DECOMMISSIONING OF WINDTURBINES – LOGISTICS BUSINESS CASE

DECOM TOOLS **2022**

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1. Introduction

This document concerns the report of the study "Decommissioning of wind turbines: logistics business case" conducted by RebelGroup on behalf of POM West Flanders.

For both onshore and offshore wind turbines, the integral value chains of decommissioning (from dismantling to recycling the materials) were mapped, and the potential role of the port of Ostend and the province of West Flanders in this was highlighted.

The report consists of the following chapters:

- Introduction: reading guide, main findings of the study and recommendations for follow-up steps
- Context: background information on the expected number of wind turbines to be dismantled, and the composition and volume of material flows; conceptual framework
- Decommissioning, transport and recycling process: description of the decommissioning value chain process
- Requirements for potential port sites: infrastructural requirements of the port sites (maritime access, quay, sites, landside access) where the dismantled offshore wind turbine components are unloaded and undergo initial processing; evaluation of the port of Ostend in comparison with alternative sites
- Key findings
- Recommendations

2. Context

2.1 Current Belgian windfarms

The Belgian windfarm market consists of two main groups, onshore and offshore windfarms, each consisting of one or more wind turbines.

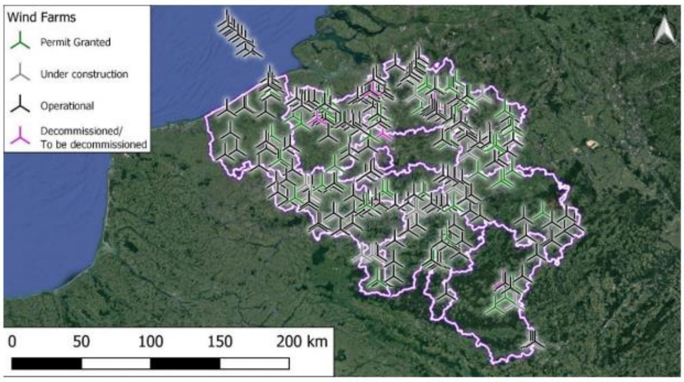

Figure 1: Overview of Belgian windfarms

Source: DECOM TOOLS Ostend - Analysis of the recycling business potential (Tractebel, 2021)

Region	# windfarms	# wind turbines	Average # of wind turbines per windfarm
Federal (offshore)	8	399	50
Flanders (onshore)	298	897	3
Wallonia (onshore)	155	638	4
Total	461	1.934	4

Table 1: Summary of key features Belgian wind farms

Source: DECOM TOOLS Ostend - Analysis of the recycling business potential (Tractebel, 2021)

The size of wind turbines keeps increasing with the years of installation. Permits for the wind turbines currently in the development phase also call for ever larger sizes.

Windfarms installed offshore are larger than those installed onshore.

Region	Average rotor diameter[1] 1999 (in m)	Average rotor diameter[1] 2020 (in m)
Federal (offshore)	127	160
Flanders (onshore)	43	102
Wallonia (onshore)	100	105
Region	Average rotor diameter[2] 1999 (in m)	Average rotor diameter[2] 2020 (in m)
Federal (offshore)	127	160
Flanders (onshore)	43	102
Wallonia (onshore)	100	105

Table 2: Wind turbine dimensions 1999-2020

Source: DECOM TOOLS Ostend - Analysis of the recycling business potential (Tractebel, 2021)

[1] Rotor diameter: The rotor diameter of a turbine is the width of the circle created by the rotating blades

[2] Hub height: The hub height is the distance from the ground to the centre of the rotor of the turbine

2.1 Composition of wind turbines

An onshore and offshore wind turbine is made up of about 25,000 parts, which are grouped into 3 different main parts:

1. Foundation (incl. connecting piece): represents most of the mass (approx. 75% on average)
2. Wind turbine generator (WTG) consisting of the tower, nacelle and rotor: represents on average about 23% of the total mass
3. Wiring: approx. 2% of total mass

A wind turbine consists mainly of metals (tower, cables and electrical components), (reinforced) concrete, composite materials and oils. Rare Earth Elements (REE) are currently only found in some offshore wind turbines because of their permanent magnets. The amount of each material depends on the size, turbine type and manufacturer.

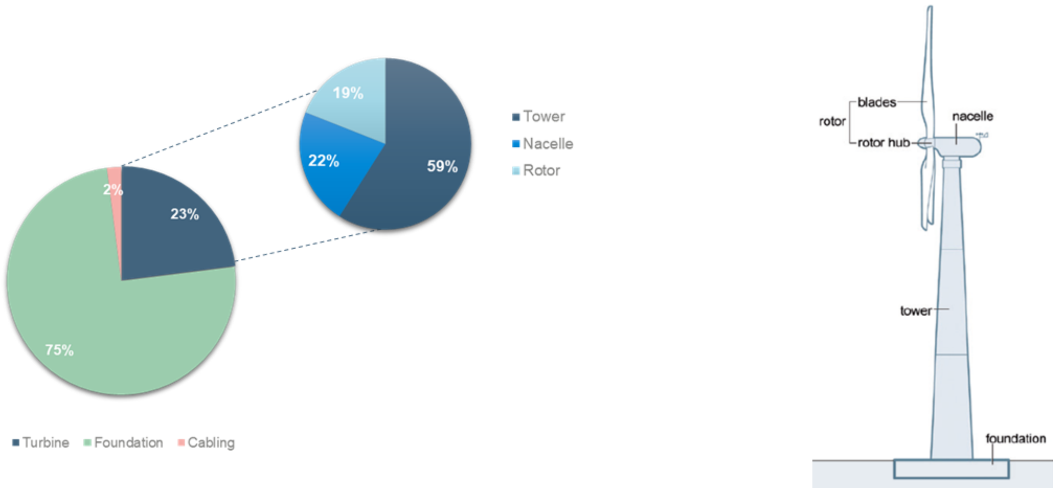

Figure 2: Composition of wind turbines (average onshore and offshore)

Source: Raw materials demand for wind and solar PV technologies in the transition towards a decarbonised energy system (European Commission, 2020) and World Steel Association

2.3 End of life strategies

There are 3 main end-of-life strategies: decommissioning (decommissioning), life extension or repower. There may be overlaps so parts of a strategy can be combined.

There is currently no standard legislation specifying 'best practice' after the end of the operational life. Decisions depend heavily on the physical condition and theoretically permissible lifetime of a wind turbine, as well as overall cost and site conditions, legislation, logistical difficulties and potential environmental impacts.

Beyond the technical lifetime of a wind turbine (20 years and more) and the concession period (usually 15-20 years), the most important parameter to determine the decommissioning date is the length of the subsidy period (15 years for onshore windfarms, 20 years for offshore windfarms).

Today's windfarms are not financially viable without subsidies. This means that the effective lifetime of a wind farm is determined not only by the design lifetime of its components, but also by the duration of subsidies.

2.4 Annual expected volumes of material flows from decommissioning onshore and offshore windfarms

The table below presents an overview of the expected amount of materials that will become available on the recycling market in the coming years due to the decommissioning of onshore and offshore wind farms.

The assumptions used in the Tractebel study (2021) to determine the annual expected material flows available on the recycling market are:

- The offshore windfarms are decommissioned after 20 years. They are not sold on the second-hand market and are directly recycled
    - The calculation does not take into account the volumes from the concrete foundations
- All onshore windfarms are decommissioned after 15 years, the end of the subsidy period.
- No distinction is made between the lifetime of onshore/offshore wind turbines in Flanders and Wallonia
- Wind turbines with a capacity of less than 1 MW are not sold on the second-hand market and are directly recycled
- Wind turbines of more than 1 MW decommissioned before the end of 2024 are sold on the second-hand market and the corresponding materials leave Belgian territory except for the concrete
- Wind turbines decommissioned after 2024 cannot be sold on a saturated second-hand market and are directly recycled.

