Technische Universiteit Delft

Decommissioning of Offshore Wind Turbines

A model-based approach to assess cost reducing decommissioning methodologies

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GustoMSC | NOV

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Abstract

The first large offshore wind farms installed in the North Sea Region (NSR) soon reach their technical end of lifetime. The wind turbines in these farms will have to be decommissioned after power production has stopped. Currently offshore wind turbines are decommissioned based on a method called reversed installation, a time consuming and therefore costly operation. This report focuses on the situation regarding decommissioning of offshore wind turbines (excluding foundations), and unveils the possibilities of potential decommissioning methods, using a jack-up, in an effort of to obtain a more cost-effective and environmentally friendly method than the currently used reversed installation. The act of decommissioning is explained, together with the expected market of decommissioning in the North Sea Region. Legislation concerning decommissioning of the five largest offshore wind producing countries in Europe are discussed. Using a multi criteria analysis on demolition methods, floating alternatives, and a model (determining the transport configuration), the most economical and least energy consuming combination is chosen. This model shows an economization of up to 66% and cutting the energy consumption by a third. Lastly, these outcomes are applied to three separate business cases including a sensitivity analysis to show the effect that variations in input values have on the results.

Contents

1 Introduction

A thorough study concerning the ins and outs of decommissioning offshore wind turbines has been performed, forming a steady base for further investigation of possible new methods of monopile founded offshore wind turbine generators (WTG's)

In 1990 the first offshore WTG was placed in coastal waters of Sweden, Nogersund. The first offshore wind farm ”Vindeby”, consisting of 11 WTG's was installed a year later near the coast of Denmark. For over a decade no new offshore wind farms were commissioned due to the relative high costs of offshore operations and maintenance compared to its onshore counterpart, until 2002 when Horns Rev I, a Danish 160MW farm, was commissioned. As time proceeded, the WTG's increased in size, capacity and offshore durability making it interesting to start installing wind farms offshore. At sea wind speeds are on average higher and more constant, making it a more energy productive place for wind energy conversion than onshore. Several different researches state the life expectancy of offshore wind turbines to be either 20-25 or 20-30 years. As some statements are taken from different researches, you may find both 20-25 and 20-30 in this report. The life expectancy is between 20 to 30 years, meaning the first offshore wind farms are about to be decommissioned in the near future. So far 34 offshore wind turbines spread over 7 different wind farms have been decommissioned in Europe. Currently there are around 5000 WTG's installed in the North Sea Region (NSR), which will all most likely have to be decommissioned the next 20-25 years [68].

Comparing the ratio of demolition & decommissioning costs over the installation/construction costs between construction businesses exposes the immense high costs of decommissioning offshore wind turbines. In the United Stated, demolition costs of buildings are an estimated \$4-\$8 per square feet (£31,74-£63.48 per m^2), whereas construction costs are between £440 and £3910 per m^2 [40] [69]. Demolition costs make up 2-7% of the initial installation costs. In Sweden, a similar research has been conducted, concluding that demolition costs make out 20-35% relative to its installation costs [36]. Meanwhile, decommissioning costs of offshore wind turbines cost 60-70% of its initial installation costs [68]. Why is decommissioning of off-shore wind turbines much more expensive and how can costs be cut is elaborated in the next chapters?

This thesis will state the problem in detail, focusing on the NSR, forming a base where the opportunities for innovations in the field of offshore wind turbine decommissioning are clearly brought forward. An answer is given why turbines must be decommissioned in the first place. Why is this there a need for new methods and how can these processes be at least as (or more) durable, economical and environmentally friendly as the known reversed installation? A market analysis is performed together with a look into the ability of recycling and reusing decommissioned wind turbines. Finally, within the legislative limits of the NSR taken into account, boundary conditions will be set to what the innovative methods must abide by. Establishing these design requirements a new method of decommissioning offshore wind turbines can be designed.

1.1. Problem statement

As of the beginning of the century, the energy transition caused a large need for renewable energy. Offshore wind farms became more common and increasingly profitable. Tenders for the first non-subsidised offshore wind farms have already been designated in the Netherlands. The sites Hollandse Kust I and II will most likely be installed without the financial support of the government [75]. Europe aims to be the first carbon neutral continent in 2050, yet the current share of renewable energy in the European Union was 19.7% in 2019. For this goal to succeed, an immense amount of renewable energy has to be installed within the next 30 years to reach the net zero carbon emission of 2050 [21]. An increase in amount of offshore wind turbines is inevitable. As offshore WTG's have a lifetime expectancy of 20-25 years and will have to be decommissioned, an increase in turbines to reach 20 years the next 15 years is shown in Figure 1.1.

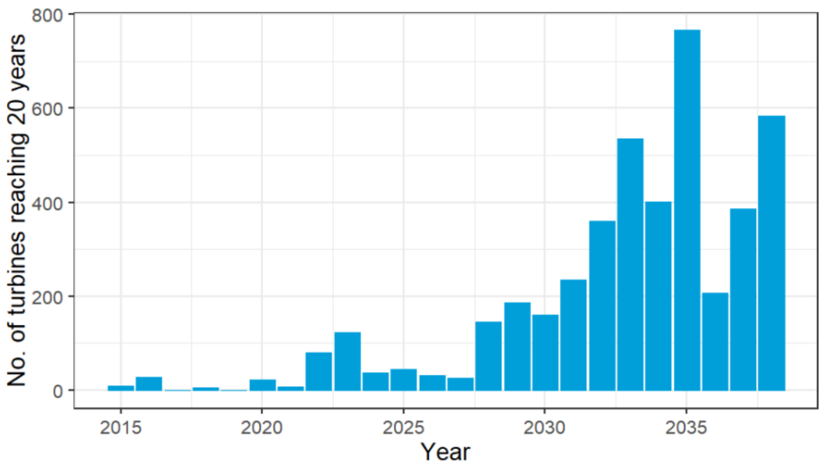
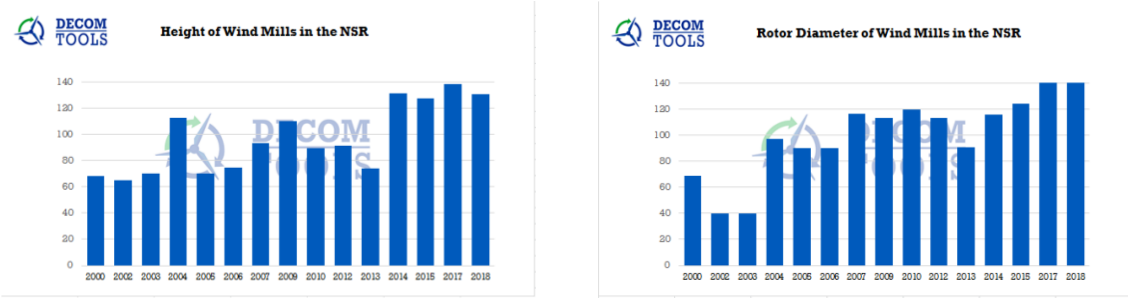


Figure 1.1: Estimated amount of turbines reaching 20 years [67]

The rated power of newly designed wind turbines increases every year. A gain in power is achieved through higher installed nacelles with a larger rotor diameter. The rising heights of the nacelle result in an increase in the weight of all the turbine components. With increasing dimensions, larger vessels will have to be used for both installing as for decommissioning. Currently all previously decommissioned offshore wind turbines and wind farms whose decommissioning plans are publicly published, have been or will be decommissioned based on a method called reversed installation, a method explained in subsection 2.2.1. This dismantling technique of WTG's requires large offshore crane units. Decommissioning rates vary between $140.000-250.000 per MW, depending on parameters such as height, rated power, weight and distance to shore. A cost breakdown will be discussed in detail in section 2.3. An increase in hub height and/or mass generally leads to the need of a larger crane unit with a higher lifting capacity.

