Offshore wind farm decommissioning

An orientation of possible economic activity in the south holland region and the rotterdam port area

Joustra, J.J.; van der Meulen, Thomas Hajonides; Bastein, Ton; Swamy, Siddharth Krishna ; Saraswati, Novita

Publication date
2020

Document Version
Final published version

Citation (APA)
Joustra, J. J., van der Meulen, T. H., Bastein, T., Swamy, S. K., & Saraswati, N. (2020). *Offshore wind farm decommissioning: An orientation of possible economic activity in the south holland region and the rotterdam port area*.

Offshore wind farm decommissioning

AN ORIENTATION OF POSSIBLE ECONOMIC ACTIVITY IN THE SOUTH HOLLAND REGION AND THE ROTTERDAM PORT AREA

smartport.nl

SmartPort is a joint venture between the Port of Rotterdam Authority, Deltalinqs, the Municipality of Rotterdam, TNO, Deltares, Marin, Erasmus University and Delft University of Technology. By inspiring, initiating and forming alliances SmartPort stimulates and finances scientific research for and by the companies in the port of Rotterdam in collaboration with knowledge institutes.

It is about developing knowledge, share and use it from one collective ambition. The transition onto the best and smartest port can only become successful when all parties involved jointly provide solutions to changes the future will bring.We are convinced that the most impact in developing knowledge is based on specific questions from the market and that the best results arise when the optimal benefit is gained from joined forces of trade and industry, authorities, and science.

www.smartport.nl | LinkedIn: smartportrdam | Twitter: SmartPortRdam | Instagram: smartportrdam

SMARTPORT PARTNERS

Deltares Enabling Delta Life | Deltalinqs | Erasmus University Rotterdam | Gemeente Rotterdam | Port of Rotterdam | MARIN | TNO | TU Delft Delft University of Technology

WITH CONTRIBUTION

provincie Zuid Holland | TKI DINALOG Dutch Institute for Advanced Logistics

OFFSHORE WIND FARM DECOMMISSIONING

Authors: Thomas Hajonides van der Meulen (TNO), Ton Bastein (TNO), Siddharth Krishna Swamy (TNO), Novita Saraswati (TNO), Jelle Joustra (TU Delft)

innovation for life

CONTENTS

-01-

The challenge of removing a large-scale offshore wind farm

A significant part of wind energy in the Netherlands is generated by offshore wind farms at sea. In the coming decades, the number of wind farms will be scaled up in line with current energy transition and sustainability objectives. What happens to these wind turbines when they reach the end of their operational life? What volumes of material are involved? How can we prevent an adverse impact of this dismantling on the environment? What forms of economic activity may result from this removal task? This chapter explains the context of these questions and also describes the research questions and structure of the document.

1.1 Overview of the situation

The transition to an energy system based on renewable energy sources is in full swing. In the Dutch, Belgian, British, German and Danish North Sea, offshore wind farms are and will continue to be built in order to contribute to a more sustainable energy mix. European policy documents outline an increase in the offshore wind power generation capacity to 174 GW in the southern North Sea by 2050[1]. Figure 1 shows the expected increase in installation capacity per year. This increase will lead to a large number of wind turbines and related off-shore systems in the North Sea subregions NL01, BE01, DE01, DK01, UK03 and UK04 (see Figure 2[2]).
The expected operational life of an offshore wind farm (OWF) is 20-30 years, after which the wind farm will be decommissioned, dismantled and removed[3]. These activities together are referred to as decommissioning. Between 2020 and 2050, offshore wind farm decommissioning will produce a growing amount of material that will need to be brought back to land from the sea. This residual material flow should then be responsibly processed in the end-of-life phase in order to minimise any negative ecological impact.

It may be assumed that business activities that may arise in the decommissioning and end-of-life phases will take place from and/or around the ports situated on the southern North Sea. A number of ports could play a role in the future, such as the ports of Aberdeen (Scotland), Esbjerg (Denmark), Sheerness and Kingston upon Hull (England), Eemshaven, Amsterdam and Rotterdam. Due to the geographical positioning, the onshore logistics facilities and established offshore shipping companies and other offshore wind chain parties of the Port of Rotterdam and the South Holland region, it is relevant to explore what and how intensive Rotterdam's role could be regarding decommissioning. This study considers the aforementioned six regions and assumes that the maximum distance between Rotterdam and an offshore wind farm within the region is 500 kilometres.

1 www.windeurope.org/wp-content/uploads/files/about-wind/reports/WindEurope-Our-Energy-Our-Future.pdf
www.ec.europa.eu/energy/sites/ener/files/documents/roadmap2050_ia_20120430_en_0.pdf

2 Adapted from WindEurope, BVG Associates (2019) Our Energy Our Future, p14

3 Repowering and lifetime extension are not a subject of research in this study

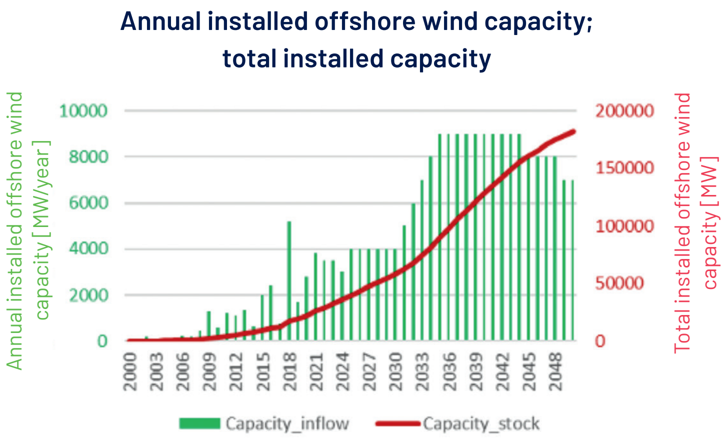


Figure 1 Expected capacity of offshore wind farms

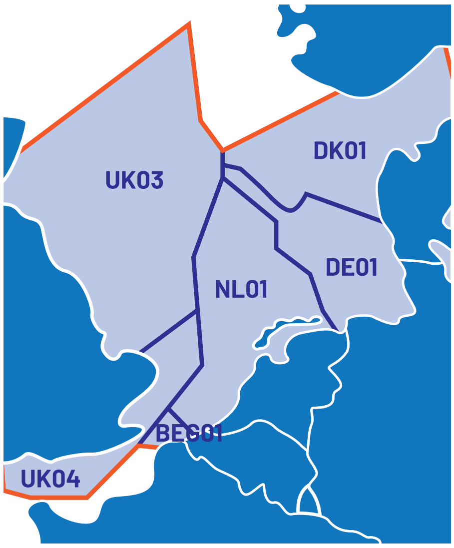


Figure 2 Subregions within the scope for this study

1.2 The challenge

The operational life of offshore wind farms is finite. Leaving the wind farms at sea is undesirable because of future use of the same North Sea area for new wind farms or other types of activities. Due to the relatively recent date of origin of offshore wind farms, there is little practical experience worldwide with decommissioning activities of such wind farms. Both from a social and an economic point of view, it is relevant to work on optimising the physical removal of wind turbines and the processing of the residual material flow (in particular flows that are not yet easy to process, such as turbine blades and permanent magnets). The following factors will make large-scale OWF removal a challenge in the coming decades[4]:

- **Large volumes:** a significant flow of systems will be released in the coming decades.
- **Lack of experience:** only limited experience has been gained with OWF decommissioning and these removal operations were on a small scale compared to future operations, both in terms of number and size of turbines (see Table 1[5]).

Table 1 Removed OWF

Turbines/wind farms	Country	Number, turbine size	Foundation	Built	End of service	Removed
Nogersund/ Blekinge/Svante	Sweden	1x220kW	Tripod	1991	2004	2007
Yttre Stengrund	Sweden	5x2 MW	Drilled MPs	2001	2015	2015
Robin Rigg (2 of 60)	UK	2x3 MW	MP	2010		2015
WindFloat	Portugal	1x2 MW	Floating	2011	2016	2016
Hooksiel	Germany	1x5 MW	Tripile	2008	2011	2016
Lely	Netherlands	4x500 kW	MP	1994	2014	2016
Vindeby	Denmark	11x450 kW	GBS	1991	2016	2017

4 Topham et al (2019) Challenges of decommissioning offshore wind farms: Overview of the European experience
5 DNV-GL (2017) Decommissioning of Offshore Wind Installations - What we can learn

- **Delayed learning curve:** direct practical experience will increase only slowly as the first installed wind farms consist of relatively small turbines in shallow and calm water.
- **Partially comparable to the oil & gas sector:** the decommissioning activities of offshore wind farms are (only) partially comparable to the decommissioning activities of oil & gas platforms.
- **Timely preparation is desirable:** determining and influencing the costs and benefits at the time of decommissioning requires general as well as site-specific and turbine-type-specific preparations. These preparations are diverse, complex and currently unclear.
- **Unclear decommissioning process:** there is currently no known clear and proven decommissioning process[6]. Decommissioning activities will initially need to be based on the previously successfully completed installation activities.
- **Specific vessels required:** specialist vessels will be used, the deployability and costs of which will be determined by the market.
- **Current regulations offer little in terms of decommissioning incentives:** although OWF decommissioning must be addressed in tender procedures, there is no direct reason to optimise or make concrete investments now (plans are only specified shortly before the decommissioning phase)[7].
- **Absence of high-quality processing of thermoset composite material:** in addition to the use of existing end-of-life chains (e.g. the steel recycling industry), the offshore wind sector will need to find solutions for the hitherto immature end-of-life destinations for the thermoset composite material[8], [9], [10]. In addition, the way in which permanent magnets must be processed is still unclear.

Because large-scale offshore wind farm decommissioning and subsequent end-of-life activities are unknown territory, there is uncertainty about the type and level of activity that could be involved. This unfamiliarity leads to unclear dependencies, costs and benefits per stakeholder involved in the entire offshore wind value chain and the waste processing sector.
This study highlights the activities aimed at the complete removal of the OWF. Activities regarding lifetime extension through component replacement or site repowering (i.e. the complete removal and reinstallation of the WTG system) require a site-specific approach and are not included in this North Sea-wide exploration.

1.3 Research questions

The aim of this study is to identify the preconditions under which business developments related to the decommissioning of offshore wind farms (including the reuse of materials from offshore wind farms) for South Holland and the Rotterdam port area can be realised. These should result in initial recommendations for further steps towards a roadmap for an ecosystem for decommissioning in South Holland.

6 WindEurope EoLIS seminar announcement: www.windeurope.org/newsroom/news/working-towards-a-european-standard-for-decommissioning-wind-turbines/
7 Kruse et al. (2019) Market Analysis DecomTools
8 Bloomberg article: www.bloomberg.com/news/features/2020-02-05/wind-turbine-blades-can-t-be-recycled-so-they-re-piling-up-in-landfills
9 Cherrington et al. (2012) Producer responsibility: Defining the incentive for recycling composite wind turbine blades in Europe
10 WindEurope, EuCIA, & Cefic. (2020). Accelerating Wind Turbine Blade Circularity

In order to identify these preconditions and make recommendations, the study answers the following questions:

How many offshore wind turbine systems (in power and numbers) and which material flows (in tonnes) will be removed from the sea as a function of time?
What activities will take place in the decommissioning and end-of-life phases? Which stakeholders can be involved?
What costs are involved in the removal, return logistics and processing of components and materials?
How are the costs and benefits of decommissioning end-of-life activities distributed among the stakeholders involved?
Based on the current market and technology, what can be said about the applications and therefore market expectations of reused components and recycled secondary materials?
Which (technological) developments will have an impact on the system life cycle phases and within what time frame will these developments affect the decommissioning and end-of-life activities?
What are the preconditions that must be met in order to deal responsibly with the decommissioned offshore wind farms?

1.4 Explanation of the document structure

This document starts with providing insight into the number of wind turbine systems and material volume flows from the southern North Sea each year in the period 2020 to 2050 (Chapter 2). Chapter 3 describes the policy, legislative and regulatory framework in which the forthcoming decommissioning and end-of-life activities will take place. These activities and the stakeholders involved are then identified per activity and described in Chapter 4. Based on the system and material flows and the identified activities, this chapter explains how much economic activity may be involved in these decommissioning and end-of-life activities. Any developments in the offshore wind sector that may have an impact on the removal and processing of the turbines are set out in Chapter 5. Finally, Chapter 6 describes three lines of action that can be followed in order to create a regional ecosystem for decommissioning, within which wind turbine systems and materials can be processed effectively.

-02-

Offshore wind farm material flows in the North Sea

In order to generate electricity at sea, various systems are integrated into a wind farm. It is possible to estimate which volumes of material will initially go to sea and return from sea after fulfilling their function as a wind farm component, based on the materials these systems are made of. This chapter describes the assumptions concerning the systems considered, the technological development included, the bill of materials per system and the final material flows per year.

2.1 System description and assumptions

The estimation of the numbers of wind farm systems and thus the volumes of material flows can only be made based on a number of assumptions relating to the total installed wind farm capacity, wind farm service life, system and material composition and technological developments. These assumptions are explained below and form the basis of the analyses in the rest of this exploration.
The number of systems and thus tonnes of material to be installed and removed in the six North Sea subregions have been theoretically approximated and modelled based on the expected installed offshore wind capacity, as described in Section 1.1. Specific systems and materials from wind farms that are already installed are therefore incorporated in the theoretical approximations.

Assumptions regarding the service life of the wind farm:

- There are various reasons that may result in the decommissioning of a wind farm. These life-limiting factors may be technological, economic, legal, commercial or organisational in nature[11]. In this study, the end of the awarded operating period of the wind farm owner is considered to be the operational life of the wind farm.
- From 2020 to 2030, the assumed normally distributed operational life of a turbine is 20-25 years. A possible longer operational life is not taken into account until 2030. From 2031 onwards, a minimum (20-25 years) and maximum (25-30 years) operating life will be assumed in two material flow scenarios.
- It is assumed that the systems and components will not be replaced. Interim material flows related to maintenance work are therefore not taken into account.

Assumptions regarding system and material composition:

In its analysis, this study takes into account various technological developments that are expected until 2050. A number of developments that may have a high degree of implementation and a major impact on the decommissioning phase, but are considered less likely, are discussed in Section 5.1.

11 Ruitenburg, R.J. (2017). Manoeuvring physical assets into the future - planning for predictable and preparing for unpredictable change in Asset Life Cycle Management. PhD thesis, University of Twente, Enschede, the Netherlands.

The following assumptions regarding technological developments were made in this study[12]:
Until 2030, the production capacity of a wind turbine will be scaled up from 2 to 5, 10 and 15 MW (see Table 2):

Table 2 Expected development of OWF installation and decommissioning

Assumed Individual wind turbine generator (WTG) capacity [MW]	Installation period	Decommissioning period (operational life 20-25 years)	Decommissioning period (operational life 25-30 years)
2	2000-2007	2020-2032	(not applicable)
5	2008-2015	2028-2040	2028-2045
10	2016-2025	2036-2050	2041-2050
15	2026-2030	2046-2055	2051-2055[13]

The offshore wind farm system as considered in this analysis consists of five subsystems, which in turn consist of one or more components. The system structure is shown in Table 3.

Table 3 Structure of offshore wind farm system

System level	Subsystem level	Component level
Wind turbine generator	Support structures	Monopile
		Transition piece
		Cable tubing and protection
		Scour protection
	Tower	Tower structure
		Internals
	Nacelle	Bed Plate
		Cover/Frame
		Mechanical break
		Yaw System
		Drive train (incl. shaft, bearings and gearbox)
		Shaft
		Gearbox (not for direct drive wind turbines)
		Generator
		Transformer
	Rotor	Hub
		Nose cone
		Pitch system
		Blades
Balance of plant	Subsea array cables	Subsea array cables

12 Roelofs, B (2020) Material recovery from Dutch Wind Energy, TU Delft. Leiden University, TNO
13 The time horizon of this study ends in 2050. Turbines that will be decommissioned after 2050 therefore fall outside the scope of this study.