Material type	Max. annual volume (in tonnes)													
	Phase 1			Phase 2				Phase 3						
	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035
Concrete	58.000	40.000	120.000	78.000	110.000	90.000	55.000	82.000	172.000	180.000	170.000	85.000	124.000	110.000
Steel	-	-	-	18.000	19.000	19.000	10.000	20.000	41.000	30.000	38.000	81.000	62.000	30.000
Aluminium	-	-	-	20	50	50	10	100	150	170	200	100	50	120
Copper	-	-	-	50	100	100	50	100	200	220	200	150	30	200
Polymers	-	-	50	1.200	1.900	1.600	1.050	1.550	2.500	3.200	2.600	2.700	3.100	2.050

Material type	Max volume that can become available in a peak year (in tonnes)
Concrete	180.000
Steel	81.000
Aluminium	200
Copper	220
Polymers	3.200

Table 3: Summary of annual expected material flows during decommissioning of onshore and offshore windfarms[3]

Source: Rebel estimate based on DECOM TOOLS Oostende - Analysis of the recycling business potential (Tractebel, 2021)

[3] Because of lack of more detailed data, no distinction can be made between the volumes of onshore and offshore wind turbines, as well as no insight into the assumptions on the extent of foundation removal and erosion protection.

Key findings:

- During the first phase, the material streams available for recycling would be quite limited. These are mainly onshore wind turbines with outdated designs[4]. Most of the newer designs are successfully sold on the second-hand market.
- In the second phase, the second-hand market is saturated and wind turbines will be dismantled as soon as their subsidy period ends, which will make larger material streams available for recycling.
- During the third phase, the first offshore windfarms will be decommissioned and larger material streams will again become available for recycling.

2.5 Second-hand market saturated by 2024

Currently, 85% of decommissioned onshore wind turbines enter the second-hand market and 15% are recycled.

- Most decommissioned onshore wind turbines in Belgium were decommissioned before the end of their technical lifetime for economic reasons (replacement by larger turbines with more power and/or applying for new subsidies). They can easily be sold on the second-hand market because they are still relatively new. They are attractive to customers eager for wind turbines quickly at an advantageous price, or for installation in areas with regulatory height restrictions.

Business in Wind, a market leader in dismantling onshore wind turbines, expects these numbers to reverse from 2024 onwards (i.e. 85% recycling and 15% reuse).

- There are several reasons why fewer sales will be found on the second-hand market in the future. First, increasing competition from second-hand turbines from Germany, Spain and Denmark. Second, turbines installed later are already so large that early decommissioning becomes less interesting and fewer relatively new turbines are being decommissioned. Those larger turbines are also more expensive to transport, making them less interesting for the second-hand market.

Key concern: offshore wind turbines do not qualify for the second-hand market. The supply of decommissioned wind turbines is always expected to exceed demand, with preference given to onshore wind turbines that have not suffered from harsh offshore conditions.

2.6 Market organisation of the decommissioning process

Wind farm owner

The wind farm owner is operationally and financially responsible for decommissioning the wind turbines at the end of their useful life or at the end of the concession period, including restoring the site to its original condition.

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[4] Some old wind turbines were built by Turbowinds and HMZ (Belgium). Those companies have stopped manufacturing wind turbines. As a result, their turbines are not suitable for reuse (and also because they are too small).

In the offshore sector, windfarm owners in both Belgium and the Netherlands are required by law to provide commissions or guarantees. The amounts of the commissions and guarantees are stipulated the legislation or in the concession agreements.

In the onshore sector, provisions are not mandatory and are not common. In the case of wind turbines already decommissioned, decommissioning costs are included in the investments for repowering or installing a new, larger turbine on the same site. The net cost of decommissioning is often small (or even non-existent) because of the resale value on the second-hand market.

Dismantling companies

The actual decommissioning is carried out by external service providers on behalf of the wind farm owner.

In the dismantling of offshore wind turbines carried out to date, offshore installation companies were also the main contractor for the dismantling. Indeed, the same types of working vessels are used for installation and dismantling.

Most of the dismantling of onshore wind turbines is carried out by specialised dismantling companies (Business in Wind, Antro Group, Inikti). These companies usually direct the entire dismantling process, including sale of the turbines on the second-hand market, transport to the new site and installation on the new site, sale of material streams to recycling companies;... They use specialised subcontractors for dismantling and transport (crane companies, exceptional transport, project cargos terminals...). Some of these subcontractors also have the ambition to take on chain management.

Wind turbine manufacturers

Wind turbine manufacturers are usually not involved in dismantling or recycling the decommissioned parts. There is no obligation to take back wind turbines at the end of their useful life (either legally or contractually).

3. Process of dismantling, transport and recycling

3.1 Terms – process steps

Decommissioning:

- dismantling
- initial processing (dividing into transportable pieces)

Transport of dismantled wind turbine components

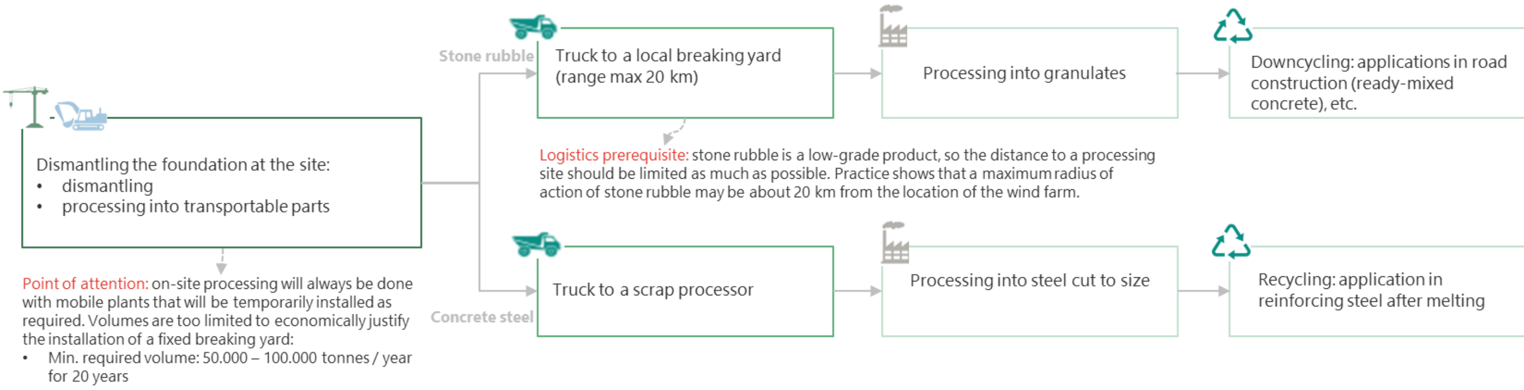
Processing by waste processor (scrap processor, breaking yard,...)

Recycling: use of processed materials by customers

The focus of this study is the logistics chain (transport), but this requires knowing the dismantling and treatment processes and locations.

3.2 Decommissioning of onshore wind turbines

Onshore foundation – process



Further explanation on the decommissioning process of onshore foundations

Type of foundation

There are 2 types of foundations: standard flat foundation and a pile foundation.

Pile foundations are similar in structure to standard flat foundations with the only difference being that pile foundations do not stand directly on the ground, but rest on piles previously set in the ground.

Decommissioning techniques

Foundations can be dismantled using a hydraulic chisel and an excavator. Due to the vibrations during chiselling, rebar can be separated from the concrete relatively easily or is already predominantly loose during excavation.

For foundation depths of more than two metres, blasting is a sensible option. After loose blasting, concrete/stone rubble and rebar are usually available separately and can be removed from the foundation pit with excavators.