A significant proportion of the decommissioning costs depend on the units' day rates. Larger crane units signify higher vessel CAPEX's (CAPital EXpenditures), thus higher dayrates [11]. IHS-Market states the following: " For 14+MW turbines, it is generally considered now



(a) Height of wind mills in the NSR

(b) Rotor diameter of wind mills in the NSR

Figure 1.2: Increase in size over years [35]

in the market that a maximum hook height of 150m or more is required to be technically able to install these turbines, with a minimum lifting capacity of 1,500T likely to be required" [41]. Kept in mind that current decommissioning plans are based on the so far only used decommissioning method: reversed installation, floating or jack-up vessels can only perform decommissioning operations given the hook height of the crane is high enough and can withstand the weight of the load. Due to the enormous amount of installed, and to be installed offshore wind turbines in the (near) future, cost reduction is clearly wanted. Reducing costs in CAPEX, automatically leads to a decrease in LCOE (Levelised Cost Of Energy), making offshore wind as a source of green renewable energy more economically attractive. Fully decommissioning an offshore wind farm is the least cost-effective strategy for owners of projects reaching the end of their lifespan, the latest analysis from ORE Catapult's new joint industry programme shows [15]. This research is supported by means of an internship at GustoMSC, a market leading company in designing offshore installation units. As installation of offshore WTG's is running at full throttle yet plans for a different, cost reducing method of decommissioning of those installed turbines remain undiscovered. Not only cost reductions are the main driver for new decommissioning processes. Sustainability and safe environmental operations are of paramount importance. Large jack-up units generally have higher emissions than smaller units. Reducing unit sizes, automatically results in less pollution, thus a more sustainable and environmental friendly option. Therefore, the following research question arises:

What concept turbine felling-aiding tool and transport procedure can be used to decommission offshore wind turbines using a jack-up unit, and how does its performance compare to existing decommissioning techniques?

1.2. Research approach

In order to familiarize with the subject and the problem context, a thorough literature study was performed. Information was gathered, laying the foundation for this research. A combination of both quantitative and qualitative data was needed to expose the problem. This data was validated by comparing the collected quantitative data to secondary data, data gathered by someone else. After data collection of the current offshore wind turbine situation in the North Sea Region, an analysis of trends seen in the offshore industry was performed. Thereafter an investigation in decommissioning methods commenced, setting out possible methods and techniques to apply offshore. Combined with a literature research in offshore transport in terms of operational cost, duration, emissions, safety and durability, a logistical model emerged, giving a clear overview of alternative possibilities on decommissioning offshore wind turbines. This model, based on substantiated assumptions is applied to a business case, showing possible gains by implementing new techniques compared to traditional procedures. In order to answer the research question, the question is divided into the following sub questions.

1. How are wind turbines currently decommissioned and what is the performance of decommissioning in terms of operational cost?
2. What parameters are of influence in the calculation & quantification of safety, sustainability and environmental impact?
3. Using a Multi Criteria Analysis, what decommissioning procedure is believed to result in the most technically feasible alternative?
4. What gains can be achieved by implementing the concept in terms of safety, sustainability, environmental impact and operational cost compared to traditional methods?
5. What future recommendations and alterations can be made to the design of wind turbines to aid decommissioning?

2
Literature review

A literature study was performed, illustrating the problem concerning offshore wind turbine decommissioning. The following sections will show the contours of the research done, giving a state of the art update of the NSR situation and the problems caused by this phenomenon.

The first section will dive into the process of installation and decommissioning. How are wind turbines installed in the first place, what is decommissioning, how are they currently decommissioned, what is reversed installation, what other methods are existent regarding offshore wind turbine dismantling and finally an overall indication of the decommissioning costs? Answering these questions will help us understand where an economical benefit is to be gained.

2.1. Installation

By understanding the installation process, reversed installation discussed in the next section will set the base of understanding the decommissioning process. The installation of offshore turbines differs greatly from farm to farm. The wide variety in weight, height and model require different installation techniques. The installation and decommissioning of offshore WTG's until now has rarely occurred with any other unit than a jack-up unit. The installation of the foundation can be done by using floating vessels or jack-up units. A jack-up unit, either self propelled or barge, will mobilise in the harbour, preparing for the specific operation offshore. Tools and support structures needed are welded to the unit to prevent components from shifting during transit. The unit travels to the location of the wind turbine which is ready for decommissioning. At the required position, the jack-up lowers the legs onto the seabed. The legs have to be preloaded before the true jacking commences. This is done to ensure the soil is capable of withstanding the maximum expected footing reaction [29]. Once the unit has reached a sufficient working height, the jack-up is ready for installation or decommissioning. Prior to installation of the WTG, the foundation is installed, often done by another (floating) vessel. On top of the foundation a transition piece is placed. Then, depending on the amount of lifts planned, first the tower is placed, followed by the nacelle, hub and blades.

The first offshore wind farm Vindeby, the turbines were placed using a single lift operation. The complete turbine was assembled onshore, shipped to its destination and with a single lift put into place. This required a relative large crane compared to the size of the turbine. As the turbine installed was 0.45MW (about 20 times as small compared to modern day turbines) single lift was a feasible option. Over the span of years the turbines have increased in size and mass, forcing most operations to break apart the lifting operation into multiple lifts. Breaking apart the amount of lift per installation, made it possible for heavier and larger wind turbine

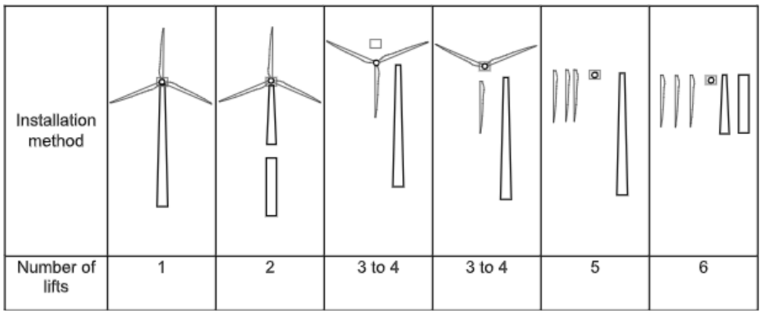


Figure 2.1: Installation methods offshore wind turbines. Source: Zhiyu Jiang [30]

components to be installed. Unfortunately, offshore installation vessels are expensive. Every additional lift causes a direct increase in operation costs, yet this is necessary for the latest turbines. Not only increasing weight is a common problem, the ever increasing hub height now plays a major role in vessel selection as hub heights reach over an expected 150m in 2035 [19], whereas the Vindeby hub height was a mere 38m.

