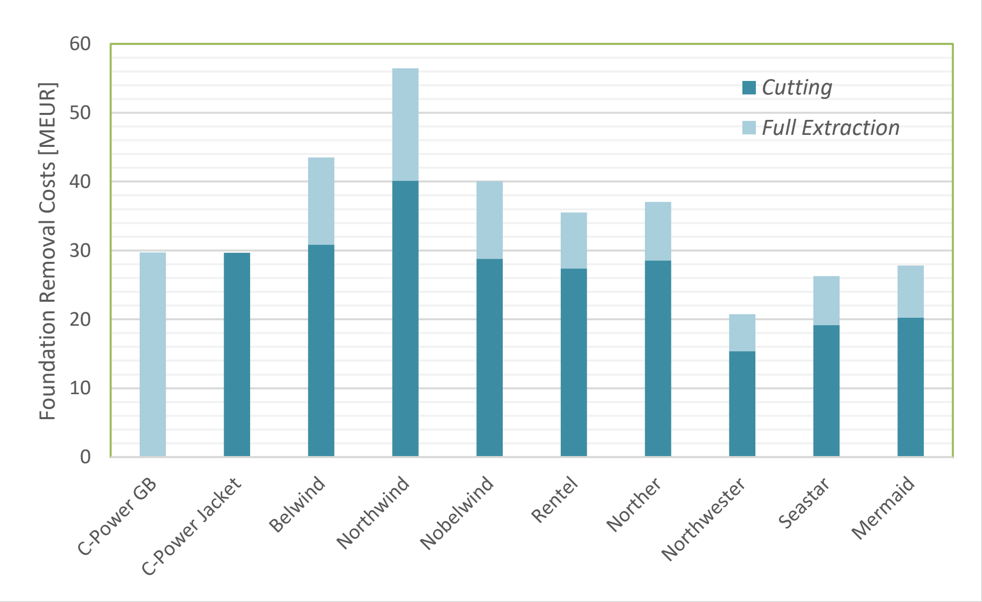


Figure 3-6 Foundation removal costs for Belgium OWF s.

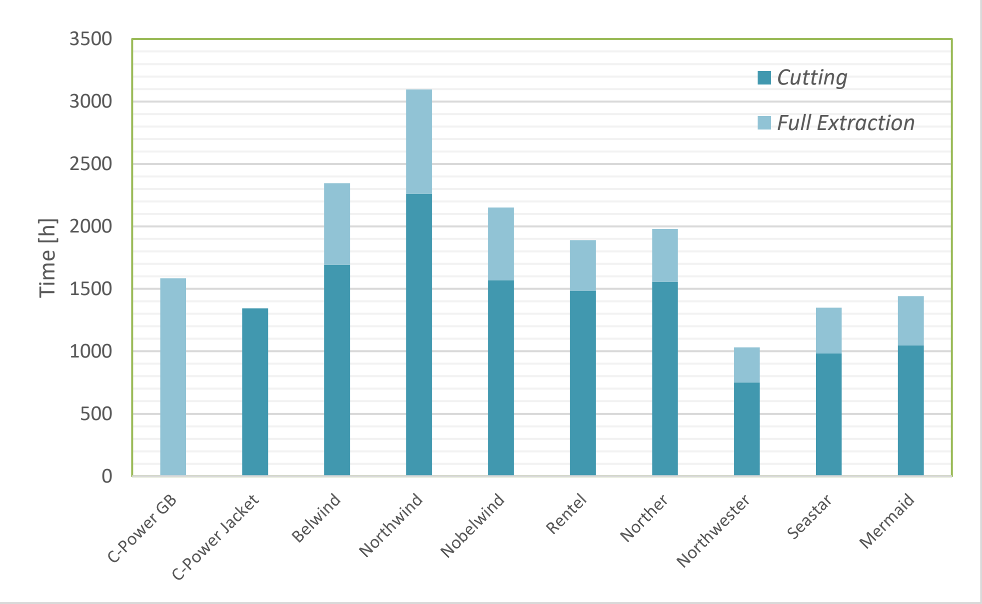


Figure 3-7 Effective foundation removal operational windows for Belgium OWFs (no MBD, no WDT, no waiting times due to (un)availability of vessels included).

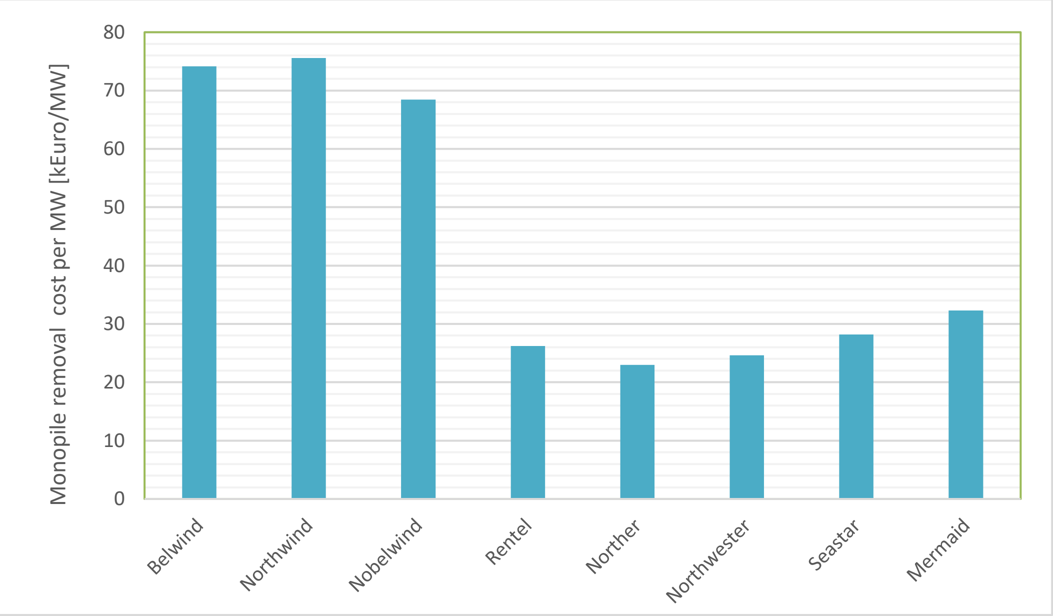


Figure 3-8 Monopile removal by extraction costs of Belgium OWFs per MW capacity

When generic OWF s' foundation removal costs are compared (Figure 3-9), the cost reduction trend with larger turbines is still visible. Two additional cases are added for larger WTG cases as sensitivity analysis. Firstly, due to the increase in weight and dimensions of these wind turbines, larger capacity vessel with 2 times lifting capacity and 2.5 times the daily rental price is included for the full extraction case and referred as "Ext. + larger vessel" in the figure. This change causes about 75% increase in the removal costs. Secondly, all durations related with foundation removal are increased 50% on top of using larger vessel and this case is referred as " Ext. + larger vessel + 50% longer duration" in the figure. To clarify, durations related with mobilisation or jacking or positioning the vessels are not included in this 50% increase – only the durations related with removing and lifting operations of the monopile is increased. In this case, total foundation removal costs increase 1.5 times compared to the original case. Even though the operations become much more expensive, 700MW OWF with 22MW wind turbines still costs almost the same as 300MW OWF with 3MW wind turbines. In addition to this, the difference between cutting or extraction of the monopile further reduces with the larger turbines. But since the technology is unknown yet for this monopile sizes, these differences and trends are not reliable anymore. Similar trends in terms of large turbine sizes and cost reductions are noticeable when generic OWF cases are compared with the Belgium OWFs (Figure 3-10).

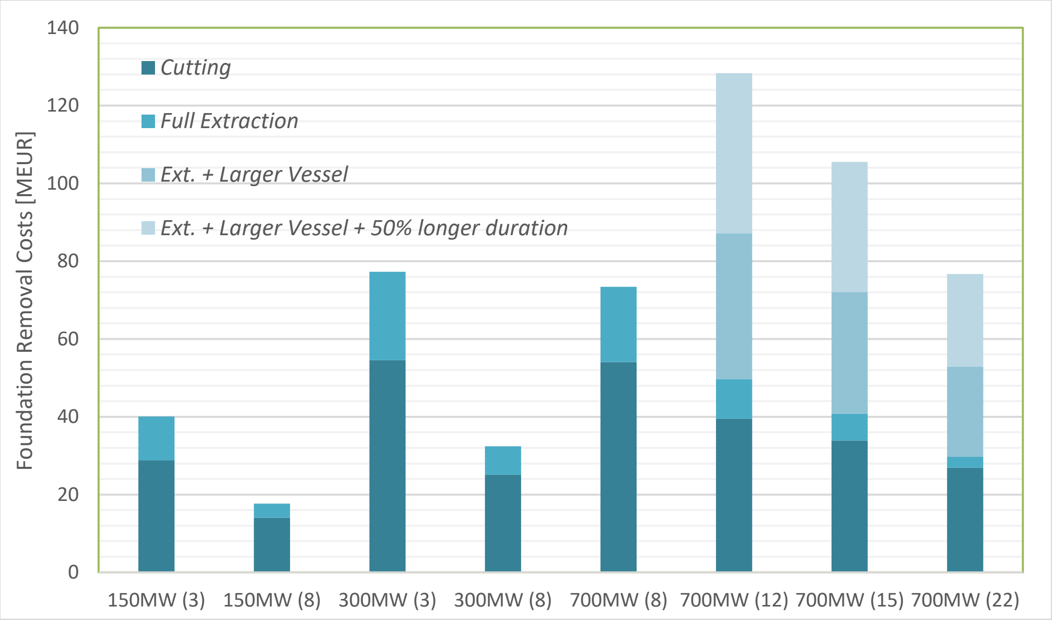


Figure 3-9 Foundation removal costs are compared for generic OWF s.

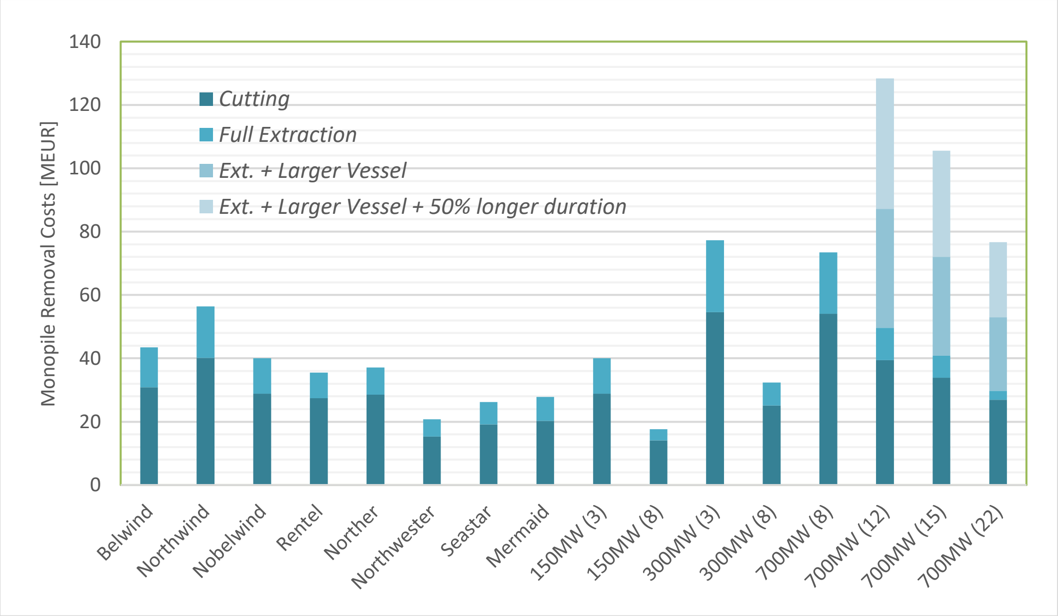


Figure 3-10 Monopile removal costs of Belgian OWFs compared with generic OWF s.

3.1.4 Total Cost of Decommissioning

Total decommissioning costs are estimated for the operational OWFs projects in Belgium. Figure 3-11 presents the share of different activities in the total cost, averaged for all OWFs in Belgium for the main removal scenarios (i.e. reverse installation type removal for WTGs and full extraction for foundations). It should be noted that these costs do not include any waiting times, or WDT, MBD related delays, or other risk margins. Normally, contingency and risk margins are added on top of these costs to cover these aspects which are not included in this study. Another attention point is about the storage costs in the port, or in other warehouses, or in land transportation of the assets once all assets are transported to shore. These costs are highly dependent on the chosen end-of-life strategy, port, company, location, and specific contracts with these companies. These costs are also not included in these results. With the current estimations, Figure 3-12 and Figure 3-13 show the impact of number of turbines being one of the most dominant parameter for decommissioning costs, except for the C-Power case because of the expensive GBF removal activities.

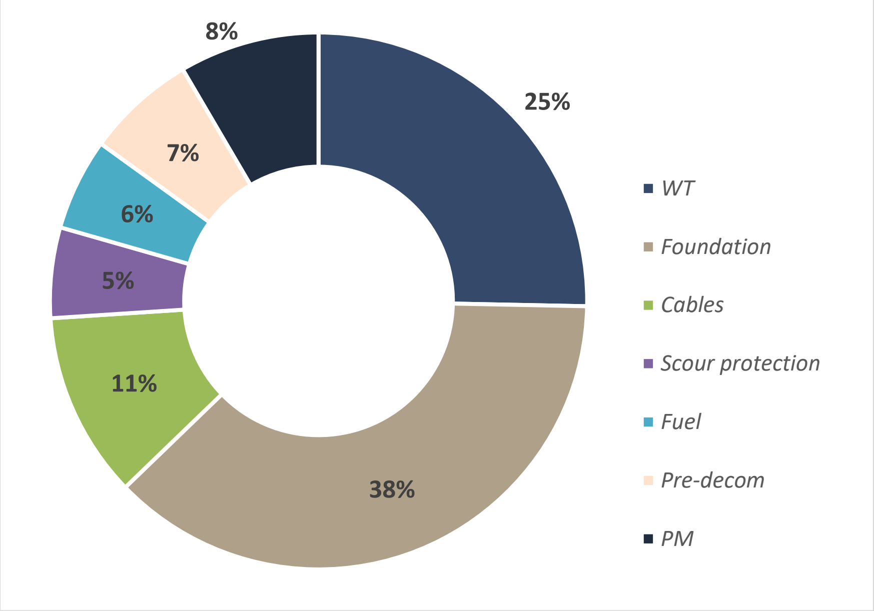


Figure 3-11 Shares of different parts of decommissioning on the total decommissioning costs shown for all Belgium OWFs.

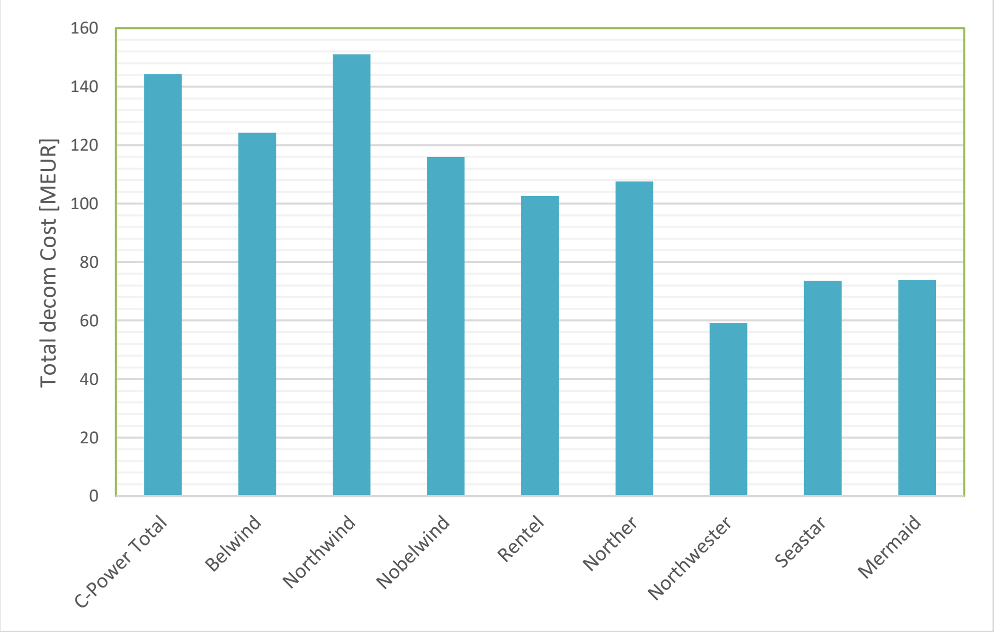


Figure 3-12 Total decommissioning costs of Belgium operational OWFs projects.

