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Reference:

Demuytere Celestin, Vanderveken Ines, Thomassen Gwenny, Leon Maria Fernanda Godoy, De Pena Laura Vittoria Luca, Blommaert Chris, Vermeir Jochem, Dewulf Jo.- Prospective material flow analysis of the end-of-life decommissioning : case study of a North Sea offshore wind farm
Resources, conservation and recycling - ISSN 1879-0658 - 200(2024), 107283
Full text (Publisher's DOI): https://doi.org/10.1016/J.RESCONREC.2023.107283
To cite this reference: https://hdl.handle.net/10067/2020440151162165141

Prospective material flow analysis of the end-of-life decommissioning: Case study of a North Sea Offshore Wind Farm

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Abstract

Early offshore wind farms approach their decommissioning phase, yet a lack of precedents, potential legal bottlenecks, inadequate treatments and a lack of applicable circularity indicators, leave the sector unprepared, encompassing a risk of valuable materials loss. This paper presents a first-of-its-kind circularity analysis of the prospective decommissioning scenario of a North Sea wind farm, introducing and applying new circularity indicators. From the site-specific primary data, a bill of materials and material flow analysis was established, differentiating between secondary applications and end-of-life destinations. The main share (80%) of the installed mass originated from scour protection, acting as hotspot to the 84% of materials remaining in situ. The collected fraction recycling rate approaches 90%. However, the substantial discrepancies between components and materials implicate a need for component or material-specific targets to avoid valuable material loss. Introducing such collection or recycling targets could encourage more circular decommissioning practices along the value chain.

Keywords

Offshore wind energy, material flow analysis, end-of-life, recycling indicators, circular economy, waste management

1. Introduction

The European Green Deal and consequent Climate law incorporate an overarching decarbonization strategy and a reduction of raw material import dependency (European Commission, 2021). To reach climate neutrality by 2050, the Climate Law introduces a net reduction in greenhouse gas emissions of at least 55% by 2030. With 76% of total greenhouse gas emissions for the EU due to energy consumption, this sector carries a heavy burden (European Union, 2022). Renewable energy sources are considered an essential part of the decarbonization and sustainable energy transition. The precise share of future renewables is unknown, but a dominance of photovoltaics and wind energy is anticipated (IRENA, 2020). For wind energy, with a push towards larger turbine height and swept areas, offshore wind energy production will be crucial. With a goal of 160 GW installed offshore wind energy, an increase is expected all around Europe (Cecchinato et al., 2021). Currently, the EU including the UK has a cumulative offshore wind capacity of 28.4 GW of which the Belgian share approximates 8%. Since 2020, the Belgian offshore wind capacity of 2261 MW makes up 8.7% of its electricity production capacity (FOD Economie, 2021). The National Energy and Climate Plans aim for an increase in offshore wind to 5.8-8 GW after a call from the Energy Ministry (Directorate-General for Energy, 2019). Compared to 2020, this would translate into a 150 to 250% increase in offshore capacity by 2030.

To estimate the future material requirements for this increase in energy demand, the Joint Research Centre (JRC) considered three energy scenarios (Carrara et al., 2020). The moderate, technical feasible scenario still describes a 700% increase in offshore wind, far exceeding the expected growth for Belgium. The material demand for Europe would expand by a factor of 3.5-5, up to 10 if climate neutrality should be reached by 2050. Even with a lower material footprint per MW and closed-loop recycling of materials, a rise in raw material input is expected (Bobba et al., 2020; Carrara et al., 2020). Therefore, with 10% of the EU's offshore wind capacity approaching its end-of-life phase from 2030 onwards, making use of these decommissioned materials and optimizing decommissioning scenarios will be a key part of meeting material needs.

However, the upcoming end-of-life phase faces major challenges due to the lack of clear legal frameworks, the lack of precedents and specific case studies, technical constraints and unpreparedness of the supply chain (Winkler et al., 2022). Issues such as blade waste management and the state of the site after decommissioning are becoming crucial as uncertainty remains on the final decommissioning obligations. Generally, Belgian offshore wind farm (OWF) sites should be returned to their original condition, implying the removal of all installed materials. For the blades, as they consist of composite fibre materials, there are only limited end-of-life options at this point. Even with mechanical, thermal or chemical recycling alternatives, most blade composite waste is either landfilled or incinerated as alternatives are presently not cost-competitive (Jensen & Skelton, 2018; Kalkanis et al., 2019; Sakellariou, 2018; WindEurope, 2020). With a push towards a unified European landfill ban for wind turbine blades, other alternatives should become more widespread. A landfill ban is in place for several countries in the EU, with Germany indirectly banning blades based on their organic content. Yet the landfill ban is not implemented on a European level and landfill exemptions can be made (WindEurope, 2020). A harmonised ban is presumed to only be an effective tool if other end-of-life treatments become technically feasible and cost-competitive at scale.

Another complication in the end-of-life phase of OWF is the assumption that decommissioning can be performed by reverse installing all infrastructure, underestimating the required equipment and potential limitations (Jadali et al., 2021; Ortegon et al., 2013; Topham & McMillan, 2017). Aside from the reverse installation, end-of-life scenarios are often missing in the commissioning documentation, scientific literature or rely on broad assumptions (Chen et al., 2021; Tazi et al., 2019). Studies or reports based on specific wind farm decommissioning are limited and none connect this phase to their specific resulting material flows. Furthermore, as the focus remains mostly on specific components such as the blades or the techno-economic assessment of end-of-life strategies, an extensive decommissioning framework is still absent (Gokhale, 2021; Jadali et al., 2021; Topham et al., 2019). In consequence, relying on limited components, one-dimensional aspects and inadequate decommissioning scenarios, leaves the offshore wind sector unprepared for its upcoming decommissioning phase.