Figure 2.1 shows the 6 different methods currently used for offshore installation. The decision for installation method will depend on the site, turbine and installation vessel.

2.2. Decommissioning

According to Marine Scotland [54], decommissioning of offshore wind turbines is the removal of the turbine and foundation included. Further, decommissioning can be summed up in three levels. Complete removal, clear seabed and partial removal. Complete removal comprises the removal of every single component above and below seabed. Clear seabed decommissioning results removal of scour protection and foundation, making the seabed suitable for trawling. Finally, partial removal enfolds some infrastructure to be left behind in the seabed. Another definition of decommissioning comes from TNO: 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. These activities together are referred to as decommissioning [73]. Due to legislative measures elaborated in section 2.7, buried cables and the foundation from 1.5m and deeper as seen from the seabed, may remain in situ, as removing might do more damage to the seabed than leaving it. Before decommissioning commences, the jack-up unit is mobilised in a similar manner as during installation. Using the commonly used reversed installation, the WTG is dismantled in a vice versa method as during installation.

2.2.1. Reversed installation

For several operational offshore wind farms, decommissioning plans have already been released. All these plans narrow down to the same decommissioning process: reversed installation. This methods describes the way of dismantling the wind turbine in an opposite manner as the installation was. Reversed installation might very well differ from turbine to turbine, in case the installation method is different.

The definition of reversed installation this report abides is not necessarily the exact reversal of the installation process. One may speak of a reversed installation if the equipment used for the installation of the turbine is comparable to the equipment used for decommissioning the turbine. Similar vessel selection, floating or bottom fixed, based on maximum hook height, lifting capacity, deck capacity and the use of barges or not will, in this report, be defined as reversed installation. Overall, the operation is the same compared to the installation method. This is clearly visible in Figure 2.2 where installation of the Danish wind turbine was done in a single lift, yet the decommissioning was spread over three lifts. First the lower blade, followed by a bunny ear lift (see Figure 2.2b) and finalized with the tower lift.

(a) Single lift installation of Vindeby Wind turbine. Source: youtube.com

(b) Bunny ear decommissioning of Vindeby Wind turbine Source: offshorewind.biz[15]

Figure 2.2: Difference in method, same equipment used.

Not only Vindeby wind farm was decommissioned by reversed installation, where the installation process differs from the decommissioning method. Table 2.1 shows three wind farms where both installation and decommissioning plans are publicly available. All three cases differ from each other, yet all methods can be filed under reversed installation.

Wind farm	**Installation method**	**Planned decommissioning method**
Thanet	Tower, Nacelle and hub, 3 blades individually (5 lifts)	1 Blade, Bunny Ear Rotor and Nacelle, Tower (3 lifts)
Gunfleet Sands	Bottom tower, Top tower, Nacelle, Rotor (4 lifts)	3 Blades Individually, Nacelle and Hub, Tower (5 lifts)
Rodsand II	Tower, nacelle, rotor (3 lifts)	Tower, nacelle, rotor (3 lifts)

Table 2.1: Reversed installation

All turbines shown in Table 2.2 have been decommissioned using the reversed installation method. The wind farms where the planned decommissioning method's have been released are the following.

- NoordzeeWind (OWEZ)
- Thanet
- Rodsand II
- Gunfleet Sands
- Sheringham Shoal
- Lincs
- Greater Gabbard
- Gwynt y Mor
- Luchterduinen
- Dogger Bank C

All above listed offshore wind farms will be decommissioned based on reversed installation. Only one other dismantling option is discussed.

2.2.2. Other methods

Kaiser [34] briefly mentions the possibility to let wind turbines fall over. This technique called "felling" has not yet been performed offshore. Onshore, multiple wind farms have been decommissioned by placing explosive charges at the base of the turbine, causing the tower to fall over after explosion. A recent example of controlled felling happened in Hunterston, Ayrshire, where a 6 MW SSE turbine has been brought down [56]. Reversed installation was the primary decision; take down the turbine by crane. However due to unknown circumstances, a safe crane operation could not be established and thus, the safest option was to use explosions for a controlled felling. The controlled felling is a more cost effective method compared to reversed installation, however, due to environmental reasons (e.g. fragmentation of steel particles) and legislative measures (e.g. exceeding maximum noise boundaries), a controlled felling by the use of dynamite to decommission an offshore WTG, is impracticable. Furthermore, near Minot, North Dakota, two towers were felled within the same day using a flame torch. The duration of the operation proves to be of minimal length [59]. In addition, no fragmentation of steel particles nor exceedance of noise boundaries was observed due to the lack of use of explosive charges.

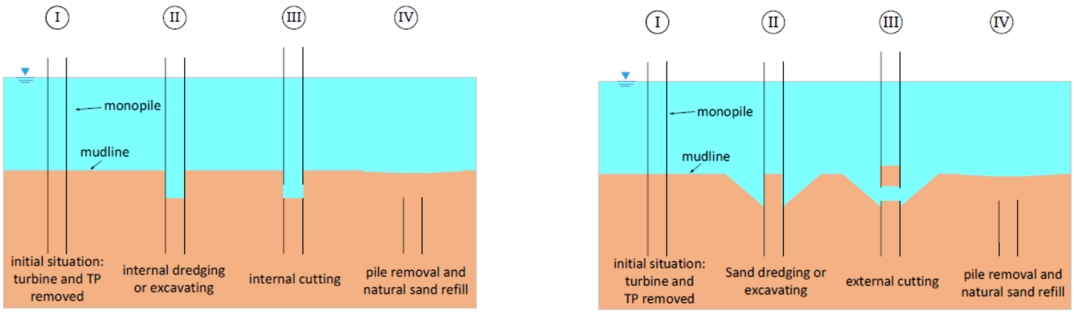
2.2.3. Foundation removal

The turbine's foundation must be removed after decommissioning of the tower. The removal is obliged by the Geneva Convention on the Continental Shelf. Article 5, paragraph 5 of the convention reads:" Due notice must be given of the construction of any such installations, and permanent means for giving warning of their presence must be maintained. Any installations which are abandoned or disused must be entirely removed." [70]. Since the complete removal of monopiles is a complicated and expensive operation, new European and local national laws have been established stating the limits and obligations. In section 2.7 laws and legislation regarding monopile driving & removal are discussed.