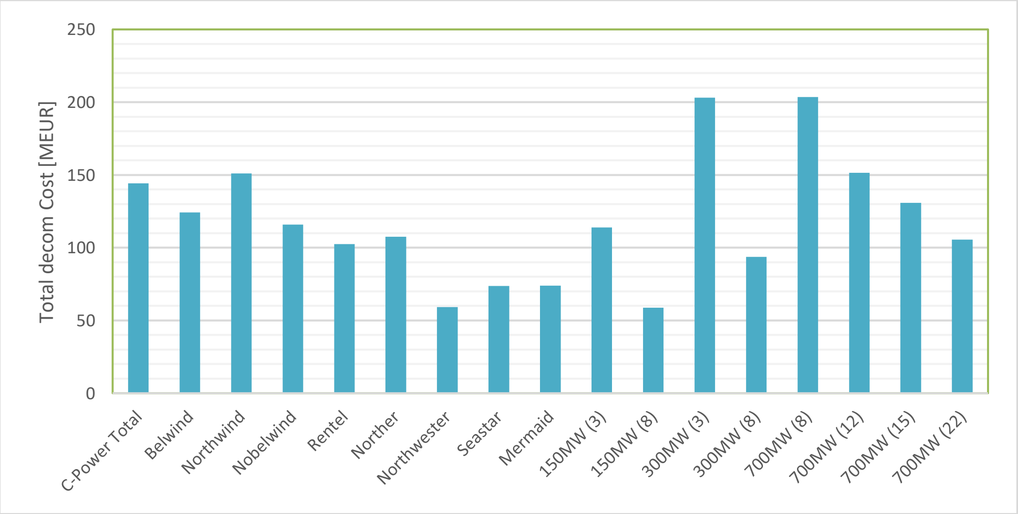


Figure 3-13 Total decommissioning costs of Belgium OWFs compared with generic OWF s.

3.1.5 Comparison with other studies

Total decommissioning costs of operational OWFs in Belgium result to approximately 952MEUR which means 421kEUR/MW. Figure 3-14 shows a comparison of decommissioning cost predictions performed by other parties in the past for different size of projects (Devoy McAuliffe *et al.*, 2018). The predicted cost per MW of this study (421kEUR/MW) is close to the average of these previous predictions. On the other hand, when only C-power Phase I OWF with GBF is considered, there is a significant difference between our prediction (1710 kEUR/MW) and Nowicob model (651kEUR/MW (513kEUR when not corrected for inflation). Since the details of the Nowicob model is unknown, it is not possible to immediately point out the reasons for this. On the other hand, GBF removal estimations in this study is very generically done, and it is possible that some costs are overestimated. This potential overestimation disappears when combined C-

Power results are presented in Figure 3-15. Predictions of this study stays close to the average value except for the farms with 3MW wind turbines which are closer to maximum value. Predicted 421kEUR average cost for Belgian OWFs projects is in good agreement with the average of the predictions available in literature. This gives further confidence on the results of the study.

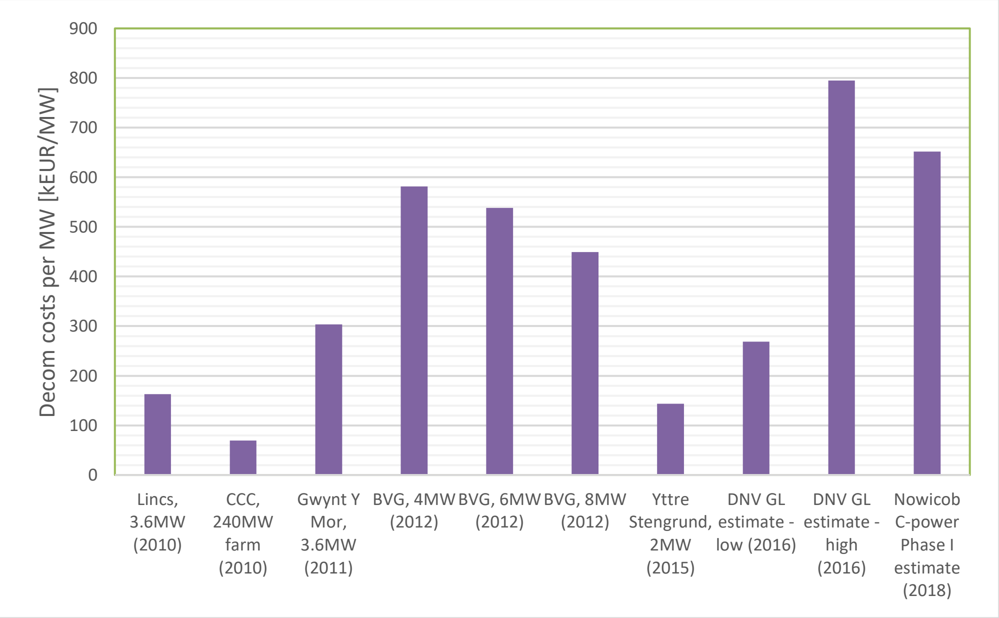


Figure 3-14 Decommissioning cost per MW predictions from several different sources compared (Devoy McAuliffe *et al.*, 2018) reproduced and inflation corrected for 2023).

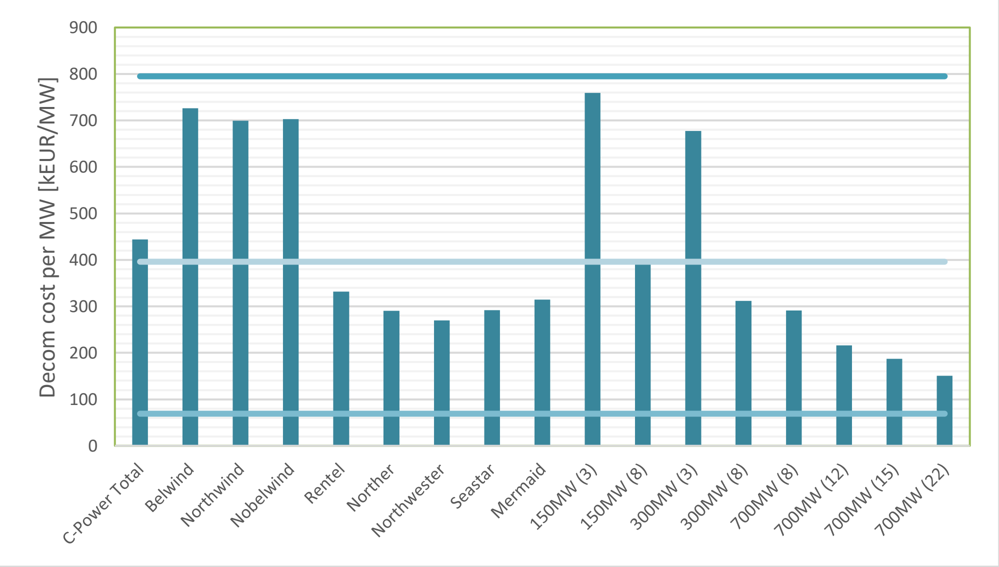


Figure 3-15 Decommissioning costs per MW for all operational Belgian OWFs compared with Min, average, max value of existing literature (Figure 3-14)

4 Offshore high voltage station decommissioning

4.1 Introduction

Tractebel Overdick Gmbh provided decommissioning costs for the associated OHVSs.

4.2 OWFs Considered

The considered OWFs are tabulated in Table 4-1 along with key high-level statistics to provide a high-level overview of the subject windfarms considered in generating the estimate inputs. The OHVS Export power to shore is HVAC current.

Table 4-1 Windfarm – High Level Statistics

OWF	OHVS water depth (m)	WTGs	Size	OHVS Capacity	OHVS Number	OHVS Foundation	OHVS Weight (tons)
C-Power	28	6	5MW	325 MW	1	4-leg Jacket	2000
		48	6.15MW				
Belwind/ Nobelwind	38	105	3/3.3 MW	336MW	2	Monopile	1100
		1	6MW				
Northwind	25	44	3MW	216MW	1	Monopile	1100
Rentel	36	42	7.35MW	309MW	1	Monopile	1100
Norther	35	44	8.4MW	370MW	1	Monopile	1100
Northwester	40	23	9.5MW	219MW	1	4-leg Jacket	1000
Seamade (Seastar / Mermaid)	40	58	8.4MW	487MW	2	Monopile	1200

4.3 Decommissioning scenarios

A basic building block approach is adopted comprising the following aspects and activities.

- Offshore decommissioning and removal of an OHVS Topside using a Sheerleg type vessel.
- Offshore decommissioning and removal of an OHVS Topside using a Heavy Lift Vessel (HLV).
- Offshore decommissioning and removal of an OHVS Jacket type support structure using a Sheerleg type vessel.
- Offshore decommissioning and removal of an OHVS Jacket type support structure using a HLV type vessel.
- Offshore decommissioning and removal of a typical OHVS Monopile type support structure using a sheerleg type vessel.

- Offshore decommissioning and removal of a typical OHVS Monopile type support structure using a HLV type vessel.

Each case is presented below along with any relevant assumptions / qualifications.

- **OHVS Topside Removal by Sheerleg Type Vessel:** In this case, it is assumed that the Topsides will be returned to the shore "on the hooks" of the sheerleg eliminating the cost of a transport barge and tow tugs and reducing onshore quayside activity costs, although movement from the quayside to the breakdown area is considered in the Breakdown / Recycling cost estimates. Sheerleg utilization is increased due to the additional time to transit from offshore to shore and return to the offshore location for jacket / monopile removal.

- **OHVS Topside Removal by HLV:** In this case the cost of a transport barge and tow tugs plus sea fastenings are considered. HLV utilization is reduced as a result but is offset by the additional barge / tug and sea fastening cost and the likely increased load in costs to remove the topsides from the barge.

- **OHVS Jacket Removal by Sheerleg Type Vessel:** In this case, again a similar situation is envisaged as above.

- **OHVS Jacket Removal by HLV Type Vessel:** In this case, again a similar situation to 3.2 above is considered, which includes a transport barge and tow tug costs.

- **OHVS Monopile Removal by Sheerleg Type Vessel:**

  Monopile removal is considered using a very large vibro-hammer. This solution is simpler compared to cutting from the logistics and preparation point of view (no dredging). This type of operation has been already performed in the North Sea with first generation small monopiles and it is in the capacity range of a large sheerleg. This operation would require the separation of the transition piece from the monopile upfront the positioning of the vibro-hammer on the pile. The cost estimate of this solution is highly uncertain as there is no historical information available regarding costs.
- **OHVS Monopile removal by HLV type vessel:** Removal by vibration is considered. Additional contingency as described previously is taken into account. In all cases outlined above, it is assumed that Inter Array (IA) cabling cutting and removal subsea along with scour protection, mattresses and the like is performed under the IA cable decommissioning contract.

4.4 Offshore Removal Calculations

A high-level summary of the cases is tabulated in Table 4-2.:

Table 4-2 High Level Offshore Removal Costs

Activity	Method	Estimate Cost [MEUR]
OHVS Topsides	Sheerleg	14,9
OHVS Topsides	HLV	24,2
OHVS Jacket	Sheerleg	11,3
OHVS Jacket	HLV	14,2
OHVS Monopile	Sheerleg	8,4
OHVS Monopile	HLV	10,2

In each case a profit allowance of 10% and a risk allowance of 10% is included in the estimated costs. Additionally, a contingency of 20% is included. Costs are based on 2023 values and are in Euro's.

It can be seen from Table 4-2 that the cost of one OHVS with monopile is 23.3MEUR and with jacket is 26.2MEUR. When all combined, total cost of removal of all operational OHVSs is about 215.7MEUR.

4.5 Breakdown / Recycling Costs

In addition to the offshore removal costs, onshore decommissioning (Breakdown) and Recycling costs are estimated including the potential revenue generated from the sale of recyclable materials to specialist recyclers.

The desk study exercise performed here is looking for estimating the dismantling, demolition, and recycling costs, separately. This is surely useful to win a general understanding of the processes involved and their economic impact. Nevertheless, it needs to be considered the contractor's point of view bidding for these activities. Dismantling and demolition contractors will prepare their proposals with all the above aspects calculated in a lumpsum (with more or less qualifications). They will include the potential revenues from the selling of various scrap materials. Therefore, it will be difficult to see the transparency of these positions in the final calculation.

The cases considered are :

- **1000t OHVS Topsides:** This case specifically considers the Northwester Windfarm OHVS.

- **1100t OHVS Topsides:** This case is applicable to the Belwind / Noblewind, Northwind, Rentel and Norther Windfarms. This case is also used to generate pro rata inputs for the Northwester and Seamade Windfarms.

- **1200t OHVS Topsides:** This case is specifically developed for the Seamade Windfarms using pro rata inputs for the 1100t topsides case.

- **2000t OHVS Topsides:** The C Power OHVS is considered as a standalone case being larger and heavier than all the other OHVS Topsides. This is attributable to it being the earliest designed and installed and likely least optimized compared to the others.

All the other OHVS topsides range from 1000 to 1200t in weight and are similar in size.

- **Support Structures:** Separate cost estimates have been generated for the C Power and Northwester Jackets. A generic typical Monopile estimate is generated for the remaining windfarms which all use this type of foundation.

4.5.1 Recyclable Materials Valuations.

Each estimate includes valuations for the sale of recovered recyclable materials which can offset the breakdown costs. The resale values used are current prices. However it should be noted these values can be highly volatile (negative and positive). In the case of high / medium voltage equipment, a factored value is used based on a 70:30 split of steel / copper recoverable. Estimations include an element of non-recyclable materials, typically grouts, screeds and cable fillers. Costs for disposal to landfill or specialist treatment e.g. transformer oil are also included.

The detailed cost estimates are summarized in Table 4-3.

Table 4-3 Breakdown / Recycling Costs

Item	Breakdown Cost [MEUR]	Recycle Value [MEUR]	Nett Cost [EUR]
1000t Topsides	2,4	0,78	1,62
1100t Topsides	2,6	0,86	1,74
1200t Topsides	2,6	0,87	1,73
2000t Topsides	4,6	1,82	2,78
C Power Jacket	1,6	0,15	1,45
Northwester Jacket	1,9	0,18	1,72
Typical Monopile	1,2	0,1	1,1

A 15% profit / risk allowance and a 20% contingency is included in the breakdown cost estimates. All values are in Euro.

4.6 Cost Optimization by combined decommissioning

Combined decommissioning contracting strategy can be a potential way to optimize the decommissioning costs. Considering the Commercial Operation Dates (COD) of the OWFs and their likely end-of-life and commencement of decommissioning, and assuming a 25 years operational lifetime, three distinct groupings of OWFs for potential combined contracts could be suggested:

- C-Power and Northwind
- Belwind / Nobelwind, and Rentel
- Norther, Northwester and Seamade

The longest schedule activity in each group is the WTGs and associated foundation removal activities. These are principally driven by the number of WTG's installed. In each of the group above, , the number of WTG's involved are similar in number.

By combining two or three windfarm decommissioning programs into one overall longer integrated schedule allows risk and contingency allowances to be holistically viewed in the context of unused allowances being "carried forward" into the subsequent windfarm decommissioning operations. This is less beneficial to the WTG decommissioning contractor but nevertheless should reduce overall costs. As an illustration, one individual windfarm decommissioning schedule might carry a 20% contingency for “waiting on weather” delays. Two windfarm decommissioning schedules combined in an extended overall schedule should not carry two 20% contingencies unless “waiting on weather” conditions were expected to be consistently adverse over several years.

Another potential benefit of combining decommissioning projects is that it allows contractors to optimize / minimize mobilization costs, combine operations at an equipment and personnel level including the opportunity to consider non project work and third party specific costs. It also encourages the development of common tooling for the windfarms considered. Another notable aspect of Belgium OWFs is that they are in relatively close proximity to each other. This would allow maximum integration and optimization of transportation activities.

5 Recycling Revenues

5.1 End of Life and Recycling

The wind turbine industry is relatively new and there is still a limited amount of practical experience in decommissioning and recycling of wind turbines components, particularly for offshore wind projects. However recycling of wind turbines is getting more attention in agendas of policymakers, researchers and the industries (Andersen *et al.*, 2014). The end-of-life (EOL) phase and decommissioning of a OWF entails different activities/processes.

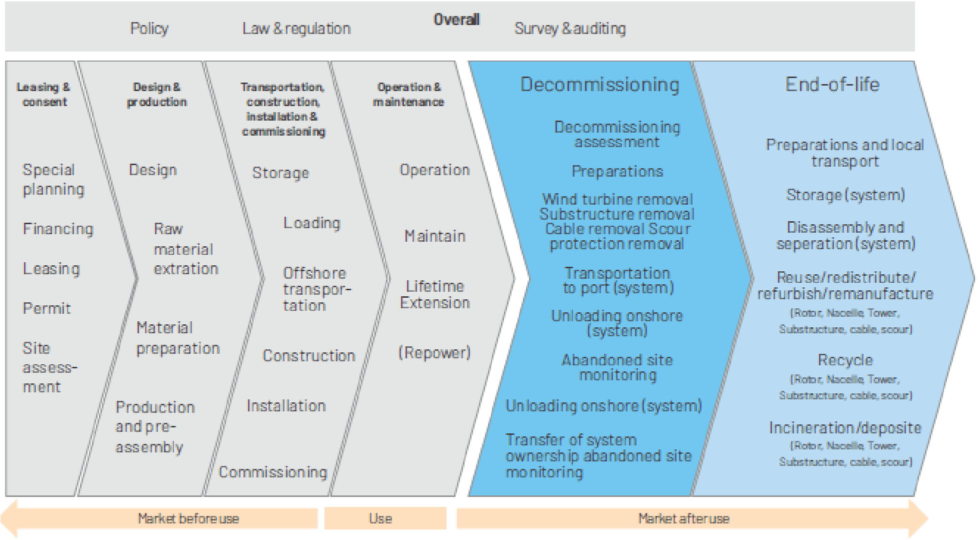


Figure 5-1 Offshore wind value chain with activities per phase (van der Meulen *et al.*, 2020).