- In this study, the following assumptions were made for the **support structure:**
  - Only monopile foundations are taken into account.
  - We will not vary the different seabed types and assume a water depth of 20m. As a result, the turbine size determines the mass of the support structure.
  - The monopile has a mass of 800-2000 tonnes per turbine. The transition piece has a mass of 300-500 tonnes per turbine.
- In this study, the following assumptions were made for the **tower:**
  - The hub height is considered as an indicator of the tower mass. Turbine capacities from 2 to 15 MW have an estimated height (h) from 80 m to 150 m. It is assumed this increases linearly.
- In this study, the following assumptions were made for the **nacelle:**
  - Hub and bed plate: 9.4 tonnes/MW will be assumed for the hub. The bed plate is estimated at 4.7 t/MW. Since more integrated, complex designs of wind turbines are expected, only cast-iron base plates will be used to enable more complex geometry in the future.
  - The weight of the shaft is estimated at 3.13 t/MW.
  - The Viebahn et al (2015)[14] study was used for the generator technology roadmap: A linear increase of up to 40% market penetration by direct-drive permanent magnet generators (DDPMGG) and an increase from 40% to 60% for geared medium speed permanent magnet generators (MSPMG) between 2020 and 2050. This assumes that the geared asynchronous generators (AG) will be phased out between now and 2050. Due to the small market share of high-speed permanent magnet generators (HSPMG), this technology is not included in the analysis.
  - The mass of the gearbox is estimated at 10.59 t/MW and is used for AG and MSPMG drive trains according to the drive scenario.
  - The mass of the generators varies with different generator concepts.
- In this study, the following assumptions were made for the **rotor:**
  - The mass of the rotor component system increases linearly with the turbine capacity.
  - For the total blade weight, 12.5 t/MW is assumed with a glass fibre content of 54.4% and a carbon fibre content of 6%[15]. The fibre density of the composite is therefore 60.4%.
  - The mass of the hub (11.5 t/MW), Nose cone (0.65 t/MW) and the pitch mechanism (2.98 t/MW) complete the rotor.
- In this study, the following assumptions were made for the **subsea array cables:**
  - 1000 metres of inter array cable are laid per wind turbine.
  - Connection pieces, J-tubes, sleeves and other cable-related components are not taken into account.

The 'bill of materials' (see Table 4) describes the composition per component. Thereby we focus on the largest material flows. This table also shows how the translation has been made from dimensions of different generations of wind turbines to material quantities.

14 Viebahn, P., Soukup, O., Samadi, S., Teubler, J., Wiesen, K., Ritthoff, M. (2015). Assessing the need for critical minerals to shift the German energy system towards a high proportion of renewables. Renew. Sustain. Energy Rev 49, 655-671.

15 Source: Thesis Bas Roelofs, TNO

Table 4 Bill of materials of OWF

Assembly	Components	Mass intensity [t/MW]	Base material(s)
Rotor	3 blades	12.5	Composite
	Hub	11.522	Spheroidal graphite cast iron
	Nose cone	0.649	Steel/aluminium structure + GFRP cover
	Pitch mechanism	2.979	Alloy steel gears/bearings + cast iron casing + copper windings
Nacelle	Overall Weight	45.04	Highly mixed
	Yaw mechanism	4.93	Alloy steel gears/bearings + cast iron casing + copper windings
	Transformer	4.85	Iron, Copper, Aluminium
	Bed plate	5	Steel/cast iron
	Cover	2.424	GFRP + structure
	Shaft DD	1.05	Alloy steel
	Shaft geared	3.13	Alloy steel
	Gearbox	10.6	
	Generator (AG)	massAG = 0.3•P2+3.65•P	Iron, copper, (magnet)
		massIron = 0.29•P2+3.19•P	
		massCopper = 0.1834P	
	Generator (MSPMG)	massMSPMG,Iron = 0.2675•P2+2.9175•P	
		massMSPMG,copper = -0.00823•P2+0.356225P	
		massMSPMG,magnet = 0.0895•P2+0.06275P	
	Generator (DDPMG)	massDDPMG = 1.2114•P2+13.324P	
		massDDPMG,iron = 1.0682•P2+11.655P	
		massDDPMG,copper = -0.0329•P2+1.4249P	
		massDDPMG,magnet = 0.0358•P2+0.269P	
Tower	Tower	massTower = 0.048h2–2.0235h+28.068	Steel
Support Structure	Transition piece	Average/turbine	S355 steel
	Foundation	Average/turbine	S355 steel
Cables	Array Cables/ Turbine	36.2 km/tonnes. Required at least 8D	Copper, steal, lead, HDPE

This bill of materials shows that 77% of the weight per MW of a 10MW turbine consists of steel components, mainly the monopile, transition piece and tower. Composite components, mainly the turbine blades, represent 6% of the weight. The rest of the weight can be traced back to components with a more complex composition. At the aggregate level, the following section will discuss the total amount of material becoming available.

2.2 Offshore wind farms and associated material flow to be removed

The wind turbine systems will need to be dismantled and removed after their operational life of 20-25 years or 25-30 years. The development of the installed power will largely determine the amount of wind turbines to be removed per year, as can be seen in Figure 3 and Figure 4. In the southern North Sea, the amount of annual capacity to be removed will increase from 20 MW to a maximum of 3700 MW between 2020 and 2050.

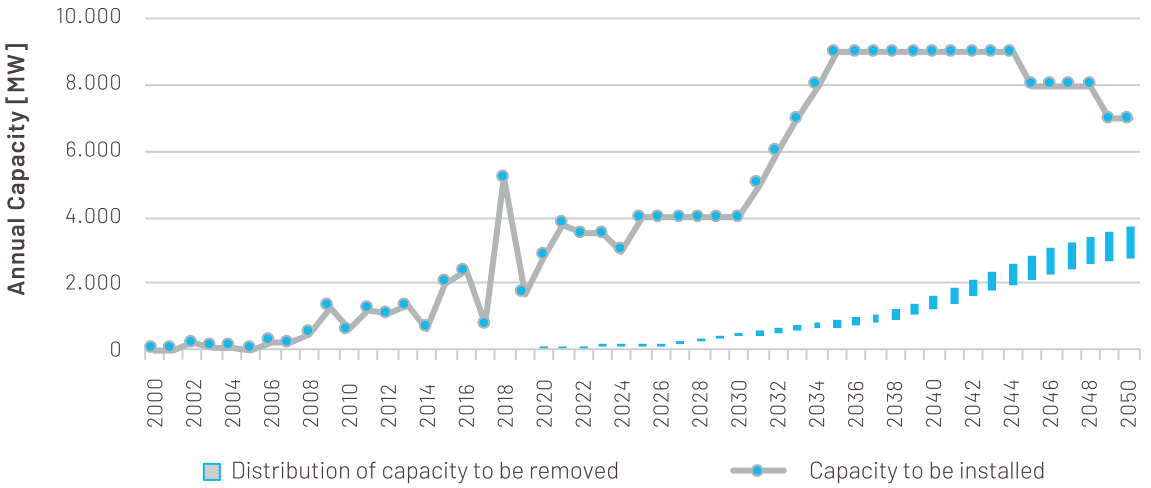


Figure 3 Projection of annual offshore wind capacity to be installed and removed [MW] (distribution is based on lifetime variation from 20-25 years to 25-30 years)

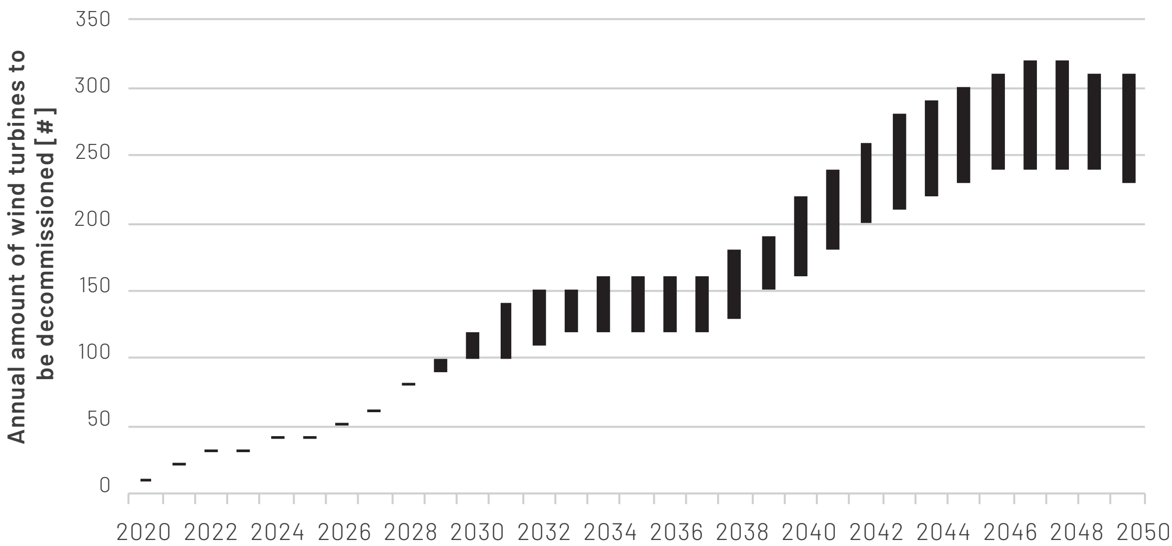


Figure 4 Projecten of annual amount of wind turbines to be decommissioned [#] (distribution is based on lifetime variation from 20-25 years to 25-30 years)

The total material flow is determined based on the annual installed capacity, operational life and the system and material compositions. The material flows with the largest size are shown in Figures 5 to 9.

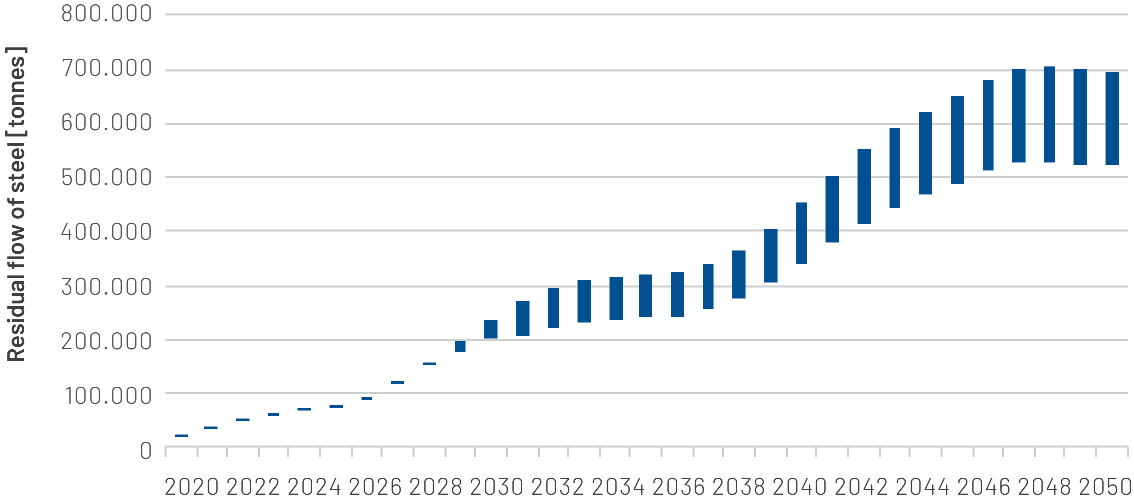


Figure 5 Residual flow of steel [tonnes] resulting from OWF decommissioning in the Southern North Sea (operational life of 20-25 and 25-30 years)

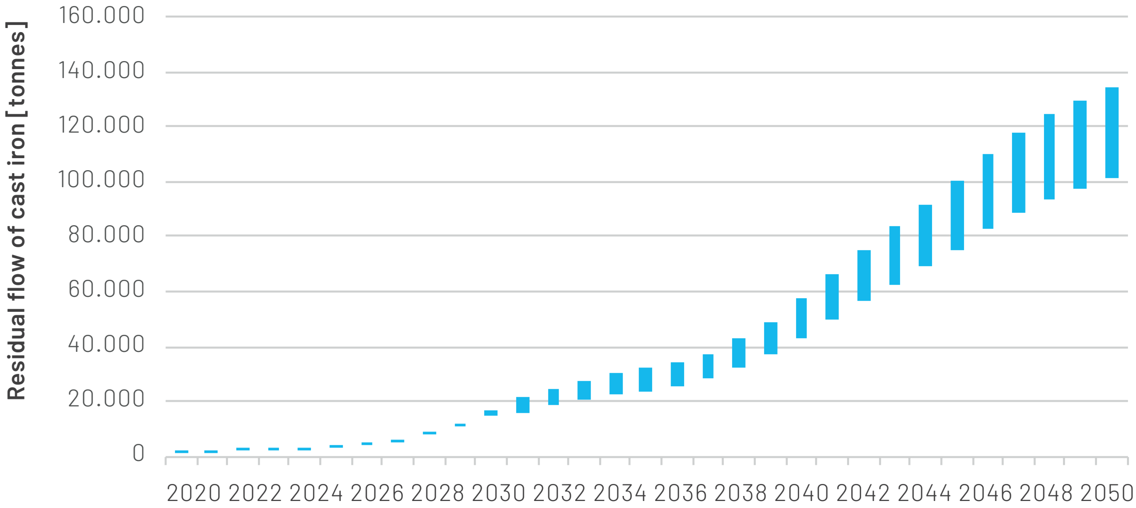


Figure 6 Residual flow of cast iron [tonnes] resulting from OWF decommissioning in the Southern North Sea (operational life of 20-25 and 25-30 years)

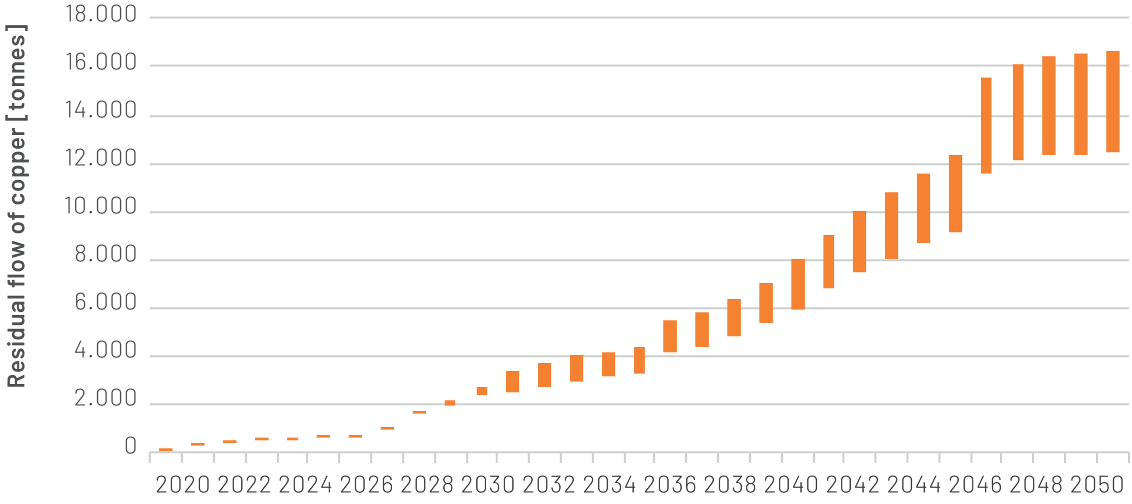


Figure 7 Residual flow of copper [tonnes] resulting from OWF decommissioning in the Southern North Sea (operational life of 20-25 and 25-30 years)