The complete removal of monopiles is a challenging operation since the force needed to pull the monopile out of the soil is too large for floating units to succeed. The pile loading capacity, the capacity needed to remove the monopile, increases over the years as a result of cyclic radial stresses in the monopile and corrosion, increasing the surface roughness, thus a higher friction and resistance. This taken into consideration, most NSR adjacent countries consent to partial removal of the monopile. Depending on local legislation, most laws agree removing the monopile 1.5 meters below seabed is sufficient. Cutting techniques can be used to cut the monopile from either the inside or outside. These cutting techniques seen in Figure 2.3 show that the majority of the buried section is left in situ. The depth of the cut-line is imposed by law and local regulations. In the article written by Hinzmann [26] regarding decommissioning of offshore monopiles, it is mentioned that removal methods can be separated into seven different methods. The two cutting techniques mentioned in Figure 2.3 and five complete removal techniques, each using a specific set of tools and principle visible in Figure 2.4. These five alternatives are possible different techniques, but less frequently used.

2.3. Cost breakdown

As stated in the chapter 1, the demolition costs of buildings is 2-30% of the total construction costs. Set side by side and compared to installation and decommissioning, the costs of dismantling offshore wind turbines, which is 60-70% of its total installation costs, is not proportional. This chapter discusses a cost breakdown of installation and current decommissioning plans.



(a) Internal pile cutting. Source: Hinzmann [26]

(b) External pile cutting. Source: Hinzmann [26]

Figure 2.3: Most commonly used monopile decommissioning methods

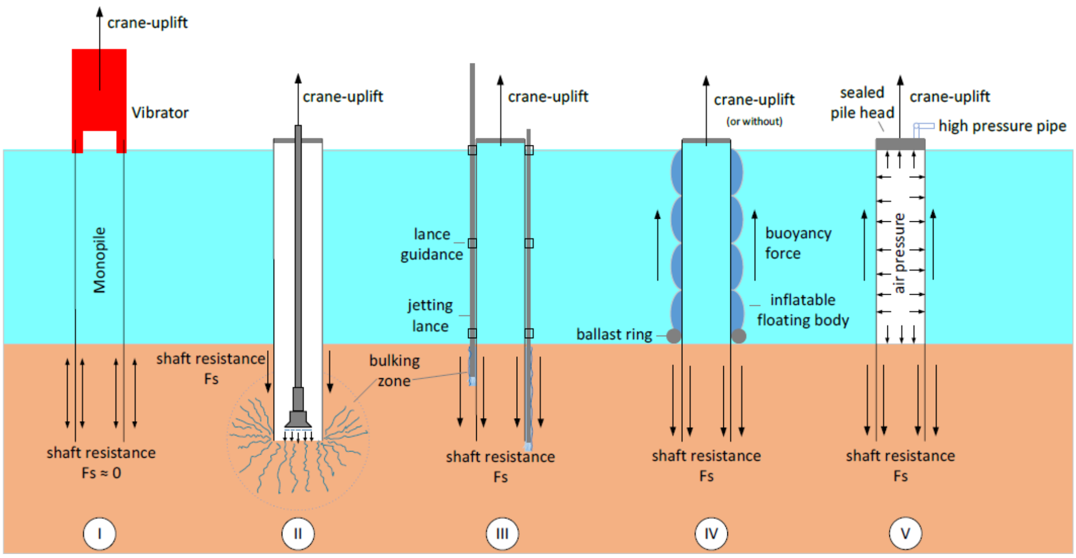


Figure 2.4: Possible offshore decommissioning techniques by Hinzmann [26]

2.3.1. Installation

Installation costs differ from farm to farm, depending on numerous parameters such as distance to shore, mobilization costs, installation techniques, amount of turbines to be placed, water depth, hub height, type of generators, choice of foundation and sea conditions. Exact numbers may vary between different farms. Nonetheless, an estimation per installed MW can be derived from other already installed wind farms. Based on reports of Malaysian life cycle costs assessment of an offshore wind farm [5] and Johnston [32], a non-recurring cost breakdown from the UK government, installation costs per MW fluctuate between $360.000 and $440.000 per MW. Installation of substations, WTG foundations and cables not taken into account, just as mobilization costs and transportation costs.

Installation costs are made up mainly by the costs of the units used for installation. as Dang [4] shows, the duration of installation also highly depends on the site. Installation per turbine (excluding foundations), can vary between 1.3-9.5 days averaging at around 70hrs or more than 3 crew days [4][50]. The day-rates of the vessels needed for decommissioning vary between $100.000 for small crane units, to $500.000 per day for heavy lift crane units [11]. Most commonly used purpose built jack-up vessels have day-rates of $150.000 to $250.000 [30].

2.3.2. Decommissioning

Reversed installation is the only used method for decommissioning offshore wind turbines yet. Dismantling such turbines require the same or comparable units as was used for installation, thus having similar day-rates. The day-rates of units are based on the CAPEX of the unit including the tools used and the crew on board. Decommissioning can be performed in a higher pace unlike installation, reducing the amount of time needed per turbine by half to 35hr, 1.8 crew days and the removal of a monopile foundation takes about 32hrs [50]. Nevertheless, mobilization and travel time stay the same. Also offshore operations are bound by weather conditions. An overall weather delay of 30% is assumed (10% summer, 70% winter)[73]. The overall estimated costs for decommissioning are $140.000-$252.000 per MW, accounting for 2.5-3% of the total capital costs assuming 25 year power production [50][5][28]. Taking the removal of foundations, cables, substations and transport costs into account, this can rise up to €500.000 per MW installed [33]. The brief cost estimation done by Kaiser [34] shows felling is a drastic less expensive method compared to reversed installation, cutting costs by 40-50%. Nevertheless technical obstacles (not mentioned by Kaiser) must be overcome before felling can be an used as an alternative method.

2.4. Market for decommissioning

Worldwide the demand for renewable energy is rising. Europe strives to be the first climate neutral continent by 2050. In the European Green Deal [20] objectives contain measures citizens and governments must take to aid the renewable energy transition. As the largest market for offshore wind is located in European waters, and the vast majority in the NSR, this report will focus on decommissioning in the NSR only. In this chapter, first the current situation of the NSR is described. Secondly this is compared with the findings of the cost section. Finally expected NSR market conclusions are drawn.

2.4.1. Decommissioned wind farms

The first offshore wind turbine was installed in 1990 in Sweden in the Baltic sea (BS) (other abbreviations: IM - IJselMeer, NS - North Sea, IS - Irish Sea, NA - North Atlantic). Shortly after, the first wind farm Vindeby was also installed in the Denmark waters of the Baltic sea. Table 2.2 states all offshore wind farms which so far have been decommissioned in Europe. As Europe is the global leading continent in offshore wind, continents other than Europe have little knowledge and experience concerning offshore wind turbine decommissioning.