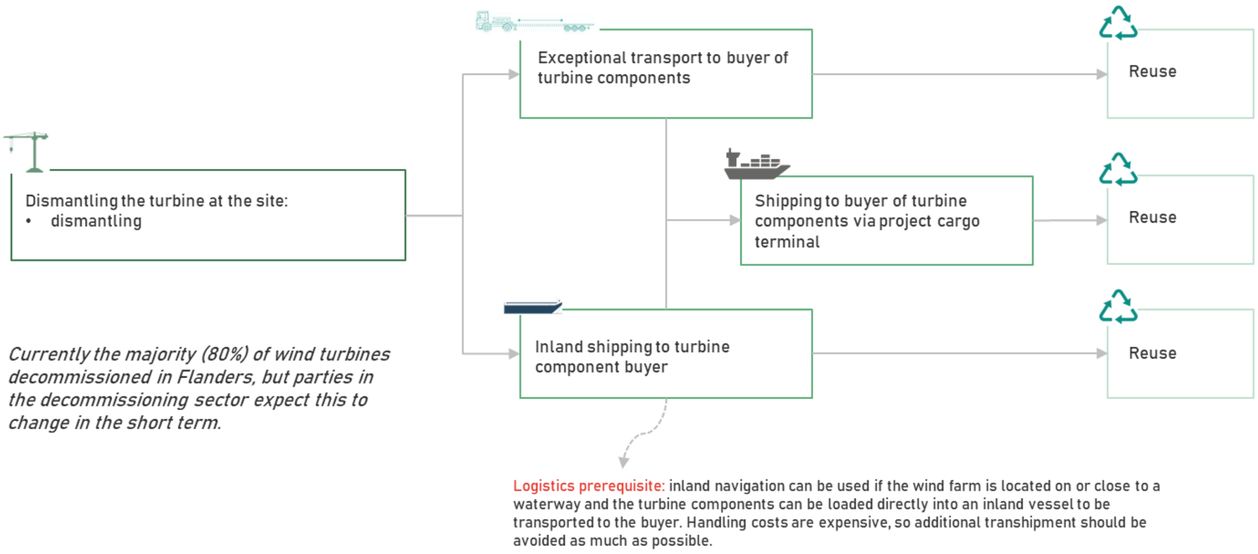
After dismantling, the rebar and concrete/stone rubble are disposed separately by truck to special facilities for further processing or recycling.

Legislation - general obligation to decommission foundations

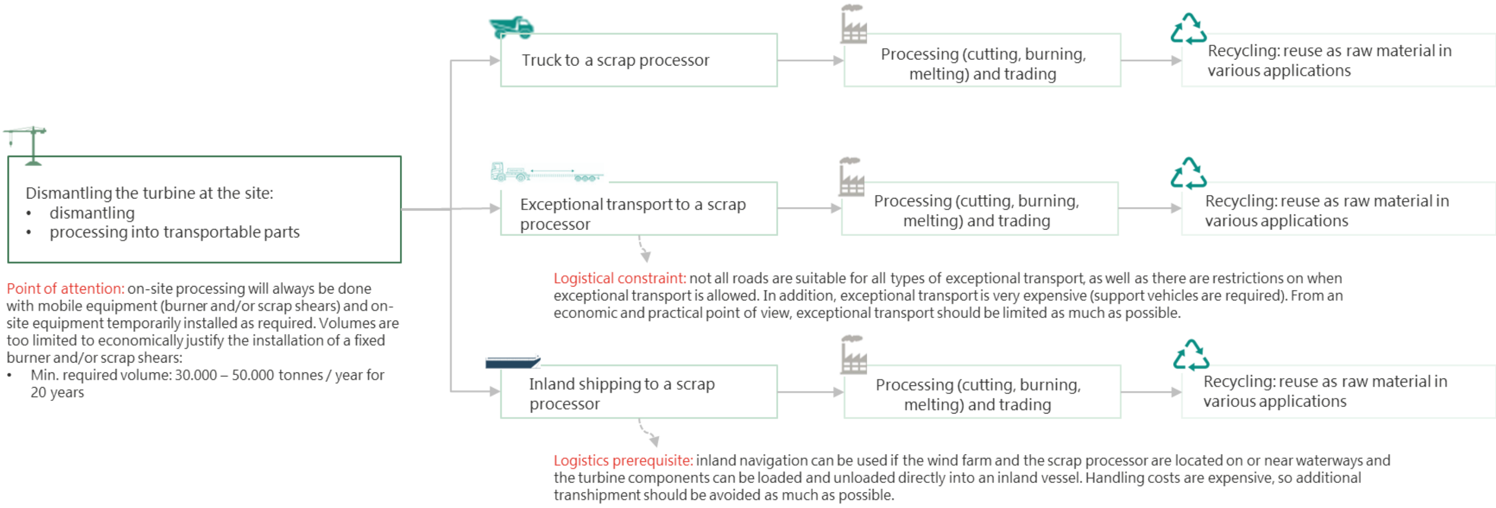
To this day, it is not entirely clear whether the foundation must be completely dismantled or only to a certain depth below ground level. The reason for the ambiguity is the different interpretation of the requirement "restoration to original condition".

- Belgian legislation: Regulations require foundations to be removed to a certain depth.
- In Wallonia, a recent decree (Walloon Government Decree of 25 February 2021 - Chapter VII - restoration to original state Art. 34) now requires the removal of the entire foundation (except the piles), whereas previously 2 metres depth was sufficient.
- Full dismantling of foundations is recommended to allow unrestricted later use of the site. However, in the case of pile foundations consisting of concrete piles or even loose piles, complete removal would lead to significant disturbance of the soil structure. The piles are therefore usually left in the deep soil layers, with the flat foundation resting on the piles being completely removed.

Onshore WTG: destination second-hand market - process



Onshore WTG: destination recycling market – process



Further explanation on the decommissioning process of onshore WTG

Reverse installation method for disassembly

The turbine is dismantled in its individual components (the 3 blades, hub, nacelle and tower)

Wind turbine components can either be sold on the second-hand market or recycled. The option chosen depends heavily on the type of project and the owners.

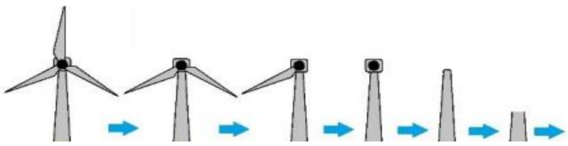


Figure 4: Reverse installation method

Source: Cost modelling for offshore wind farm decommissioning (DecomTools, 2022)

Logistical organisation of second-hand market

The second-hand market is organised by the decommissioning companies (including Business in Wind (already 80 turbines decommissioned), Inikti, Roth, Antro Group). These parties organise everything from decommissioning, transport to refurbishment and reinstallation on the new site.

- Inikti also has a warehouse of recycled spare parts from dismantled wind turbines. Business in Wind and Inikti are very active in Belgium.
- Parties like Aertssen and Sarens are partners, but do not do decommissioning themselves (Aertssen is interested, but is still waiting for the market to be bigger).

The decommissioning process is decentralised. The components of the decommissioned turbine go as directly as possible from the original to the new site. Intermediate storage and transhipment are minimised (and if possible completely avoided) because heavy-duty crane services are very expensive and have to be ordered long in advance.

- Blades, hub and nacelle: loaded directly on heavy transport trucks (exceptional transport) and transported to the destination of the agreed buyer of the turbine components
- Tower: dismantling of the individual steel tower sections, then direct loading of the individual steel tower sections onto heavy transport trucks (exceptional transport) and transport to the destination of the agreed buyer of the turbine components

In the best case scenario, the old owners of the wind turbines do not have to pay anything, or even receive an amount for the takeover. The second-hand value of the turbine covers all decommissioning costs.

Logistical organisation of wind turbines destined for material recycling

The dismantling process of wind turbines for recycling materials is also decentralised. Wind turbine components travel as directly as possible from the dismantling site to the processor.

- Hub and nacelle: are loaded in their entirety on heavy transport trucks (exceptional transport) and transported to a specialised waste disposal company
- Blades and tower: depending on the contractor appointed to dismantle the wind turbine, the blades and/or the steel tower parts are (1) directly loaded onto heavy transport trucks (exceptional transport) or (2) cut into transportable pieces on site ('resize to fit container') and loaded onto standard vehicles and transported to a specialised waste disposal company
- For example: when the old turbines along Pathoekeweg in Bruges were dismantled, the tower segments were transported to Galloo Ghent (for processing into scrap for the steel industry), and the nacelles and blades to Galloo Menen (for dismantling, shredding....).