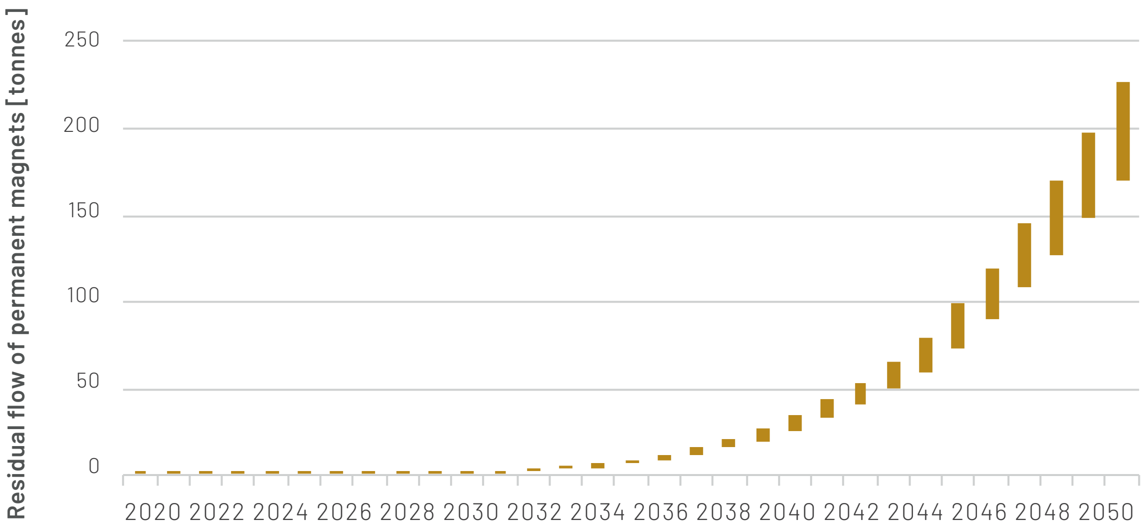


Figure 8 Residual flow of neodymium alloy permanent magnets [tonnes] (NdFeB) resulting from decommissioning in the Southern North Sea (operational life of 20-25 and 25-30 years)

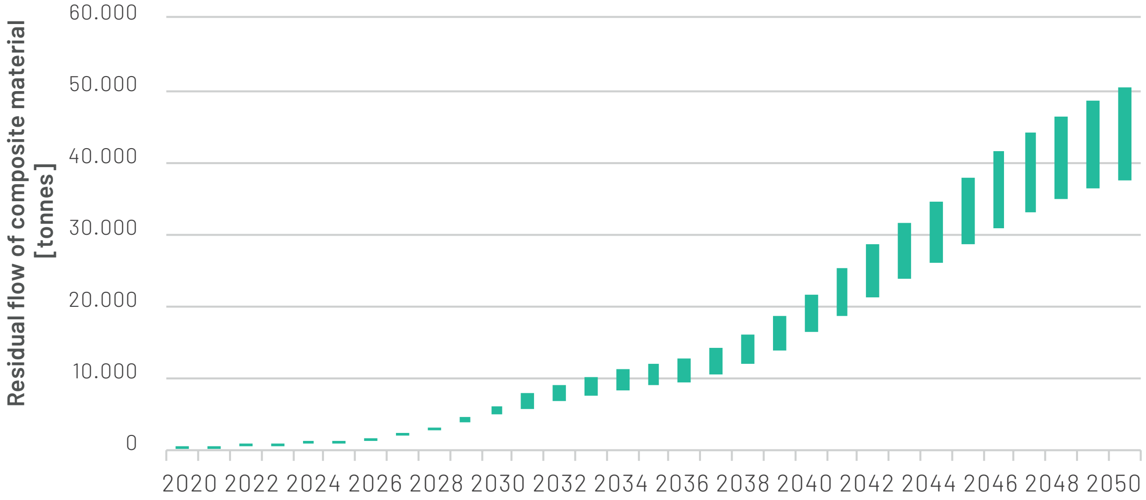


Figure 9 Residual flow of composite material [tonnes] resulting from OWF decommissioning in the Southern North Sea (operational life of 20-25 and 25-30 years)

An estimate of the possibly associated economic activities is made in Chapter 3 based on these analyses.

-03-

Regulations and decommissioning of offshore wind farms

3.1 Agreements in Dutch and foreign tender procedures

The degree of reflection and investment in decommissioning OWF (in the absence of direct urgency from the market) is largely determined by the way in which decommissioning is regulated during the tender procedure. The possible difference in regulations between countries around the southern North Sea plays an important role in the ambition of the Netherlands to play a role in the dismantling of OWF in that entire area.
The report 'Market Analysis DecomTools'[16] provides an overview of current policies in the Netherlands, Belgium, Germany, the United Kingdom and Denmark. A brief overview is given below.

In Belgium, no specific regulations have been adopted and reference is made to the considerable uncertainties still surrounding decommissioning. A bank guarantee for decommissioning must be issued before the permit can be used and an obligation to leave the site in its original state, to be determined at a later date, has been included in the tender rules.
In Denmark, the construction permit includes an obligation for the wind farm owner to take responsibility for decommissioning and restoring the soil to its original state. An integrated plan for decommissioning must be submitted at least 2 years before final decommissioning. Denmark requires a bank guarantee that must be issued no later than 12 years after commissioning.
This amounts (for an entire wind farm) to at least EUR 80 million (of which at least EUR 14 million must be issued by a financial institution).
There is a strong focus in Germany on meeting asset targets and regulations for decommissioning and the end-of-life phase have not yet been defined.

The United Kingdom is the only country to have prepared a full decommissioning programme[17]. Before permits are issued, a plan must be available in which the developer indicates how the installation will be dismantled and how the costs will be covered.

16 DecomTools report sponsored under Interreg North Sea Region - Project Number: 20180305091606, main author Mirko Kruse (Hamburg Institute of International Economics)

17 www.assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/80786/orei_guide.pdf

Similar regulations are in force in the Netherlands. These regulations are laid down in the Water Act and the so-called Wind Farm Site Decision. Again, the permit (currently issued for 30 years) states that during decommissioning, all installed materials must be disposed of (although this may be deviated from by the Minister). A bank guarantee of EUR 120,000/MW, managed by the RVO, must be presented when the permit is issued. It is unclear what the estimate issued by the Ministry of Infrastructure and Water Management is based on[18]. At least 12 years after the start of operation, this amount shall be reassessed by the Ministry. This amount is indexed annually by 2% and a decommissioning plan only needs to be submitted shortly before final decommissioning (maximum 8 weeks).

3.2 Waste disposal guidelines

In the Netherlands, the treatment of all waste is laid down in the National Waste Prevention Plan LAP3. Where LAP3 prescribes 'recycling' as the minimum standard for metals, the situation with regard to fibre-reinforced composite is more complicated. The LAP3 establishes that the minimum waste treatment method is 'recovery, including main use for fuel'. Specifically, for thermoset plastics (including composites), LAP3 states 'If the cost of processing thermoset plastics is so high that the cost of disposal by the producer/consumer would exceed EUR 205/tonne, the minimum standard is "primary use as a fuel (as a form of recovery)" within facilities where emission controls are regulated in specific regulations and/or permits based thereon'.

In Germany, it is possible to use fibre-reinforced composites in the so-called cement kiln route. Partly as a result thereof, landfill has been banned in Germany and the cement kiln route has been made compulsory.

18 Removal of energy installations (Part I): offshore installations, M.J.J. van Beuge, https://www.houthoff.com/media/Houthoff/Publications/mvanbeuge/De_verwijdering_van_energie-installaties__Deel_I___offshore_installaties__NTE_2016_5_PDF

-04-

The value chain and cost-benefit distribution

4.1 Activities and stakeholders

Organising activities related to decommissioning requires the presence of a complete value chain. Understanding the roles and functions of actors in that value chain provides insight into the relationships that connect the actors in the network and thus also into the preconditions necessary for the development of business activities. Insight into the value chain is also necessary in order to assess the impact of (for instance technological) changes in the position of different players. Based on the activity analysis, actor-specific costs, benefits and requirements can be determined and follow-up steps towards an ecosystem for decommissioning and end-of-life activities in South Holland can be set out (NB: an overview of regional chain partners can be found in Table 11, on page 51).

The following assumptions were made during the elaboration and analysis of the decommissioning and end-of-life activities:

- This study focuses on the complete removal of OWF. Activities focused on lifetime extension through component replacement and site repowering (i.e. the complete removal and reinstallation of the WTG system) require a site-specific approach and are not taken into account.
- The distance between the wind farm and the harbour varies per wind farm from 20 to 500 km.
- Decommissioning activities will take place throughout the year. An average weather delay of 30% has been assumed (10% summer, 70% winter).
- The vessels[19] used for the installation of the wind farm will be able to carry out the decommissioning activities. However, the market for installation vessels is constantly evolving in line with changing market requirements. It is assumed that original installation vessels will not be dismantled, or that new vessels of similar capacity can be used at equal cost.

The decommissioning and end-of-life activities are the last two phases of the total offshore wind value chain (see Figure 10).

19 Roelofs, B (2020) Material recovery from Dutch Wind Energy, TU Delft. Leiden University, TNO

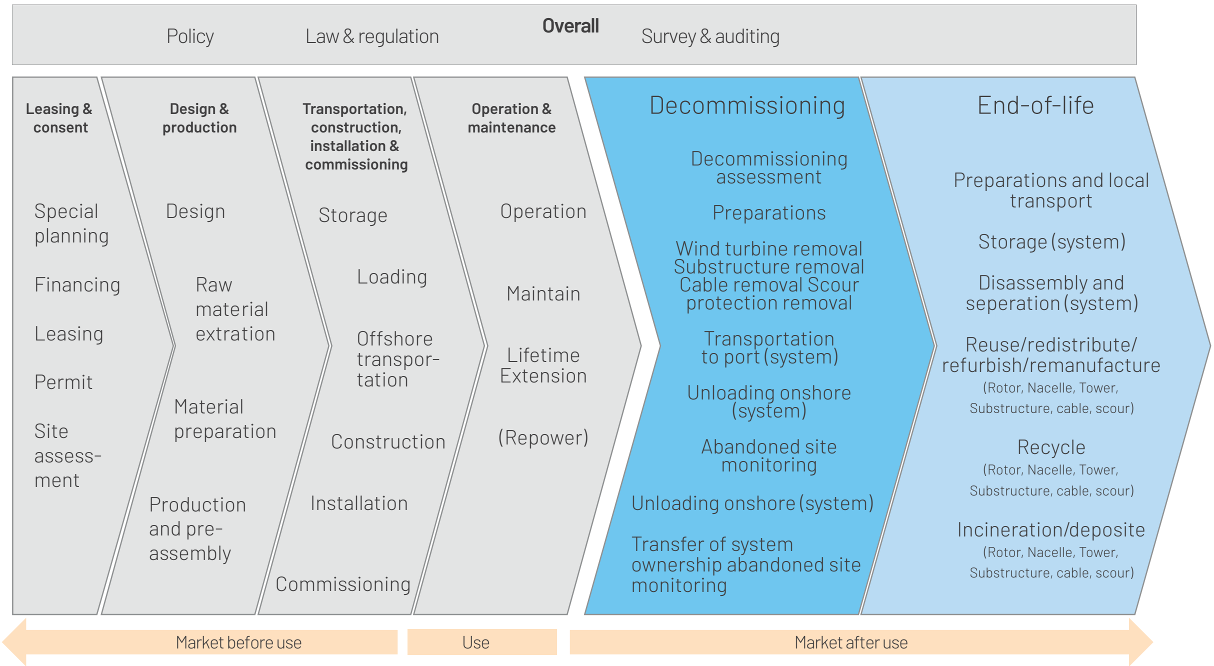


Figure 10 Offshore wind value chain with activities per phase.

Six activities will be implemented in phases during the decommissioning phase[20]:

Decommissioning assessment (D1):
Parties involved: wind farm owner, decommissioning service provider.

- End-of-life strategies of wind farms require long-term planning in which time uncertainty plays a major role: the moment at which the wind farm is actually decommissioned may vary greatly in the distant future for a variety of reasons. The wind farm owner will need to draw up an end-of-life strategy.
- A decommissioning assessment will be required prior to the removal of the systems. This assessment should include: budget and timetable, waste management, activities in the receiving port and onshore, reference to relevant laws and regulations, the decommissioning process and methods, public relations management, identification of hazardous materials, risk identification and mitigation. In addition, an environmental impact assessment (EIA), applications for permits and demonstrable compliance with regulations and the elaboration of the tendering process are valuable preparations.

Preparations (D2):
Parties involved: wind farm owner, decommissioning service provider, logistics coordinator, maritime contractor, port authority.

- Various preparations will need to be made before the removal operations can be carried out:
  - Vessel-specific preparations: a Wind Turbine Installation Vessel, heavy lift vessel and cable-laying vessel or vessels with similar capacities will carry out the removal. The vessels used for the installation of the wind farm will also be able to dismantle the wind farms. There is, however, a risk that - at the time of dismantling - the original installation vessels themselves may have been dismantled because the market for installation vessels has evolved on the basis of demand for other desired installation activities. Vessels will also need to comply with emission, noise and hazardous

20 Chapter 22 ODIN-WIND: An Overview of the Decommissioning Process for Offshore Wind Turbines Johan Finsteen Gjødvad and Morten Dallov Ibsen: https://link.springer.com/content/pdf/10.1007%2F978-3-319-39095-6.pdf

substances guidelines of the receiving port.
- Preparations in the port: the port from which the decommissioning activities will take place will need to meet specific requirements. These requirements will depend on the systems to be received and the vessels to be deployed. Examples of necessary preconditions in ports include: fairway width and depth, clearance height, acceptable ship length in the port, quay capacity (tonnes per m2), mobile cranes present on the quay, seabed quality (in the case of self-handling jack-up barges) and (temporary) storage space in the port.
- Preparations within the wind farm: disconnecting electronic equipment, disconnecting and hoisting subsystems, etc.

Removal and transport of WTG (D3):
Parties involved: decommissioning service provider, logistics coordinator, maritime contractor.
- The removal of the wind turbine system (rotor, nacelle and tower) can be approached as a reverse installation process. Preconditions are: availability of a complete and correctly documented installation process. After removal, the subsystems are transported to the receiving port.

Removal and transport of support structure (D4):
Parties involved: wind farm owner, decommissioning service provider, logistics coordinator, maritime contractor, port authority.
- The removal of (part of) the support system (transition piece, foundation) can be approached as a reverse installation process. The same preconditions apply: the availability of a complete and correctly documented installation process. Various technological developments are underway to make the process more efficient (see Chapter 5).
- After removal, the subsystems are transported to the receiving port.

Removal and transport of inter-array cables (D5):
Parties involved: decommissioning service provider, logistics coordinator, maritime contractor.
- The removal of the inter-array cables can be approached as a reverse installation process. Preconditions: the availability of a complete and correctly documented installation process. After removal, the subsystems are transported to the receiving port.

Onshore unloading (D6):
Parties involved: decommissioning service provider, logistics coordinator, maritime contractor, port authority.

Transfer of ownership of systems (D7):
Parties involved: wind farm owner, recycling specialist, material-specific recycling specialist, consumers of reusable/recycled materials.
- The transfer of the further processing of the dismantled systems and materials will be the last activity in the decommissioning phase.
- The decommissioning phase is followed by the end-of-life phase[21], which consists of various processing methods and preparations. The activities are explained below.