With these rising material demands and early wind farms approaching their decommissioning phase, a circular wind sector is considered essential, along with durable designs, refurbishments and reuse (Geissdoerfer et al., 2017; Morseletto, 2020). Even with a large availability of circularity indicators, characterisation of relevant metrics remains difficult (Graedel et al., 2011). Recycling or collection rates are frequently defined in different ways for many life cycle stages, left undefined or only applicable for a certain product. For example, for waste electrical and electronic equipment (WEEE), the collection rate is based on the weight of EEE placed on the market in the three preceding years (European Commission, 2012). Such interpretation is inapplicable for wind turbines with an expected lifetime of more than 20 years, especially considering the expected growing OWF installations and discrepancy between the amount of EoL turbines. Additionally, recovery and recycling rates can vary by different methodologies and calculation points in the recycling value chain. For plastics recycling in Flanders, this issue was made apparent as the interpretation of mass recovery rate led to differences of up to 41% (Thomassen, Van Passel, et al., 2022). Thus, clear definitions and implementation of metrics will become crucial. However, currently, no recycling or circularity targets exist for the decommissioning phase of offshore wind farms.

To tackle the need for site-specific literature, this study presents the anticipated decommissioning phase of a Parkwind-owned offshore wind farm in the Belgian North Sea. This was achieved by constructing the bill of materials (BOM), compiled in collaboration with the wind park operator, and a most likely decommissioning scenario, established on the conditions of the commissioning permit. This study takes into account current legal prospects and expert input from stakeholders along the value chain. The resulting OWF material composition and mass flows are analysed by use of material flow analysis (MFA). By including all offshore and onshore processes up until a final destination or secondary product, adapted collection and recycling metrics could be defined. This counteracts a collection bias, giving a skewed view by leaving out the material fraction which is deemed irretrievable. This study aims to provide a first basis for developing specific circular economy (CE) metrics and the development of a holistic decommissioning approach while giving the opportunity to prepare the supply chain and close the loop of OWF materials for future demand.

2. Methodology and data

2.1. System definition

This study covers a prospective MFA of the anticipated decommissioning phase of a Parkwind-owned offshore wind farm. Based on the commissioning permit and the projected service time of 20 years, this phase should be expected in 2030 at the latest. Taking into account lifetime extensions, this phase could shift up to 2035-2040. During the installation phase, limited decommissioning options and capabilities were available and the removal of the wind farm was described as the inverse of the installation process. Advancing from this initial plan, a most likely scenario was constructed, based on expert input from stakeholders along the value chain. Where needed, this was supplemented with assumptions based on an extensive literature review. The system boundaries of this study cover the full end-of-life of the offshore wind farm, including offshore infrastructure although omitting onshore parts (Figure 1, red dotted line). The decommissioning presumes simultaneous end-of-life for all components, irrespective of their condition. Scenarios such as repowering or lifetime extension, which could involve component replacement or wind turbine upgrades, are beyond this study's scope. The focus remains on the anticipated material flows from the originally installed Parkwind-owned offshore wind park.

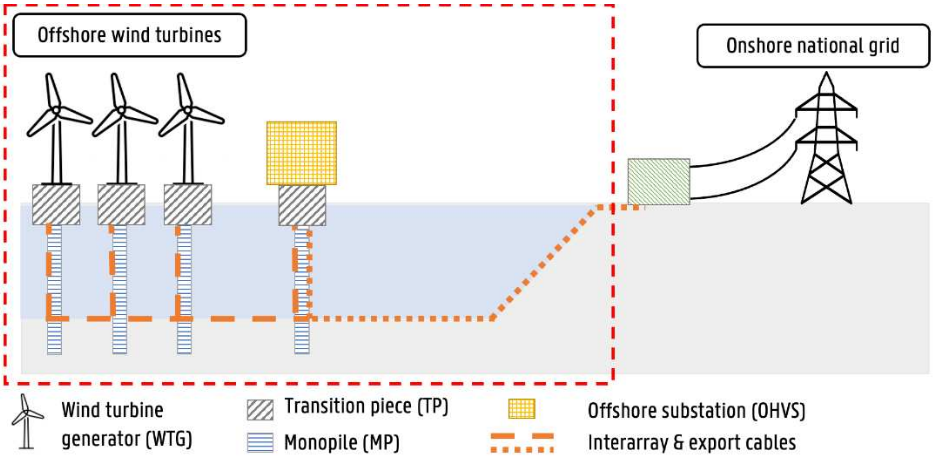

Figure 1: Schematic representation of the offshore wind farm with system boundaries for the material flow analysis. The system boundary is represented by the red dotted line. The WTG consists of the turbine tower, the nacelle with the rotor and the blades.