The legal framework

The legal framework conditions are numerous, partly still uncertain, but do not seem to cause any major constraints.

- Distinction between waste shipments and recycling streams:
    - Shipments of waste by road, sea or inland waterway are regulated at European level (Regulation 1013/2006). A permit must be requested for cross-border shipments of waste (this also applies to shipments of waste between the 3 regions).
    - Onshore wind turbine - destination second-hand market: when an onshore wind turbine or part of it is dismantled for sale on the second-hand market, the end-of-waste criteria* are met, which means that the dismantled wind turbine or parts of it do not fall under the scope of waste legislation.
    - Onshore wind turbine - destination recycling market: when an onshore wind turbine is dismantled for destination recycling market, certain elements such

as metals, wood and concrete chunks fulfil the end-of-waste criteria[5], meaning that waste legislation no longer applies. For other elements that do not meet the end-of-waste criteria (including composite coming from the blades or concrete debris not eligible for recycling), waste legislation does apply if the shipment is cross-border. Since Flanders has a dense network of breaking yards and scrap/waste processors, these streams will in most cases be processed locally and will also be exempt from legal obligations.

- Exceptional transport
    - To transport a decommissioned wind turbine or part of a decommissioned wind turbine from land to sea via a Flemish port, a licence must be applied for from the Flemish Agency for Maritime Services and Coast. However, there is currently no implementing decree from the Flemish Government regarding the application procedure for obtaining the licence or the further specification of special and exceptional transports.
    - There is currently no specific legislation for transporting a decommissioned wind turbine or its components by road (e.g. weight, speed, etc.).

3.2 Decommissioning of offshore wind turbines

Types of offshore foundations

There are 3 types of foundations for offshore wind turbines:

1. Gravity-based foundation: concrete cone filled with sand.
2. Monopile foundation: a steel cylinder suitable for a depth of up to 30 metres anchored directly to the seabed. Monopile foundations are the most commonly used foundations in offshore wind turbines. To protect the steel foundation from erosion, erosion protection is applied (about 2,500 tonnes of stone rubble).
3. Jacket foundation: a latticework with an anchoring point on the seabed

The logistics chain for decommissioning offshore foundations varies depending on the type of foundation:

- Decommissioning gravity-based foundations
- Dismantling of monopile and jacket foundations

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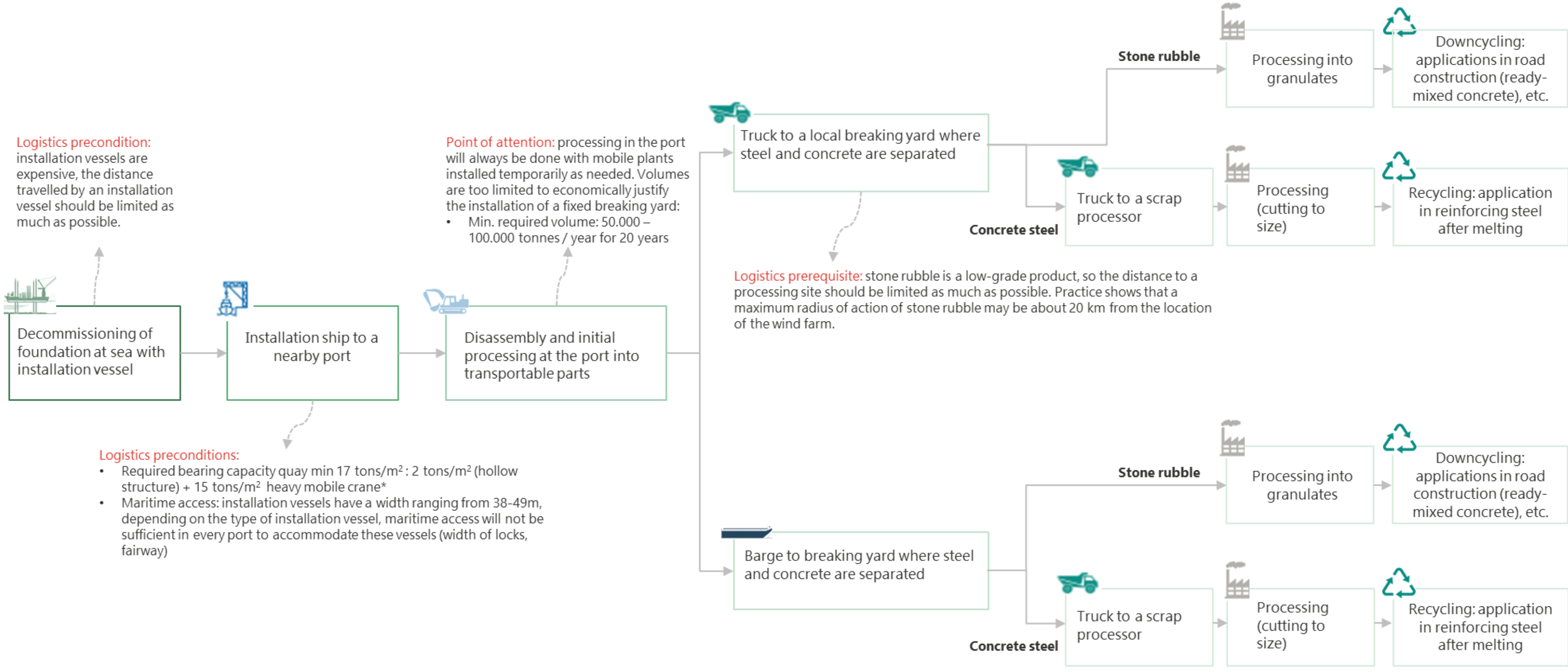
[5] Waste ceases to be a waste if it has undergone a recovery operation including recycling. Recycling means any recovery operation in which waste is reprocessed into products, materials or substances, either for the original purpose or for another purpose.

Wind farm	Year of construction	# wind turbines	Type of foundation
C-power	2009	6	Gravity-based foundation
Belwind	2010	55	Monopile
Belwind 2	2013	1	Monopile
C-power 2	2013	48	Jacket foundation
Northwind	2014	72	Monopile
Nobelwind	2017	50	Monopile
Rentel	2018	42	Monopile
Norther	2019	44	Monopile
Northwester 2	2020	23	Monopile
Seamade	2020	58	Monopile