Recycling of materials starts at the end of decommissioning phase with the transfer of ownership of systems. The (material-specific) recycling specialist and the consumer of reusable materials will accept the materials and continue in the end-of -life phase.

The different steps before finishing the EOL phase are listed below:

- **Preparation and land transport:** transport from the port to the location where the next EOL activity will take place, including possibly required (mechanical) reduction of large system parts.
- **Storage:** Storing systems in line with the wishes and/or requirements of the owner of the systems and the applicable laws and regulations.
- **Dismantling and separation:** Depending on the next activity, systems will need to be disassembled and/or materials will need to be separated. Depending on the type of material, specific safety regulations apply.
- **Reuse of systems**: This can take place in the original function or in another type of function, this can be by the original manufacturer of reuse via an independent market participant. When it is reused in another function it will become part of another supply chain and there we can make a distinguishment between high-quality or low-quality reuse.
- **Recycling of materials**: Recycling can be done through existing chains or through new chains.

- **Incineration or deposit:** incineration can be used to generate energy and deliver this to customers for materials that cannot be recycled. However this process can lead to an increase of harmful gas emissions and should be avoided. Landfill deposit is not sustainable as well and laws and regulations differ per country

Recycling materials from decommissioned OWFs represents an integral step toward embracing the principles of a circular economy. For more information on the different components of a WTG and their materials, a reference is made to Annex 8A.1 of this report.

5.2 Considerations

Recycling offshore WTG components carries both environmental and economic implications that are closely intertwined.

Recycling turbines could not only reduce the burden on landfills but also conserve natural resources and materials. It significantly reduces the energy and raw materials required for manufacturing new structures, contributing to a sustainability. However, the costs associated with recycling must be weighed against the economic benefits, including potential revenue from recycled materials.

Recycling materials from decommissioned offshore wind turbines could also reduce the demand for virgin resources. This includes materials like steel, copper, and rare earth elements. By conserving these resources, recycling contributes to the reduction of environmental impacts associated with mining, extraction, and manufacturing processes. Responsible recycling practices minimize the volume of waste sent to landfills or incineration. WTG components, if not recycled, can take up considerable space in landfills and may contain materials that can leach into the environment, potentially causing harm.

Recycling typically requires less energy than producing new materials from scratch. For example, recycling steel consumes significantly less energy compared to making steel from iron ore. This results in reduced greenhouse gas emissions and a smaller carbon footprint. And by extending the lifecycle of materials through recycling, the offshore wind industry can reduce its overall carbon emissions. The saved energy is estimated to approximately 81 TJ. The reduction in emissions related to the recycling of WTG material totals approximately 7351 ton CO2 (Jensen, 2019). This aligns with global efforts to combat climate change and supports the industry's sustainability goals.

Recycling offshore WTG components involves costs related to disassembly, transportation, and processing. However, these costs can be offset by potential revenues generated from the sale of recycled materials. For instance, recycled steel and copper can be sold to manufacturers, while recovered rare earth elements can have significant market value. The balance between costs and revenues is a critical economic consideration. The recycling industry can create employment opportunities in regions where decommissioned OWFs are located. Recycling facilities, transportation, and related services contribute to local economies, supporting job growth. Adhering to recycling requirements and environmental regulations is essential for offshore wind project developers. Non-compliance can result in legal penalties and reputational damage. Therefore, understanding and meeting recycling obligations are crucial economic considerations.

The EU's Circular Economy Package stands as a comprehensive strategy promoting sustainability by enhancing resource efficiency, minimizing waste, and promoting recycling. Within this framework, specific directives play pivotal roles: the Waste

Framework Directive forms the legal backbone for waste management, emphasizing the waste hierarchy and extended producer responsibility.

The Waste Electrical and Electronic Equipment (WEEE) Directive, addressing electrical and electronic waste, extends its reach to components from offshore wind turbines, mandating their proper recycling and disposal.

While EU member states possess their unique recycling regulations, they often align with broader EU mandates. Developers of offshore wind projects navigate a landscape of permits and reporting obligations, ensuring compliance with decommissioning and recycling norms, often involving environmental impact assessments and recycling plans.

Staying updated of these regulations isn't just a legal duty but a means to showcase environmental stewardship and nurture a positive industry image. Moreover, regional initiatives like the Flemish Materials Decree delve deeper than EU directives, stressing sustainable material use and waste management, evident in programs like the Flemish Materials Program, emphasizing recycling initiatives and exploring alternatives to incineration as a waste treatment method. The Materials decree dates back to 23/12/2011 (later enforced) and concerns the general framework. The effective implementation of this decree is translated in VLAREMA with implementation provisions (Decision of the Flemish Government determining the Flemish regulation regarding the sustainable management of material cycles and waste) from 17/02/2012."

5.3 Industry readiness

An important aspect of the viability of recycling techniques is the technological readiness or maturity of these techniques. Useful recycling methods may not be viable in reality because the facilities to utilize the techniques at an industrial scale might not exist. On the other hand, recycling techniques with a lower value retention may be easily scalable and low cost, making them more appealing as alternatives. This is of special importance for the recycling of WTG blades, where many of the high level material reclaim recycling methods being relatively new and not yet feasible at industrial scale (DecomTools, 2021). Figure 5-2 shows the different recycling techniques for WTG blades ordered based on their Technology Readiness Level (TRL).

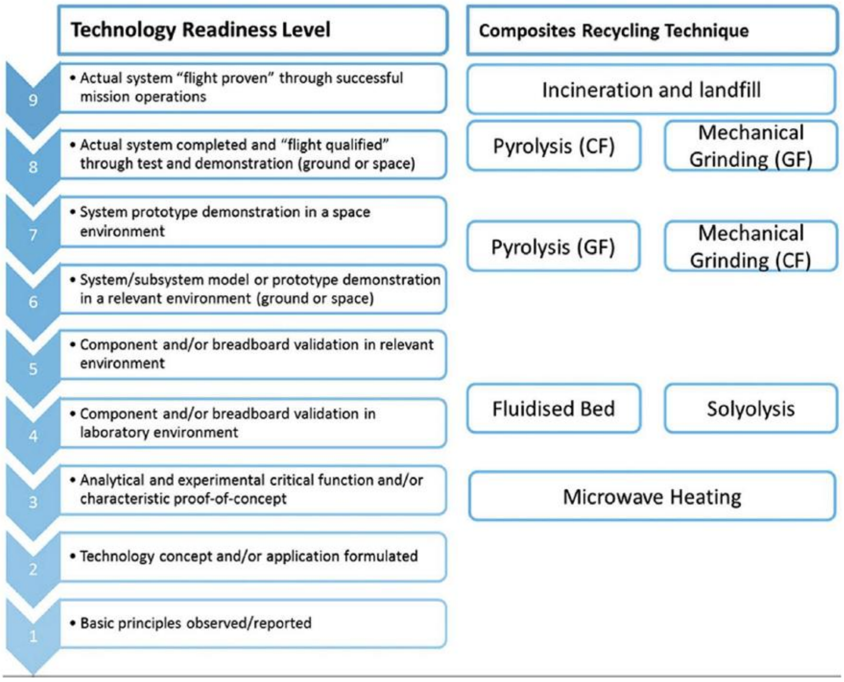


Figure 5-2 Recycling strategies for WTG blades ordered based on their technological readiness level (Rybicka *et al.*, 2016).

Landfill and incineration are currently the most commonly used techniques for the disposal of composite materials. As such, the TRL of these techniques is 9, with successful facilities at industrial scale. For Carbon fibre reinforced polymers, pyrolysis is the technique with the highest TRL. Companies like ELG Carbon Fibre Ltd. can recycle carbon fibres from composite materials at an industrial scale (ELG carbon Fibre Ltd., 2016).

For glass fibre reinforced polymers, mechanical grinding has the highest TRL and is ready to be used on industrial scales. Pyrolysis for glass fibres and mechanical grinding for carbon fibres have a lower TRL due to various reasons (Rybicka *et al.*, 2016). The low price of glass fibres make a relatively expensive recycling process like pyrolysis less attractive to investors. Mechanical grinding of carbon fibres has to deal with abrasive carbon materials and their negative effects on the machinery. Technical or financial challenges prevent investment, adoption and upscaling of recycling techniques, leading to a lower TRL of these techniques. Techniques such as fluidised bed and Solvolysis are mainly performed at lab or pilot scale. These techniques might be promising, but are not ready to be used in the industry at larger scale. More research and/or investment is needed to scale up these techniques to an industrial level (Hagnell and Åkermo, 2019).

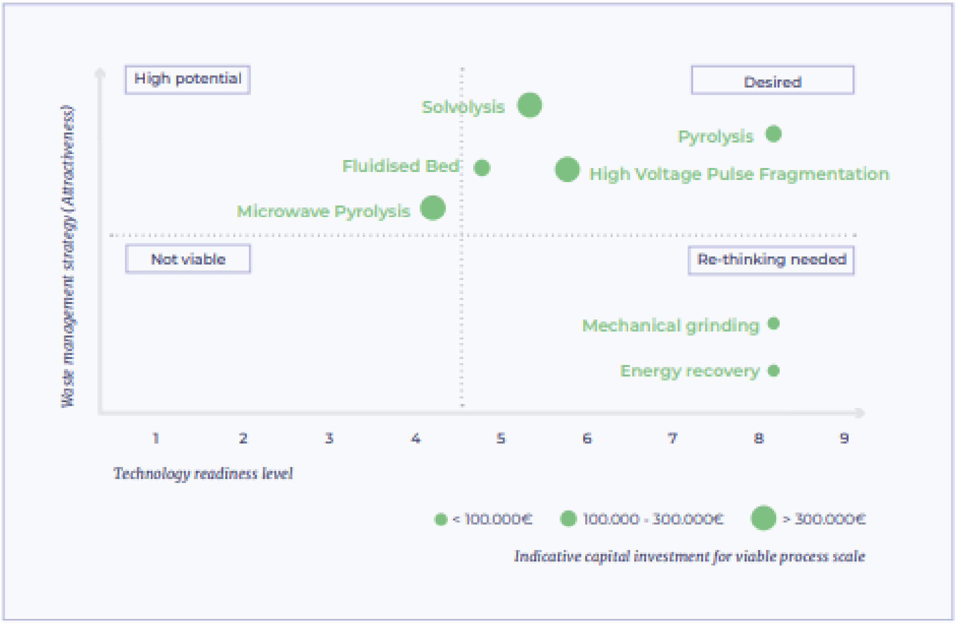


Figure 5-3 Attractiveness and maturity of composite material recycling techniques. The size of the dots shows the size of the investment needed to make the technique viable at large scales (SusChem, 2018).

5.4 OWF recycling

The main share of the original installed mass of an OWF is the scour protection and contributes to around 80 % of the total mass (Demuytere *et al.*, 2024).

A decommissioned WTG consists of a mixture of various materials. The main materials used are **cast iron, steel, copper, aluminium, fibreglass epoxy and rare earth magnets with neodymium and dysprosium.** Today's recycling rate of a WTG lies between 80 and 90% (DecomTools, 2021), but each OWF has its own WTG design and composition may vary between models. Based on an overall design shown in Table 5-1 an estimation is made for all compartment materials Table 5-2.

5.4.1 Recyclable materials

When assessing the amount of material used per turbine it's important to notice the different models used in each windfarm . For the purpose of this study an average was used based on literature studies and former LCA studies. When assessing the amount of material used per turbine, another important element to analyse is the foundation type, since there is a significant amount of recoverable materials there as well (Topham *et al.*, 2019). Most frequently used foundation is the monopile because of its adaptability to the seabed conditions. Other types are jackets, tripods, suction buckets, gravity bases and floating. All foundation structures are primarily fabricated in steel. This is mainly due to the material's strength, flexibility and resistance to marine environments, while being 100% recyclable, making it a fundamental part of the circular economy.

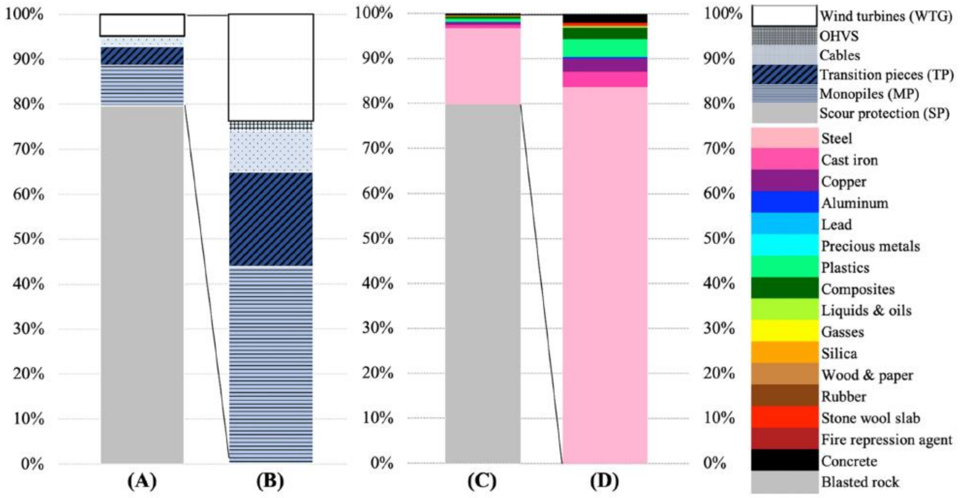


Figure 5-4 Relative mass distribution over the defined OWF components, with (A) and without (B) the blasted rock fraction (with WTG consisting of the turbine tower, the nacelle with the rotor and the blades). Relative mass distribution over the 17 main material groups of the OWF (C) and rescaled by excluding the blasted rock fraction (Demuytere *et al.*, 2024).

Steel accounts for the second largest share at 17%, encompassing the blasted rock, or 84% excluding this component. Plastics (3.9%), cast iron (3.4%), and copper (3.0%) collectively constitute less than 10% of the remaining materials. Composites, mainly linked to blade fiberglass, the nacelle cover, and the nose cone, represent 2.6% of the total material mass. Around 1900 tonnes of plastic are primarily attributed to cables, with filler and insulation materials making up 79% of all plastics used in the OWF . Smaller portions, such as concrete (slightly over 1000 tonnes) and stone wool slab material (about 250 tonnes), stem from specific sources—the transition piece grout and the OHVS, respectively (Demuytere *et al.*, 2024).

From all the materials, the composites reinforced with glass fibre are the most challenging parts. Currently a mixture of glass and carbon fibre can be found in more recent turbine blades as transition to a complete carbon fibre design. Based on the material compositions and measurements of the existing wind turbines and estimation was made on the volumes for different materials in the current windfarms.

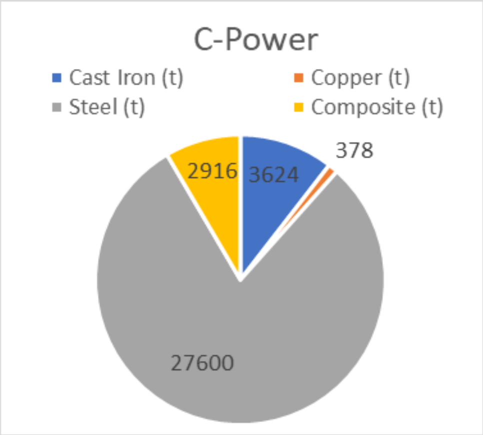
Table 5-1 WTG components and sub-component breakdown (Some components are not always present depending on the model) (Roelofs, 2020).

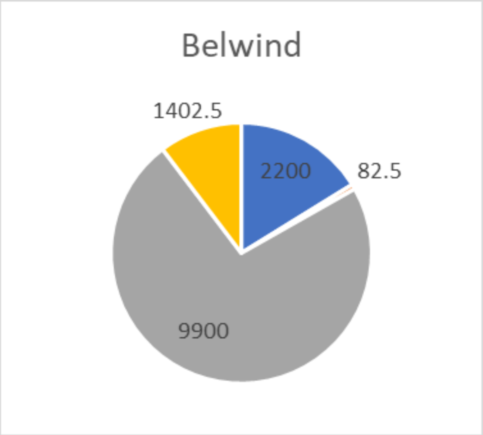
Component	Sub-component
Rotor	Hub
	Nose cone
	Pitch system
	Blades
Nacelle	Bed plate
	Cover
	Mechanical brake
	Yaw system
	Drive train (generator, shaft, gearbox, bearings)
	Other (e.g. measuring equipment
Tower	Power cables, ladder, etc.
Foundation	Jacket or monopile
Other	Power electronics, cables etc.