The offshore wind farm is part of the Belgian-commissioned projects, consisting of over 45 Vestas 3MW turbines, connected in six strings to the offshore high voltage station (OHVS), carried over one export cable to the onshore infrastructure and national grid. The wind turbines are connected with a transition piece (TP) to the monopile (MP), acting as an anchor which is hammered into the seabed (Figure 1). Later 6MW turbine additions were left out of the study. The three-bladed turbines have a gearbox-doubly fed induced generator (GB-DFIG) configuration, with the hub linked to the gearbox without the traditional main shaft. For this setup, no permanent magnets are involved in the generator unit (Vestas Wind Systems, 2006). The OHVS consists of one high-voltage, two medium-voltage and two low-voltage transformers with all associated components. The inter-array and export cables were identified as copper-type AC cables.

2.2. Case study and BOM

For the decommissioning, six overarching units were defined: the wind turbine generator (WTG), its TP, MP as well as the OHVS, the cables and the scour protection. The WTG, will be partitioned into the blades, the turbine tower and the nacelle with the rotor. These resulting nine components are the basis for the MFA and CE metrics. A site-specific bill of materials was compiled from the gathered data and as-built plans of the wind farm infrastructure, supplemented with an extensive literature review. Several data gaps of unaccounted mass in the rotor, nacelle and OHVS were identified. For the rotor mass, 27% was undefined and was deduced to be steel parts. The nacelle and OHVS had a mass balance gap of 16 and 14%, respectively, concluded to be electrical components. These were identified as the control and monitoring systems, and the electrical and HVAC systems, which would be decommissioned in accordance with other small EEE for which average compositions were established by de Meester et al. (2019). Apart from the ferrous and non-ferrous fractions, this latter reported WEEE stream contained predominantly gold (Au) and palladium (Pd) as precious metals. This assumption was corroborated by the consulted stakeholders. The different components of the wind farm were allocated into 17 material groups, elaborating on commonly adopted shares in literature, mainly reported as steel, aluminum, copper, polymers and non-specifics (Chen et al., 2021; Tazi et al., 2019). The material groups for this study are: steel, cast iron, copper, aluminum, lead, precious metals, plastics, composites, liquids & oils, gasses, silica, wood & paper, rubber, stone wool slab, fire repression agent, concrete and blasted rock. Trace elements were not incorporated as separate material group.

In the wind farm setup, in sequential order of the anticipated decommissioning, the blades, nacelle and tower could still be reverse-removed by unbolting these components. For all other parts, either an offshore dismantling and removal process has to be performed or if unfeasible at this point, left in situ. As complete monopile removal is not yet a broadly established method, it is expected that it will be cut two meters below the seabed level, as documented in the environmental permit (Ministerieel Besluit FOD, 2008). After unbolting the blades, rotor and nacelle, the tower will be disconnected from the transition piece and transported onshore by jack-up vessel. As the transition piece is anchored to the monopile with concrete grout, part of the monopile will be cut and transported together as one piece to be processed onshore. The monopile is thus divided into three pieces, consisting of the section left in situ, the part attached to the transition piece and the middle section transported onshore as such. The OHVS was installed and welded as one single unit on the transition piece. After offshore removal of hazardous elements such as sulphur hexafluoride (SF6), the complete OHVS unit will be transported onshore for further dismantling of the underlying components. Based on expert input, the cable removal is expected to be performed by a similar vessel which was part of the installation phase. In this way, the complete cable could effectively be removed without significant losses.

From the decommissioned components, the bolts, the middle section of the monopile and the wind turbine tower have no additional onshore dismantling or separation process. These components are reduced in size by use of a heavy-duty shear or cutting torch to enable convenient transport as it is sent to a smelter for recycling. All other components are further processed for recycling, downcycling, incineration or landfilling. The blades and composite parts are cut or shredded to make landfilling feasible and comply with density protocols. The rotor and nacelle will follow the WEEE separation steps after disassembling all infrastructure and mechanics, splitting metals from mainly electrics and composites. The separation of the transition piece from the monopile is done by demolition hammering the concrete grout anchor, where insignificant losses are assumed, after which the concrete will be downcycled to road materials. Dismantling of the OHVS onshore is performed similarly to the rotor and nacelle, with additional fractions coming from batteries, insulation materials, fire repression agents and the five transformer systems. The rates for WEEE material and battery treatments were derived from (Li et al., 2016; Smaniotto et al., 2009; Van Eygen et al., 2016; Vest, 2002). For the removal of liquids, oils, gasses, fire suppression agents as well as the stone wool insulation slab, sector experts (Galloo and Indaver, n.d.) were involved. Their insights were further broadened from literature by CEMBUREAU and Online Fire Protection Group (n.d.) and Wiprächtiger et al. (2020). For the cables, both inter-array and export, the oversheath and armour layers are stripped first. After separating the plastic fillers and internal sheaths, the isolated conductor and fibre optic cables are processed correspondingly. The work of Pita & Castilho (2018) was considered for the dismantling and end-of-life of the cable materials. The full overview of dismantling and end-of-life rates can be found in the Supplementary Information.

2.3 MFA and CE metrics

In order to evaluate the secondary material quality and destination, cascading levels were introduced (Desing et al., 2021; Thomassen, Dewulf, et al., 2022). Using this approach, a distinction can be made between high to low-end applications, as well as the fraction lost in landfills or irretrievable destinations. Furthermore, this classification allows for the calculation of CE metrics with focus on material or quality preservation. For this study, the lowest cascading level CL6 was adapted to include the fraction left in situ, considering the scattered distribution of materials. The examples for this case study are given in Table 1, ranging from closed-loop steel smelting to downcycling of concrete and the fraction left in situ. Material Flow Analysis (MFA) is a widely used methodology quantifying the flows of materials within a specific system, defined by temporal and spatial boundaries (Brunner & Rechberger, 2016). It is commonly employed to reproduce historical flows and stocks of resources, tracking the fate of materials across different boundaries and applications (Corona et al., 2020; Giljum et al., 2011; Tazi et al., 2019). MFA provides a comprehensive understanding of how materials are used, reused, stored, and lost within an industrial system. Accordingly, the mass flows for all material groups, wind farm components and final destinations are analyzed. As this material flow analysis builds upon the principle of mass and energy conservation, it can be used to visualize and calculate metrics such as collection and recycling rates. e!Sankey was used to illustrate material flows (iPoint software).