21 Chapter 22 ODIN-WIND: An Overview of the Decommissioning Process for Offshore Wind Turbines Johan Finsteen Gjødvad and Morten Dallov Ibsen: https://link.springer.com/content/pdf/10.1007%2F978-3-319-39095-6.pdf

Preparation and land transport (EOL1):
Parties involved: logistics service provider, waste processing company.

- The transport from the port to the location where the next end-of-life activity will take place, including possibly required (mechanical) reduction of large system parts.

Storage (EOL2):
Parties involved: material-specific recycling specialist, recycling specialist, waste processing company.

- 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 (EOL3):
Party involved: waste processing company.

- Depending on the subsequent activity (EOL4 A-C), 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 (EOL4A):
Party involved: recycling specialist and end user.

- Reuse (reuse, redistribute, refurbish of re-manufacture) can take place in the original function or in another type of function.
- There are roughly two options for the reuse of systems with the aim of once again fulfilling a function as an offshore wind farm component: reuse in collaboration with the original manufacturer or reuse via an independent market participant.
- The reuse of systems to perform a different type of function means that the systems become part of other supply chains. Depending on the final function, it may concern high-quality or low-quality reuse.

Recycling of materials (EOL.4B):
Parties involved: material-specific recycling specialist, waste processing company.

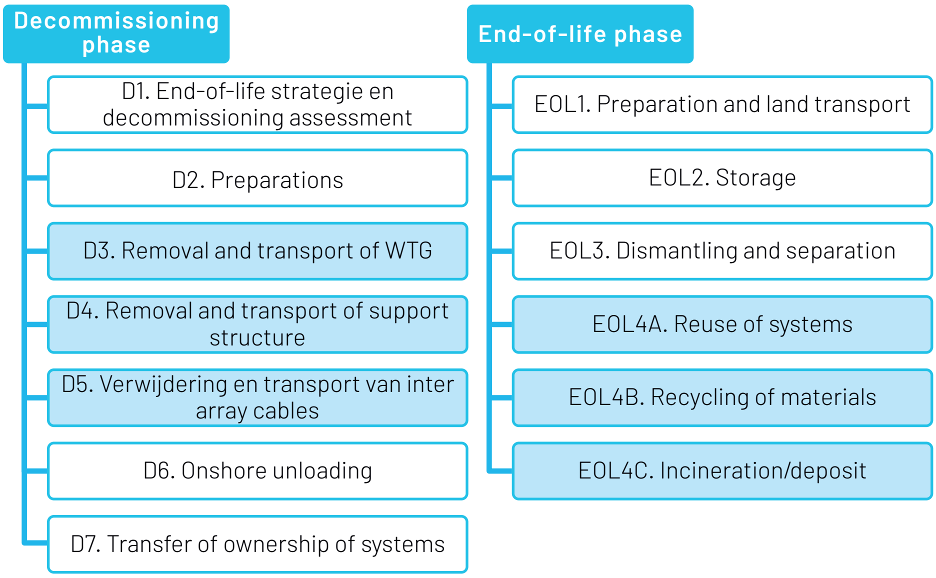
- Recycling through existing chains: The waste treatment process for components with high percentages of metal will be able to be processed into recycled metal using current chains. The residual value of this recycled material will to a large extent be determined by the market price for recycled metals and the quality of the recycled metals in relation to new material.
- Recycling through new chains: if there is no waste treatment chain to recycle specific components and materials, new chains may emerge if the business case for the service to be provided is positive and the underlying business model is sound.

Incineration, deposit (EOL.4C):
Parties involved: waste processing company, waste heat consumer.

- Partial waste incineration to generate energy and deliver it to customers is an option for materials that cannot be recycled. Incineration of plastics may lead to gas emissions that are harmful to the environment and health and/or significant slag formation, which would need to be disposed of in landfills. Depositing waste is an option in specific situations. Laws and regulations concerning incineration and landfill differ per (European) country.

4.2 Economic activity

Based on the system and material flows (Chapter 2) and the activities described in the previous section, an initial exploration can be made of the (basis for) economic activities that may arise within the decommissioning phase and end-of-life phase. The following activities shown in blue are described in more detail in the following sections.



4.2.1 Removal and transport of WTG, support structure and inter-array cables (D3-5)

The removal task can be seen as a logistical optimisation problem with various variables. Examples of variables are: the location of the wind farm, distance from the port, required vessel types and equipment depending on turbine type, weather patterns, overland transport facilities and onshore waste treatment facilities. The uncertainty regarding these variables, the interdependencies and offshore wind sector developments between 2020 and 2050 mean that only a rough estimate of potential economic activity from a Dutch port can be made.

This is based on the assumption that the removal and processing task is carried out from the South Holland region, given the previously chosen scope. Based on the expected decommissioning of wind turbine systems per year and the assumptions described in Table 5, it can be estimated that the three removal activities together could lead to an annual economic activity as shown in Figure 11, and the total activity as shown in Figure 12.

Table 5 Effort assumptions for decommissioning of OWF

Parameter	Assumption
Distance between wind farms and port	20 to 500 kilometres
Vessel A Lifting and carrying capacity 2-10 MW turbines	5,000 tonnes
Vessel A daily rate	EUR 200,000 per day
Vessel B Lifting and carrying capacity 15 MW turbines	10,000 tonnes
Vessel B daily rate (upper limit)	EUR 400,000 per day
Operational hours on-site per WTG, support structure and array cable	17, 26 and 14 hours
Percentage of weather-related delay	30%
Crew size of vessel	75
Crew rate	EUR 140/hour

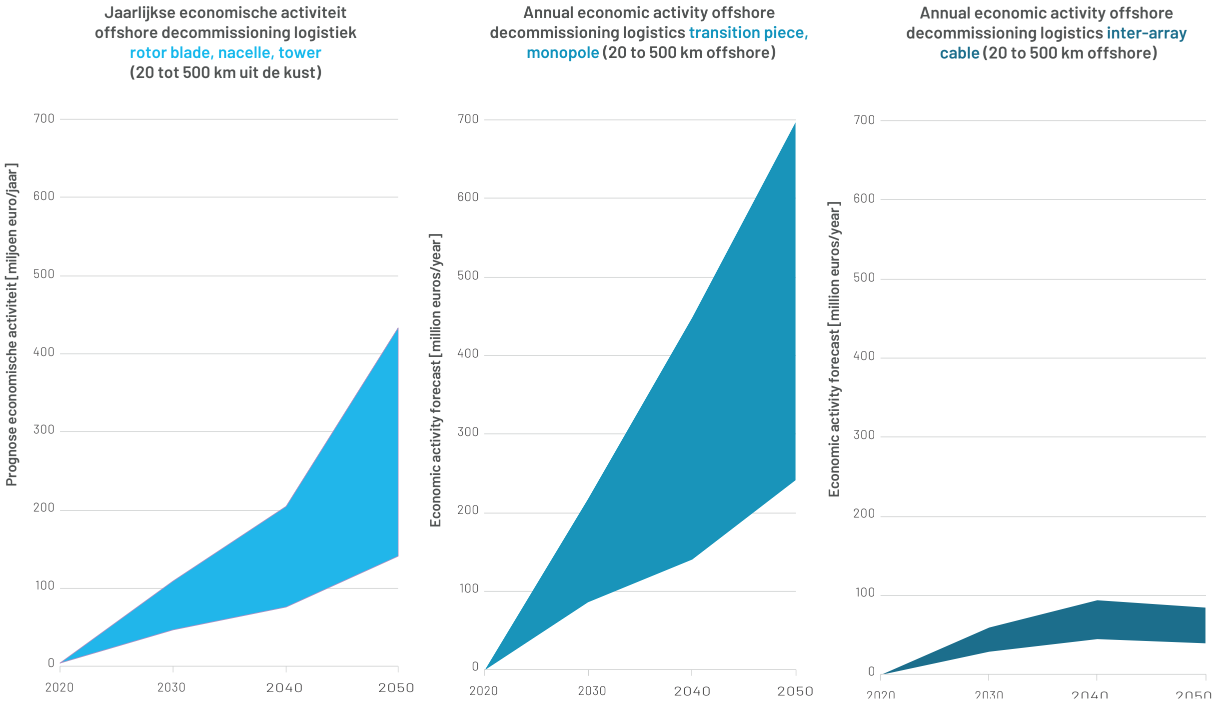


Figure 11 Decommissioning costs of OWF (with estimated lifespan of 20-25 years)

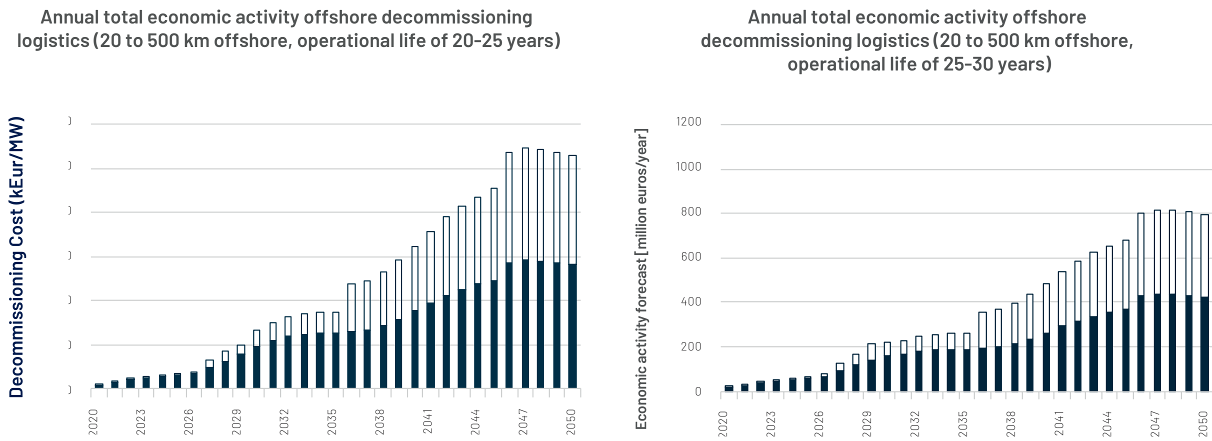


Figure 12 Total logistic costs of decommissioning for a lifespan of 20-25 years (left) and 25-30 years (right)

If the decommissioning assessment (D1) accounts for 10% of the total costs, preparation (D2) for 5% and onshore unloading (D6) for a further 10%[22], the cost allocation for the decommissioning phase is as shown in Figure 13.

22 Estimates based on interviews with parties involved in the offshore chain.

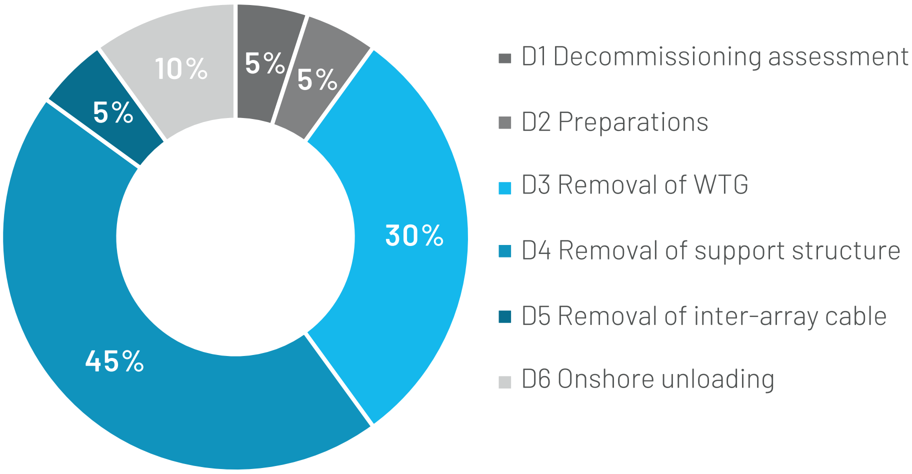


Figure 13 Distribution of costs of decommissioning activities

Based on the assumptions, it is also possible to estimate the extent to which the removal costs depend on turbine capacity (which varies between 2 and 15 MW) (see Figure 14). The removal of one 2MW turbine may cost EUR 1.6M, while the removal of a 15MW turbine may cost EUR 3M. This leads to the estimate that decommissioning costs may amount to 8-20% of the CAPEX costs the total cost of ownership if the CAPEX of an offshore wind farm are EUR 1.5-2M per MW. An important question for further development and innovation will be to what extent these costs can be reduced in order to minimise the investment risk of offshore wind farms. The developments outlined in Chapter 5 can be seen in that light.

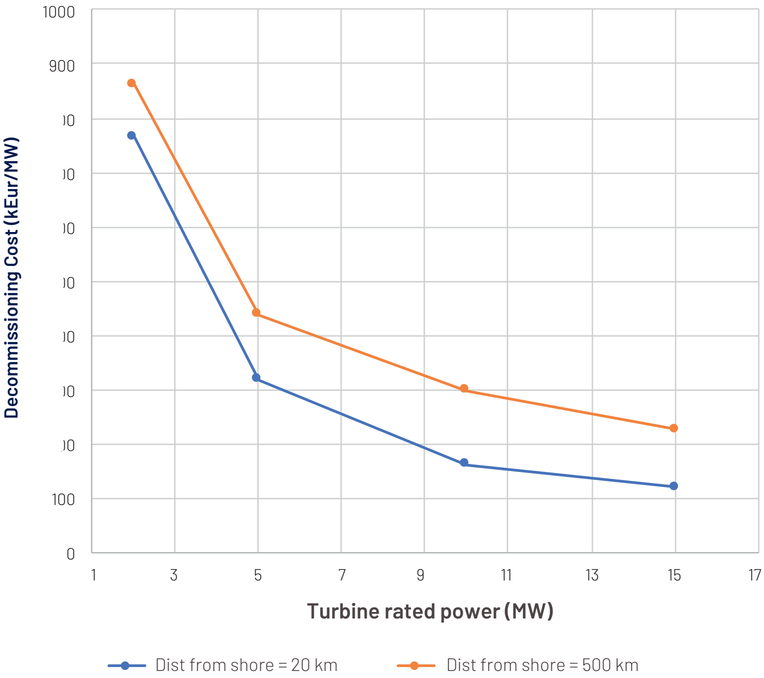


Figure 14 Decommissioning cost per MW as a function of turbine power (blue: OWF at 20 km; orange: OWF at 500 km)

Previous studies provide estimates of 300-500 kEU/MW for 3-4 MW turbines (DNV-GL[23]) and 40 kEU/MW (CCC[24]). The bank guarantee currently required by the RVO[25] for wind farm removal amounts to 120 kEU/MW. Based on the assumptions and results of this study, it appears that this amount is not sufficient to pay for the removal at sea, especially for the smaller turbines. Incidentally, the costs and benefits of processing the residual materials are not included.

4.2.2 Reuse of systems (EOL4A)

High-quality reuse of components ('Circular Wind Farms') could also lead to high-quality activities (Bakker et al., 2018; Balkenende et al., 2017).
Currently, there is no independent market for the reuse of subsystems and components in their primary function as part of an off-shore wind farm. There are two reasons for this:

- There is a lack of opportunities to exchange components between turbine types and different manufacturers. Standardisation could enable this. However, the focus of the sector is on optimising technical and economic performance and the resulting scaling-up of the turbines.
- Location-specific forces to which the offshore wind farms are subjected lead to location-specific design choices. The assessment and acceptance of possible safety risks during operations including forces will be necessary to be able to reuse complete turbine systems. This additional risk is undesirable from an investor and operational safety perspective of the wind farm owner.

For the time being, OEMs focus on the design and production of new products and the reuse of materials is limited to the spare part market. Specifically for wind turbine blades, various studies have been conducted into profitable and functional applications for the fibre-reinforced (thermoset) composite[26], [27]. These explore whether the composite can fulfil a new function such as:

- bank protection;
- sound barrier;
- bridge or pedestrian bridge;
- roof elements;
- playgrounds.