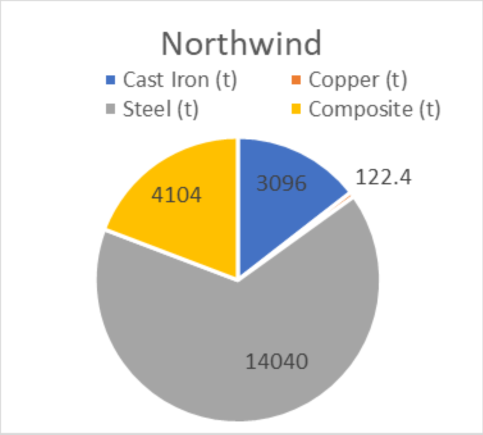
Table 5-2 Split of total amount of material mass in a WTG over the different components obtained through data from previous LCA studies (DecomTools, 2021).

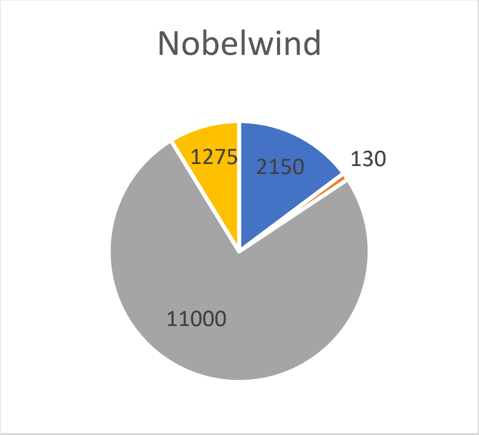
Component	Materials	Split (%)
	Cast iron	31.3 %
Rotor	Steel	3.3 %
	Fibre glass	79.4 %
Tower	Epoxy	100 %
	Steel	76.6 %
Nacelle	Aluminium	100 %
	Copper	100%
	Magnet (rare earth materials)	100 %
	Steel	20.0 %
	Cast iron	68.7 %
	Fibre glass	20.6 %

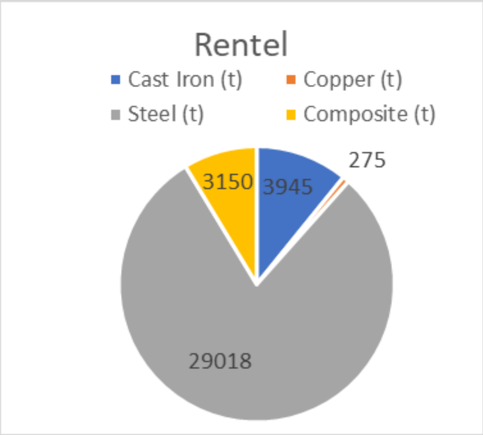
Using the information above a high level estimation was made on the different shares of steel, cast iron, composite material and cupper. Below the pie charts represent the main components and their share for the different windfarms in the BPNS.

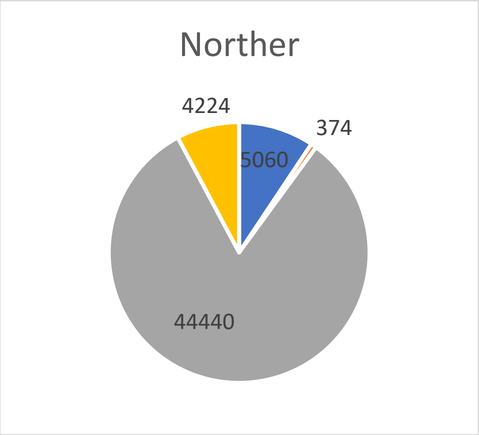


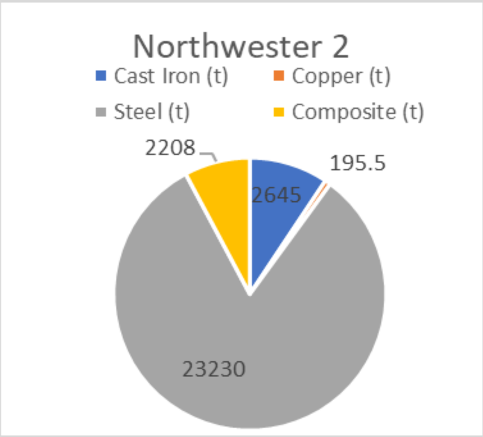


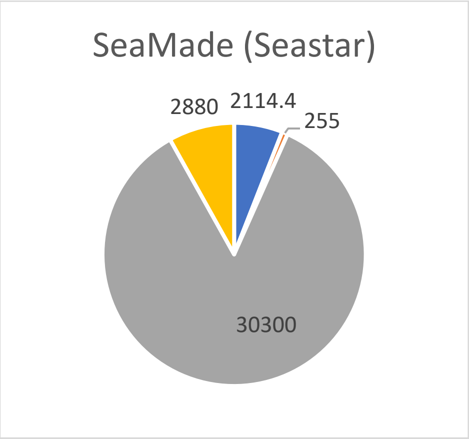

Northwind
■ Cast Iron (t)
■ Copper (t)
■ Steel (t)
■ Composite (t)
3096
122.4
14040
4104


Nobelwind
2150
130
11000
1275


Rentel
■ Cast Iron (t)
■ Copper (t)
■ Steel (t)
■ Composite (t)
3945
275
29018
3150


Norther
5060
374
44440
4224


Northwester 2
■ Cast Iron (t)
■ Copper (t)
■ Steel (t)
■ Composite (t)
2645
195.5
23230
2208


SeaMade (Seastar)
2114.4
255
30300
2880

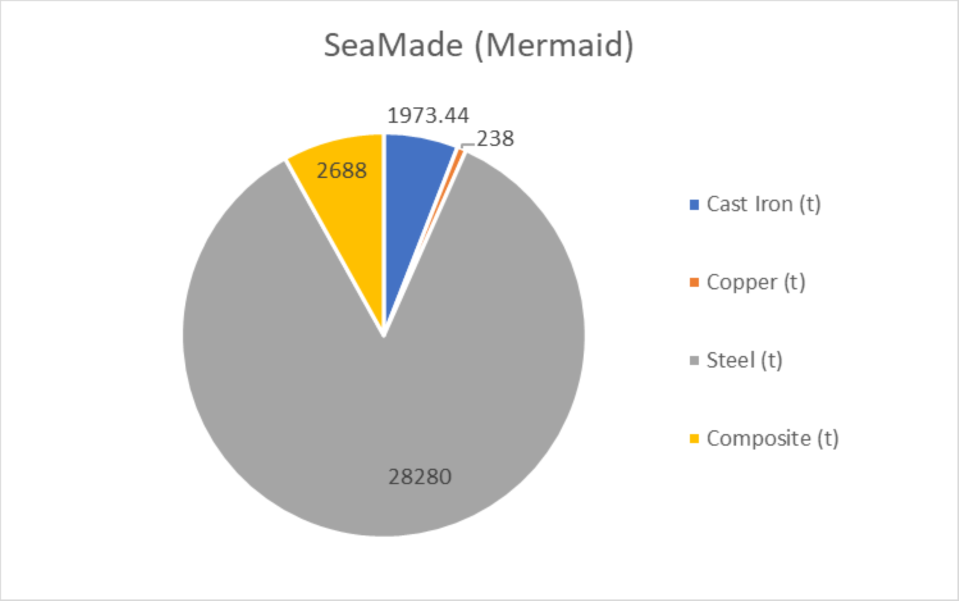


Figure 5-5 Pie charts showing the amount of steel (grey), cast iron (blue), copper (brown) and composite material (yellow) in tonnes per windfarm for WTG components.

Figure 5-5 shows the share of cast iron, steel, copper and composite materials in the different OWF s. The recycling rate of steel is 92 % and cast iron is 98% which means the major part of the WTG is recyclable. Copper also has a high recycling rate of 98 % but comprises a smaller volume of the wind turbine. Composite materials comprise a weight percentage of the WTG of similar size as cast iron, but has a lower recycling rate.

For the magnets recycling can take place as magnet-to-Rare Eart Element (REE) or magnet-to-magnet (reprocessing). Critical REEs specifically neodymium (Nd), dysprosium (Dy), Praseodymium (Pr) and Terbium (Tb) are present in varying quantities in permanent magnets (Roelofs, 2020). A study from 2016 showed an overall REE extraction efficiency of 75 % (Schulze and Buchert, 2016).

Scour protection material used in Belgian Windfarms are rocks dumped around the foundations and over cable crossings.

The volumes of materials in tonnes, that are expected after decommissioning are shown below in Figure 5-6 and show an abrupt increase between 2037 and 2039 when different windfarms will arrive at their EOL stage. A smaller increase is seen around 2034 when the first and oldest with smaller wind turbines are expected to be decommissioned.

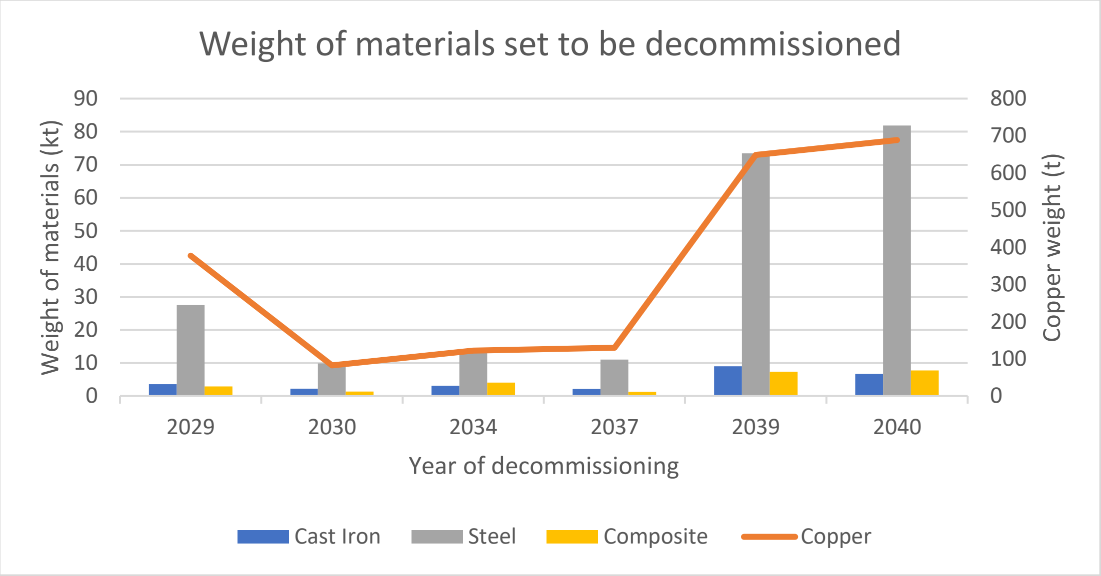


Figure 5-6 Time series of estimated mass of materials of wind turbines from Belgian offshore windfarms to be decommissioned.

5.4.2 Recycling resale values

Recycling or collecting rates are frequently defined in different ways for the life cycle stages or left undefined or only applicable for a certain material (Demuytere *et al.*, 2024) For example, for waste electrical and electronic equipment (WEEE), the collection rate is based on the weight of EEE placed on the market in the three preceding years (European Commission, 2012). This cannot be used for OWF as they have an expected lifetime of more than 20 years. Also recovery and recycling rates can vary by different methodologies and calculation points in the recycling value chain.

Based on current market values an estimation was made on the resale values that can be expected of the six main materials with the highest recyclability of the OWF s.

Additional expenses that need consideration in determining recycling revenues include:

- Distance from port to OWF (WF)
- Costs associated with vessels (+ Daily rate for vessel crew)
- Operational hours required on-site for each WTG generator (WTG), support structure, and array cable
- Expenses incurred due to weather delays
- Port storage charges
- Transport costs from the inland area to recycling facilities
- Expansion expenses for scaling up of recycling facilities or creating new facilities.

When calculating the cost and/or revenue of recycling materials from OWF the net cost (C_{net}) can be written as follows:

$$C_{net} = \sum (C_{disassembly} + C_{transport} + C_{recycling}) - \sum (I_{material} + I_{energy})$$

$C_{dissassembly}$ = the cost for disassembling the WTG and its components

$C_{transport}$ = transportation cost to recycling infrastructure/company

$C_{recycling}$ = cost based on chosen recycling technique

$I_{material}$ = revenue from material source (cast iron, steel, cupper, composite, rare earth materials)

I_{energy} = revenue from energy recovery

Table 5-3 Resale value unit prices (€/tonne)

Material	Resale value
Copper	7.900 €/tonne
Cast Iron	190 €/tonne
Steel	180 €/tonne
Glass fibre	250 €/tonne
Carbon fibre	1.300 €/tonne
Neodynium	61.750 €/tonne
Dysprosium	365.750 €/tonne

Table 5-4 Material volumes in ton (t) per windfarm

Name OWF	Cast Iron (t)	Copper (t)	Steel (t)	Composite material (t)	Neodynium (t)	Dyprosium (t)
C-Power	3.624	930	20.760	2.916		
Belwind	2.200	615	47.854	1.402		
Northwind	3.096	500	60.875	4.104		
Nobelwind	2.150	672	53.964	1.275		
Rentel	3.945	717	76.828	3.150		
Norther	5.060	836	71.102	4.224		
Northwester 2	2.645	424	48.389	2.208		
SeaMade (Mermaid)	1.973	487	60.738	2.688	41	3
SeaMade (Seastar)	2.114	504	65.076	2.880	29	2
Total existing OWFs (t)	26.808	5658	512.425	24.847	71	5
Hypothetical OWF (700 MW 15MW Vestas)	9.517	1481	160.159	2.825	34	2
Hypothetical OWF (700 MW 15MW DD turbines)	5.992	1481	160.159	2.825	176	13
Hypothetical OWF (700 MW 12MW Vestas)	9.558	1484	160.477	2.837	35	2
Hypothetical OWF (700 MW 12MW DD turbines)	6.018	1484	160.477	2.837	153	11

Table 5-5 Overview Recycled material resale values for cast iron, copper, steel and composite materials and rare earth metals. Costs for recycling have not been included. Prices were taken at time of writing of this report (unit prices Table 5-3).

Name OWF	Cast Iron (MEUR)	Copper (MEUR)		Steel (MEUR)			Composite material (MEUR)	Neodymium (MEUR)	Dyprosium (MEUR)
		wind turbine	**cables**	**Turbines**	**Monopile (complete)**	**Monopile (partial)**			
C-Power	0,7	2,9	4	4,6	/	/	8,2		
Belwind	0,4	0,6	3,9	1,6	6,8	3,8	3,9		
Northwind	0,6	0,9	2,7	2,3	8,4	4,7	11,5		
Nobelwind	0,4	1	3,9	1,8	7,7	4,1	3,6		
Rentel	0,7	2,1	3,2	4,8	8,6	4,4	8,8		
Norther	0,9	2,9	3,3	7,3	4,8	2,6	11,8		
Northwester 2	0,5	1,5	1,7	3,8	4,5	2	6,2		
SeaMade (Mermaid)	0,4	1,8	1,8	4,7	5,8	3,2	7,5	0,1	0,06
SeaMade (Seastar)	0,4	2	1,8	5	6,2	3,4	8,1	0,1	0,04
Total Current OWF	5	15,9	26,4	36	53	28	69,6	0,2	0,1
700 MW 15 MW Vestas	1,8	5,5	5,6	12,4	15,4	8,4	7,9	0,1	0,05
700 MW 15 MW DD turbines	1,1	5,5	5,6	12,4	15,4	8,4	7,9	0,5	0,2
700 MW 12MW Vestas	1,8	5,5	5,6	12,4	15,4	8,4	7,9	0,1	0,05
700 MW 12MW DD turbines	1,1	5,5	5,6	12,4	15,4	8,4	7,9	0,5	0,2

5.5 Recycling Scenario’s

Figure 5-7 shows different options for the removal of wind turbines based on the different components. Only option M4 and M5 are considered in this study.