	Cascading level	Secondary application (example)
CL0	Closed loop recycling	Steel for monopiles and towers
CL1	Open-loop recycling to high-end application	Steel in construction
CL2	Open-loop recycling to medium-end application	Repurposing turbine blade
CL3	Open-loop recycling to low-end application	Concrete granulates for road construction
CL4	Energy recovery	Turbine blade incineration
CL5	Lost in landfill	Turbine blades in landfill
CL6	Left in situ	Blasted rock/part of monopile left in situ

Table 1: Definition of the cascading levels with specific examples for this study (based on Desing et al., 2021; Thomassen et al., 2022).

Due to incompatible definitions and calculations for the offshore wind sector, current EU Waste Directive guidelines or WEEE/CE metrics are not suitable for this study. The collection rate is site-specific, and therefore not referenced to the overall material brought on the market as included in the WEEE guidelines (CL0-5, Equation 1). To distinguish between recycling rates of the installed wind farm and the fraction reaching an onshore destination, the metrics are coupled with the collection rate (Equation 3 and Equation 4). The metrics further take into account the different cascading levels. For Equation 1-4, $M_{i,CL(j)}$ represents the mass of the material group i (1-17) for cascading level j (0-6, Table 1). The total mass of the installed wind farm is thus represented by the sum of all material groups in all cascading levels while the onshore share contains all materials in cascading levels 0 through 5.

Equation 1

$$\text{Overall collection rate } (\mathrm{CR_{total}}) = \frac{\sum_{j=0}^{5}\sum_{i=1}^{17} \mathrm{M_{i,CL(j)}}}{\sum_{j=0}^{6}\sum_{i=1}^{17} \mathrm{M_{i,CL(j)}}}$$

Equation 2

$$\text{Material recycling rate } (\mathrm{RR_{total}}) = \frac{\sum_{j=0}^{3}\sum_{i=1}^{17} \mathrm{M_{i,CL(j)}}}{\sum_{j=0}^{6}\sum_{i=1}^{17} \mathrm{M_{i,CL(j)}}}$$

Equation 3

$$\text{Collected material recycling rate } (RR_{collected}) = \frac{\sum_{j=0}^{3}\sum_{i=1}^{17} M_{i,CL(j)}}{\sum_{j=0}^{5}\sum_{i=1}^{17} M_{i,CL(j)}}$$

Equation 4

$$\text{Collected material recycling rate, high quality } (\mathrm{RRHQ_{collected}}) = \frac{\sum_{j=0}^{2}\sum_{i=1}^{17} \mathrm{M_{i,CL(j)}}}{\sum_{j=0}^{5}\sum_{i=1}^{17} M_{i,CL(j)}}$$

3. Results and discussion

3.1. Bill of Materials

With a total mass of 242 056 tonnes, the material intensity amounts to approximately 1 500 tonnes/MW for this specific wind farm. On a component level, the scour protection (blasted rock) and the monopiles (foundations) have the dominant shares, with respectively 80 and 9% (Figure 2-A). Excluding the blasted rock material (Figure 2-B), the monopiles become the main share (44%) with the above-sea-level wind turbine structure (24%) and transition pieces (21%), encompassing approximately 90% of the offshore wind farm. Similarly, Figure 2 (C-D) illustrates the OWF on material group level for the complete wind farm, including and without the blasted rock. As in the component distribution, the blasted rock, makes up 80% of the material group mass. Without the blasted rock, the total mass shifts from 1 467 tonnes/MW to 298 tonnes/MW. With more than 40 000 tonnes installed, steel makes up the second largest fraction, 17% including the blasted rock or 84% without this fraction. Plastics (3.9%), cast iron (3.4%) and copper (3.0%) take up less than 10% of the remaining materials. Composites, mainly associated with the blade fibreglass material, the nacelle cover and the nose cone represent 2.6% of the material mass. The plastic fraction of approximately 1 900 tonnes can mainly be traced back to the cables, for which the filler and insulation materials embody 79% of all plastics in the installed offshore wind farm. Smaller fractions such as concrete (just over 1 000 tonnes) and stone wool slab material (ca. 250 tonnes) originate from single sources, respectively the grout of the transition piece and the OHVS.