Table 4: Type of foundations in Belgian offshore wind farms

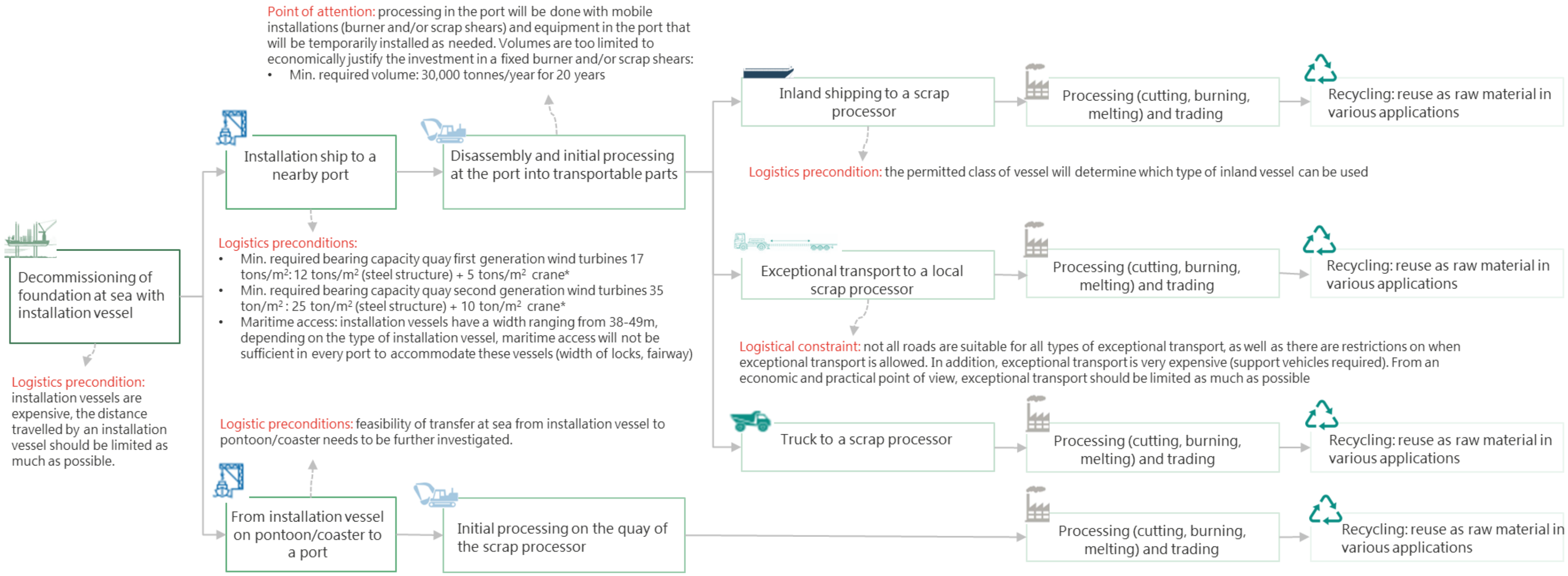
Source: Rebel

Gravity based foundation – Process



**This is an initial estimate based on the in-depth interviews, further research is required to determine the exact required bearing capacity of the quay. The required bearing capacity will vary depending on the decommissioning technique.*

Monopile and jacket foundation – Process



Point of attention: removal erosion protection is currently mandatory based on legislation and may require additional tools and steps. Currently there is no clarity on how the erosion protection will be removed, the technique depends very much on the type of erosion protection and how this stone debris will be recycled. Further research is required.

**This is an initial estimate based on the in-depth interviews, however, it is not clear up to this point how the steel structures will come ashore and then be processed. Required bearing capacity will vary depending on the decommissioning technique.*

Further explanation on the decommissioning process of offshore foundations

For the removal and transport to shore of offshore foundations, the same type of vessels that were used for their installation are used. Those vessels can reach the REBO quay (38-49m wide).

As specialised work vessels are required, conventional offshore companies are naturally involved. As with installation, dismantling companies look for suitable port terminals and conclude agreements with them. However, Business in Wind has the ambition to enter the offshore market too, and with a radically different approach (they are investigating the feasibility of floating recycling pontoons at sea).

Gravity-based foundation

Based on the literature and market interviews, two options can be identified:

- Option 1: the concrete foundation is demolished on site with hydraulic demolition shears, a hydraulic hammer and with milling tools. The concrete elements/stone rubble are then collected and placed on a pontoon for transport to the port (applied in the decommissioning of the Vindeby wind farm in 2017)[6]
- Option 2: removal of the foundation in one piece (after pumping away the ballast), and transport to land on pontoon or towed in the case of self-floating foundations. This option is foreseen for most wind farms with gravity-based foundations, but has not yet been implemented in practice because the farms concerned are still in operation.

Monopile foundation

Most of the already decommissioned offshore wind turbines had been placed on monopiles. In one windfarm, the monopiles were completely removed, including the erosion protection (Lely in the Netherlands). In the others, the monopiles were cut a few metres above or below the seabed, and only the upper part was removed. The erosion protection remained behind.

Techniques are being developed to loosen and remove the monopile in one piece. These techniques are still at an experimental stage (e.g. HyPE-ST project).

Jacket foundation

The piles securing the jacket to the seabed are cut several metres below the seabed and removed with a single lift. The entire structure is brought to shore.

Belgian legislation

The environmental permits for wind farms require that a complete decommissioning must be carried out and the site restored to its original state, unless the minister responsible for the Marine Environment decides otherwise. This means that the entire foundation incl. erosion protection and cabling must be removed. The foundations must be removed to at least 2 metres below the seabed. Wind farm operators must make a provision for decommissioning costs.

[6] To date, the only decommissioning of gravity-based foundations, according to literature sources consulted.

Social and financial considerations removal offshore foundations

Complete removal of the foundation will leave a hole in the seabed, of which it is unclear what will happen to it.

Research shows that leaving the erosion protection on the seabed should not cause problems for the future use of the seabed. Marine life has flourished around the erosion protection, making it difficult to determine whether it is better to remove the erosion protection or leave it in place. In general, industry prefers to keep the erosion protection in situ.

Today, no working vessels exist that can efficiently remove entire foundations and erosion protection.

Dimensions offshore foundations

As already described in the context of this study, the size of wind turbines (rotor diameter and height) and foundations increases with the years of installation. The increasing dimensions have a major impact on the potential logistics chains for decommissioning offshore wind turbines. In this respect, it is relevant to distinguish between the dimensions of first-generation and last-generation offshore wind turbines (Table 5 and Table 6).

In addition, there is ambiguity to date regarding the removal of the offshore foundation. Table 7 presents an overview of the assumptions as included in the base case that determine the design of the logistics chains.

	First-generation offshore wind turbines (3-5 MW)	
	Weight (in tonnes - bandwidth)	Length (in m - bandwidth)
Tower	170	80
Nacelle	170	-
Blades (3)	36	44/wick
connector	250	-
Monopile/jacket foundation	1.000	80 (of which 20m above the sea, 30m depth and 30m in the seabed)
	Second-generation offshore wind turbines (up to 9 MW)	
	Weight (in tonnes - bandwidth)	Length (in m - bandwidth)
Tower	805	100
Nacelle	390	-
Blades (3)	105	80/wick
connector	500	-
Monopile/jacket foundation	2.000	80

Table 5: representative dimensions first and last generation offshore wind turbines - monopile and jacket foundation

Source: assumptions Rebel based on literature review and information gathered from in-depth interviews

Gravity-based foundation	
Total tonnage (in tonnes)	15.000
Share of reinforced concrete - hollow structure (in tonnes)	3.000
Share of backfill - sand/stone rubble/… (in tonnes)	12.000