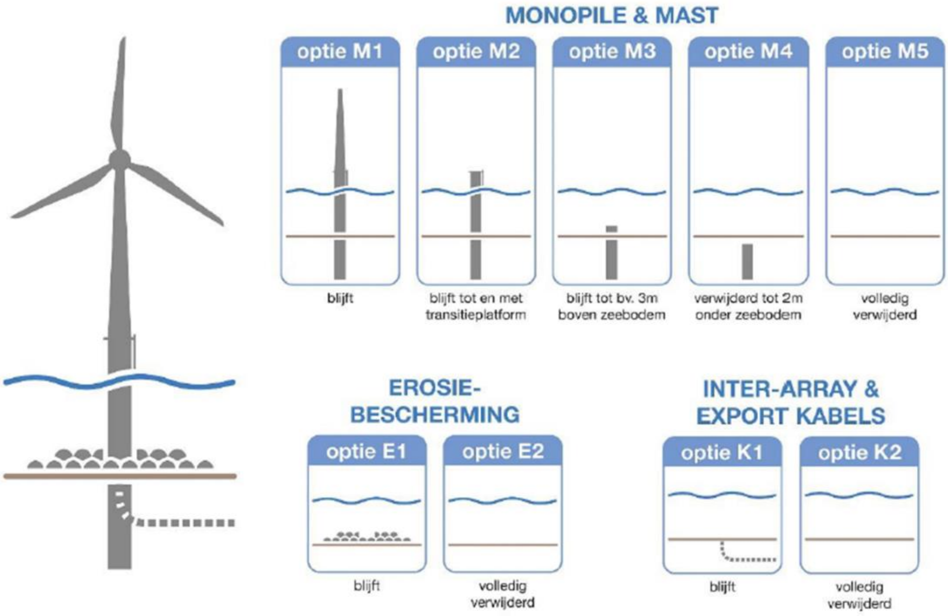


Figure 5-7 Different strategies for OWF decommissioning (Van Maele *et al.*, 2023)

5.5.1 Option M4 : Cutting below the seabed

Figure 5-8 illustrates the material movement of an OWF when the foundation is cut below the seabed. Around 84% of the materials, primarily rock and a small portion of steel, remain in place. This equates to roughly 23% of the initial steel used. Post dismantling and removal, approximately 16% of all materials find their way onshore. This material assortment largely comprises steel, polymers, and other metals, accounting for over 80% of the transferred materials. Among these, about 2.8% undergo downcycling for low-quality applications, while 3.2% are slated for incineration with potential energy recovery. Currently composite materials have not many cost-competitive applications and are mostly landfilled[11]. These composite materials represent a significant portion of landfill waste, accounting for approximately 47% of all materials destined for landfills. The remaining landfill materials include smaller quantities from various sources such as stool wool slab, WEEE, and secondary processing losses.

Currently in this decommissioning scenario, still a large portion would end up in landfills. Surprisingly, with only 6.9% of materials treated onshore, more mass is lost in landfills than the combined amount sent for incineration and downcycling.

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[11] Landfill is not allowed in Belgium (Source: OVAM).

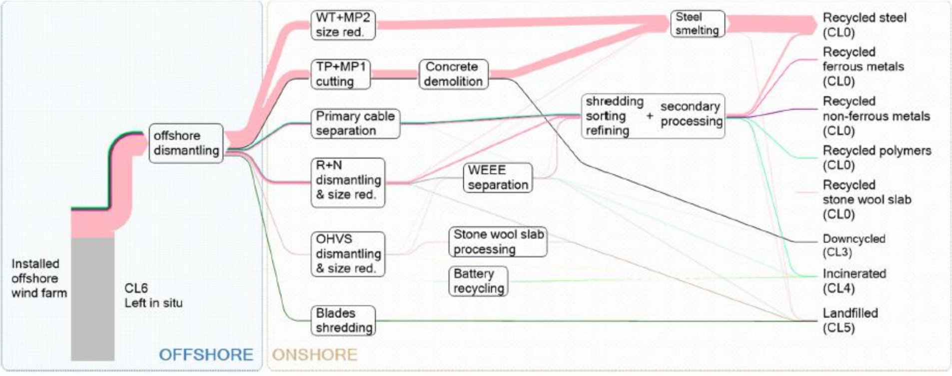

Figure 5-8 Material flow analysis of the offshore decommissioning and end-of-life treatment scenario (WT: WTG tower, MP2: second/middle part monopile, TP: transition piece, MP1: first part monopile, R + N: rotor + nacelle, OHVS: offshore high voltage station, WEEE: waste electrical and electronic equipment, CL: cascading level, size red.: size reduction).

When cutting the monopile at 2 m below the seabed (Topham *et al.*, 2019) roughly 57 % of the monopile is left on site. Which means the collection rate of steel of the foundation is significantly less than complete removal. Table 5-6 gives an overview of the resale values of the foundations in the case of partial removal of the monopiles.

The shares of EOL destinations for the material groups are shown in Figure 5-9.

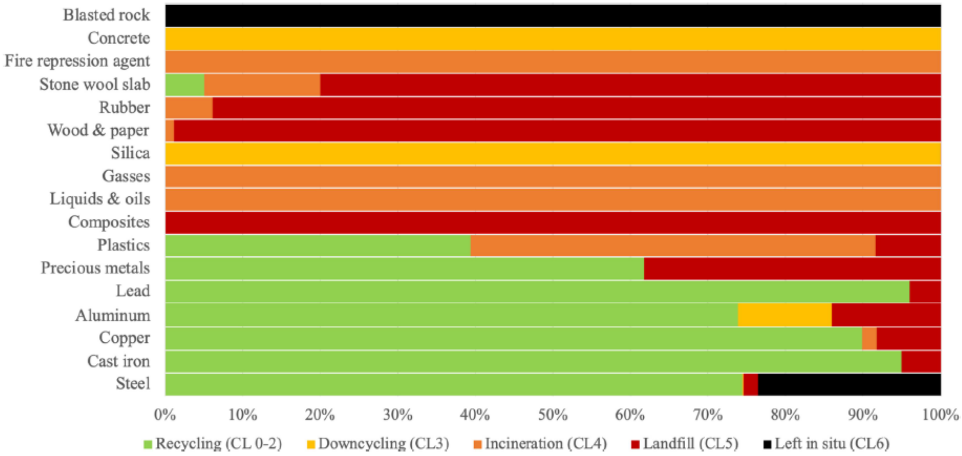

Figure 5-9 End-of-life destination of the material groups, relative to its installed mass in the OWF (CL: Cascading level) (Demuytere *et al.*, 2024)

The two scenarios based on the location of the recycling processes can also be implemented in option M4.

- Scenario 1, the recycling process for offshore wind energy materials occurs directly at the port.
- Scenario 2 involves transporting these materials to specialized companies for recycling.

Table 5-6 Total resale values for the partial foundation monopiles when completely removed per OWF . Steel was priced at 180 eur/tonne at time of writing

Name OWF	Steel foundation revenues (MEUR)
C-Power	/
Belwind	3,8
Northwind	4,7
Nobelwind	4,1
Rentel	4,4
Norther	2,6
Northwester 2	1,9
SeaMade (Mermaid)	3,2
SeaMade (Seastar)	3,4
Total existing OWFs (Eur)	28,2
Hypothetical OWF (700 MW 15MW Vestas)	8,4
Hypothetical OWF (700 MW 15MW DD turbines)	8,4
Hypothetical OWF (700 MW 12MW Vestas)	8,4
Hypothetical OWF (700 MW 12MW DD turbines)	8,4

5.5.2 Option M5: Complete removal

For the recycling phase, there are two scenarios based on the decommissioning process. The total amount of weight of materials that is decommissioned and thus available for possible recycling route, differs between these scenarios.

In strategy M5, it is assumed that the monopile foundations of the wind turbines are completely removed from the sediment and decommissioned. This allows for a greater amount of steel to be collected and recycled. The dimensions of the monopiles (and thus the amount of steel) differ between each OWF . The length of the monopiles is typically proportional to the water depth, while the diameter and thickness of the monopiles are proportional to the size of the wind turbines that are installed on top of it. The length and weight of the transition piece (TP) is also proportional with the size of the wind turbine. Table 5-7 shows the total resale value of steel, originating from the monopile and transition pieces, per OWF in the case of complete monopile removal.

Regardless of monopile removal, there are two other expected scenarios based on the location where the material will be (partially) processed when choosing for a full decommission.

In scenario 1, the recycling process for offshore wind energy materials occurs directly at the port. This setup allows for a more centralized approach, potentially reducing transportation distances and associated costs. Materials like blades, towers, and other components can be sorted, disassembled, and processed in specialized facilities within or adjacent to the port area. However, the infrastructure and capacity at the port need to be considered for efficient processing.

Conversely, scenario 2 involves transporting these materials to specialized companies like Reprocover for recycling. While these companies may have advanced technologies and expertise in recycling offshore wind energy materials, the transportation of these components from the port to these specialized facilities might incur higher costs. Despite potentially superior processing capabilities, the logistics involved in transporting materials to these distant facilities can impact overall efficiency and sustainability, primarily due to increased transportation emissions and expenses. Balancing these considerations is crucial in determining the most effective recycling scenario for offshore wind energy materials.

Table 5-7 Total resale values for the foundation monopiles when completely removed per OWF . Steel was priced at 180 eur/tonne at time of writing.

Name OWF	Steel foundation revenues (Eur)
C-Power	/
Belwind	6,8
Northwind	8,4
Nobelwind	7,7
Rentel	8,6
Norther	4,8
Northwester 2	4,5
SeaMade (Mermaid)	5,8
SeaMade (Seastar)	6,3
Total existing OWFs (Eur)	53,0
Hypothetical OWF (700 MW 15MW Vestas)	15,3
Hypothetical OWF (700 MW 15MW DD turbines)	15,3
Hypothetical OWF (700 MW 12MW Vestas)	15,3
Hypothetical OWF (700 MW 12MW DD turbines)	15,3

5.6 Recycling techniques

Recycling offshore WTG components presents a multifaceted challenge due to the diverse materials used in their construction. While each component requires tailored recycling approaches, several key techniques are emerging. This chapter covers the techniques that are already available in Belgium. Currently the Belgian industry is investing in upscaling to prepare for the large quantities that are expected by 2030.

The different recycling options are based on the hierarchy of the preferred options (Figure 5-10)

Figure 5-10 preferred options based on the recycling hierarchy ((Schmid *et al.*, 2020))

5.6.1 Repurposing and Reuse

Even though the reuse and repurpose route is an interesting option, the geometric and structural design of the composite structures often limit the number of feasible new applications after end of life. Furthermore, repurpose projects are not easily repeated, since boundary conditions are different for every project. Several studies about reuse exist, but implementation is still rare.

Repurposing involves finding new applications for decommissioned components, extending their useful life. This technique includes:

- Steel Towers: Disassembled steel towers may be repurposed for various construction projects, including bridges and buildings.
- Blade Repurposing: WTG blades can find second lives as components in architectural and artistic installations, furniture, or they can be used as structural elements in infrastructure projects, such as bridges, bike sheds (Figure 5-11), sound walls and cell-phone towers. Parts of the blades can also be used as beam and sheet materials in construction. This requires some processing but could still be considered as repurposing.

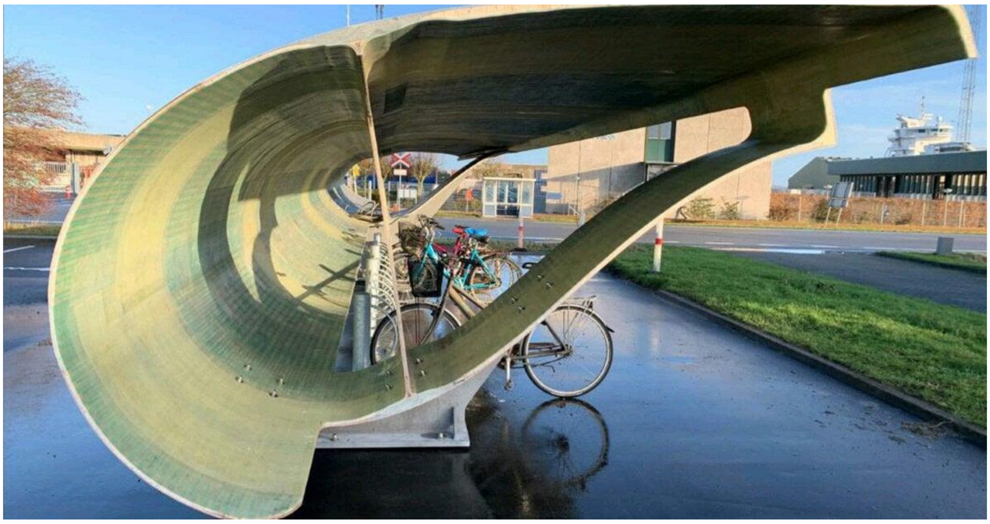

Figure 5-11Bike shed made from WTG Blade in Denmark (image from Chris yelland [https://www.designboom.com/design/denmark-repurposing-wind-turbine-blades-bike-garages-09-27-2021/]).

Recycling of metals is well-established for common metals such as iron, steel, copper and aluminium.

New upcoming energy industries such as floating solar PV are also considering the re-use of OWF materials when designing the installations. However research was still not published on this topic.

5.6.2 Advanced Composite Recycling

Recycling WTG blades, primarily composed of composite materials, poses unique challenges. The individual materials in composites are hard to separate, making recycling difficult. Furthermore, the value of primary and secondary materials is an important aspect. Primary glass fibre is inexpensive and secondary glass fibres have degraded material properties, which leads to a low incentive to try to recycle these materials.

Carbon fibre is more expensive, and more durable. Therefore, it might be more economically interesting for extensive recycling methods (Vo Dong *et al.*, 2018).

The recycling techniques of composites can be divided into two categories: low level material reclaim and high level material reclaim. In low level material reclaim, there is a complete loss of the physical structure of the fibres in the composites. High level material reclaim sees the recycling of composites with the goal of reusing the recycled fibres in other industries for their physical characteristics. The value of the recycled materials is lower when using low level material reclaim techniques than when using high level material reclaim techniques. Figure 5-12 gives an overview of different recycling techniques sorted based on material reclamation (Hagnell and Åkermo, 2019).

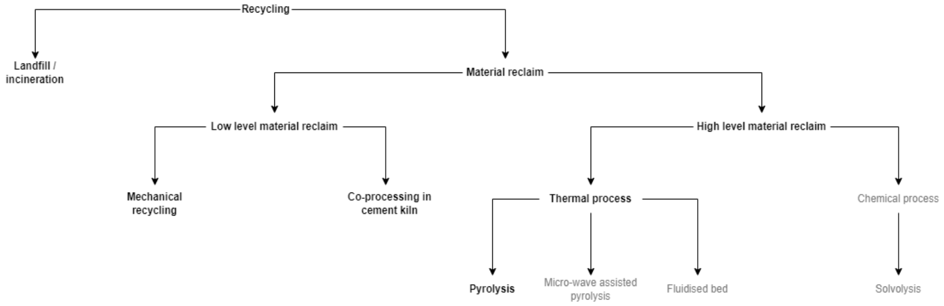

Figure 5-12 Recycling strategies sorted on level of materials reclaimed. Technologies at lab or pilot scale are shown in grey (Hagnell and Åkermo, 2019).

Low level material reclaim techniques for composite materials include but are not limited to:

- Mechanical Recycling: Mechanical methods involve grinding or shredding WTG blades into smaller particles. The recycled products, very short fibres and ground matrix, can be used as fillers in construction materials or reinforcement in other composites. Mechanical grinding is the most commonly used technology due to its effectiveness, low cost and low energy requirements. However, the recycled materials have a significantly lower value than the primary materials. Due to the potential negative effects of abrasive carbon materials on machinery, this recycling method is currently only used at large scales for glass fibre reinforced polymers.
- Co-processing in cement kiln: Mineral constituents (fibres) are converted into cement clinker that can be used in cement production as binder. Additionally, around 12MJ/kg composite waste can be recovered as energy in the form of heat, by combustion of the organic resin (Job, 2013). Around 100% of fibre material (67% of total material) can be converted into cement clinker and the CO2 emissions can be reduced by 16% due to the replacing the coal or natural gas with resin in cement production. As the mineral constituents of the fibres are used for cement clinker, this recycling method is only useable for glass fibre reinforced composites.

In current high level material reclaim techniques, fibres are recycled and kept in relatively useful conditions by separating them from the resin matrix. This separation can be done by dissolving the resin matrix using either thermal processes or chemical treatments.

High level material reclaim techniques include:

- Thermal recycling: Pyrolysis is a process that operate at high temperatures (450 – 700 °C) and involves thermal degradation of the resin matrix material. It allows for the recovery of the fibres and the matrix (in the form of ash). The matrix can be turned into oil or powder, which can be used as energy source or chemical building blocks, while the fibres can be reused in other industries. Due to the high processing temperature, the fibre surface is often damaged, leading to a loss in mechanical properties. A derivate of pyrolysis, called microwave pyrolysis, uses microwaves to allow for an easier control of the heating process and therefore reducing the temperatures needed and limit damage to the fibres. However, microwave pyrolysis is currently only performed at lab scale. Pyrolysis is currently the only economically viable solution for carbon fibre recovery (Schmid *et al.*, 2020).