4.2.3 Recycling of materials (EOL4B) and Deposit/incineration of composites (EOL4C)

Economic activity based on the recycling of residual material streams can be generated by (1) performing the recycling process and (2) the transaction of the recycled materials from a recycling batch to a customer. The operational cost per tonne for the recycling process varies according to the type of material, composition and manufacturing method of the decommissioned system and the quality in which the recycled materials are subsequently purchased by a market participant. The recycling process costs per type of material have not been taken into account in this study.

Residual material flows can roughly be divided into two groups: a group of residual flows that can be structurally linked to a positive market value, and a flow where structural support is needed to achieve high-quality and environmentally responsible processing (in other words: processors charge a gate fee for environmentally responsible and permitted processing). That in itself does not make much difference to any activity that may arise as a result. The difference lies mainly in the nature or origin of the necessary finances. For the first group, turnover will depend on the prevailing market value of the residual

23 DNV-GL (2015) Logistics and Cost Reduction of Decommissioning Offshore Wind Farms
24 Climate Change Capital (2010) Offshore Renewable Energy Installation Decommissioning Study [withdrawn report]
25 www.rvo.nl/onderwerpen/duurzaam-ondernemen/duurzame-energie-opwekken/woz/windenergiegebied-hollandse-kust-noord-kavel-v
26 Ten Busschen, A (2020 Industrial re-use of composites Reinforced plastics vol 64
27 www.researchgate.net/project/Re-Use-and-Recycling-of-Decommissioned-Composite-Material-Wind-Turbine-Blades

product. For the second group, it is important what requirements are imposed on processing by the regulatory authority (e.g. the maximum costs that may be charged for high-quality processing).

Table 6 shows the assumed residual values for some metals. Based on these market values and the annual residual material flows (with an assumed 5% material loss during the recycling process), the table shows the economic value of reselling recycled materials. The uncertainty of the material market value in the future translates into an uncertainty in the target residual values. Figure 15 to Figure 17 show the expected residual values of steel, cast iron and copper.

Table 6 (Assumed) market value for scrap metals

Recycled materials	Scrap market value (min - max) [EUR/tonne]
Steel	100 - 300
Cast iron	50 - 150
Copper	500 - 6000
Neodymium[28]	40000 - 80000

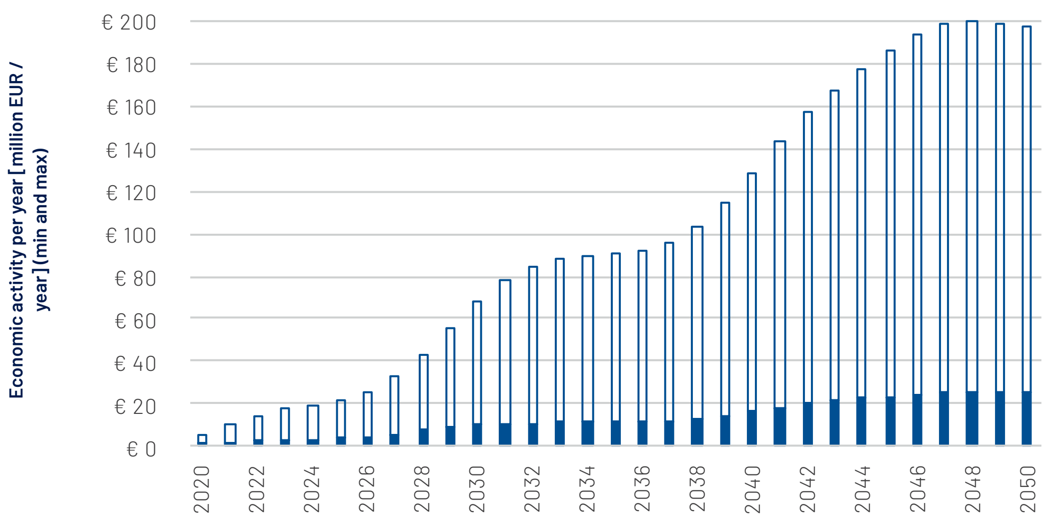


Figure 15 Potential value of recycled steel

28 There is no scrap value for rare earth metals such as neodymium. We have taken the value of 'virgin' material, under the assumption that high-quality reuse can only take place when reprocessing to virgin quality.

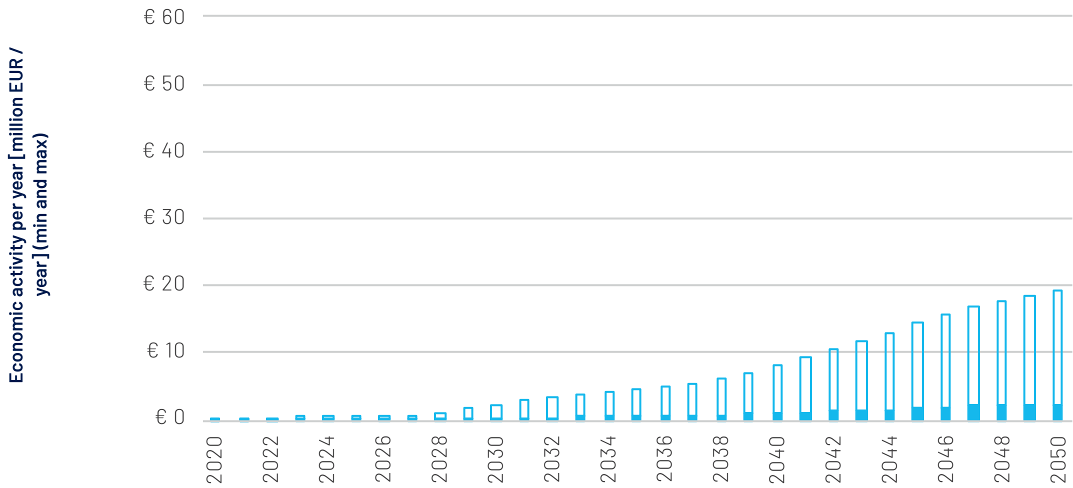


Figure 16 Potential value of cast iron recycled from OWF

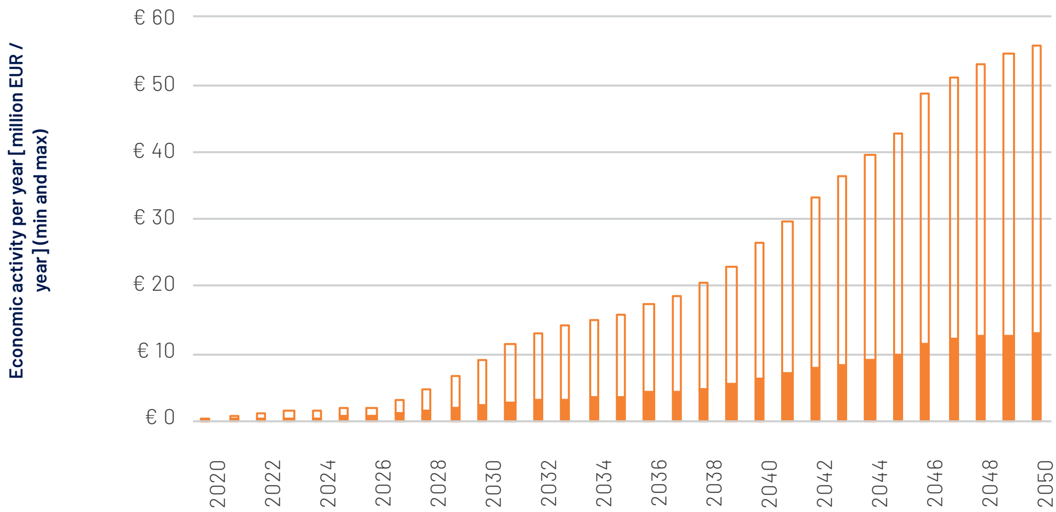


Figure 17 Potential value of copper recycled from OWF

As explained by Topham[29], the moment at which scrap material is offered to the market has a major impact on the residual value that the waste stream will represent.

4.2.4 In-depth elaboration: wind turbine 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. Despite a great deal of research into the mechanical and chemical processing of these materials (which also originate from boat hulls and silos, among other things), there is currently hardly any high-quality use of the structures or components.

The difficulties in processing the blades can be attributed to various factors. Rotor blade material is a complex structure made of different parts and materials which, depending on the manufacturer and the year of production, will have different material properties.

29 Topham et al (2019) Challenges of decommissioning offshore wind farms: Overview of the European experience

At the end of the operational life, blades will be in different states, depending on their design and the reason for decommissioning. Direct reuse is therefore only possible for applications for which the strength of the structure is not relevant, or where the material properties can be sufficiently validated for use.

Currently (in the absence of alternative processing routes) we can only estimate the 'market value' in economic activity based on the gate fees of permitted processing methods for GFRPs. In the Netherlands, the incineration of blades is allowed if the transfer costs to the waste processing party exceed EUR 205/tonne[30]. In Germany, depositing is prohibited and the cement kiln route is followed thanks to the presence of a cement production site, with a minimum gate fee of EUR 150/tonne for the turbine owner. The costs and preconditions for using this cement kiln route from the Netherlands have not been investigated in more detail.

The cost assumptions for the different steps are provided in Table 7. It is assumed that cutting and transport are required for any follow-up activity. Depositing, incineration and cement kiln processing are different end stations for the composite material. The possible annual turnovers given in Figure 18 follow from the previously estimated volumes of composite.

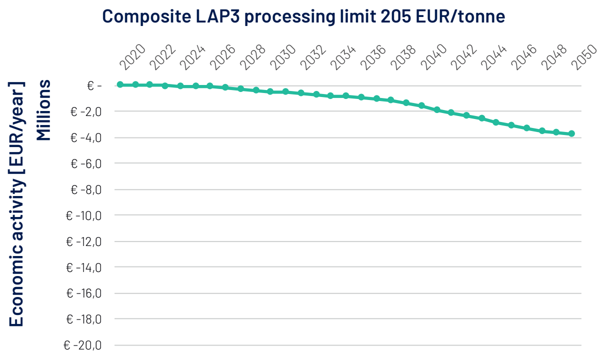
Table 7 Cost assumptions for steps in the GFRP processing process

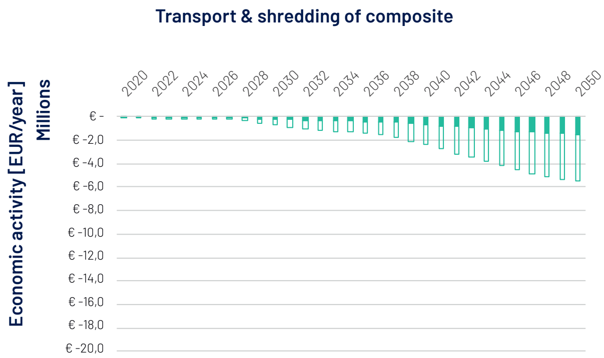
Activity	Minimum [EUR/tonne]	Maximum [EUR/tonne]
Cutting (80x80 cm) and Transport	20	50
Shredding	55	55
Depositing	120	120
Incineration	100	200
Cement kiln processing[31]	200	300

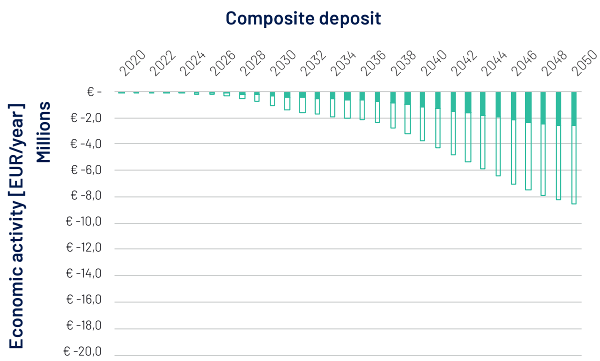
Two categories of recycling processes are being developed for the processing of the blades into qualitatively acceptable materials: chemical (e.g. via thermal pyrolysis) and mechanical (use of shredded material).
The available literature shows that the quality of glass fibres in current chemical recycling 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.

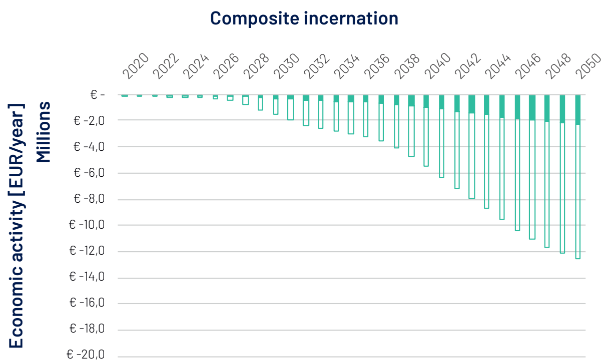
Mechanical processing is investigated by Windesheim and others. Windesheim shows that it is possible to process (up to) 70% EoL GFRP in sheet and board material that can serve as shoreline protection. Pilot projects have been carried out by the Zuiderzeeland Water Board and show that the water board is prepared to pay an additional price compared to azobe hardwood, the usual material for this application, based on the assumed longer lifespan and thus lower total cost-of-ownership (TCO). Production of this application will then need to compete with the current price for hardwood sheeting of around EUR 55/m2 (or EUR 1375/m3). Here, too, scaling up is required in order to achieve industrial production, while, on the other hand, the scale of long-term market demand will need to be examined critically.

30 https://lap3.nl/publish/pages/120604/lap3_sp11_kunststof_rubber_19_07_2019.pdf
31 Currently, processors charge 450 EUR/t for the integral cement kiln route (reduction, shredding, transport, gate fee) (information from interview with Albert ten Busschen, 30 June 2020).









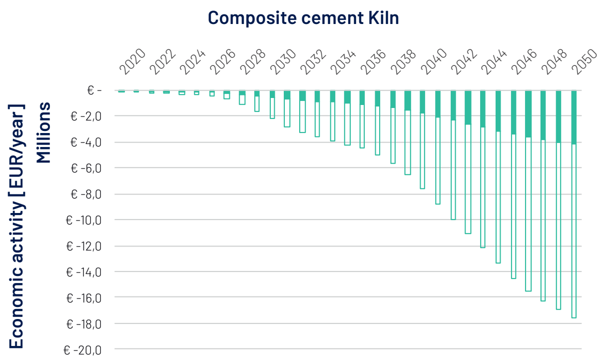


Figure 18 Turnover for four different processing steps of composite and the LAP3 limit value for GFRP processing.

The development of a market will not only depend on the technological progress of (mechanical and chemical) recycling processes, and on the scale leading to efficiency, but certainly also on regulations in this field (also see Chapter 3). Current regulations set a limit of EUR 205/tonne for processing routes before incineration or deposit may be considered. Changing this limit or (as is the case with hazardous substances) a total ban on such processing methods could give a further boost to the development of large or larger-scale processing routes. Currently, developments in the determination of the business case must take account of a gate fee of EUR 205/tonne to be charged to the disposer.

Extended Product Responsibility (EPR) has not yet been introduced in the wind sector. EPR can, on the one hand, lead to more sustainable design and production choices and, on the other hand, provide sufficient (financial) resources and incentives for cost-reducing innovations for responsible waste management. Given the scale and international nature of the problem of blade recycling, a level playing field is required between EU countries and cooperation with other sectors where composite waste streams arise is needed. Although high-quality processing of EoL composites is a challenge, it is undoubtedly a challenge that the entire chain must tackle together with the government. The creation of this waste stream is a consequence of socially desirable developments: the transition to an energy system based on renewable energy sources.