Table 6: dimensions gravity-based foundation

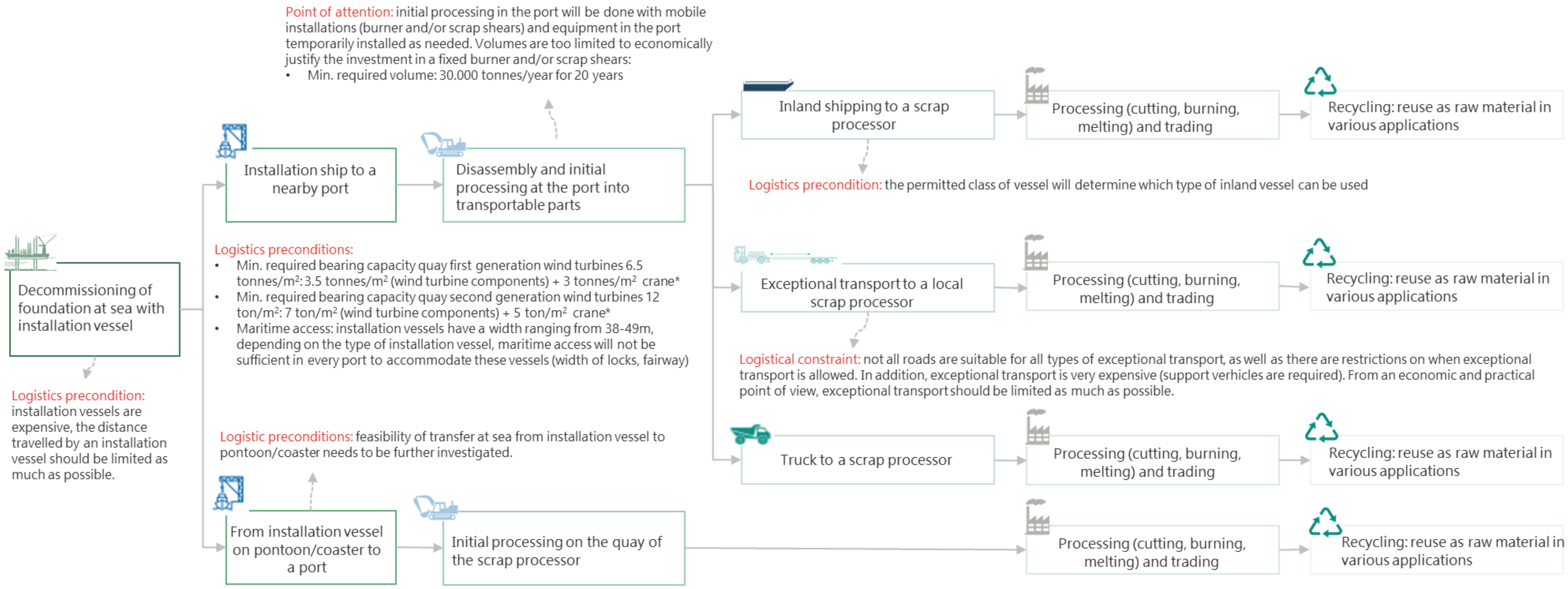
Source: C-Power

Removal offshore foundation
Erosion protection is left in situ
Gravity-based foundation: complete removal of hollow structure
Monopile/jacket foundation: removal for approx. 2/3rds of the weight

Table 7: Base case assumptions

Source: assumption Rebel based on literature review and information gathered from in-depth interviews

Offshore WTG – Process



**This is an initial estimate based on the in-depth interviews, however, it is not clear up to this point how the wind turbine components will come ashore and then be processed. Required carrying capacity will vary depending on the decommissioning technique.*

Further explanation on the decommissioning process of offshore WTG

To date, there is no single 'best' method for decommissioning an offshore wind turbine. Factors such as time saving, cost and environmental impact are the main aspects that will influence the decision on which method to implement.

Based on the insights from the market interviews and the literature, method V can be put forward as the preferred method of most parties:

- Method V minimises operations at sea, which is desirable from both an economic and environmental point of view.
- Dismantling/processing wind turbines at sea has a number of drawbacks:
    - safety cannot be guaranteed due to unpredictable weather conditions at sea;
    - it is very complex;
    - ship and labour costs are higher;
    - the impact on the marine environment is greater.
- *Method VI contains even fewer offshore operations, but is not feasible due to the size of the wind turbines*
- *Business in Wind and others are investigating the feasibility of further processing at sea on floating recycling lanes. If this proves possible, there will be less need for port sites for dismantling and interim storage of wind turbine parts. Indeed, this will then be done on the floating recycling platform.*

The dismantling and transport of decommissioned offshore wind turbines will probably use the same types of installation vessels that were used during installation.

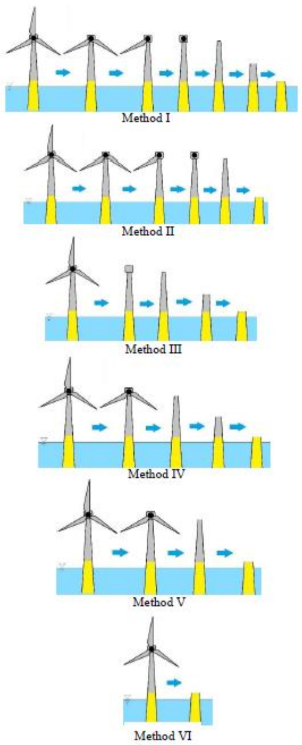


Figure 5: Decommissioning techniques offshore wind turbine

Source: Cost modelling for offshore wind farm decommissioning (DecomTools, 2022)

4. Recycling of wind turbines components

4.1 Recycling of concrete

Onshore wind turbines: downcycling

Stone rubble (aggregates) cannot be reused as raw material, currently it is mainly processed as "downcycling" (concrete properties decrease during recycling) and used in less stringent applications (e.g. foundations roadworks,...).

The standards are gradually becoming less stringent and there is active research into the reuse of waste concrete (aggregates) as a raw material for new concrete. Moreover, concrete from wind turbine foundations would contain fewer impurities than concrete from the construction industry, allowing better properties and use in structural applications.

Offshore wind turbines: downcycling through salt intrusion

Salt intrusion ensures that waste concrete/stone rubble is likely to be processed exclusively as "downcycling". Recycled aggregates cannot be reused as raw material in reinforced applications (e.g. new ready-mixed concrete). Instead, it should be used in less stringent unreinforced applications (e.g. road construction, erosion protection, etc.).

Point of attention: no research has yet been conducted into the properties of concrete/stone rubble derived from offshore foundations. Thus, at present, it is also not clear for which applications recycled aggregates derived from offshore foundations will effectively be considered in the future.

Belgian players active in concrete recycling:

- Top-Mix
- De Brabandere
- Colas
- Interbeton
- Recytour
- Tradecowall
- The Meuter
- Seuz

4.2 Recycling metal

The properties of metals allow for almost unlimited recycling of these materials and can be reused as raw materials all the time.

A distinction should be made between ferrous (steel) and non-ferrous (copper and aluminium) metals.

- Ferrous: steel can be found mainly in the tower of the turbine and in smaller quantities in the nacelle
- Non-ferrous: copper can only be found in the nacelle, aluminium can be found in both the tower and the nacelle. In addition, copper and aluminium can also be found in the submarine cables

Belgian players active in metal recycling: 19 industrial players (7 in Wallonia, 1 in Brussels and 11 in Flanders), including:

- Galloo (West Flanders)
- AIM Recycling Europe (West Flanders)
- BST
- Derichebourg
- Keyser
- Dubail recycling
- Ecore

4.3 Recycling composite

Incineration and co-incineration

Currently, there is no economically interesting solution for recycling composites in Belgium. Incineration in waste incinerators and co-incineration in cement kilns are currently the most economically viable solutions (dumping is prohibited in Belgium).

- Composite materials can be recycled or recovered by mechanical milling, thermal (pyrolysis, fluidised bed), thermochemical (solvolysis) or electromechanical (high-voltage pulse shredding) processes, or a combination of these, but these alternative recycling technologies are at different stages of development and are not yet available on an industrial scale.
    - Blade made: currently the only party (Netherlands) recycling composite materials (application in sound walls, among others)
    - Belgian player: Terre et Pierre (working on the Recypale project - pilot phase)
- The main reason why no site specifically dedicated to composites recycling is being established to date is the uncertainty regarding the demand for these recyclates and consequently uncertainty about large customers.

If the blades were made entirely of carbon fibre, they could be processed in an alternative way. Based on the current information on the composition of the blades, it can be concluded that the blades are not made exclusively of carbon fibre, but are mainly carbon fibre-reinforced (60-70%) and consequently cannot be processed in a more high-quality way (relative to combustion).

4.4 Recycling REE

Recycling by specialised waste management companies

REE occur exclusively in offshore turbines. Some offshore wind turbines contain permanent magnets, either in the generator or in the tower for fixing internal attachments. There are various assemblies of permanent magnets, which may or may not use rare earth elements (REE).

Recycling REE is not easy. Magnets should be separated from other parts as much as possible, should be free of coating and should be perforated before undergoing thermal treatment to be demagnetised. Thereafter, demagnetised pieces could be processed by waste management companies.