With a mere 34 offshore WTG's being decommissioned in the history of offshore wind, given with the fact that 5000+ turbines are installed in the NSR only, exposes the need of new efficient decommissioning methods. A complete list of active wind farms in the NSR is given in Appendix A.

2.4.2. North Sea Region

The NSR is ideally suited for offshore wind farms due to the high constant wind speeds combined with the relative shallow water depth. Therefore the past 20 years a great amount of wind turbines were placed in the north sea. In Europe the installed offshore wind capacity in 2020 was 25GW, where 22GW was installed in the North Sea. The 22GW installed power comes from nearly 5000 different turbines ranging from 2MW to 9.5MW in the NSR. Figure 2.5 states all offshore WTG's in Europe. However, the focus of this report is only the NSR.

As the first large offshore wind farms were installed since 2002, and the expected lifetime of offshore wind turbines is between 20-30 years, the first farms will soon have to be decommissioned. In addition, the installation of turbines has increased exponentially, hence the decommissioning will also increase.

Decommissioned offshore wind farms								
Location	Name	Country	Amount	Rated power [MW]	Total installed power [MW]	Foundation type	Date commissioned	Date decommissioned
BS	Nogersund Blekinge Svante	Sweden	1	0.22	0.22	Tripod	1990	2018
BS	Vindeby	Denmark	11	0.45	4.95	GBS	1991	2016
IM	Lely Farm	Netherlands	4	0.5	2	MP	1992	2015
BS	Utgrunden 1	Sweden	7	1.5	10.5	MP	2000	2019
NS	Blyth	UK	2	2	4	MP	2000	2020
BS	Yttre Stengrund	Sweden	5	2	10	MP	2001	2017
NS	Hooksiel	Germany	1	5	5	Tripile	2008	2016
IS	Robin Rigg	UK	2	3	6	MP	2009	2015
NA	Windfloat 1	Portugal	1	2	2	Floating	2011	2016

Table 2.2: Decommissioned offshore wind farms.

Overview of grid-connected offshore wind power projects at the end of 2020

COUNTRY	NUMBER OF WIND FARMS CONNECTED[1]	CUMULATIVE CAPACITY (MW)	NUMBER OF TURBINES CONNECTED	CAPACITY CONNECTED IN 2020 (MW)	NUMBER OF TURBINES CONNECTED IN 2020
UK	40	10,428	2,294	483	69
Germany	29	7,689	1,501	219	32
Netherlands	9	2,611	537	1,493	172
Belgium	11	2,261	399	706	81
Denmark	14	1,703	559	0	0
Sweden	5	192	80	0	0
Finland	3	71	19	0	0
Ireland	1	25	7	0	0
Portugal	1	25	3	17	2
Spain	1	5	1	0	0
Norway	1	2	1	0	0
France	1	2	1	0	0
Total	116	25,014	5,402	2,918	356

Figure 2.5: Total installed offshore wind in NSR in 2020. Source [53]

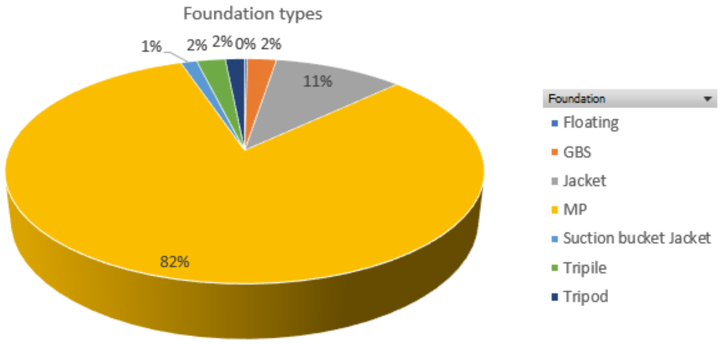
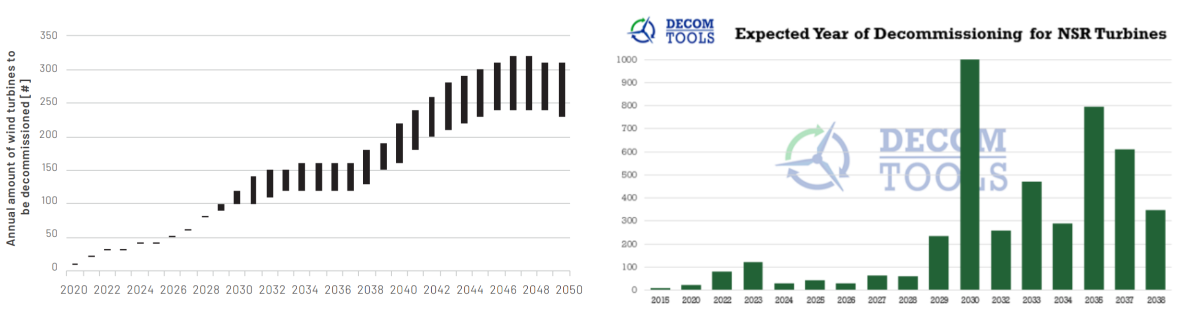


Figure 2.6: Foundation types of WTG's in the NSR

Figure 2.6 displays the percentage of used foundations for offshore wind turbines in the NSR. Decommissioning methods vary for every separate foundation. As monopile foundations represent 82% of the NSR foundations, this report will focus on decommissioning of NSR located, monopile based WTG's. As mentioned in the Problem statement, Figure 1.1 shows an exponential increase in expected turbines reaching 20 years in the NSR. An increase in installed offshore wind automatically results in an increase in offshore decommissioning projects with a 20-25 year delay. In Appendix A all installed offshore turbines of the NSR are listed, implicitly showing the need for large decommissioning projects in the near future. Figure 2.7a shows the expected amount of wind turbines in the NSR ready for decommissioning over the next 30 years. This projection is supported by research done by Decomtools, results to be seen in Figure 2.7b



(a) Source: TNO [73]

(b) Source: Decomtools [35]

Figure 2.7: Estimated amount of offshore WTG's in NSR to be decommissioned annually.

In the UK currently more than 10GW of offshore wind is installed. Combined with the estimated 140.000-252.000$ per MW decommissioned from section 2.3, this will add up to a projected market of $1.46-$2.6bn over the next 20-25 years. This rough estimation is backed up by investigation of the UK government, which foresees a total cost of decommissioning market of £1.03bn - £3.64bn ($1.41bn - $4.99bn) in the UK only [10]. Given that the total installed power in the NSR is 22GW, this estimation can be extrapolated to an assumption of $3.10bn - $10.97bn in the NSR the next 20-25 years. The large uncertainty between the lower and upper boundary of estimated decommissioning costs is a consequence of uncertain future regulations, changing decommissioning techniques, decreasing unit day-rates and the parameters given in subsection 2.3.1

2.5. End of lifetime

The reasons for decommissioning offshore wind turbines vary greatly. The most logical reason is to decommission a wind turbine when the turbine has reached its technical end of lifetime due to wear and tear, and therefore not able to produce any power anymore. This was the case of the inshore Lely farm in the IJselmeer. One of the turbines lost its full rotor including blades as a result of metal fatigue [74]. Investigation stated that the other three turbines did not suffer from fatigue, decommissioning was not obligatory, yet it was performed. Not only technical end-of-lifetime can be the trigger to decommission a turbine or farm. Full decommissioning of a wind turbine is an operation with a large price tag. Before the decision is made to decommission a wind turbine, all alternatives are explored. The following sections explain possible triggers to decommission turbines.