4.2.5 In-depth elaboration: reuse of permanent magnets

This study assumes - in part based on the Viebahn study
- a steady penetration of direct-drive generators, requiring the use of permanent magnets based on NdFeB. Although several studies point to the (mainly geopolitically caused) low security of supply of in particular neodymium (Nd; as one of the rare earth metals) and the growth expectation of the deployment of Nd that exceeds the growth expectation of the mining capacity, there are hardly any activities that are aimed at high-quality reuse or recycling of these materials and components. This can be attributed to various factors:

- China has a quasi-monopoly position not only in the extraction of raw materials, but also in numerous downstream infrastructures. As a result, there is then no processing capacity in Europe for the possible recycling of rare raw materials and a trade relationship will need to be established with producers of magnetic materials.
- The recycling of magnets themselves has so far not produced a process with a high TRL. The absence of an increase in the market price (after the huge peak in 2011, the price first fell and then remained constant) does not provide an incentive for faster technological development.
- The processing and/or transport of materials with a high magnetic permanence will not be without risks, which will contribute to the total processing costs.
- The absence of standardisation in the development of wind turbines leads to a difficult-to-predict flow of components and an uncertain reuse of these components.
- An example of recent research developments with regard to end-to-end recycling is a subsidised project by Mkango Resources Ltd, which investigates how recycled materials can be incorporated into new permanent magnets for electric cars.

Against this background, it is clear that it is currently impossible to assess the possible economic activities that could arise in relation to the high-quality processing of the technical heart of wind turbines. At the same time, this is also an indication that the processing of permanent magnets requires attention in research and development projects, in addition to the attention paid to processing turbine blades as responsibly as possible from an environmental and cost point of view. In particular, parties on the production side of wind turbines should play an important role in this respect.

4.3 Distribution of costs and benefits

The potential economic activity described in the previous section will in all cases lead to the transfer of physical products or services between the parties. This necessary cooperation in the chain inevitably leads to costs for one party and benefit for the other. The value network and relationships are illustrated in Figure 19.

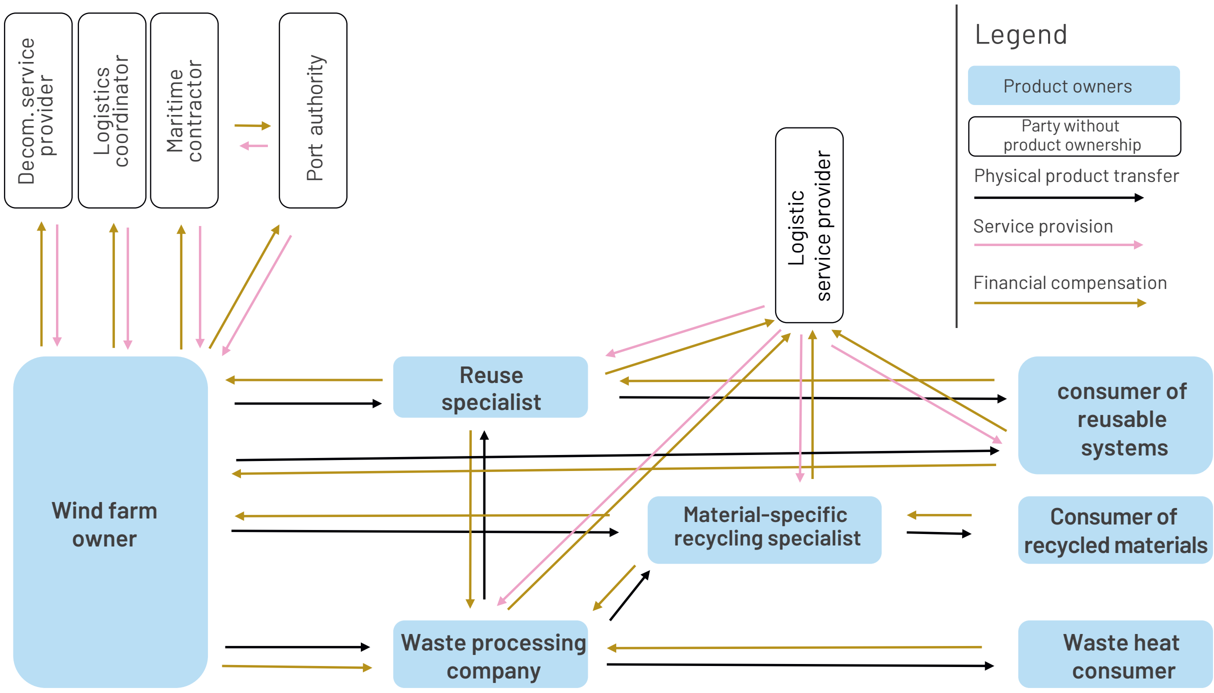


Figure 19 Value network regarding the decommissioning of OWF

Table 8 and Table 9 show which costs and benefits can be expected per party and per activity. The dark red and dark green areas correspond to the economic activities as shown in the previous section. 'Red' means: the indicated chain party pays for the activity in question; 'green' means: the chain party acquires income from the activity in question. A financially sound business model will require a positive balance per party between the party-specific costs and benefits across all the party's activities (including, for instance, operating income that is not specified here). Incidentally, costs and benefits relevant to a party may lie outside the decommissioning and end-of-life phase.

The extent to which economic activities increase or decrease as a result of the introduction, change or elimination of chain activities depends on the place this activity occupies within the current activities in the chain. A reduction in process costs will lead to a reduction in the operational costs of the party implementing the process. Based on traditional market forces, a reduction in costs for the party purchasing services is also to be expected. In conclusion, a reduction in process costs will therefore lead to a net reduction in economic activity in the chain as a whole.

Table 8 Distribution of costs and benefits within the value chain in the decommissioning phase

Decommissioning and end-of-life phase activities / Party involved	Wind farm owner	Decom service provider	Logistics coordinator	Maritime contractor	Port authority
D1. End-of-life strategy and decommissioning assessment	Service procurement	Sale of services			
D2. Preparations	Service procurement	Sale of services	Sale of services	Sale of services	Sale of services
D3. Removal and transport of WTG	Service procurement	Sale of services	Sale of services	Sale of services	
D4. Removal and transport of substructure	Service procurement	Sale of services	Sale of services	Sale of services	
D5. Removal and transport of array cables	Service procurement	Sale of services	Sale of services	Sale of services	
D6. Onshore unloading	Service procurement	Sale of services	Sale of services	Sale of services	Rental of space

Table 9 Distribution of costs and benefits within the value chain in the end-of-life phase

Decommissioning and end-of-life phase activities / Party involved	Wind farm owner	Logistics service provider	Port authority	Waste processing company	Reuse specialist	Material-specific recycling specialist	Consumers of reusable/ recycled materials/ waste heat
D7. transfer of ownership of systems	System sales				System procurement	System procurement	System procurement
EOL1. Preparation and land transport		Sale of services		Service procurement	Service procurement	Service procurement	Service procurement
EOL2. Storage			Rental of space	Storage costs	Storage costs	Storage costs	
EOL3. Dismantling and separation				Process			
				Sale of services	Service procurement	Service procurement	
EOL4A. Reuse of systems					Process		
					System sales		System procurement
EOL4B. Recycling of materials						Process	
						Sale of materials	Materials procurement
EOL4C. Incineration/ deposit	Service procurement			Sale of services			
				Process			
				Sale of heat			Purchase of heat

dark red/dark green: costs and benefits taken into account in this study

light red/light green: costs and benefits outside the scope of this study

-05-

Impact of developments in offshore wind farm technology

There are various developments underway in the offshore wind sector that may have an impact on the implementation and costs of decommissioning and end-of-life activities. Table 10 summarises the developments that are expected (1) to occur before 2035 and (2) to have a large-scale impact on wind farms in the southern North Sea. This overview was created based on of discussions with experts who provided their assessment of the expected impact and likelihood of large-scale implementation. These are therefore the most promising technologies.
We also give examples of market players that have so far been involved in the development of the aforementioned technologies, and identify opportunities that these technologies offer for a possible business case.
Section 5.1 details the developments and their impact per lifecycle phase. In addition, we will provide a perspective of the implementation of the developments in the current offshore wind sector (5.2). We will return to the role that these developments could play in any future developments in Rotterdam and South Holland in Section 6.3.

5.1 Developments affecting decommissioning and end-of-life

Eight developments have been identified that have a direct impact on the decommissioning and end-of-life phase. Table 10 shows the developments and their impact. Each of the developments identified is then discussed in more detail.
The European TRL scale and estimates of the experts involved were used to estimate the current status and the development required for upscaling. The TRL scale ranges from 1, research of the basic principles or idea, to 9, demonstration of the system in a commercial and marketable operating environment.

Increased structural reuse of composite

In the case of structural reuse, parts of the blade are directly reused for another function. In order to scale up, the processing process, cutting pattern and follow-up applications need to be further developed. This is particularly difficult due to the variety of sizes, shapes and material compositions of different blades. If the reuse complies with safety guidelines for the new function and is economically competitive, a positive impact in the end-of-life phase can be expected thanks to higher-quality reuse. The impact during the decommissioning phase can be negative (e.g. cutting activity in an offshore environment) and positive (e.g. easier transport of smaller components). The owner or purchaser of the blades then in fact becomes a supplier of sheet metal and beams, which can be used in many other applications. Direct structural reuse can provide high-quality elements for a relatively low investment; the processing process is less intensive than mechanical and/or chemical recycling.

Table 10 Overview of developments in OWF decommissioning

Impact scale:
Simplified
No influence
More difficult
Unclear

Development	Policy	Leasing & consent	Design & production	Transportation, installa-tion, commissioning	Operation & maintenance	Decommissioning	End-of-life
Market-driven structural reuse of GRP composite	Unclear	No influence	Unclear	No influence	No influence	Simplified	Simplified
	Unclear	No influence	Unclear	No influence	No influence	More difficult	Unclear
Mechanical recycling process	No influence	No influence	Unclear	No influence	No influence	Unclear	Simplified
Chemical recycling process	No influence	No influence	Unclear	No influence	No influence	No influence	Simplified
Direct-drive permanent magnet generator upscaling	No influence	No influence	Unclear	No influence	Simplified	No influence	More difficult
Monopile foundation extraction technology: hydrau-lic removal	No influence	No influence	More difficult	Unclear	Unclear	Simplified	No influence
Monopile foundation extraction technology: vibration removal	No influence	No influence	No influence	No influence	No influence	Simplified	No influence
Design for decommissioning	No influence	No influence	More difficult	Unclear	Unclear	Simplified	Simplified
Decommissioning strategies and policies	Simplified	Unclear	Unclear	Unclear	Unclear	Simplified	Unclear

Structural reuse is estimated at TRL level 4-5. The approach has been described and experimented with several times. Until now, mainly large parts have been reused, so it has been limited to occasional applications. Scaling up requires developments in the processing process and in market applications. The principle of structural reuse has been researched by several consortia, including within the RAAK-MKB project consortium, Ecobulk, GenVind and Re-Wind. Parties involved include Windesheim, TU Delft, Siemens-Gamesa and SuperUse studios.

Mechanical recycling process of composite materials

The operational sound scaling up of mechanical recycling (shredding) will require a balance between supply, processing capacity and market demand for recycled materials. With an increasing supply and demand of blades, the recycling capacity and market application will (have to) grow along with it, leading to a positive impact of more activity in the end-of-life phase and the related maturing of developers of products related to recycled blade material. Possible additional design and production wishes may arise, which may be seen as additional requirements during the design and production phase.

Mechanical recycling has a TRL 8-9 level, it is already being used to process composite material from various sources. However, the system is not yet balanced, especially with the increasing amount of material that will need to be processed. This will increase the need for more and high-quality applications for the recycled material, possible related to the different types and qualities of recycled composite. The varying, and often partly unknown, material composition of fragments after shredding poses a clear challenge. In the Netherlands, companies such as Virol and Demacq International focus on the development of this recycling technique.

Chemical recycling process of composite materials

The implementation of cost-effective chemical recycling technology on an industrial scale may enable the processing of composites into reusable fibres and/or resin in the end-of-life phase. The product characteristics of the recycled material will determine its entry as an economically competitive alternative for various applications. Current chemical recycling processes reduce the quality of the fibres in terms of fibre length, orientation, strength, stiffness and surface quality. Developments that produce material of higher quality and value can contribute to a positive business case.

TRL levels 3-4 are reported for chemical recycling. The highest TRL levels were achieved in plants with production residues as feedstock. Another option is to focus on integration with the existing industry and infrastructure, particularly in order to enable the direct reuse of the released hydrocarbons.

Thermal recycling, pyrolysis, is at TRL 4-8 and carbon fibre is already commercially exploited by ELG Carbon Fiber (UK) and CFC recycling (DE). However, greater loss of quality and low production costs of new material make commercial exploitation of fibreglass difficult. This could possibly be achieved by further development and improvement of the chemical or thermal recycling processes and the development of recyclable materials, especially resins. This offers the prospect of better quality, more valuable recyclate. If suitable applications, i.e. a market, are found for these materials, the value can increase, resulting in a positive business case.

Increasing use of permanent magnets in generators

The pursuit of techno-economic performance optimisation leads to an increase in direct-drive configurations with permanent magnets. Among other things, direct-drive simplifies maintenance. The (long-term) availability of the raw materials for these magnets is uncertain. An ecosystem for the recycling and reuse of the magnets is not in sight and during the end-of-life phase, permanent magnets can cause safety problems due to the very strong magnetic fields. Insights from the end-of-life phase can have an impact on future design choices.
The direct drive permanent magnet generator has a TRL 9. This technology is already being used in various types of wind turbines, e.g. by Siemens-Gamesa, Enercon, Lagerwey, EWT and GE. For large-scale use, GE is currently testing a 12MW turbine in the port of Rotterdam. Its reuse requires the system of collecting and processing permanent magnets to be further developed.

Hydraulic removal of the entire monopile foundation

Steel monopiles are easy to recycle, taking the alloys into account. Since complete removal from the seabed is a time-consuming activity with large forces in play, they are, in the limited situations that have occurred so far, often cut off, leaving part of the monopile behind.
If regulations require the foundations to be completely removed, new technologies will be required. The HyPE-ST project is developing a hydraulic removal method for this purpose. After disassembling the turbine, the monopile is sealed and pressurised with water. This releases the entire monopile from the seabed. The cover and the filling opening could be installed on-site; however, in view of the high costs involved in offshore work, it is more appealing to include this in the design and production process.

Hydraulic removal has been demonstrated in lab experiments (TRL 4) and in a related full-scale project. The challenge lies in also applying this process to monopiles that have been installed for a long time, due to subsidence of the seabed. HyPE-ST was a GROW project with Deltares, TNO, DOT, IHC, RWE, Sif and Jan de Nul as partners.

Complete removal of the monopile foundation by vibration

For complete removal of the monopile during the decommissioning phase, it is also being studied whether the friction between the monopile and the seabed can be overcome with different vibrations. This technology does not appear to require any modifications to the design or installation equipment. PVE-Holland has used this technology for the first time during a project. During the removal of wind farm Lely (NL) it was demonstrated that four monopiles of the 0.5MW turbines could be removed in 3 hours.

This technology is estimated to have a TRL level of 5. The lab tests were performed with scaled models in a sandy soil. Further research is being performed into different types of soil, such as clay, and scaling up to large-diameter monopiles. Gentle driving of piles (GDP) is being investigated in the GROW consortium of Boskalis, Deltares, DOT, Eneco, IHC, RWE, Seaway, Shell, Sif, TNO, TU Delft, Van Oord and Cape Holland.

The proposed vibration and hydraulic techniques enable faster, easier and complete removal of monopiles. Cost savings and perhaps the benefit of the larger quantity of steel contribute to a better business case.

Design for decommissioning

Despite the growing awareness of sustainability and decommissioning issues, little or no attention is paid to these in the design process.
This is in part due to split incentives and the long time frames over which these problems arise. There is a gap of at least 20 years between design and decommissioning. This creates a wait-and-see attitude.