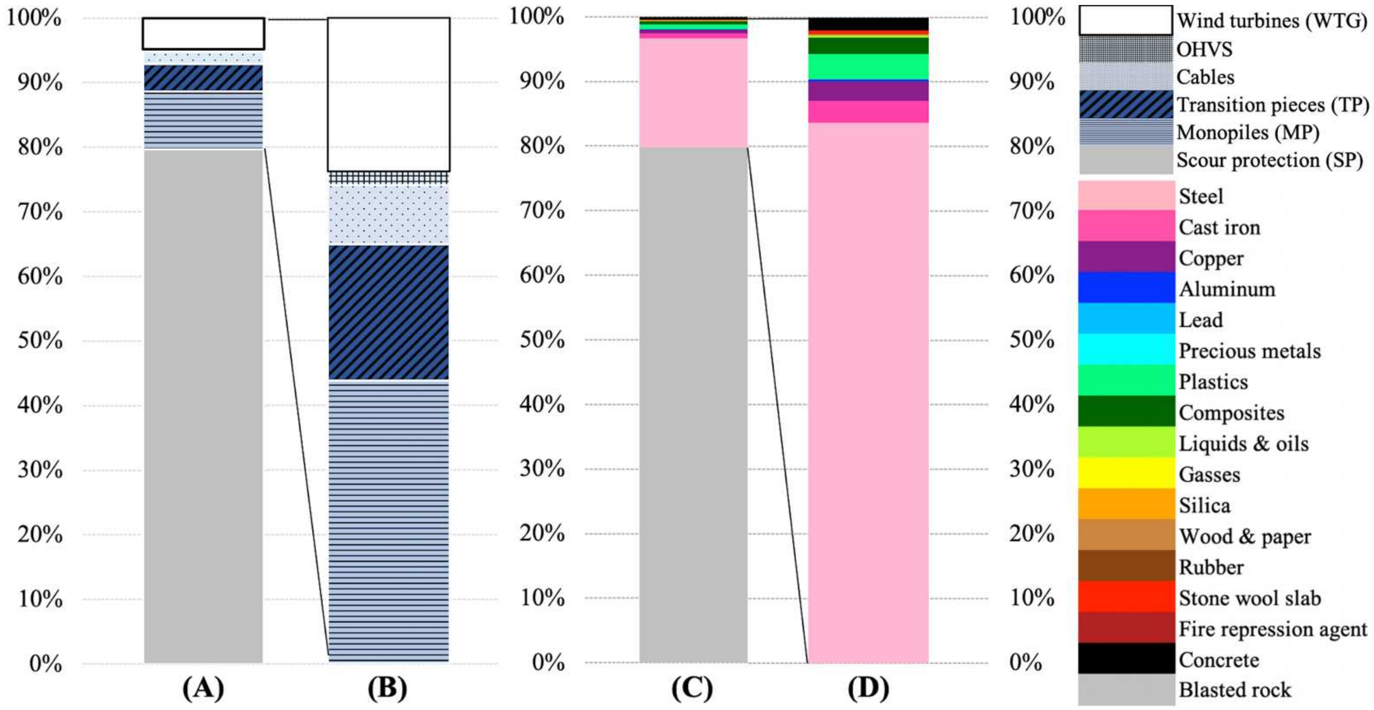

Figure 2: Relative mass distribution over the defined wind farm components, with (A) and without (B) the blasted rock fraction (with WTG consisting of the turbine tower, the nacelle with the rotor and the blades). Relative mass distribution over the 17 main material groups of the offshore wind farm (C) and rescaled by excluding the blasted rock fraction (D).

3.2. MFA

Figure 3 shows the results of the MFA. Of all installed materials, 84% is left in situ. This fraction is mainly the blasted rock material with a total mass of over 192 000 tonnes. Though smaller than the blasted rock fraction, almost 10 000 tonnes of steel would remain on-site in this decommissioning scenario due to the cutting at 2m below seabed level. This corresponds to 23% of all installed steel of this wind farm. After offshore dismantling and removal, 16% of all materials would thus reach an onshore destination. This collected material stream is predominantly steel, polymers and other metals, accounting for more than 80% of this flow. Overall, 2.8% of all materials with an onshore treatment are downcycled to a low-quality application, while 3.2% will be incinerated for which energy recovery is possible. Composite materials have currently not many cost-competitive applications and will be landfilled. These composites make up an important fraction of all landfilled materials with almost 1 300 tonnes or 47% of all landfilled materials. The residual landfilled fraction consists of smaller flows from the stool wool slab, WEEE and secondary processing losses. For this prospective decommissioning scenario, more than 2 700 tonnes would be landfilled. With 6.9% of onshore treated materials, more mass is lost in landfills than the combined incinerated and downcycled stream.

From the Sankey diagram, the disparities between components are apparent. The wind turbine tower and middle section of the monopile are cut into smaller pieces to be remelted in a steel factory with limited losses due to the high purity of the input material. In comparison, the complexity of the OHVS results in more processing steps and substreams where materials can be lost. Due to the high fraction of metals in the OHVS, almost 60% turns out as recycled or downcycled material. In comparison, blades have low complexity in end-of-life treatment yet with 0.44% of the total installed mass, the blade fraction is responsible for 40% of all landfilled materials. By landfilling the blades, internal steel and wood structures are lost, totalling 75 tonnes of non-composites. The balsa wood enclosed in the blades makes up 94% of all wood material in the offshore wind farm.