2.5.1. Roadmap to end of lifetime

Before a turbine is prepared for decommissioning, other options are examined. Repowering or life extension of a turbine may economically and/or environmentally be the significant better option. Inspection and analysis of every distinct turbine can preclude total decommissioning if wear & tear are within reasonable limits. If so, turbines can undergo a life extension operation. This comes in two different forms. Life extension and repowering.

Life extension

Life extension can be performed if corrosion levels of the foundation and tower are below minimum recommended limits. This means the structural strength is large enough for extending the life of the turbine. If, and only if, the turbine will be able to operate for more than 2 years, life extension can be executed. Corrosion of wind turbine components due to wind, waves and saline water is inevitable. The foundations, transition pieces and towers are designed to withstand acceptable levels of corrosion. These corrosion rates can be found in Table 2.3.

Large maintenance is carried out and crucial parts are replaced. Life extension is the only option if the electrical infrastructure has already operated at its maximum capacity. In the event of an energy grid not functioning at its maximum capacity yet, an expansion of installed power is possible. This is called repowering.

Repowering

Similar to life extension, the corrosion levels of the tower and foundation, as well as wear & tear, must fall within the minimum recommended limits. Depending on the state of the components of the turbine and expansion possibilities, new components will be installed on the existing foundation. Usually a replacement of the nacelle, hub and a larger diameter rotor lead to an increase in rated power. An increase in rotor diameter automatically leads to a higher power production. On the downside, installing a state of the art nacelle on a tower which was installed 20 years ago, might not be possible due to major differences in dimensions between the new nacelle and tower. Research from Sebastiann Himpler [25] shows repowering is of its greatest economical value after 11-15 years of its installation. This might be a solution if the newly added revenue shall outweigh the repowering costs. Matter of course, depending on the state of the components, repowering is a more durable option than full decommissioning and installation of a new turbine as large components like the foundation and tower can be reused. Gravity based foundations could last up to 100 years, making repowering a more feasible option. Buried cables can last 50 years without deteriorating [67]. However, these cables must be able to withstand the power the re-powered turbines produce.

2.5.2. Decommissioning

Decommissioning is the process of removing the blades, hub, nacelle, tower and foundation. As stated before, removal of cables and substations is not investigated in this report. The process of decommissioning an offshore WTG can be started for various reasons discussed in the next sections.

Legislative obligation

First of all, every (offshore) wind farm is bounded by contracts with the government of the country the turbines are placed in. These contracts differ per country whereas most of these state the following: Duration of the project, installation and decommissioning process, environmental and ecological impact, local legislation and active shareholders. Also, offshore wind farms must obey to legislation from UNCLOS (United Nations Convention on the Laws Of the Sea) and OSPAR (OSlo & PARis); a convention for the protection of the marine environment of the North-East Atlantic. These contracts state the maximum duration of the lease of the tender the farm is placed in. In the Netherlands, the contracts are made for 30 years, with a possible extension of 10 years. Before this contract expires, the tender has to be returned to its original state. More about legislation in section 2.7. The government benefits from green energy to reach the net zero emission goals of 2050 and thus is likely to extend the given contracts for another 10 years. However, contracts may not be prolonged due to re-purposing sites. Meaning the site will be used for other purposes such as fishing, sand winning or zones used for military purposes.

Reaching technical end-of-lifetime

Compared to onshore, conditions at the North Sea are harsh. The combination of high wind velocity, wave impact and the saline water result in a harsh environment for structures offshore. The deterioration of the structural integrity is of greater impact than on land. Over the span of 20-25 years, the wind turbine wears out. Wear and tear occurs in every component of the turbine. Gearboxes (if present), blades, the generator and even the tower and foundation slowly lose their structural integrity. As MDPI [49] states, the foundation and tower experience intense contact with salt water. Current, wave impact, and salt water lead to corrosion. The foundation and tower can be divided into five zones, each with their own corrosion rate shown in Figure 2.8 together with the corrosion rates per zone in Table 2.3. After 20-30 years it might not be economically feasible to replace parts of the turbine in order to keep it in power production, thus decommissioning is the most probable option. As already stated above, the Lely wind farm, an inshore farm existing from four turbines was decommissioned when the rotor of one of the turbines broke off, together with its blades, and plummeted into the IJselmeer. The Lely wind farm incident led to hazardous situation, giving reasonable arguments for the full decommissioning of the Lely farm.

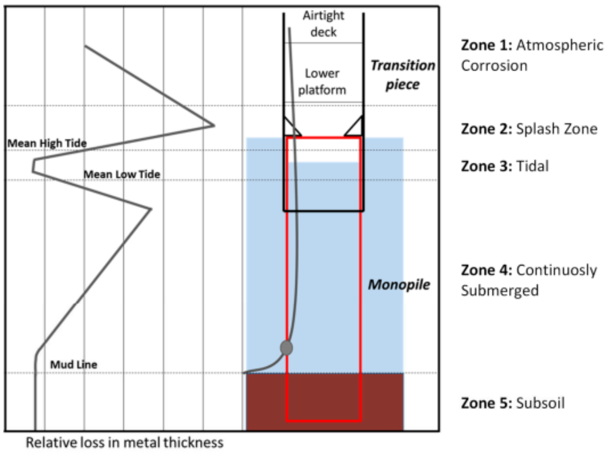


Figure 2.8: Suggested relative loss of metal thickness of unprotected steel on offshore wind turbine structure in seawater. Source: MDPI [49]

Figure 2.8 and Table 2.3 contains information from MDPI [49] used for showing the deterioration due to a steady corrosion rate per year on the monopile and transition piece. Deteriorating monopile foundations can cause a reduction in structural integrity. Repowering and life extension are only possible if the corrosion is within limits for reusage.