Design for decommissioning is therefore still at an exploratory stage. The concept is well known and has been researched on a small scale. No specific technological developments are required; therefore, no TRL level applies. Its implementation requires further research into the design space. Specifically for the wind turbine blade, this means the design of the outer contour of the blade, possible adjustments for decommissioning activities and separation of materials during end-of-life processing.

Decommissioning and end-of-life strategies and policies

Interviews with those directly involved in the chain show that many parties still consider the 'hard issues' relating to decommissioning as something that does not involve them. Concrete plans only need to be submitted shortly before the actual decommissioning, no fund is set up for decommissioning and the costs are estimated to be relatively low anyway compared to the operating income during operations. In order to stimulate the development and implementation of new technology, effective policy and/or laws and regulations are needed. This can be achieved by setting up funds from which decommission activities can be developed and financed, setting up an EPR, narrowing the boundaries from when incineration or depositing composites is possible, or adapting the design and other requirements submitted to tendering parties.

Policy on decommissioning and end-of-life cannot be expressed in TRL terms either. Although regulations for wind farm decommissioning are not yet clear, it can be noted that similar regulations are already in force in other sectors, including the offshore oil and gas sector. It is to be expected that this will also be introduced for wind turbines or specific components or materials. Players are industry associations NWEA and WindEurope as well as European innovation platform ETIPWind.
Regulations can play a role in realising and driving a sustainable, circular system of offshore wind farms.

5.2 Implementation of developments within the current OWF chain

At present, there are no requirements at the design and production phases that would simplify the decommissioning and end-of-life phase. Without regulation and mandatory tender requirements, adjustments in this area will generally lead to so-called 'split incentives' in which different players in the value chain are affected by the costs and benefits of adjustments. Only by including the requirements in tender packages will they lead to different choices in material composition, connections and product configurations. The aim of the change in design and/or production choices should be to simplify and make decommissioning and/or end-of-life activities more efficient. Additional requirements will most likely lead to additional costs, which will require concrete incentives for the party bearing the costs. There is also talk of the possibility of leaving pieces of the monopiles in the seabed. Any change of policy in this area will have major cost implications. The main driver in this area will be the extent to which the local marine environment is damaged by the removal of monopiles.

By initiating these changes, it would be possible to link drivers and capacities from the waste treatment sector with offshore wind farm owners, component producers and subcontractors. Furthermore, in order to achieve economies of scale and accelerate developments, a level European playing field will have to be guaranteed in order not to encourage a 'race to the bottom'.

The current motives for design optimisation are mainly economic with the aim of reducing the levelised cost of energy. Currently, designs with minimal environmental impact would, in many cases, result in economic sub-optimalisation. Four developments have been identified in the offshore wind sector that could potentially have a positive impact on the decommissioning and/or end-of-life phase after 2050:

1. system designs for an operational life of more than 30 years (with the main 'circular' effect of a lower net material input for wind power generation);
2. the large-scale application of non-virgin material in the production process of offshore wind farm systems;
3. the application of new transport methods for large components;
4. the application of high percentages of carbon fibre in wind turbine blades in line with increasing turbine blade length and load profiles (resulting in a potentially economically viable recycling process due to the intrinsic value of carbon fibres compared to glass fibres).

The current idea-to-market period in the sector of about 10 years will result in sustainability measures in the chain being reflected with substantial delay in physical wind farms and therefore also in the decommissioning phase of those same wind farms. The insights from forthcoming decommissioning and end-of-life experiences could be of great value in shaping effective European and national policies and could also provide valuable input for further developments in the design and production phase.

-06-

Conclusions and call-to-action

European policy documents outline an increase in the offshore wind power generation capacity to 174 GW in the southern North Sea by 2050. In the current offshore wind sector, the production capacity per individual wind turbine is being rapidly scaled up. The scaling up of an average of 3 to 15 MW per turbine until 2030, combined with the variety of wind turbine technology available on the market, results in a wide variety of systems at sea. These systems have a finite operational life of 20-25 years with a possible lifetime extension to 25-30 years. Figure 4 shows the sharp increase in wind turbines that need to be removed between 2020 and 2050 (the spread depends on the exact lifespan).

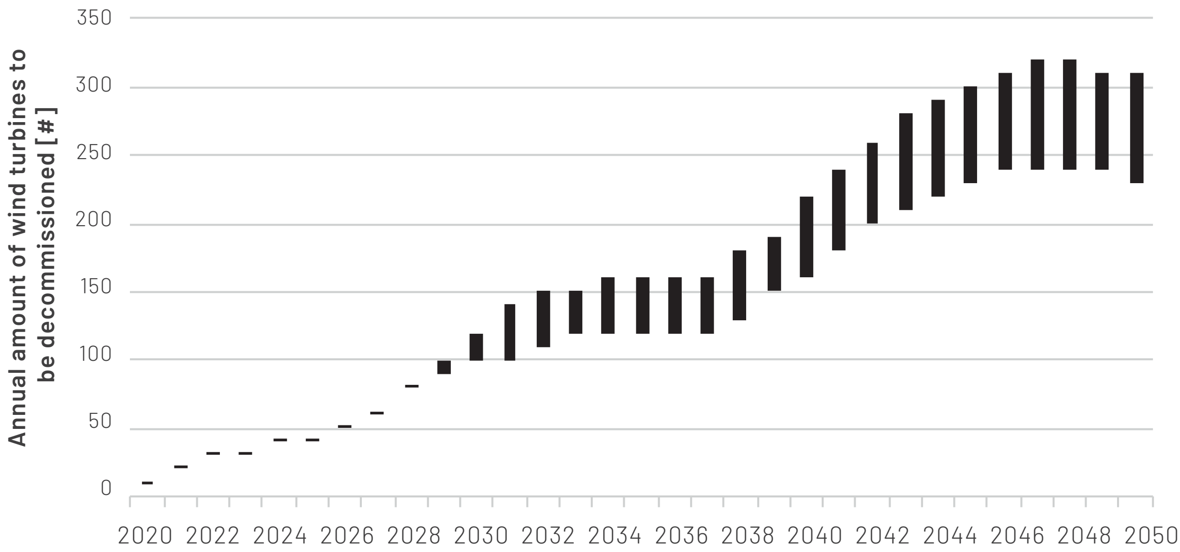


Figure 4 (repeated) Projecten of annual amount of wind turbines to be decommissioned [#] (distribution is based on lifetime variation from 20-25 years to 25-30 years)

Because large-scale offshore wind farm decommissioning and subsequent end-of-life activities are unknown territory, there is uncertainty about the type and scale of activity that could be expected. Based on the insights described in this study, the following situations can be expected in a scenario with no major disruptions in the offshore wind sector:

- Wind farms in the Southern North Sea will inevitably have to be removed. The extent to which the support structure, scour protection and inter-array cables remain on the seabed is unclear. An unclear percentage of the removal and transport activities during the decommissioning phase may take place to/from the port of Rotterdam. A wide range of uncertainties will affect the quantity, quality and timing of systems to be removed, including: offshore weather conditions, equipment required on vessels, absence of specific clarifying laws and regulations and the fact that each wind farm has unique characteristics (e.g. sea depth, turbine type and distance to ports).
- The operational life of the wind turbines largely determines the moment at which removal takes place and the residual material flow starts: the longer the average lifespan, the later the flow starts to scale up.

- When the residual flow arrives in the port, the components of the wind farms will flow in two directions:
  - Materials and components with a positive market value: if the waste stream (as a component or material) has a net positive market value, it will enter an existing reuse or recycling chain.
  - Materials and components with a negative market value: if there is no cost-neutral process to process waste as a waste stream, it creates a process with an unprofitable top margin. Additional removal fees or 'gate fees' are then required to achieve acceptable processing. This will require legislation, for example in LAP3, to prevent socially undesirable processing. The export of materials to other countries with less strict landfill regulations, or the storage of materials so that future generations will need to look for processing solutions, could be considered undesirable. In order to solve this social problem of waste in an ecologically and socially responsible way, appropriate on both national and European level will have to be taken if the market does not achieve acceptable waste disposal on its own. Examples of successful waste stream processing with unprofitable top margins are asbestos remediation and car landfill in the Netherlands.

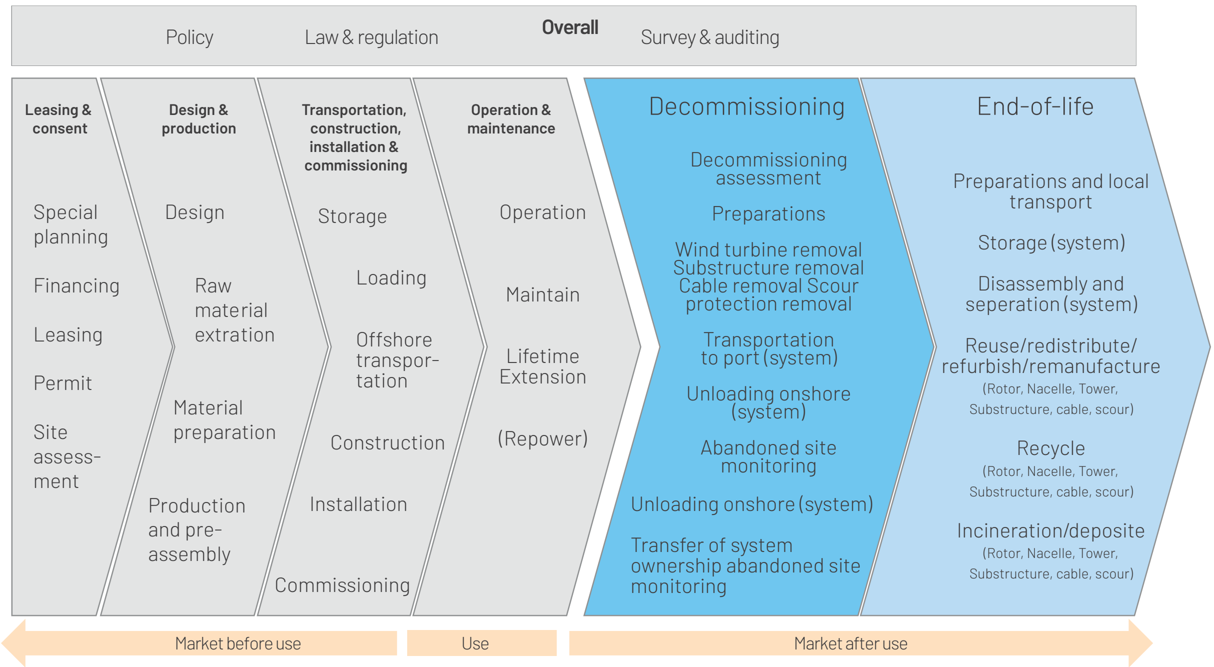


Figure 10 (repeated) summarises the expected activities in the decommissioning and end-of-life phases.

The lack of practical experience results in unclear dependencies, costs and benefits per stakeholder involved in the entire offshore wind value chain and the waste processing sector. Activities in the decommissioning and end-of-life phases are directly dependent on choices and situations made or arising in the previous life-cycle phases.

6.1 Conclusions and dependencies per phase

The following observations and conclusions reflect the dependencies between activities in different offshore wind farm life-cycle phases:

Leasing & consent phase

- Bidding procedures seldom include concrete agreements on the nature of the activities regarding the end-of-life phase. Current regulations are limited and vary from country to country. Owners meet the requirements set by the national and regional government. Desired changes can be introduced through policies, laws and regulations. The competitiveness and level playing field of the offshore wind sector requires legislation at EU level to provide clarity to the offshore wind sector.
- Owners of Dutch wind farms comply with the 'remove everything' regulations, as stated in the current Dutch Water Decree Act. 6.161 and local zoning plans by public authorities. At the same time, developments are taking place aimed at accepting the abandonment of support structure systems, array cables and scour protection on the seabed.
- For Dutch wind farms, a bank guarantee of 120kEUR/MW is issued at the start of the operation; our analysis shows that this does not cover the expected decommissioning and waste processing costs.
- Shifts towards the extension of permits and of the lifespan up to 40 years are in the pipeline and will have an impact on the incentives to actively work on optimising the decommissioning phase.
- Insight into the costs and benefits of end-of-life activities is desirable for lifecycle costs (LCC) and total cost of ownership (TCO). However, in order to address the costs and benefits of decommissioning and end-of-life activities and methods in a timely manner and include them in the financial analyses (e.g. levelised cost of energy and a positive low-risk business case) of offshore wind farms, practical experience with large-scale decommissioning activities is required.

Design and production phase

- The current motives for design optimisation are mainly economic with the aim of reducing the levelised cost of energy. The offshore wind turbine market is driven by the demand of the wind farm owner to achieve a high economic return per surface area at low risk. The existing proven technology is therefore leading in wind farm realisation. At the same time, wind turbines are rapidly being scaled up to convert as much wind energy into electricity as possible.
- Currently, design for minimal ecological impact does not play a significant role due to the dominance of the economic aspect. Legislation is probably needed to break this trend.
- Reuse and recycling applications for offshore turbine components have not (yet) been developed in the current market, as a result of which reuse is not part of the current design requirements. OEMs may adapt to any changing market demand in the future.

Transport and installation phase

- The decommissioning activities can be based on the previously successfully completed installation activities. However, the requirements for the decommissioning phase are different in nature: components can be brought ashore in lower quality for further waste processing. This provides opportunities for the development of decommissioning methods and processes.
- Availability of as-built documentation from the owner during the decommissioning phase will be valuable in the preparation of removal operations. The long period (20+ years) between starting up and removing the wind farm means that receipt and storage of the (correct) documentation during and after construction requires attention.

Operation & maintenance phase

- End-of-life strategies of wind farms require long-term planning under great uncertainties. Because these strategies focus on activities that take place 20 to 30 years after a wind farm has been commissioned, the development of these strategies is rarely on the agenda of the wind farm owners.

- The costs for only the removal operations in the decommissioning phase are estimated in this study to be higher than the bank guarantee of EUR 120k per MW to be reserved for Dutch wind farms (NB: this does not include possible but volatile scrap material revenues). It became clear from our analysis that the costs for each OWF can vary significantly, making it unclear how much financial reserves would need to be included to cover the costs in the decommissioning and end-of-life phase. This topic requires attention in offshore wind tenders and from the wind farm owners.
- The development of proactive end-of-life strategies provides a timely impetus for collecting and analysing information related to the decommissioning activities. Analysis of installation data can contribute to the efficient organisation of decommissioning at minimum risk and cost.
- The lack of experience with large-scale wind farm disposal and waste processing results in a lack of knowledge about expected responsibilities, costs and benefits.

Decommissioning phase

- The current principle is the complete removal of an offshore wind farm after the agreed period of use.
- The cost of removing systems from the seabed will be substantial. Economic-ecological considerations relating to total or partial removal will be necessary for these systems. It concerns the following systems: export and inter-array cables between the wind turbines, the wind turbine foundation and the scour protection that protects foundations. Clear EU-wide policies, regulations and directives are required to ensure a level European playing field in the competitive offshore wind market and to provide clarity to all parties involved.
- The implementation of removal operations may, certainly in the short term, be based on the installation activities of the system concerned. Room for more efficient and cost-efficient handling of these activities is possible, through innovation in both the logistics and waste processing phases.
- The capacity of the port from where the logistics activities will take place will have to be in line with the specialist vessels to be used. Typical preconditions for these vessels include clearance height, sufficient quay capacity (tonnes per m2), mobile cranes present on the quay and (temporary) storage space in the port.
- The necessary storage of volumes of wind farm systems is directly related to the balance and coordination of delivery from sea and purchase by end-of-life activities per unit time. This classic stock-flow situation makes it difficult to provide an exact estimation of storage space that may be required.
- The costs of return logistics are driven by regulations, wind farm location, port location, required vessel types and equipment, and weather patterns and water depth. The preparation of the decommissioning activities can thus be approached as a cost optimisation problem with multiple variables.