Belgian players:

- Umicore

5. Requirements for port locations

5.1 Potential port sites for receipt, storage and possible initial processing of decommissioned offshore wind turbines

The ports under consideration as potential sites for decommissioning offshore wind farms in the Belgian North Sea are:

- Ports that have heavy lift terminals in Belgium, the Netherlands and France:
    - Ostend
    - Flushing
    - Rotterdam
    - Scheveningen
    - Amsterdam
    - IJmuiden
    - Den Helder
    - Harlingen
    - Eemshaven
    - Le Havre
- Other seaports:
    - Zeebrugge
    - Ghent
    - Antwerp
    - Dunkirk

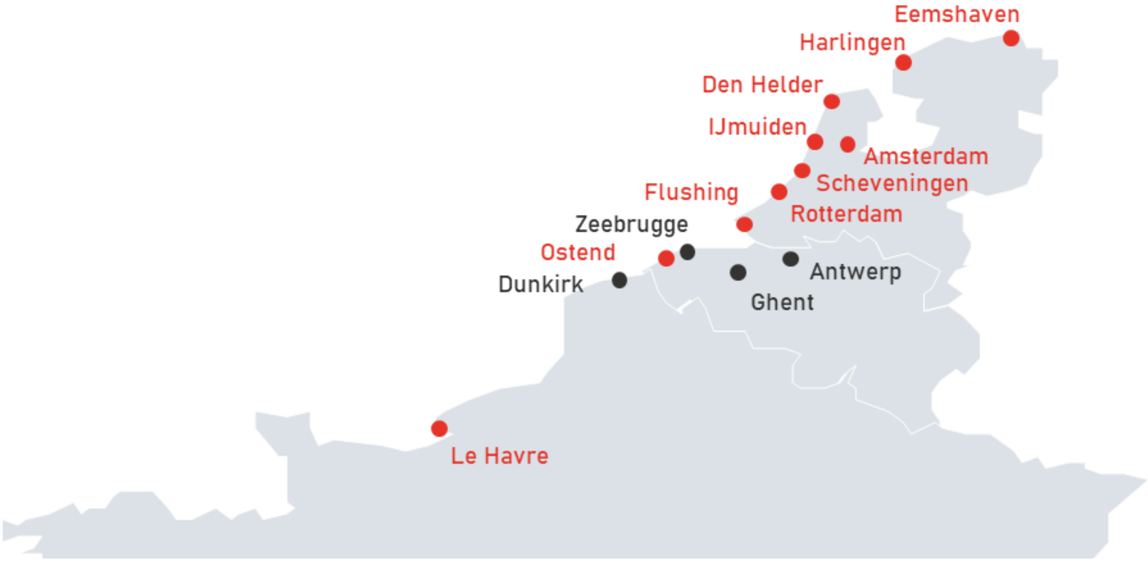


Figure 6: Overview of potential port locations decommissioning offshore wind turbines

Source: Rebel

Port	Ostend	Flushing	Rotterdam	Scheveningen	Amsterdam	IJmuiden	Den Helder	Harlingen	Eemshaven	Le Havre
Carrying capacity (tonnes/m2)	20	15	10	20	20	16,5 - 23,5	> 4	4	20	25

Table 7: Overview of load-bearing capacity quay heavy-load terminals

Source: Hollandse Kust: Where wind & water works (Netherlands Enterprise Agency, 2017)

5.2 Port choice is determined by a combination of factors

There are a number of infrastructure requirements that potential port sites must meet to be eligible for the dismantling (disassembly and initial processing) of offshore wind turbines.

Infrastructure requirement:

- Location / geographical location of the port: the distance from the port to the offshore windfarms should be as short as possible to minimise the sailing time of the expensive installation/decommissioning vessels.
- Maritime access: there should be sufficient space in the port to accommodate installation/decommissioning vessels
- Bearing capacity of the quay and grounds: these should be of sufficient size to support the heavy pieces, as well as the cranes and moving platforms used to move the pieces.
- Site area: there should be sufficient space in the port for interim storage of the wind turbine components and/or initial processing of the wind turbine components into transportable parts.
- Hinterland side access: good access by all modes - inland waterway, road and exceptional transport - is essential to ensure efficient transport to processing sites and sufficient flexibility.

5.3. Assessment of suitability of potential port sites

Given their location, the ports of Ostend and Vlissingen are the most obvious choices to facilitate the decommissioning of offshore wind farms in the Belgian North Sea. In addition, it were the ports that participated in the installation of the Belgian offshore windfarms

The table below presents an overview of the infrastructure constraints in the alternative potential port locations.

Rotterdam	Location: distance from the port to offshore wind farms is great
Scheveningen	Location: distance from the port to offshore wind farms is great
Amsterdam	Location: distance from the port to offshore wind farms is great
Ijmuiden	Location: distance from the port to offshore wind farms is great
Den Helder	Location: distance from the port to offshore wind farms is great
Harlingen	Location: distance from the port to offshore wind farms is great Load-bearing capacity of quay limited: 4 tonnes/m2

Eemshaven	Location: distance from the port to offshore wind farms is great
Le Havre	Location: distance from the port to offshore wind farms is great
Zeebrugge	Maritime access limited by width of New Sea Lock Space: limited available for decommissioning activities
Ghent	Location: distance from the port to offshore wind farms is great Maritime access: limited by width of Ghent-Terneuzen lock
Antwerp	Location: distance from the port to offshore wind farms is great Maritime access: limited by width of Kieldrecht lock

Table 8: Overview of infrastructure constraints potential port sites

Source: Rebel

5.4 Assessment of suitability of the port of Ostend (compared to Vlissingen)

With the REBO terminal, Ostend has the infrastructural requirements to serve as a port for transhipment and first processing. Now that the last windfarm in the Eastern zone has been finished, the REBO terminal is available for decommissioning activities. The wind turbines installed from the port of Ostend can also be dismantled via that port.

The main competitive location is Vlissingen, from where the foundations of all Belgian windfarms and part of the wind turbines are installed. There is currently a perception among consulted market participants that Vlissingen is better than Ostend. However, there are no clear indications to support this perception.

- Maritime access in Vlissingen is wider than in Ostend, but the accessibility of the REBO terminal is sufficient for the installation vessels that have installed the current wind turbines of the Belgian windfarms (and which may be used for decommissioning)
- Vlissingen has more quay length and a larger terminal and warehousing area than the port of Ostend.
- The carrying capacity of the REBO terminal is equivalent to the heavy lift terminal in Vlissingen and most other terminals in Belgium and the Netherlands.
- Access along the hinterland side is better in Vlissingen than in Ostend (greater inland waterway accessibility and easier accessibility for exceptional road transport).
- Authorisation procedures in Dutch ports are considered less complex than in Flemish ports, but there are no concrete facts to support this perception.

The table below presents a comparative overview of the infrastructure characteristics of the ports of Ostend and Vlissingen.

Port	Maritime access - width of fairway (in m)	Total plot length (in m)	Load bearing capacity quay (in tonnes/m2)	Terminal (in ha)	Warehousing (in sqm)	Hinterland access
Ostend (REBO terminal)	150	800	20	15*	7000	• Inland navigation limited to CEMT class IV • More difficult access to REBO heavy lift terminal for exceptional transport (height restriction connection R31 - Stapelhuisstraat, connection Konterdamkaai - R34)
Flushing (BOW terminal)	350	• 525 (heavy load quay) • 1.400 (waiting and mobility activities	15	35	60.000	• No restrictions

**Included part issued in concession to Nectar Group.*

Table 9: Benchmark port of Ostend and Vlissingen

Source: Rebel

5.4 Role port of Ostend as export port of decommissioned onshore turbines

Decommissioned onshore wind turbines destined for reuse at an overseas location must be shipped through a port. Project cargo terminals are used for this purpose. Decommissioned wind turbines in Flanders and the Netherlands often find a second life in the UK, where in many regions only smaller wind turbines are allowed. Four recently decommissioned wind turbines in the Netherlands were even exported to Australia.

The REBO terminal is eligible for shipping dismantled onshore wind turbine components destined for reuse. This does not require accessibility for installation vessels.

- In general, they wish to minimise expensive land transport with exceptional transport. Ostend will therefore mainly be considered for the shipment of wind turbines from the province of West Flanders.
- Due to the absence of liner services Ostend only qualifies if the sea transport is by tramp service.