- Chemical Recycling: Solvolysis is a technique being studied that chemically dissolves the resin matrix. The technique can offer a multitude of possibilities due to operating at a wide range of temperature, pressure and solvents. It requires lower temperatures compared to pyrolysis, resulting in cleaner fibres, with lower degradation. The use of super-critical water as a solvent seems to be the most promising option. However, solvolysis has a high energy consumption due to the high temperature and pressure of some processes. Furthermore, currently only carbon fibres can be retrieved using this method and solvolysis is mainly performed at lab or pilot scales (Schmid *et al.*, 2020).

The actual materials in these composites form an important aspect for their recycling. Some techniques can only be used on certain composites, and the development of new composites can give rise to new and improved recycling techniques. Current trends in the wind energy industry indicate that with the increasing size of wind turbines, carbon fibre reinforced polymers will be used more instead of the current glass fibre reinforced polymers. This would result in a change in recycling options for WTG blades. However, future trends suggest an increased use of thermoplastic composites instead of the current thermoset ones. The recycling of thermoplastic composite material may be fundamentally different. Studies have shown that a new thermal recycling exists for thermoplastic composites called dissolution (Cousins *et al.*, 2019). Dissolution addresses some of the downsides with current pyrolysis techniques, but is limited to thermoplastic composites, which are scarce in the current wind energy sector. Furthermore, innovators are exploring the creation of new composite materials that are more easily recyclable, reducing future recycling challenges.

These recycling techniques represent an ongoing effort to address the sustainability of offshore wind energy by reducing waste and conserving resources. As technology continues to advance, the offshore wind industry is poised to implement increasingly efficient and environmentally friendly recycling methods.

6 Conclusions and discussions

Eight OWFs (from nine concessions) with 2.26GW capacity in Belgium North Sea will be decommissioned between 2034 and 2045. This study has estimated both decommissioning costs of all these assets and revenues from recycling and other end-of-life scenarios. Total cost of decommissioning of all existing OWFs in Belgium (all assets, inner and export cables, except OHVS) is estimated approximately 952MEUR which translate to 421kEUR/MW. Estimated material resale value of all these assets is 234.5MEUR. This means that in the best case scenario, a maximum of a quarter of the decommissioning costs can be earned back. When OHVS decommissioning estimations based on experience and lessons learnt from oil&gas platforms' decommissioning, appx decommissioning cost of all OHVS in Belgium estimated as 215.7MEUR.

In total of seventeen OWFs; nine of which are the existing OWF projects, and the rest are generic wind farms as part of trend analysis. For foundations, full extraction of the monopiles are considered and compared with the monopile internal cutting. For WTG removals, reverse installation method (i.e., first blades are removed one by one, then nacelle, and then the tower) and bunny ear configuration (i.e., one blade is removed first and then complete rotor with two blades are removed at once, followed by nacelle and tower removals) are estimated. These major offshore works are performed with a JUV supported by BVs and TBs, except for the GBF decommissioning. For this foundation, it is assumed that the foundation is de-ballasted, refloated and then towed to the shore. Both inner array and export cables are removed completely from the seabed, as well as the scour protection around the foundations. Foundation and WTG removal are found to be responsible from 63% of all decommissioning costs. Both for the existing OWFs and the generic OWFs modelled for the trend analysis, a decrease in decommissioning costs is found with increasing WTG capacity. Predicted 421kEUR/MW cost agreed well with the other studies found in the literature.

On the other hand, estimating OWF decommissioning cost accurately is a challenging task. It highly depends on the selected decommissioning strategies per asset, availability and cost of the vessels, workable weather windows, condition of the assets during decommissioning period, etc. Furthermore, especially for the full extraction of XL or XXL sized monopiles, the technology is still being developed and not ready yet. Cost predictions in this study assumed these equipment to be available and proven its capabilities by the time of the decommissioning. Although the results presented here and the approach can be used as guideline, more detailed and dedicated studies, supported by field inspections of assets are required to predict the actual OWF decommissioning costs. It can also be expected that until the OWFs in the PEZ are decommissioned, which is not expected before 2055, more dedicated and cheap technologies will be available, more standard procedures will be developed and more experience in the industry will be collected. Also with the help of utilisation of higher WTG capacities in these new wind farms, decommissioning costs could be further reduced.

Recycling techniques of OWF materials are still in development and national and international markets are preparing for the increase in volumes to be processed when OWF will be decommissioned. Currently landfill is used mostly for glass and carbon fibre but with upcoming restrictions, re-use is being considered in different industries. Components such as steel, cast iron, aluminium and copper already have established recycling routes and can ensure a high resale revenue that could compensate a part of the decommissioning costs. However decommissioning costs are still quite high and resale values will never offset these costs. Recycling and re-use of materials such as rare earth materials and carbon and glass fibre should be considered from an environmental point of view as they will decrease CO_2 emissions, landfilling and mining (REE).

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Annex A Components of Offshore Wind Turbines

A.1 Components and subcomponents

Before delving into recycling options, it's crucial to understand the various components of offshore wind turbines (Figure 8-1). Offshore wind turbines are complex structures composed of several key components, each designed to withstand the harsh marine environment. These components are made from various materials, and their recyclability varies.

Figure Annex A-1 Components of offshore WTG
(source: https://www.cleanenergywire.org/factsheets/resources-and-recycling-needs-germanys-wind-turbines)

A.1.1 Towers and Foundations:

Tower sections are typically made of steel, and foundations are constructed using materials like concrete or steel monopiles. These components are massive and require careful consideration in recycling strategies.

Steel components have high recyclability rates. The steel from towers and foundations can be recycled, often through a melting and reprocessing process. This reduces the demand for virgin steel production, which is energy-intensive and generates significant greenhouse gas emissions. Recycled steel retains its strength and durability, making it suitable for various applications, including construction and manufacturing.

Steel and cast iron recycling industry has been established for many years thus these materials are easily recycled.

Foundations are usually 51.10% of your total WTG mass and have a recycling rate of 50%. The recycling rate varies according to the quality of the material, the concentration in a component and available infrastructure.

A.1.2 Nacelles

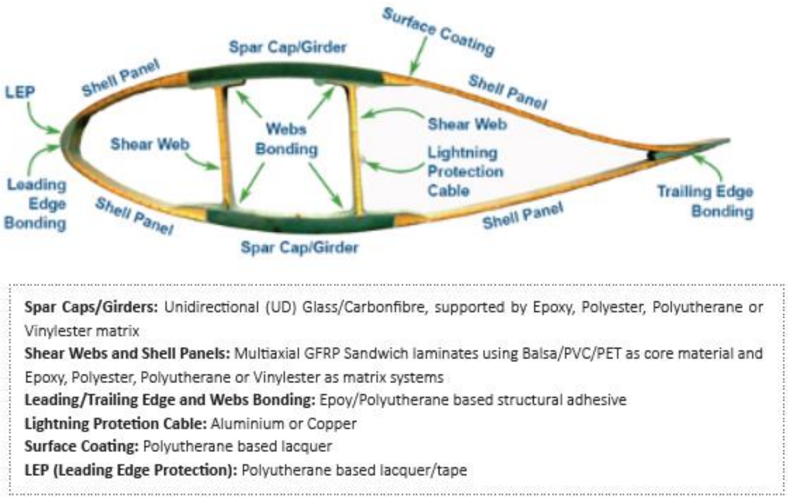
The nacelle houses the gearbox, generator, and control systems. They contain valuable materials such as copper wiring and rare earth magnets.

The recyclability of nacelles depends on the materials inside. Steel components are highly recyclable and can be melted down and reused. Copper wiring and other electrical components can also be recycled. One area of particular interest is the recovery of rare earth magnets, which are used in the generator. These magnets contain valuable materials like neodymium and dysprosium and are crucial for various high-tech applications. Developing efficient methods to recover and reuse these materials from decommissioned nacelles is an ongoing research focus.

NdFeB (neodymium-iron-boron) magnets are most commonly used due to their 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. Similarly, copper and aluminium is mainly recycled as they have a large monetary value

A.1.3 Blades

WTG blades are made from composite materials like fiberglass reinforced with epoxy raisin. Some newer blades may also incorporate carbon fibre. WTG blades present a unique recycling challenge due to their size and composition.



Spar Caps/Girders: Unidirectional (UD) Glass/Carbonfibre, supported by Epoxy, Polyester, Polyutherane or Vinylester matrix
Shear Webs and Shell Panels: Multiaxial GFRP Sandwich laminates using Balsa/PVC/PET as core material and Epoxy, Polyester, Polyutherane or Vinylester as matrix systems
Leading/Trailing Edge and Webs Bonding: Epoy/Polyutherane based structural adhesive
Lightning Protetion Cable: Aluminium or Copper
Surface Coating: Polyutherane based lacquer
LEP (Leading Edge Protection): Polyutherane based lacquer/tape

Figure Annex A-2 Generic cross-section of a rotor blade (Schmid et al., 2020)

Recycling WTG blades presents unique challenges due to their composite construction. Traditional recycling methods like melting down the materials are not well-suited for composites.

Recycling WTG blades is an active area of research and development, driven by the need to find sustainable solutions for these large, composite structures. The expected amount of blade waste in Belgium is shown in Figure 8-3. In 2040 a very large quantity of 12.000 tonne is expected for composite recycling companies which is a major challenge.

Figure Annex A-3 Total blade mass that will be decommissioned in the Belgium OWFOWFs starting from the year 2029 (source: CompositeLoop Project Final Report)

A.1.4 Cables

Offshore power cables are critical conduits of renewable energy and present both challenges and opportunities in recyclability after decommissioning. The recycling potential heavily relies on the cable's design and materials used.

These cables consist of distinct layers serving crucial functions. At their core lie conductors, typically made from copper or aluminium, facilitating electricity transmission. Surrounding these conductors are insulation layers, often composed of materials like polyethylene or cross-linked polyethylene, safeguarding against electrical leakage and environmental factors. Armouring, comprising steel or other robust materials, fortifies the cable, shielding it from external pressures such as seabed conditions and potential impacts. The outer sheath, usually made of thermoplastic or thermosetting compounds, provides additional protection, sealing the cable assembly. This complex design of components ensures the durability and efficiency of offshore power cables, enabling the seamless transmission of renewable energy across vast distances.

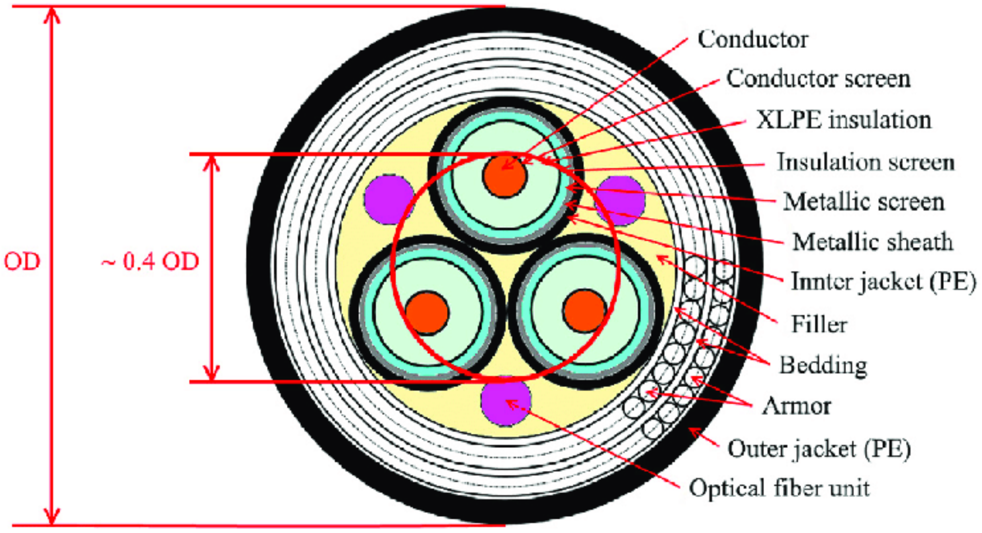


Figure Annex A-4 Typical cross section of a three phase double armour cable

Separating these materials efficiently is key to successful recycling. Innovations in cable design focus on enhancing recyclability, emphasizing eco-friendly materials and easier disassembly methods. While challenges persist, advancements in recycling technologies and the growing demand for sustainable practices propel ongoing efforts to optimize the recyclability of offshore power cables, ensuring a more circular approach to renewable energy infrastructure.

A.2 Material revenues

In Belgium, a total of 9 OWFs are currently in use and are set to be decommissioned between 2029 and 2040. A total of 10 WTG models are used in these OWF s, ranging from 3MW to 9.5 MW.

To calculate the revenues from recycled materials for existing OWF s, we conducted a comprehensive analysis based on the current market value of recyclable materials derived from decommissioned turbines. This involved assessing the quantities and types of materials—such as steel, copper, fiberglass, and other components—recovered through recycling processes. By estimating the market prices of these materials and considering the quantities obtained from decommissioned turbines in existing OWF s, we extrapolated these figures to predict the potential revenues for new OWFs equipped with 12 and 15 MW turbines. An overview of the different OWFs in Belgium can be found in Figure 1-1 of this study.

This extrapolation involved factoring in the increased material volumes and compositions expected from larger turbines, allowing us to project potential revenue streams from recycling materials in the context of these new OWF installations.

A.2.1 Aluminium

Recycling aluminium is considered an important part of the aluminium industry because of its significant reduced environmental impact compared with primary production. It can be recycled repeatedly without a significant loss of properties. However, impurities will most likely be picked up and will be dissolved during the cycles. The average recycling rate of aluminium is 27% but can vary between sources in literature. The benefits of recycling aluminium are well-documented (Jensen, 2019).

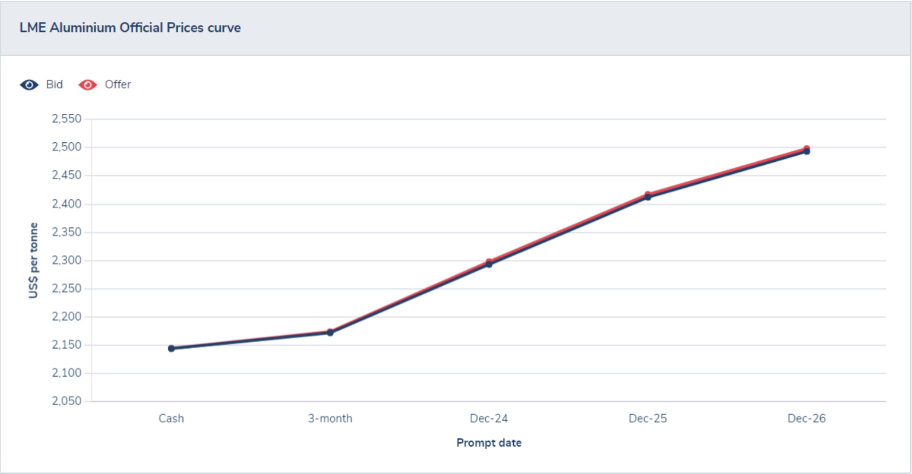


Figure Annex A-5 US$ per tonne aluminium untill december 2026
(source: London Metal Exchange)

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

However, some elements integrated in the products along with copper can cause problems, eg, aluminium (Jensen, 2019).

In general, copper makes up 1% of the material composition of a wind turbine, with ranges between 0.51 and 1.25 t/MW depending on the WTG model (Topham *et al.*, 2019). The average amount of copper in a WTG lies around 0.89 ± 0.23 t/MW.

A study from 2019 calculated the copper amount implemented in several WTG models, some of which are also used in the Belgian OWFs (figure 3-1). The only WTG models that are present in Belgium but not included in the aforementioned study are the Siemens SWT-7.0-154 7.35MW and the Siemens Gamesa SG 8.0-167 DD 8.4MW turbines. Excluding these models, the total amount of copper in the Belgian OWFs is estimated to be around 1282 tons. If the assumption is made that the SG 8.0-167 DD turbines contain a similar amount of copper as the Vestas V164 turbines (due to similar size and power output), the total weight of copper increases 1690 tons. For the final WTG that was not calculated (SWT-7.0-154), the average weight of copper per MW (0.89 t/MW) is used to calculate the total weight. This is an underestimation, since large wind turbines use disproportionally more materials, but is necessary to give an idea about the amount of copper available in Belgian OWF s. The total weight of copper in the offshore turbines would be around 28240 tons. Important to note is that this weight is calculated using only the copper present in the turbines. Cables, which also include copper, are not taken into account.