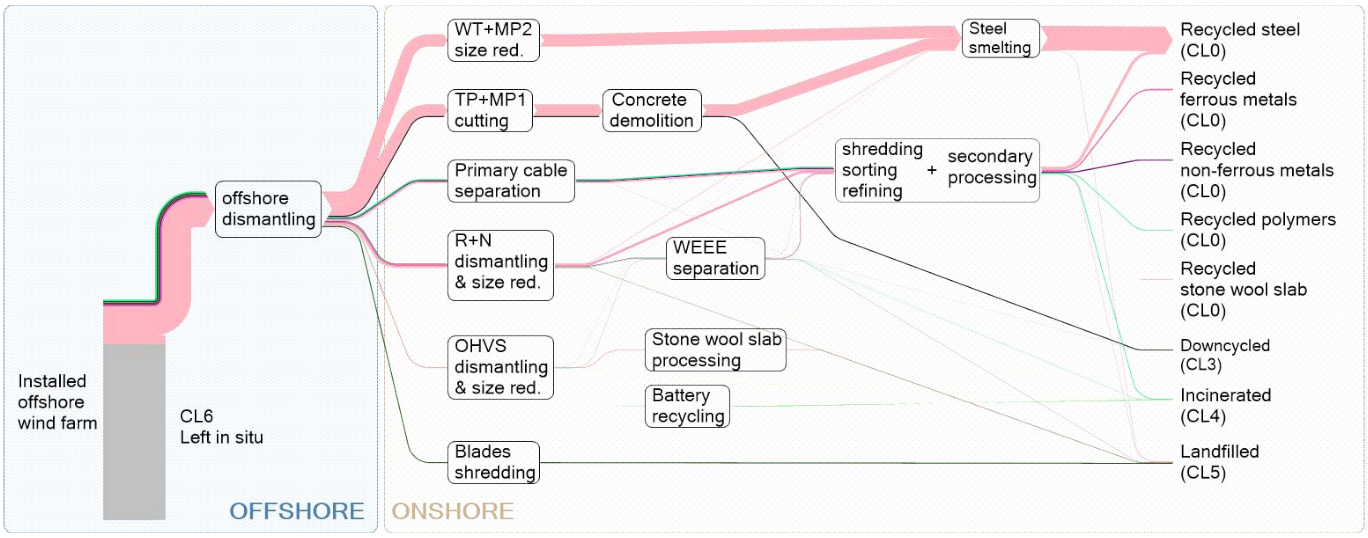

Figure 3: Material flow analysis of the offshore decommissioning and end-of-life treatment scenario (WT: wind turbine tower, MP2: second/middle part monopile, TP: transition piece, MP1: first part monopile, R+N: rotor + nacelle, OHVS: offshore high voltage station, WEEE: waste electrical and electronic equipment, CL: cascading level, size red.: size reduction).

3.3. Collection, recycling and collected material recycling rates

Using the BOM and Sankey diagrams, specific collection, recycling and collected material recycling rates could be calculated on material group and component level. The anticipated decommissioning scenario has an overall collection rate (CR_{total}) of 16%, mainly driven by the scour protection and monopile part left in situ. All other installed materials are expected to be fully retrieved, resulting in a best-case collection rate for most material groups and components. Excluding the blasted rock from the decommissioning requirements would increase the collection rate from 16% to 80%. Table 2 gives the results for the collection and recycling rates for the different components The main driver of the high recycling rates is steel as it counts for almost 31 000 tonnes of recycled steel, which is 89% of all high-quality recycled materials.

End-of-life segments	CR_{total}	RR_{total}	$RR_{collected}$	$RRHQ_{collected}$
Blades	100	0	0	0
Rotor + nacelle	100	86	86	85
Wind turbine tower	100	98	98	98
Transition piece	100	98	98	91
Monopile	69	67	98	98
Cables	100	78	78	78
Offshore High Voltage Station	100	56	56	55
Scour protection	0	0	0	0

Table 2: Component collection and recycling rates (in %).

The shares of end-of-life destinations for the respective material groups are given in Figure 4. All composites, concrete, liquids, oils and gasses are collected, yet not recycled in a high-quality application. Furthermore, more than half of the material groups have material recycling rates under 10% (CL0-2, excluding downcycling). For ten out of sixteen materials groups that have an onshore destination, the end-of-life destination is material downcycling at best, with eight out of those ten having incineration as highest cascading level. Yet, the combined mass fraction of these poorly recycled material groups is below 7% of the materials brought onshore or around 1% if compared to the total wind farm. Nevertheless, most metals have high recycling rates for the fraction reaching an onshore destination, with a small part of metals lost to incineration or landfill, mainly due to WEEE recycling and secondary material processing. Concrete originating from the grouted anchor is demolished by hammering and downcycled to road materials. Overall, metals have the highest recycling rate while organic compounds are predominantly incinerated or landfilled. Inorganics, mainly concrete and blasted rock are downcycled or left in situ.