Zone 1	The atmospheric zone has the least amount of corrosion due to the only contact with seawater coming in the form of droplets from seawater spray, the protection method is a coating on the outside of the turbine. Corrosion rates 0.050–0.075 mm/year.
Zone 2	In the splash zone, the corrosion effects are amplified compared to that of the atmospheric zone. The waves continually splashing on the surface causes there to be a continual wetting and then removal of water to allow for the movement of ions. This allows for deep pits to form in this area if left unprotected. Heavier external protection would be used in the area but internally there is usually no protection and corrosion is allowed due to the less of a wave effect internally. Corrosion rates 0.20–0.40 mm/year.
Zone 3	The tidal zone has a mix between both Splash and Submerged zone. The wetting and drying effect aren't as aggressive here with it only happening as the tide rises and falls. This causes there to be an overall lower rate of corrosion but there can be more aggressive local corrosion spots. The cathodic protection is designed to help this area when in high tide. Corrosion rates 0.05–0.25 mm/year with localised corrosion rates up to 0.50 mm/year
Zone 4	When submerged, the main corrosion protection method is the use of cathodic protection. This has to be changed regularly and maintained. This is often used internally but might not be checked and changed as regularly, with some corrosion allowance. Pits in immersed zones are usually broad and shallow with growth rates 0.20–0.30 mm/year. Uniform corrosion rates 0.10–0.20 mm/year.
Zone 5	When looking at the structure underneath the seabed it can be assumed that there is low uniform corrosion but there can be pockets of localised corrosion around the mudline. While it is not yet decided in the industry what is the best course of protection for buried areas, cathodic protection is most likely the best though. Corrosion rates of 0.06–0.10 mm/year are expected, however reports show possible pitting rates up to 0.25 mm/year.

Table 2.3: Wind turbine corrosion zone source: MDPI [49]

Ecological/environmental hazards
Besides a technical or contractual end of lifetime, external factors might be the cause for decommissioning. Vessel collision, earthquakes, lightning strike or any relatable impact, leaving irreversible damage, can and might be hazardous for the ecosystem surrounding the turbine and will be the direct cause for decommissioning. In the Kavelbesluit V [55] the risks of collision with vessels with and without bounded routes, divided between larger and smaller than 24m are calculated based on two different alternatives. Alternatives consisting of either 95 8MW turbines, or a farm with an equivalent power output consisting of 76 10MW turbines.

Economical end of lifetime
So far, all turbines that have been decommissioned have been dismantled due to technical end of lifetime. A future scenario might be that the rated power of innovative turbines exceed the power production compared to the already installed wind farms. The contract time for wind farms in the Netherlands are 30-40 years. If an economical advantage is feasible by dismantling a fully functioning wind farm and replacing it by the new innovative, high power productive turbines, one might speak of economical end of lifetime. This scenario has not occurred yet but can be seen as an extreme form of repowering.

2.6. Materials and processing

After decommissioning, the turbine components have to be processed. Part of reaching a net zero carbon emission in 2050 is not only reusing components & materials and preventing depletion of resources but also recycling as much as possible. Durability and sustainability is of great importance. This chapter deals with the processing of used components. From what materials is an offshore WTG composed of, what is the waste hierarchy, what happens with turbine components after decommissioning and what conditions must components abide by for processing.

2.6.1. Materials

The materials a wind turbine is composed of depends on the type of foundation used and placement on or offshore. Onshore foundations are generally gravity based, meaning made out of concrete. On the contrary, offshore turbines are often based on monopile or jacket foundations, made out of steel. As seen in Figure 2.6 only 2% of the foundations found in the NSR are gravity based foundations made of concrete, the rest of the foundations are made from steel. Figure 2.9 shows materials used per section of the most common turbine in Sweden.

Monopile & Transition Piece
The monopile is often used as foundation of offshore WTG's. Constructed on top of the monopile the transition piece is located. This piece forms the bond between the monopile and the tower. The monopile foundations are completely made out of steel. Similar for the transition piece, this component is completely made out of steel.

Tower
The tower is almost completely made out of steel (95-100%). Other materials found in the centre of the tower are aluminium (0-2%), copper (0-1%) and glass fibre reinforced plastics (0-4%)

Nacelle
The nacelle is the drivetrain of the wind turbine, containing the generator, gearbox and all electronics needed to convert rotational kinetic energy into electrical energy. The housing

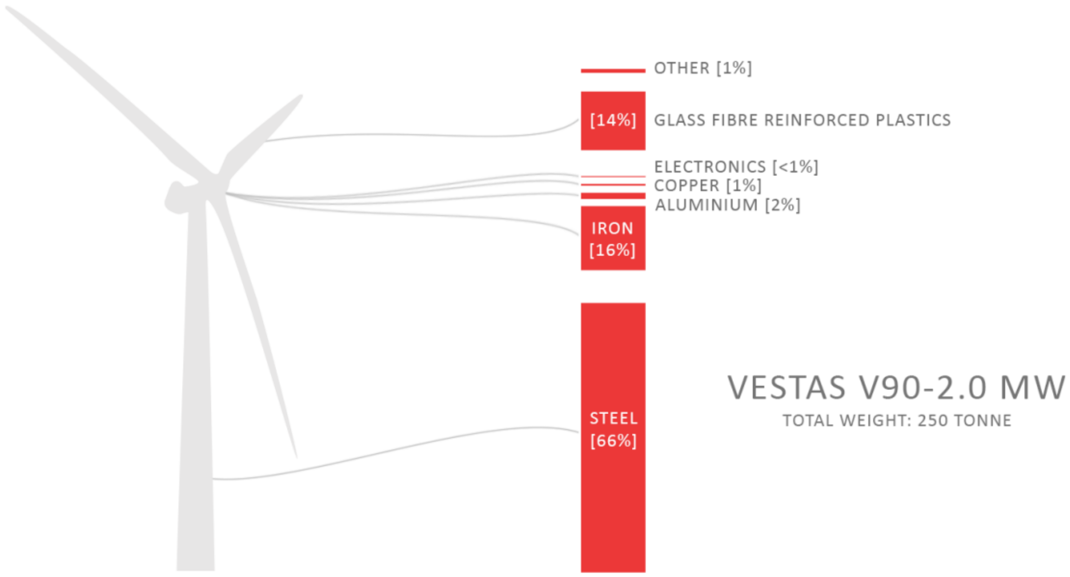


Figure 2.9: Materials found in the Vestas V90-2.0 MW [6]

is usually made out of GFRP (Glass Fibre Reinforced Plastics) and held together by steel framing. Two types of drivetrains are commonly used: direct drive and a doubly fed induction generator using a gearbox. The generator and gearbox (if present) are largely made out of iron, aluminium, copper, electronics and lubricants.

Rotor

The rotor consists of three blades mounted on the hub. The blades are commonly composed of GFRP and epoxy. This relative cheap material is strong and stiff. An alternative to GFRP are Carbon Reinforced Plastics (CRP). CRP is a stronger material compared to GFRP but this material is more expensive. For increasing rotor diameters, CRP could provide the solution since the material weighs less than GFRP, thus reduces stresses on the turbine. The hub is made from cast iron and connects the blades to the drivetrain in the nacelle.