6. Key findings

6.1 Dismantling, transport and recycling process

Based on the literature and interviews with companies involved, the process of dismantling, transporting and recycling both offshore and onshore wind turbines was mapped and described, each time distinguishing between the foundation on the one hand and the other components of the wind turbine (tower, nacelle, rotor) on the other.

The process of decommissioning, transport and recycling has not yet been definitively and fully determined. Today, there is very little experience worldwide with the decommissioning of offshore wind turbines (about six in Europe, none in Belgium). There is already more experience in the onshore segment (including in Belgium). The process will be further optimised through research and "learning by doing". However, the broad outlines are already clear and described in chapter 3.

Today, there is no operational synergy between the decommissioning of onshore and offshore wind turbines. The logistics chain is different between the two. Port sites are necessary when dismantling offshore wind turbines. The dismantled wind turbine components cannot be transported directly from the offshore site to processing facilities. Transshipment at a port is necessary. Initial processing also takes place at the port to reduce the dismantled components to transportable pieces. Ports also play a role in the transport of onshore wind turbines destined for reuse elsewhere, but only if this transport is done overseas.

To what extent the pieces of dismantled offshore turbines are reduced at the port, and the mode of transport to the final processing site (coaster, sea barge, barge, truck, exceptional transport) depend on the specific circumstances. From a cost-efficiency perspective, there is a preference for water transport over road transport, a preference for road transport over exceptional road transport, and a preference for unimodal transport without intermediate transhipment.

The main material streams are concrete and steel. Although significant volumes are involved, the flows are relatively small compared to existing processing capacity. There is therefore no need to establish additional processing capacity for wind turbine decommissioning.

However, it cannot be ruled out that material handling capacity will be established at the discharge port. This is not necessary because of the need for additional processing capacity (it is already sufficient). But it might turn out that the savings in landside transport costs outweigh the investment costs in processing capacity.

6.2 Requirements for potential port sites

The requirements for an unloading port (where parts dismantled at sea are transhipped and further reduced in size) cover:

- Location (sufficiently close to the wind farms to reduce the sailing time of the expensive installation/decommissioning vessels)
- Maritime access (sufficiently spacious for installation/decommissioning vessels)
- Load-bearing capacity of the quay and grounds (being of sufficient size to support the heavy pieces, as well as the cranes and moving platforms used to move those pieces)
- Site area (sufficient space for interim storage and first processing)
- Hinterland access (all modes - inland, road and exceptional road transport - to provide sufficient flexibility)
- Knowledge, know-how and industrial network

The exact load and space requirements of the terminal are not yet known due to the lack of concrete experience with decommissioning. Broadly speaking, the same requirements apply as for installation (as decommissioning follows as much as possible the reverse process of installation).

6.3 Assessment of suitability of the port of Ostend (compared to Vlissingen)

Decommissioning of offshore wind turbines

Most of Belgium's first-phase (2009-2020) wind farms were installed from Ostend. The REBO terminal (15 ha) could potentially play the same role in decommissioning those wind turbines as in installing them. Indeed, according to current understanding, the decommissioning process will largely be like a reverse installation process, with similar infrastructure and space requirements.

- A prerequisite is that sufficient space is made available. If decommissioning of windfarms is carried out within the same time frame as their installation, the entire

area of the REBO terminal is needed for dismantling and storage of turbine components.
- Part of the REBO terminal has been given in concession to a breakbulk handler in 2022. A 7,000 m² storage shed will be built on the site (1 ha site intake), reducing the area of open storage space by the same amount. The concessionaire's operations are combinable with the transshipment and handling of dismantled wind turbines. Dismantling offshore wind turbines represents a market opportunity for the breakbulk terminal operator. But there is no commitment from the concessionaire to effectively provide space for this purpose.

The main competitive location is Vlissingen, from where wind turbines for the Belgian offshore wind farms are also installed. There is a perception among consulted market players that Vlissingen is better suited than Ostend in all areas: greater availability of space, greater carrying capacity of quay and sites, cheaper labour and better permitting climate. Apart from space availability (which is significantly higher in Vlissingen), there is no evidence to support this perception. However, the lack of (committed) space and Ostend's other perceived weaknesses currently make Vlissingen the preferred base for decommissioning old wind turbines in Belgian wind farms.

Decommissioning of onshore wind turbines

The REBO terminal is eligible to export decommissioned onshore wind turbines in West Flanders and Hainaut to overseas destinations (UK, Sweden).

7. Recommendations

7.1 Further investigation on decommissioning process

Detailed logistics studies, preferably based on a concrete "use case"

- Today, there are still many uncertainties about the most efficient decommissioning process for offshore wind turbines (e.g. how the dismantled wind turbine parts will be stored and processed at the port - standing, lying down, degree of downsizing; possibilities for more far-reaching dismantling at sea so that the parts can be transported by sea pontoons or coasters directly from the offshore site to final processing locations).
- Investigate potential for use of inland navigation in the decommissioning of onshore windfarms located on or near waterways and possible role of the Port of Ostend as a transhipment point for inland navigation.
- The REBO terminal is eligible for exporting decommissioned onshore wind turbines to overseas destinations (such as UK and Sweden). Especially for wind turbines in West Flanders and Hainaut, for which Ostend is the closest port. The new concessionaire has already handled wind turbine parts.

Better understanding of the assumptions behind existing estimates of expected annual material flows from the decommissioning of onshore and offshore wind turbines.

- Including distinction between onshore and offshore wind turbine volumes, and assumptions on the extent of foundation removal and erosion protection

- This understanding is needed for a more reliable estimate of material flows and the assessment of the economic and financial feasibility of additional processing capacity at the port of Ostend and the province of West Flanders.

Further investigation of recycling potential

- Quality of reinforced concrete from gravity-based foundations (impact of salt intrusion) and determination of potential recycling applications (given concrete quality standards)
- Currently, there is no recycling technology for composites in Belgium and they are incinerated. Opportunities to engage in research and development to develop composites recycling activities in the port of Ostend.

7.2 Further research on actions to strengthen the assets of the port of Ostend

Port of Ostend should actively pursue the realisation of a number of preconditions such that companies can carry out decommissioning activities competitively.

- Actively pursue space reservation or creation (min. 15 ha) in the next 6 years.
- Stronger anchoring of the offshore logistics cluster in Ostend, which had a strong presence for installations but less for decommissioning. This requires, among other things:
    - Explore broader strategic cooperation with the Flemish Dutch Delta (VND) to maintain the cluster, and consequently its strength relative to northern French ports (Dunkirk). Are there European projects whose resources could be better used (e.g. European project through the NWEA - Dutch Wind Energy Association)?
    - Involve decommissioning decision-makers, including park operators, likely directors of the logistics process (offshore marine contractors and potential new onshore competitors such as Business in Wind, Inikti and Antro Group) and the operator of the REBO terminal.
    - Establish knowledge and training centre for development and dissemination of techniques for dismantling offshore and onshore wind turbines (e.g. in terms of project management of dismantling operations, and efficient and environmentally friendly dismantling and recycling techniques). This centre could be integrated into Bluebridge, for example.
- Resolve (perceived) weaknesses of the Port of Ostend compared to competing ports:
    - Identify and solve logistics bottlenecks (e.g. access for exceptional transport)
    - Identify any regulatory bottlenecks for wind turbine decommissioning in the port of Ostend and solve them together with the stakeholders involved at all levels of government (e.g.: can permit procedures be simplified?)

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Annex 1: Overview of parties interviewed

Offshore activities

- DEME Group: Lucien Romagnoli, BU Director Renewables
- Aertssen - Jelle Van Gestel, Project Manager

Onshore operations

- Business in Wind - Wim Robbertsen, CEO

Recycling activities

- Galloo - Wim Guillemyn, Site manager Roeselare
- De Brabandere - Pieter De Brabandere, Director