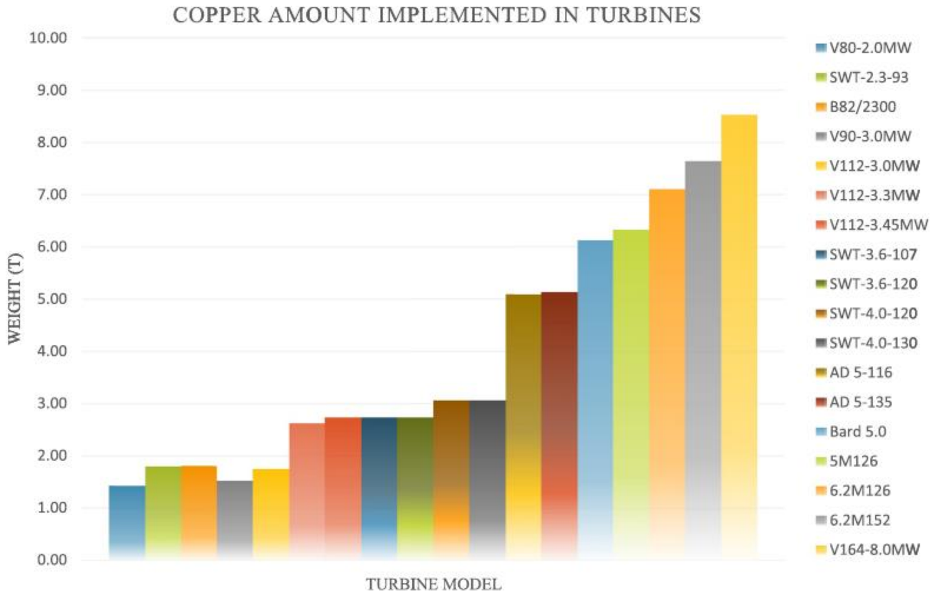


Figure Annex A-6 Calculated copper weight implemented in different models of wind turbines (Topham et al., 2019).

Copper has a well described recycling route and is already implemented at an industrial scale for quite some time. Companies like Belgian Scrap Terminal, A.G. Metals Recycling and many others process copper scrap along with other metals. The price of copper scrap is relatively volatile and can have drastic differences between months or years. Figure 3-2 shows a time series of the copper scrap price. Using an average value of 7900 euro per ton copper scrap and a recycling rate of 0.98, the Belgian OWFs contain around 10 million euro in copper. If the new Siemens Gamesa turbines are assumed to contain the same amount of copper as the Vestas V164 turbines and the SWT-7.0 turbines having an average weight of copper, this value increases to over 15.2 million euros. As mentioned before, copper derived from export cables is not taken into account. Figure

3-3 shows the projected potential value of copper that is recycled from OWFs in Belgium from 2020 up to 2050.

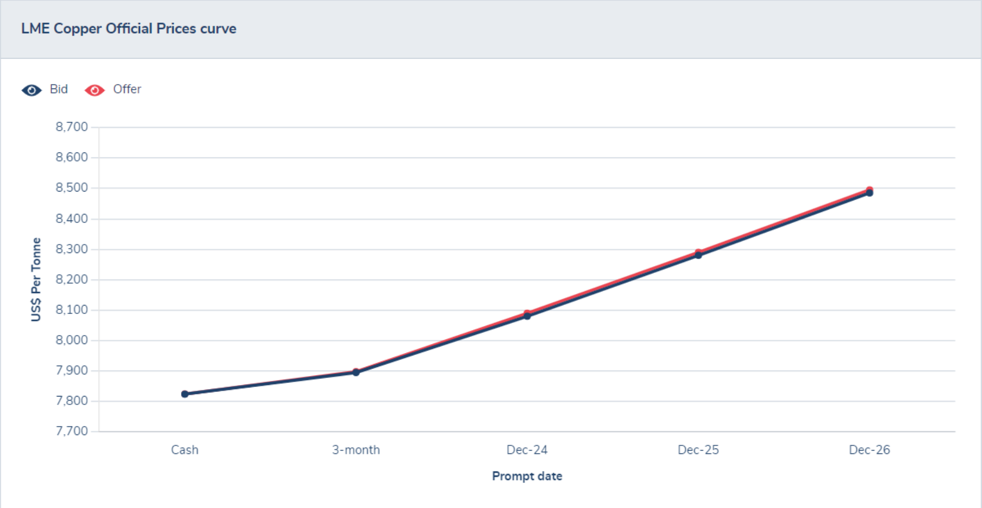


Figure Annex A-7 Time series of the official prices for copper scrap from the London Metal Exchange.

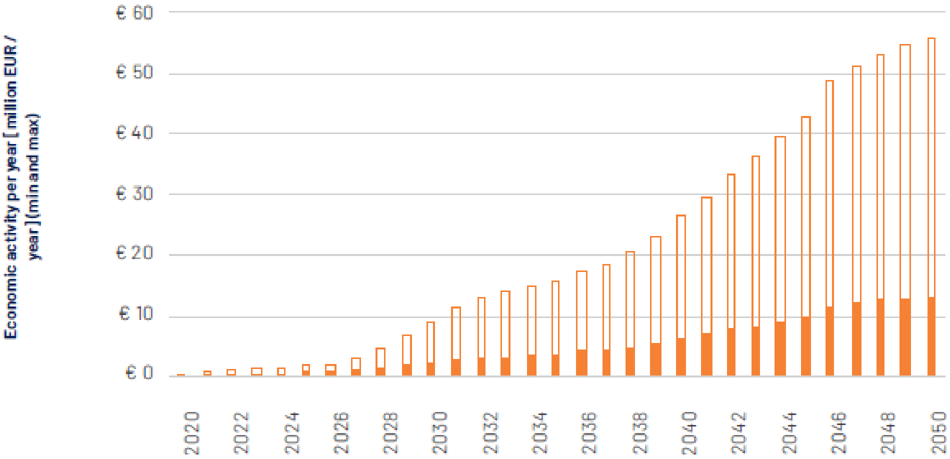


Figure Annex A-8 Potential value of copper recycled from OWF (van der Meulen et al., 2020)

A.2.2 Steel

Ferrous metals are the most common material in wind turbines. Steel can be recycled numerous times and is the most common recycled metal with a well-functioning market for secondary market existing.

Steel makes up the bulk of the weight of wind turbines (~83%), with an average weight of 94 ± 22.53 t/MW for offshore wind turbines in Europe. As with copper, the study from Topham *et al* also calculated the mass of steel that is implemented across multiple turbine models (Topham *et al.*, 2019). Figure 3-4 shows the steel weight graphed for the turbine models.

The steel in the Belgian OWF s, taking into account only the models that are included in figure 3-3, adds up to around 130210 tons of steel. When the same assumptions as for copper are made, this number increases to around 207700 tons of steel. The steel from monopile foundations, which are arguably an even greater source of steel, are not taken into account in this number. Monopiles can contain 700 tonnes of steel each. There are a total of 382 monopile foundations installed for Belgian OWF s. If these monopiles are completely decommissioned, using vibration hammering methods, another 267400 tons of steel could be recycled.

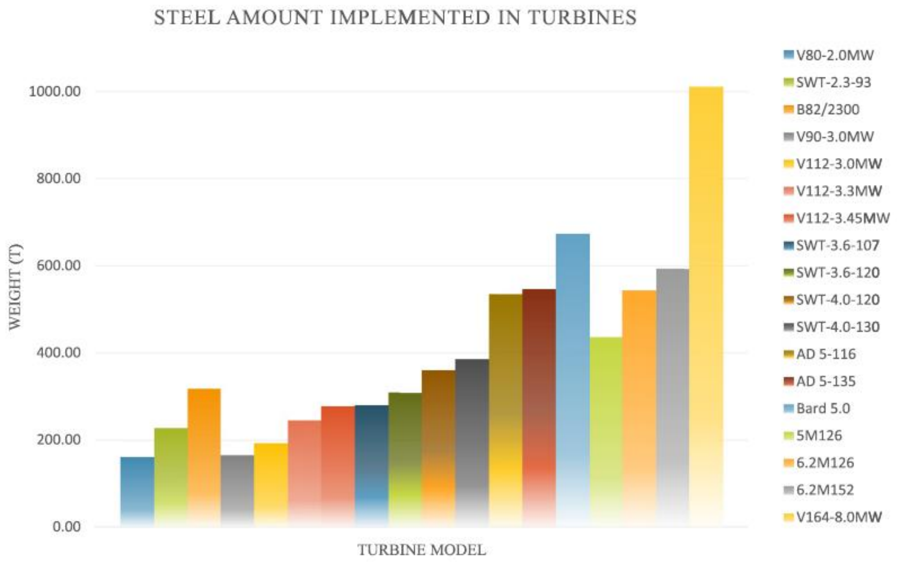


Figure Annex A-9 Calculated steel weight implemented in different models of wind turbines (Topham et al., 2019).

Like copper, steel is easily recyclable at an industrial scale. Most of the recycling companies mentioned for the recycling of copper do also recycle steel. The value of steel is heavily dependent on the quality and the period. Sources list prices ranging from 115 euro per ton all the way to 640 euro per ton (Figure 3-5), depending on whether the steel is structural steel or alloyed steel. A conservative estimate of 180 euro per ton is used in the calculations in this report. Considering only the turbine models included in figure 3-4, and a recycling rate of 0.92, the total value of steel in the wind turbines is around 21.5 million euros. Including the other models present in Belgian OWF s, this number increases to 34.3 million euros. Steel from the monopiles is valued as an additional 44.3 million euros, bringing the grand total to 78.6 million euros of recycled steel. Figure 3-6 shows the potential value of recycled steel from 2020 to 2050.

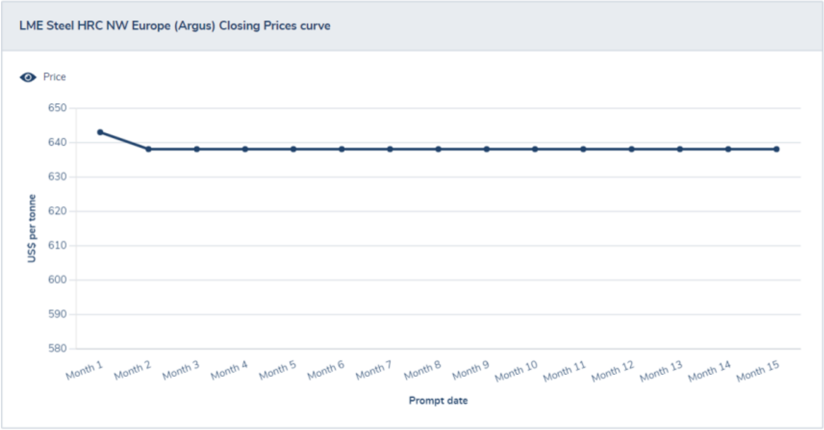


Figure Annex A-10 Time series of steel scrap prices at the London Metal Exchange.

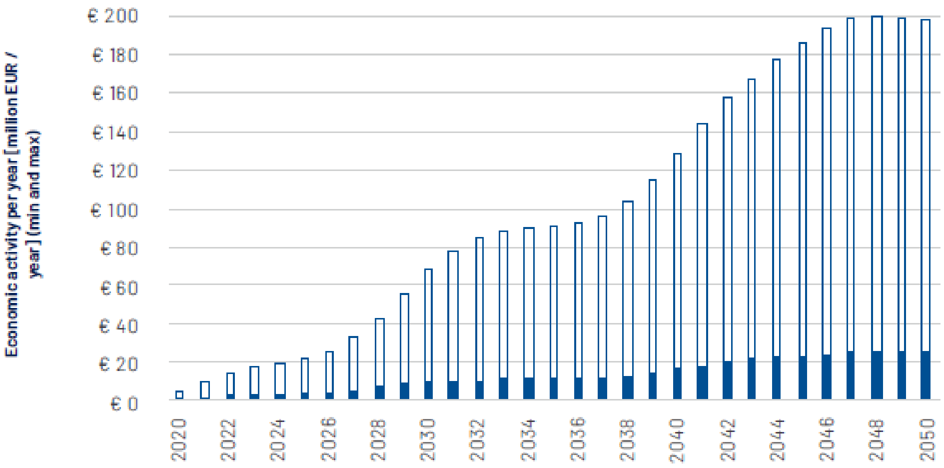


Figure Annex A-11 Potential value of recylcled steel (van der Meulen et al., 2020)

A.2.3 Cast iron

Cast iron is the second most used material in wind turbines, comprising around 11% of the weight of the turbine. The average weight of cast iron across WTG models in Europe is 12.78 ± 1.79 t/MW. Based on the turbines that are present in Figure 3-7, around 18775 tons of cast iron is present in the Belgian OWF s. Including turbine models that are not listed in this graph, this number increases to 26808 tons of cast iron, based on the same assumptions made for copper and steel. However, since the turbines from Siemens Gamesa don't have a gearbox, they contain less cast iron than geared turbines with similar dimensions from Vestas.

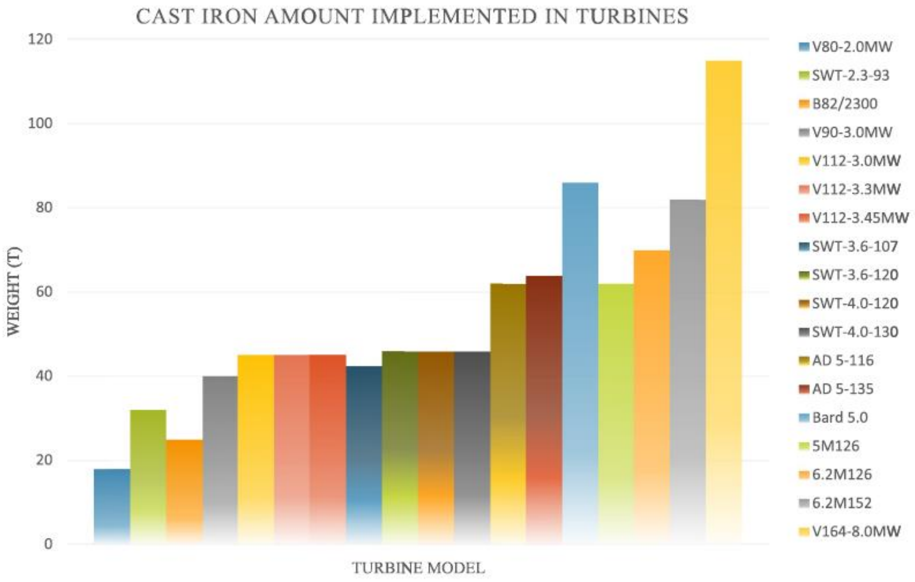


Figure Annex A-12 Calculated cast iron weight implemented in different models of wind turbines (Topham et al., 2019).

Cast iron is mostly recycled as scrap, with a recycling rate around 98%. Cast iron, in particular spheroidal graphite cast iron (SG-iron) contains critical magnesium (Mg), which might be of interest to be selectively recycled. However, since cast iron is less valuable than alloyed steel, the main recycling route is still the use of scrap iron in primary production. The prices of scrap cast iron can fluctuate in time, but hover around the 190 euro/t (see Figure 3.8). The Belgian OWFs contain almost 3.5 million euros worth of cast iron, when considering only the turbine models in Figure 3-7. When assumptions are made for the newer turbine models, the value increases to almost 5 million euros. Figure 3-9 shows the predicted potential value of recycled cast iron from Belgian OWF s, from 2020 to 2050.

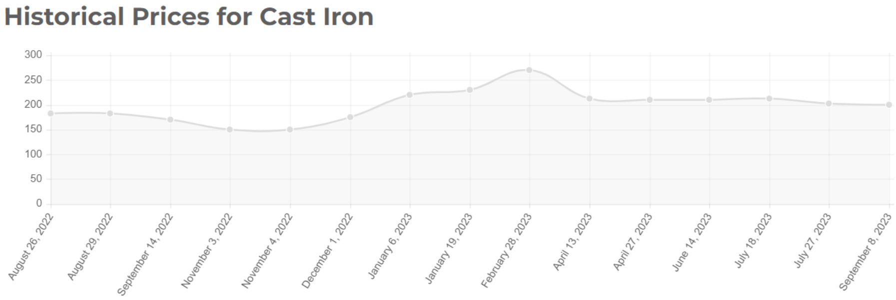


Figure Annex A-13 Time series of the price of scrap cast iron at the London Metal Exchange.

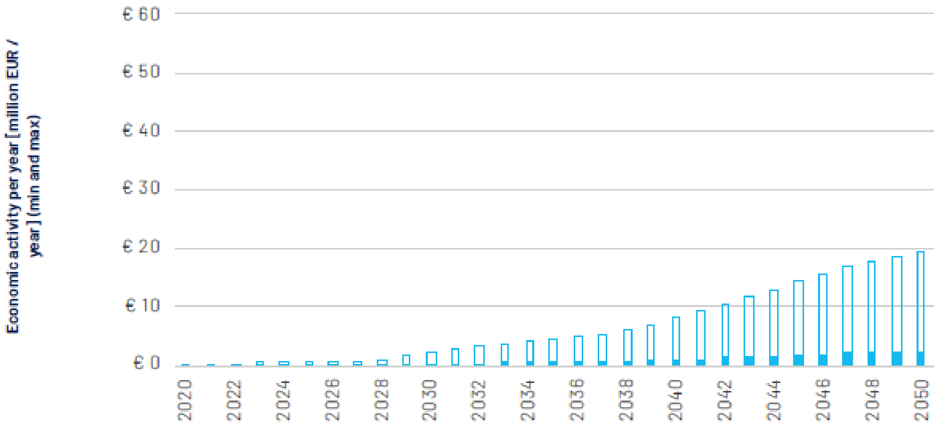


Figure Annex A-14 Potential value of cast iron recycled from OWF(van der Meulen et al., 2020)

A.2.4 Blade recycling

The most intensively discussed topic in the recent literature on the decommissioning of wind turbines is the processing of the turbine blades consisting of glass fibre-reinforced (GFR) composite (van der Meulen *et al.*, 2020). Rotor blade material is a complex structure of different parts and materials which have different properties. After their lifetime, blades can be in different states depending on their design and reason for decommissioning. Therefore direct reuse of the blades is only possible when the strength of the structure is not highly relevant or when it can be sufficiently validated for reuse.