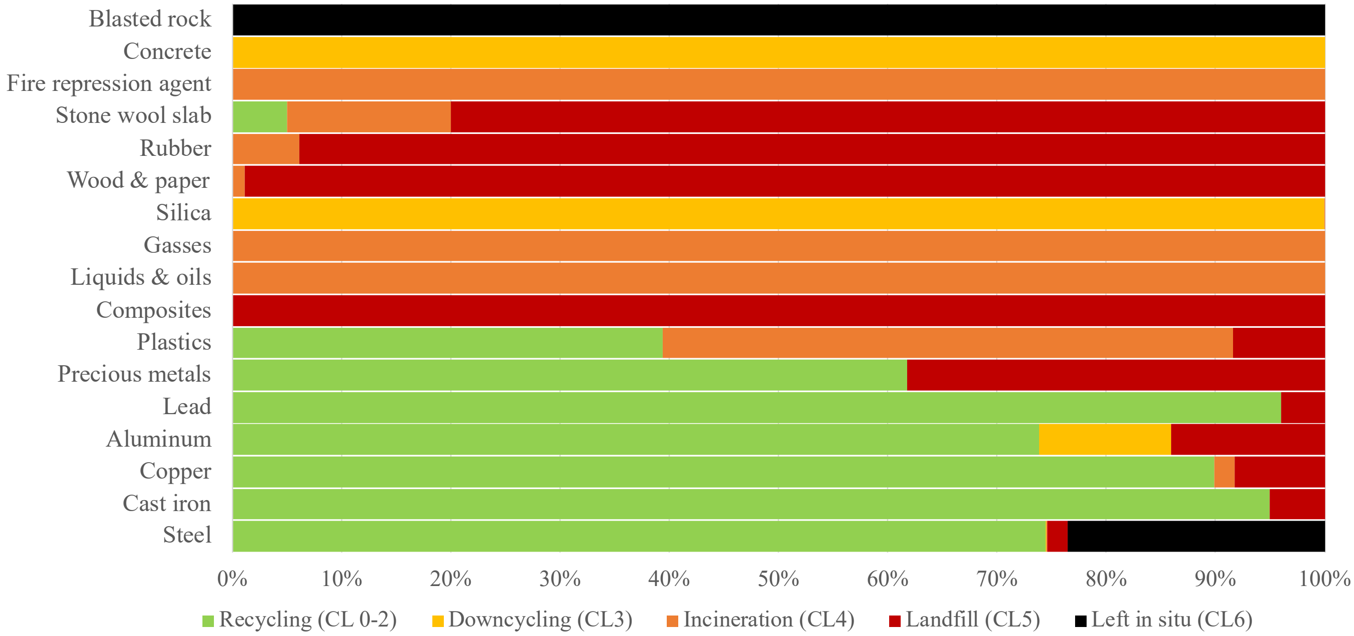

Figure 4: End-of-life destination of the material groups, relative to its installed mass in the offshore wind farm (CL: Cascading level).

3.4. Discussion

Currently, non-permanent magnet wind turbines are less frequently installed, yet are still abundant in the current stock approaching their end-of-life, both in onshore and offshore applications. With the expected surge in material demand, early wind farms are essential, representing a large material stock that could be exploited after decommissioning. Closed-loop recycling could be a key part, yet would need proper end-of-life strategies and a prepared supply chain as the process of decommissioning results in material mass flows that do not follow a continuous pattern. Instead, these flows occur in distinct waves, characterized by periods of higher input and higher strain on the sector, reflective of the nature of decommissioning projects, which are often conducted in stages rather than continuously. From this case study, with a collection rate of 16%, the anticipated decommissioning still results in large material losses.

Moreover, it is unknown if all components of early wind farms will be retrievable after the complete wind farm service lifetime. The availability of suitable vessels and infrastructure, such as small or large jack-up vessels and heavy-lifting vessels, will be crucial. Vessel types and sizes are not solely critical from a time perspective but likewise have the potential to influence operation abilities and thus collection and recycling rates. This is reflected in case cable vessels are not suitable for decommissioning or in the event cables have degraded too much to be pulled from their location, deteriorating both the collected and recycled fraction. Another component for which full retrieval is uncertain is the hotspot scour protection material. Though the environmental permit cites restoring the original state, scour protection is not directly mentioned and options still remain. With no large-scale tests performed for the complete removal of the scour protection or monopiles, it is necessary to acknowledge the inherent limitations and uncertainties that accompany scenarios of anticipated material flows. Nevertheless, the offshore oil and gas sector has called for relaxing their complete removal requirements and leaving infrastructure on-site, citing technical difficulties (Fowler et al., 2020). In conclusion, as offshore wind farm components are left in situ, this will have further-reaching implications, from repowering projects to potentially affecting other sectors such as maritime transport and fishing activities.

Just as implications on other sectors, biodiversity impacts are not contemplated in the permit but similar to the installation phase, complete removal of the blasted rock would cause biodiversity losses (Degraer et al., 2012; Degraer, S., Brabant, R. & Rumes, 2011; Vaissière et al., 2014). Even if the blasted rock would be left in situ, other decommissioning processes could still affect the local marine habitats, leading to partial decommissioning as the preferred proposed solution in order to retain local marine diversity (Degraer et al., 2012; Hall et al., 2022; van der Molen et al., 2014).

Due to a lack of precedents and possible changes in the legal framework, little information is available on decommissioning plans for specific wind farms. Despite rigorous efforts to ensure the accuracy and completeness of available data, inherent biases or errors could stem from variations in material compositions or the recycling efficiencies across different sources as well as temporal and technology changes. Therefore, while the findings provide valuable insights, inferring universal applicability may be limited to offshore wind farms with similar designs, locations, or regulatory contexts. Building on this study, future research will explore alternative scenarios, different offshore wind farm design choices as well as include aspects such as environmental impacts and energy flows for the studied decommissioning case.

Since the specific decommissioning scenario is currently only considered at the end-of-life phase of the wind farm, implementing CE targets could trigger and influence both research and industry partners in the development of new materials and technologies. Depending on the definition and calculation of these metrics, the eco-design of components could shift the focus to the material and design phase to optimize for recyclability and potentially reduce costs. However, recycling targets are set by policies and could change over time.