End-of-life phase

- Based on the circular economy paradigm, the quest for high quality material use and reuse will require a variety of waste processing activities after removal from sea in order to give the residual flow of systems and materials a high-quality destination.
- There is hardly any reuse of offshore wind farm systems expected after 20+ years years of offshore operation because the design is adapted to site-specific requirements and the remaining useful lifetime of the system is uncertain due to, for example, material fatigue of components. The absence of standardised components in the sector does not help either. In the current market, only the use as a spare part for identical wind turbine types is considered feasible.
- The vast majority of offshore wind turbine systems consist of metals (steel, cast iron and copper) which could be recycled by existing industries. The residual value of these metals is highly dependent on the volatile materials market and the achieved quality of the recycled material compared to virgin material.
- Current (mechanical and chemical) composite recycling technologies are costly and not yet mature enough for market introduction. Developments in recycling processes, scale, market demand and market value relative to alternative and virgin materials as well as regulations are needed to make this possible.

- Current Dutch waste processing rules allow incineration of composite waste if the cost of disposal of the disposer exceeds €205 per tonne of material. This limit currently determines the feasibility of alternative solutions.
- The current functioning of the offshore wind farm value chain shows that there are sufficient opportunities in the South Holland region, driven by logistics activities and (high-quality) waste processing that is hosted in this region.

6.2 What developments can have an impact on market development?

If the following developments in the offshore wind farm sector actually take place, they will affect activities in the decommissioning and/or end-of-life phase:

- The structural reuse of composite material (glass fibre-reinforced polymers) in view of a market demand that is still to be developed.
- The reuse of composite fibres or resins in view of a market demand that is still to be developed, by means of the development of the mechanical, chemical and thermal recycling processes needed for this purpose.
- The scaling up of the use of (direct-drive) permanent magnets based on NdFeB and an end-of-life process to be further developed (aimed at recycling, re-manufacture or reuse).
- The further development of two monopile removal technologies: hydraulic removal and vibration removal.
- Adapting the design of wind turbine systems to the wishes and requirements of the decommissioning and end-of-life phases.
- The tightening of policies, laws and regulations regarding decommissioning and end-of-life activities, and in particular the way in which the decommissioning phase is explicitly taken into account early on in the process of tendering and installation.

The timeline of the above developments and the moment at which they could possibly be implemented are difficult to estimate and are also interdependent. The hydraulic removal of monopiles, for instance, may be more cost-effective than cutting off the foundations underwater. Or developments may accelerate as a result of a change in regulations (e.g. it is prohibited to leave monopiles behind in the seabed, and they will need to be completely removed).

6.3 Lines of action

The development of economic activity related to decommissioning of offshore wind farms in South Holland and the Rotterdam port area will benefit from actions that ensure that:

- the volume of dismantled offshore wind farms served from and transported to the South Holland region is maximised;
- the highest possible efficiency and conservation of value is achieved for the further processing of the system and material flows.

The developments will benefit from synergy with: (a) other activities within the offshore wind chain, in particular with regard to the installation of OWF, and (b) other chains and sectors, such as other suppliers of composite waste materials. This will enable achieving economies of scale that will allow for a competing proposition with respect to other EU ports.

Executing the call-to-action can take place within three themes: Application, R&D and Policy.

1 **Application: Early and large-scale development of an integrated infrastructure for the decommissioning and end-of-life phases in order to minimise the total costs for each individual party involved.**

The party primarily responsible for the successful removal of the offshore wind farms is the wind farm owner. It is unclear what the total costs of this removal and waste disposal will be. This study shows that the kEUR 120 per MW to be set aside through the required bank guarantee will not be sufficient to finance the complete decommissioning activities. This conclusion does not include the full costs and benefits in the end-of-life phase. There is no doubt that it is in the interest of an owner of an offshore wind farm to find an optimal balance between the cost-effective removal and processing of the wind farm after operation, and compliance with applicable laws and regulations.

If the total costs of these operations can be minimised thanks to an effective and scalable organisation of the decommissioning and end-of-life ecosystem, this will benefit both the wind farm owners (lower costs) and other parties and chain parties (attracting activities to the region because of the attractive costs due to large scale).

This decommissioning 'one-stop shop' can aim for minimal interim storage and logistical movements by setting up the operation based on the expected local flows and (buffered) stocks.
Four focus areas should be developed in parallel to achieve cost-effective and (thus) large-scale processing capacities in the South Holland region:

I This is necessary in order to offer scalable processing of turbine blades within the applicable laws and regulations and with mature technologies;

II It is also necessary to offer scalable processing (reuse, remanufacturing, recycling) of permanent magnets within the applicable laws and regulations and with mature technologies;

III The nacelle forms a compact subsystem which contains a very large number (50,000+) of components. The disassembly and separation of these components are expected to be mainly manual work. A safe working environment is a prerequisite for this work.

IV Given the high content of steel in the turbines, the precise volume flow per year will need to be in line with the logistics and steel processing capacities to avoid the need for large local storage of components in impractical or costly locations.

Future activities related to logistics services, storage and reuse and/or recycling activities will be driven by future market demands from linked product chains and sectors outside the offshore wind sector.

2 R&D: stimulating knowledge development, product and process innovations that benefit the efficient removal and processing of decommissioned offshore wind farms

The Dutch business community has a strong international position in numerous activities within the current offshore wind chain and the offshore sector in general. By building on this existing expertise and relationships, existing economic activity can be expanded. From the current business activities, the expertise in particular can be used in the areas of: soil investigation, turbine design, rotor blades, foundations, farms, and installation/maintenance methods, monopile foundation manufacturing and shipbuilding for the construction, installation and maintenance of wind farms. Chapter 5 discusses technological developments that contribute to these issues and thus to a possible future for decommissioning activities.
The increase in the required wind energy flexibility and system integration also raises major R&D issues with regard to the integration of wind farms with other systems, such as hydrogen or storage. Even offshore solar energy within a wind farm is being investigated as part of the Hollandse Kust Noord wind farm.

Various organisations, including WindEurope, Top Sector Energy, NWEA, GROW and TKI Wind at Sea, strive to expand and share knowledge and expertise in the Dutch (offshore) wind sector. The integration of the activities to be developed in the decommissioning and end-of-life phases within these existing knowledge networks will enable us to draw on multidisciplinary knowledge.

3 Policy: (contribute to the) clarification and development of decommissioning and waste management laws and regulations at the regional, national and international level.

Chain parties, including wind farm owners, think and act within the set laws and regulations during the development, operation, removal of wind farms and the eventual residual flow processing after removal. In order to achieve a more sustainable chain on a large scale, the development of consistent policies will determine the efforts of designers and manufacturers of the systems to be supplied. Competition between manufacturers of offshore wind farm systems, the level playing field and the risk-averse investment behaviour of investors in offshore wind farms[32] require rules at EU level. These rules will need to provide the sector with clarity about future decommissioning requirements. Only then will there be developments for the long term (e.g. with regard to the processing of composites).

An active role for South Holland and the Port of Rotterdam Authority in this is desirable in order to bring the opportunities outlined above closer, based on a one-stop shop and the desired scale.

32 PBL (Netherlands Environmental Assessment Agency, 2016). Wind energy technology. A report drawn up in the broader context of the report 'The importance of a home market for the export of eco-innovations. Insights from practice'. The Hague, Netherlands Environmental Assessment Agency.

6.4 The role of the region and the port of Rotterdam: regional interpretation of the lines of action

The analysis in this report does not specifically address the potential attractiveness of the South Holland region or the port area of Rotterdam in terms of decommissioning activities. Indeed, Rotterdam has not had a strong profile as a leading player in the field of wind energy or dismantling drilling rigs in the past. Nevertheless, there are a number of reasons to assume that Rotterdam and the region could play a stronger role in this. These reasons are:

- The presence of relevant players from the chain in the region
- Reorientation of the Port of Rotterdam Authority towards offshore activities
- Characteristics of the port as a logistically developed hub

The presence of relevant players from the chain in the region

As indicated in Section 6.3, an attractive proposition could be created by developing large-scale integrated decommissioning of OWF, which would lead to cost optimisation. These minimum costs are necessary for Rotterdam's port area and the province of South Holland to be competitive with other possible decommissioning hubs.

This cost optimisation requires a coordinated sequence of activities. Successful coordination of the flow and accumulation (stock) of material flows in order to achieve the most efficient processing will require contributions from each party in the previously outlined value chain (Figure 19).

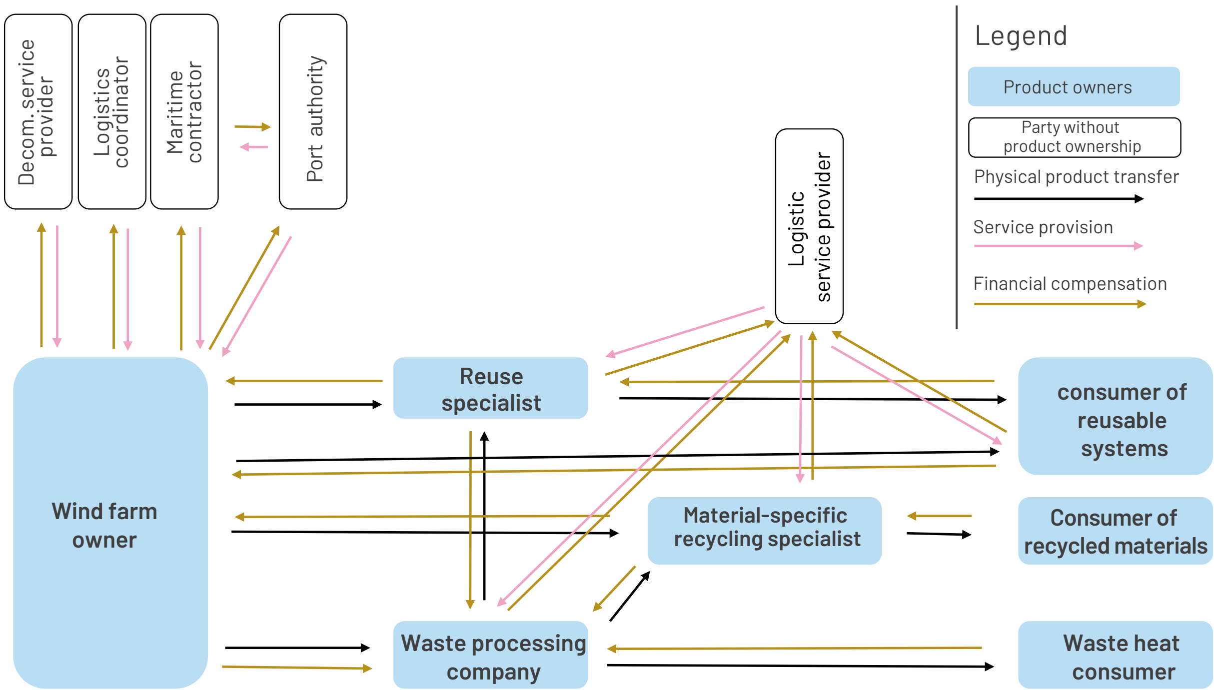


Figure 19 (repeated) Decommissioning and end-of-life phase value network

Many companies are located in the Rotterdam port area and the province of South Holland that could take up a possible place in this network. A summary of examples of such parties can be found in Table 11.

Table 11 Regional examples value network actor type

Asset lifecycle phase	Actor type	Example of regional party
Decommissioning	Wind farm owner	Orsted, Eneco, Shell, Engie, Vattenfall
	Decommissioning service provider	Certion, Business in Wind
	Logistics coordinator	Rhenus logistics, Royal Roos
	Maritime contractor	Subsea7, DEME, Heerema, Van Oord, Boskalis, Jumbo offshore, PVE Holland
	Port authority	Port of Rotterdam
End-of-life	Logistics service provider	Rail Service Center Rotterdam Inland navigation, road transport
	Recycling specialist	Interior builder, composite structure manufacturer
	Reuse customer	Siemens-Gamesa, GE, Enercon, Vestas, Water Boards, provinces, municipalities, office furniture consumers
	Material-specific recycling specialist	TATA Steel, Virol
	Consumer of recycled materials	SIF, Smulders, Goudsmit
	Waste processing company	Renewi, SUEZ, Remondis
	Waste heat consumer	Eneco, heat network operators
Lifecycle overarching	Government, social interest	Municipality of Rotterdam, Province of South Holland, Ministry of Infrastructure & Water Management, RVO
	Laws and regulations	

Combining this network and organising commitment to long-term developments can be an important starting point for the development of the new role at the end of the offshore wind value chain for the region.

Reorientation of the Port of Rotterdam Authority towards offshore activities
The Port of Rotterdam has not had a strong profile as an area for offshore activities in the past. This has changed as witnessed by the following text on the PoR website[33]:

'The port of Rotterdam has the ambition to be the main offshore port in Europe. The Port of Rotterdam Authority is fully committed to this and has no restrictions in realising offshore ambitions. Projects of all sizes can be accommodated in the port of Rotterdam and the possibilities will only increase in the years to come.
What the port of Rotterdam has to offer:

- Sufficient space for offshore development, both on land and in the water
- Innovation facilities
- Collaboration on branding and marketing
- Wide range of repair and maintenance facilities

33 www.portofrotterdam.com/nl/zakendoen/vestigen/vestigingsmogelijkheden/offshore (dated 1 October 2020)

- Sheltered berths with a water depth of up to 26 metres, close to the North Sea
- Large, existing maritime cluster'.

In addition, PoR also offers extensive test and other facilities on Maasvlakte 2 for the development of offshore wind developments[34]. The zoning plan for Maasvlakte 2 has already been adapted for this purpose.
Visible evidence of this ambition is the establishment of the SIF-Group on Maasvlakte 2 (first pile was driven in 2015)[35].
SIF produces and ships monopiles for offshore wind farms with a diameter of up to 11 metres and a height of up to 120 metres. Based on an initial discussion with PoR, it was already concluded that this installation-oriented activity could, over time, also be reversed, because the logistical and spatial questions for installation and decommissioning are similar. This has created the spatial preconditions for the development of a cluster.
It is the aforementioned ambition of the port that is essential if the challenges outlined in this call-to-action are to be met and sustained.

34 www.portofrotterdam.com/nl/zakendoen/vestigen/vestigingsmogelijkheden/offshore/maasvlakte-2-test-en-demolocatie-voor-offshore

35 https://sif-group.com/nl/wind/fundaties

-07-

Acknowledgements

The results of this study were achieved thanks in part to the involvement of the following persons and parties:

Companies involved: Eneco, Ørsted, Certion, Siemens-Gamesa, Heerema, WPT Virol, RVO, Subsea7, Business in Wind, GE-LM windpower, Rhenus logistics

Involved representatives of knowledge-based institutions: Ruud Balkenende, Julie Teuwen, Jeroen Hoving, Maarten Bakker (TU Delft), Bernard Bulder, Harald van der Mijle Meijer (TNO), Albert Ten Busschen (Windesheim)

Colophon
©SmartPort
October 2020

Design: IJzersterk.nu
Photography: Shutterstock

Disclaimer

SmartPort has taken the greatest possible care in compiling this document. Nevertheless, SmartPort accepts no liability for any inaccuracies in the information, nor for any damage, nuisance or inconvenience or other consequences arising from or related to the use of this information.

connecting
knowledge

DO YOU HAVE
ANY QUESTIONS?

SmartPort
info@smartport.nl
tel. 010 402 03 43