Contrary to metals like aluminium or copper, no well-established recycling routes exist for composite materials. Composite material is the main material in the blades and often the nacelle as well. The current WTG blades typically consist of glass fibre as a reinforcement fibre, epoxy as a plastic polymer, balsa wood as a core material and a polyurethane coating and lightning conductors with the same main materials. The use of composite materials is increasing and, now carbon fibres are often used in combination with glass fibre or new WTG blades are completely built using carbon fibre.

A multitude of techniques exist or are currently being researched for the recycling of WTG blades. 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, due to the low heating value of composites means that around 60% of the scrap is left behind as ash. 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. The fibreglass can also be treated with fluidised bed gasification operating at about 450 °C for better energy recovery. 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. The available literature shows that the quality of glass fibres in current high level material reclaim recycling processes is deteriorating significantly and can no longer be used for applications in which strength requirements are imposed on the materials. Further research is carried out for viable commercial applications and 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.

Since these techniques lead to a wide range of recycled products, the market value of recyclates also varies. For example, the value of the recycled product attained by mechanical grinding of composites will be lower than products attained with pyrolysis, where the fibres are reclaimed in a useable form. Furthermore, the value of recycled materials depends on the acceptance of recycled fibres in the market. Figure 3.4 Shows the costs and potential values of recycled materials of different technologies. Studies have calculated that recycled carbon fibre has a value around 13-19 $/kg while recycled glass fibres have a value of 0.25 $/kg (Vo Dong *et al.*, 2018)

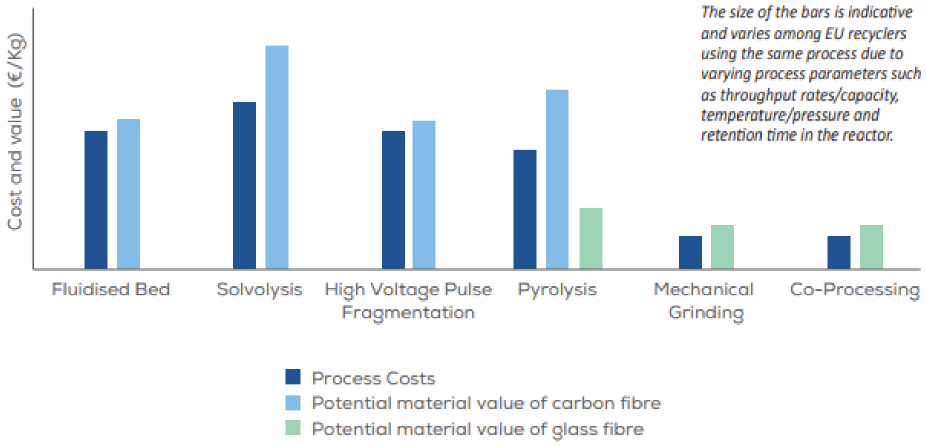
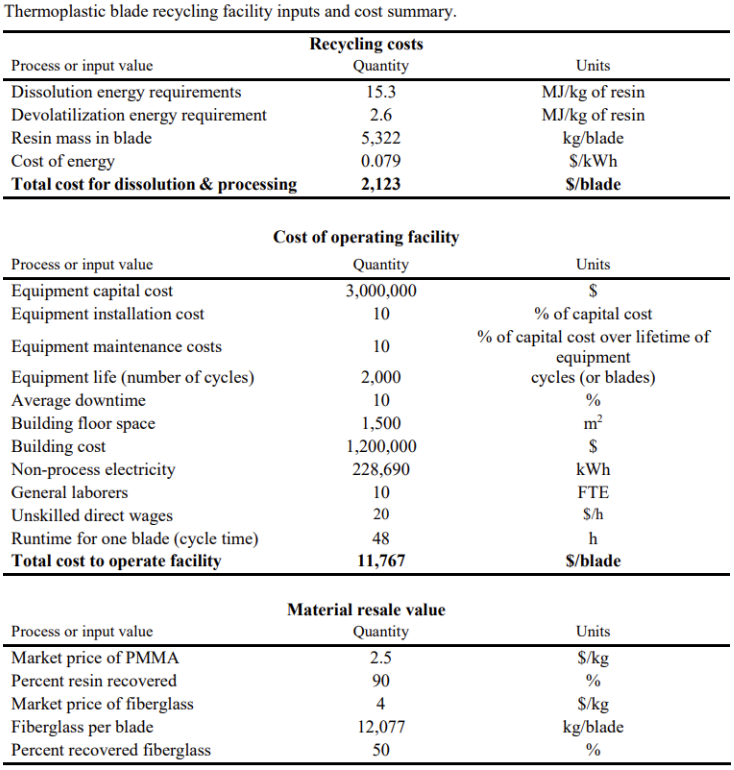


Figure Annex A-15 Estimated relative costs and values of composite recycling technologies (Schmid et al., 2020).

Recycled carbon fibre products resulting from solvolysis demonstrate superior value, attributed to the process's use of lower temperatures that salvage less compromised fibres. Pyrolysis also generates high-value carbon recyclables. Among methods, mechanical grinding emerges as the most financially rewarding technique for glass fibre composites. Presently, the assessment of economic worth in handling Glass-Fiber-Reinforced Polymers (GFRPs) relies on the gate fees of approved processing approaches, given the absence of alternative methods.

In the Netherlands, blade incineration is permissible if the transfer costs to waste processors surpass EUR 205/tonne. Meanwhile, in Germany, deposition is banned, and a cement kiln route is favoured due to existing cement production sites, charging turbine owners a minimum gate fee of EUR 150/tonne. However, a detailed exploration into the costs and prerequisites for utilizing this Dutch cement kiln route remains outstanding.

The fibreglass and epoxy resin within blades and hubs stand as pivotal topics within the industry. Disposing of fibreglass proves challenging due to component size, recycling intricacies, and a limited market value. The composite makeup of blades comprises diverse materials with distinct properties, particularly the thermoset composite of Glass-Fiber-Reinforced Polymer (GFRP), which, in its curing process, undergoes an irreversible transformation, complicating recycling efforts. Initiatives backed by the European Union (EU), such as ReFibre, Dreamwind, Genvind, and LIFE BRIO, are dedicated to exploring novel disposal processes for blades.



Thermoplastic blade recycling facility inputs and cost summary.

Recycling costs

Process or input value	Quantity	Units
Dissolution energy requirements	15.3	MJ/kg of resin
Devolatilization energy requirement	2.6	MJ/kg of resin
Resin mass in blade	5,322	kg/blade
Cost of energy	0.079	$/kWh
Total cost for dissolution & processing	**2,123**	**$/blade**

Cost of operating facility

Process or input value	Quantity	Units
Equipment capital cost	3,000,000	$
Equipment installation cost	10	% of capital cost
Equipment maintenance costs	10	% of capital cost over lifetime of equipment
Equipment life (number of cycles)	2,000	cycles (or blades)
Average downtime	10	%
Building floor space	1,500	m^2
Building cost	1,200,000	$
Non-process electricity	228,690	kWh
General laborers	10	FTE
Unskilled direct wages	20	$/h
Runtime for one blade (cycle time)	48	h
Total cost to operate facility	**11,767**	**$/blade**

Material resale value

Process or input value	Quantity	Units
Market price of PMMA	2.5	$/kg
Percent resin recovered	90	%
Market price of fiberglass	4	$/kg
Fiberglass per blade	12,077	kg/blade
Percent recovered fiberglass	50	%

Figure Annex A-16 (Source: Recycling glass fibre thermoplastic composites from WTG blades).

Two categories of recycling processes are being developed for the processing of the blades into qualitatively acceptable materials: chemical (e.g. via thermal pyrolysis) and mechanical (use of shredded material).

The available literature shows that the quality of glass fibres in current chemical recycling processes is deteriorating significantly and can no longer be used for applications in which strength requirements are imposed on the materials. Various initiatives are being taken to address this demand for quality (and, at the same time, market demand). The increasing supply of turbine blades, which is also shown in this study, should be a driver for such research and also a driver for cost reduction of any resulting process.

A.2.5 Re-use of permanent magnets

NdFeB magnets are indispensable in clean energy applications such as wind turbines, they are composed of rare earth elements such as neodymium and dysprosium. The unique properties of rare earth elements and lack of alternatives of their application generates a substantial supply risk and in order to attenuate the supply risk recycling of NdFeB magnets from EOL products are very promising. An LCA shows that the value recovery system has significantly less environmental impact than virgin production (Jin *et al.*, 2016).

In 2009, the price of neodymium oxide rose from \$19.1/kg to \$234.4/kg in 2011, and that of dysprosium oxide rose from \$115.7/kg to \$1449.8/kg during the same period (Golev *et al.*, 2014).

Various recycling approaches for the recovery of sintered NdFeB magnets have been explored by industry and academia. These include direct reuse, waste-to-REE, wasteto-alloy, and magnet-to-magnet approaches. Except direct reuse, these processes may use hydrometallurgical methods, pyrometallurgical methods, gas-phase extraction, or hydrogen decrepitation or others (Jin *et al.*, 2016).

Figure 8-17 show the results in terms if the environmental impact of producing new virgin magnets and recycled NdFeB magnets. The recycling approach has significantly less environmental impact than the virgin magnet production in all of the impact categories.

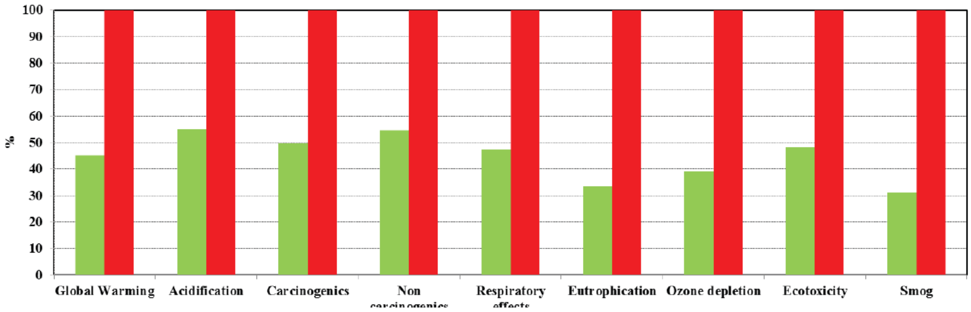
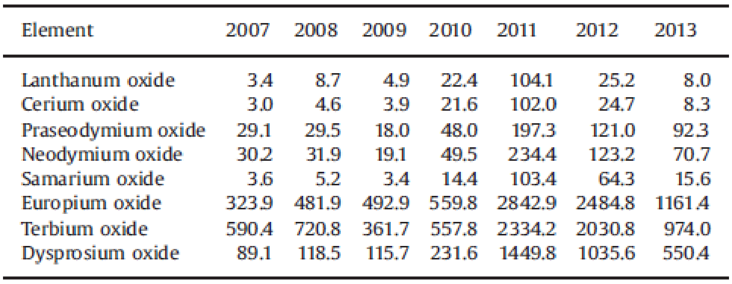


Figure Annex A-17 Impact assesment for virgin (red) and recycled (green) NdFeB magnet production (Jin et al., 2016).

Table Annex A-1 Price dynamics of selected rare earth materials between 2007 and 2013 in US$/kg



Element	2007	2008	2009	2010	2011	2012	2013
Lanthanum oxide	3.4	8.7	4.9	22.4	104.1	25.2	8.0
Cerium oxide	3.0	4.6	3.9	21.6	102.0	24.7	8.3
Praseodymium oxide	29.1	29.5	18.0	48.0	197.3	121.0	92.3
Neodymium oxide	30.2	31.9	19.1	49.5	234.4	123.2	70.7
Samarium oxide	3.6	5.2	3.4	14.4	103.4	64.3	15.6
Europium oxide	323.9	481.9	492.9	559.8	2842.9	2484.8	1161.4
Terbium oxide	590.4	720.8	361.7	557.8	2334.2	2030.8	974.0
Dysprosium oxide	89.1	118.5	115.7	231.6	1449.8	1035.6	550.4

A.2.6 Cable recycling

Cables play an important part in recycling plans for OWF. Many kilometres of complex/composite construction around the cables are needed to protect them from the harsh environments offshore. There is a considerable environmental impact from the manufacturing of the cable, and since they consist of many different materials, they are also difficult to dismantle for recycling.

A.2.7 Other materials

Other materials include lamps, batteries and lubricating oil/.When lubricating can be properly drained and can be of value. Oil can be re-refined into a base stock for lubricating oil. It can be recycled indefinitely because the lubricant property will not wear out. The recycled oil must be cleaned of contaminants such as dirt, water, used additives and fuel (Jensen, 2019).

A.3 Decommissioning costs per OWF

Table Annex A-2 Overall cost estimation results per wind farm per cost element (Note: kEUR/MW result for the Total OWFs is presented as average value.)

OWF	Capacity [MW]	Overall costs [MEUR]	[kEUR/MW]	WTG removal [MEUR]	Foundation removal [MEUR]	Cables removal [MEUR]	Scour protection removal [MEUR]	Fuel costs [MEUR]	Pre-decom cost [MEUR]	PM cost [MEUR]
C-Power GB	30	51.3	1710.1	5.9	29.7	5.0	0.0	2.67	3.7	4.3
C-Power Jacket	295	93.0	315.2	28.7	29.7	10.0	5.5	5.01	6.2	7.9
C-Power Total	325	177.2	545.3	34.6	59.4	15.1	5.5	7.68	42.7	12.2
Belwind	171	124.2	726.2	32.5	45.2	14.5	6.0	7.10	8.3	10.5
Northwind	216	151.0	699.3	41.7	58.6	10.4	8.3	9.33	10.0	12.8
Nobelwind	165	116.0	702.8	29.8	41.7	14.6	5.7	6.48	7.8	9.8
Rentel	309	102.6	331.9	25.5	37.1	12.2	6.8	5.59	6.7	8.7
Norther	370	107.6	290.7	26.5	38.7	13.2	7.1	5.85	7.1	9.1
Northwester	219	59.1	270.0	15.1	21.8	6.7	3.6	3.05	3.9	5.0
Seastar	252	73.6	292.1	18.9	27.5	7.3	4.8	3.99	4.8	6.3
Mermaid	235	73.9	314.5	17.9	29.1	7.3	4.5	4.03	4.9	6.3
Total OWFs	*2262*	952.3	*421.0*	*242.6*	*359.0*	*101.3*	*52.2*	*53.1*	*63.3*	*80.8*

OWF	Capacity [MW]	Overall costs [MEUR]	[kEUR/MW]	WTG removal [MEUR]	Foundation removal [MEUR]	Cables removal [MEUR]	Scour protection removal [MEUR]	Fuel costs [MEUR]	Pre-decom cost [MEUR]	PM cost [MEUR]
C-Power GB	30	54.1	1802.8	6.9	29.7	6.4	0.0	2.7	3.9	4.6
C-Power Jacket	295	117.4	397.9	36.5	36.6	12.9	7.2	6.5	7.7	10.0
C-Power Total	325	171.5	527.6	43.4	66.3	19.3	7.2	9.2	11.6	14.5
Belwind	171	159.1	930.4	41.5	57.8	18.7	7.8	9.2	10.6	13.5
Northwind	216	194.0	898.2	53.5	75.1	13.3	10.7	12.1	12.8	16.5
Nobelwind	165	148.4	899.4	37.9	53.2	18.9	7.4	8.4	9.9	12.6
Rentel	309	131.0	424.0	32.3	47.2	15.8	8.8	7.3	8.6	11.1
Norther	370	137.5	371.6	33.7	49.3	17.0	9.2	7.6	9.0	11.7
Northwester	219	74.5	340.4	18.9	27.3	8.5	4.6	4.0	4.9	6.3
Seastar	252	93.3	370.4	23.8	34.7	9.3	6.3	5.2	6.1	7.9
Mermaid	235	93.7	398.9	22.4	36.8	9.3	5.9	5.2	6.2	8.0
Total OWFs	*2262*	*1203.1*	*531.9*	*307.4*	*447.6*	*130.2*	*67.9*	*68.2*	*79.7*	102.1

Table Annex A-3 Overall cost estimation results by taking 30% delay in operations due to weather. This is integrated by considering 30% longer offshore operation