Generally, CE strategies focus on preserving the function of products, components or materials with a possible reference to a linear economy scenario (Moraga et al., 2019). Nevertheless, recycling rates are often based on mass-based targets, without a clear view on quality or economic implications. This can therefore lead to a recycling focus on high-mass components, independent of their final destination application, quality, value, criticality or scarcity. By applying the cascading level approach in this study, a distinction can be made between high to low-end applications and materials. Linking such metrics with material passports could aid in retaining both the quality of the material as well as its value by avoiding low-value contamination. However, the circularity metrics are still purely mass-based. Components with a low overall mass share could be significant on an economic scale without impacting the OWF recycling rates. For instance, assuming either all monopiles are cut at the seabed level or all monopiles would be recovered, the overall collection rate would only range from 16% to 20%. In this case study, the scour material dominates the mass balance, yet this metric does not have the ability to reflect other valuable insights from the recycled material such as economic value or scarcity. Further research should focus on aspects such as economic value, embodied energy and criticality, giving a more comprehensive view of implications that are not covered by mass-based CE targets or guidelines, as presented by Thomassen, Dewulf et al. (2022).

With the European Commission striving to leave downcycling out of the scope of recycling, many processes should be investigated in order to classify the final application of the product (European Commission, 2020; Geissdoerfer et al., 2017; Morseletto, 2020). For example, recycling encompasses not only downcycling of concrete in road materials, but includes co-processing composites in cement kilns. This is due to the part of the material which is incorporated into the cement, even though the original characteristics are lost. Banning the blades from co-processing and landfilling by activating an EU-wide ban would severely impact the wind sector as no widespread alternatives are present, neither in design, manufacturing or recycling.

Although not present in the studied OWF, a dominance of installed permanent magnet turbines in OWFs is expected by 2050. Permanent magnets contain critical raw materials, such as several rare earth elements. The use of these elements, mainly niobium, neodymium and dysprosium is concentrated in the generator structure, permanent magnets and high-strength alloys. Though these materials are only a fraction of the wind park, they have a meaningful impact on the environmental, social and economic impact (Blengini et al., 2020; Jensen, 2019; Kinnaird & Nex, 2022; Moss et al., 2013). Implementation of guidelines with a well-connected and prepared supply chain will thus become ever more important in order to support the wind sector and policymakers to deal with the rising demand for renewable energy and materials.

This study provides a basis for further research into alternative scenarios and different OWF designs with regard to the implication on recyclability and anticipated CE metrics. This can further fuel innovation while preparing the supply chain to tackle the inflow of materials. Clear mapping of future bottlenecks and specific case studies help both development towards a circular economy as well as research into the substitutability of materials and design for recycling, all essential in preserving high-quality materials.

4. Conclusion

This study describes the anticipated decommissioning case of a Parkwind-owned offshore wind farm, located in the Belgian North Sea. This wind farm has an overall material intensity of 242 056 tonnes, consisting 80% of blasted rock around the monopile structure. This fraction may be left in situ, together with part of the monopile below the 2m below-seabed level. The anticipated material collection rate of this decommissioning scenario is therefore only 16%. Complete removal of the monopile would only raise the collection rate to 20%. With all other components deemed fully retrievable, material recycling rates for most non-metals are nonetheless low. For ten out of sixteen materials groups with an onshore destination, the end-of-life destination is material downcycling at best. Eight out of those ten have incineration as highest cascading level, yet their total fraction is only around 1% of the installed wind farm.

Blades make up less than 0.5% of the total installed mass, yet are responsible for 40% of all landfilled materials in the described decommissioning scenario. At this point, large discrepancies between component-specific recycling rates are observed. With an overall recycling rate of 87% for the onshore materials, recycled steel is the main driver with more than 30 000 tonnes, accounting for almost 90% of high-quality recycled materials. Overall, the low collection rate and disparity of CE metrics between components are crucial factors to take into account for further developments in the offshore wind energy sector.

This study presents a first step in visualizing the large-scale decommissioning of an offshore wind farm, based on specific site data and involved decommissioning partners. Coupling the constructed bill of materials with the material flow analysis gives insight into the main materials present and the resulting flows of the anticipated decommissioning. Introducing collection or recycling targets on component or material level could have big implications on future material design.

CRediT authorship contribution statement

Célestin Demuytere: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Visualization, Writing – original draft, Writing – review & editing. **Ines Vanderveken:** Conceptualization, Data curation, Investigation, Methodology, Writing – review & editing. **Gwenny Thomassen:** Conceptualization, Supervision, Writing – review & editing. **María Fernanda Godoy León:** Conceptualization, Supervision, Writing – review & editing. **Laura Vittoria De Luca Peña:** Conceptualization, Supervision, Writing – review & editing. **Chris Blommaert:** Conceptualization, Supervision, Writing – review & editing. **Jochem Vermeir:** Conceptualization, Supervision, Writing – review & editing. **Jo Dewulf:** Conceptualization, Funding acquisition, Project administration, Resources, Supervision, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This research was supported by the consortium partners of the Flemish CTO ICON project, who provided insight and expertise that greatly assisted the research, contributing both on the specific case as well as internal knowledge. This paper was performed in concordance with the CTO consortium partners, although they may not agree with all of the interpretations/conclusions of this paper. The authors acknowledge the financial support received from the Flemish administration via the CE Center (Policy Research Centre Circular Economy). This publication contains the opinions of the authors, not that of the Flemish administration. The Flemish administration will not carry any liability with respect to the use that can be made of the produced data or conclusions.

Supplementary materials

Supplementary materials associated with this article can be found through the online version. [LINK DOI]

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