2.6.2. Waste hierarchy

After decommissioning, the components of the WTG are transported to shore where further processing can be degraded to useful materials. In Figure 2.10 the waste hierarchy is displayed, showing the most favourable approach to reduce the usage of materials to a minimum. The first step of the hierarchy is prevention. How can objects and components be produced with less raw material, whilst keeping the structural integrity or characteristics. Since the turbines in the NSR have been installed already, prevention is not applicable to this situation. However, further investigation can be done on how prevention of material usage can be carried out. The next step in the hierarchy is re-use. Can the components be reused in its entirety, or by executing small alterations so the materials are re-purposed. If re-purposing is not an option, the solution is sought in recycling of the materials, where waste is converted to new product or material. Next in line is recovery. When it is impossible to convert the waste into new product, as much as possible energy is retrieved from the waste for example by incinerating the waste. Finally, when all above was not an option, the waste materials are disposed. This can be done by incineration without energy recovery or landfill.

Figure 2.10: Waste hierarchy. Source: ORE [62]

Monopile, Transistion Piece & Tower
The monopile, transition piece and tower are almost completely made out of steel. The corrosion caused by weather and saline water results in the structure losing its integrity over the years as described in subsection 2.5.2. Reuse or re-purposing of these structures is not feasible. On the other hand, steel is a material that lends itself for recycling, as little to none material is lost in the process. As the DecomTools report [7], steel has a recyclablility of 92%. All sections will be sold as scrap metal, generating a significant cashback.

Nacelle
As stated, the nacelle exists of iron, aluminium, copper, magnets, electronics and GFRP. The drivetrain of the nacelle is subjected to wear and tear. Reinstalling this generator will economically not be feasible. The Swedish Energy agency, combined with several other Swedish wind power associations, concluded that a second hand market for used wind turbines will not happen. The technological improvements and innovations in the WTG are so rapid, the market for second hand turbines will not exist [7], for now ruling out reuse or repurposing of the generator. In Table 2.4 a list of materials and its capability of recycling is shown.

Rotor
The hub is mostly made of cast iron, proven to be a perfect material for recycling. The turbine blades are constantly exposed to heavy winds and large rotational velocities. These forces combined with salt water lead to leading edge corrosion, negatively influencing the aerodynamics of the blade. Re-use of blades is therefor not possible. Unfortunately GFRP is not only a tough material to recycle, incinerating is also an expensive method to dispose. Likewise for CRP, it is a tough material to recycle. However, research done by Zhang [76] sheds light on the future possibilities of recycling CRP's, even enhancing the structural integrity of CRP's after recycling. Turbine blades generally will need repair every 2-5 years[44]. Offshore blades up to four times as much compared to onshore turbines [12]. With offshore blades occasionally being re-purposed as bridges, homeless shelter roofing, bike shelters or children's playground [1], these options soon run out. The vast majority of the decommissioned turbine blades are discarded as landfill. In the Netherlands, the incineration of blades is allowed if the transfer costs to the waste processing party exceed EUR 205/tonne30 [73]

Materials	Recycling rate
Copper	98%
Cast Iron	98%
Aluminium	95%
Steel	92%
Cables	90%
Foundations	50%
Fibre glass	15%
Epoxy	15%
Magnet	5%

Table 2.4: Recyclability of materials. Source: Decomtools [7]

Figure 2.11 from Joeman [31], shows the materials used in a WTG, the method to recycle or discard the materials in any other way. Combined with the information stated in Table 2.4, the overall capability to recycle an offshore wind turbine is around 80%-84% [6] [7].

2.7. Legislation

Installation, the duration of exploitation and decommissioning are bounded by laws and regulations. Both national and international legislation state regulations concerning offshore wind farm decommissioning operations, operators and installers have to abide by. This chapter will help us focus on setting boundary requirements for future research.

Figure 2.12 displays the share of offshore wind energy production in Europe in 2020. For that reason, the legislation of the top 5 contributing countries, alongside the international regulations will be discussed in this chapter.

2.7.1. International law

The United Nations Convention on the Law of the Sea (UNCLOS) is an international agreement concerning marine and maritime activities. This agreement presents regulations towards installation and removal of offshore structures. Article 60, paragraph 3 states the following: ”Due notice must be given of the construction of such artificial islands, installations or structures, and permanent means for giving warning of their presence must be maintained. Any installations or structures which are abandoned or disused shall be removed to ensure safety of navigation, taking into account any generally accepted international standards established in this regard by the competent international organization. Such removal shall also have due regard to fishing, the protection of the marine environment and the rights and duties of other States. Appropriate publicity shall be given to the depth, position and dimensions of any installations or structures not entirely removed.” [45]. Together with the standards from the International Maritime Organization (IMO):”Guidelines and Standards for the Removal of Offshore Installations and Structures on the Continental Shelf and in the Exclusive Economic Zone” [23]. Article 1, paragraph 1 states: ”Abandoned or disused offshore installations or structures on any continental shelf or in any exclusive economic zone are required to be removed, except where non-removal or partial removal is consistent with the following guidelines and standards.” Finally the Oslo - Paris (OSPAR) convention. This convention pronounces, as did UNCLOS and IMO, that disused offshore structures, pipelines and installations for the sake of offshore activities will have to be removed and may not be left in situ without proper permits of the contracting parties. However, the term ”offshore activities” does not include wind energy production as ”offshore activity”. Thus, these regulations do not apply to wind farm decommissioning. UNCLOS states in Article 208 that regulation of prevention, reduction and control of the pollution from seabed activities is subjected to national jurisdiction. National legislation of the top five wind energy producing countries will be discussed next.

2.7.2. National legislation

UNCLOS made clear, is that international standards and guidelines depend on local legislation. Laws imposed by the country the project is situated in. However, in most of the top five countries seen in Figure 2.12, besides a financial guarantee that decommissioning can and will be paid for, no strict regulations concerning decommissioning have been stated.

Belgium
In Belgium it is obliged to issue a bank guarantee before the permit is requested and the site must be returned to its original state after decommissioning. No strict dates have been set due to the noticeable uncertainties regarding decommissioning.

Denmark
Danish law does not include specific requirements regarding decommissioning of offshore wind farms. Decommissioning liabilities are regulated in the construction licence and in the electricity production authorisation issued by the Danish Energy Agency (DEA), as well as in the concession agreement (if the wind farm is established following a tender procedure) [47]. This agreement also includes a guarantee for payment for decommissioning and thus varies from farm to farm. The decommissioning plan has to be submitted two years at most after the last energy production. The seabed must be returned to its original state, no remaining parts may be exposed as a consequence of natural, dynamic changes in the seabed.

Germany
Germany has guidelines of maximum noise emission during installation and decommissioning. No more than 160dB [43] may be produced at a distance from 750m from the sound source. Other end-of-life phase regulations have not been defined.

Netherlands
The regulations regarding offshore decommissioning in the Netherlands is to be found in the Water Decision. All offshore installations, including cables have to be removed once it is not in use anymore. However, exemptions can be made by the responsible minister if more damage is made to the marine environment by removing the structures. For instance, the partial removal of a monopile support after the lifetime has finished is permitted. The monopile has to be cut at least 1.5m below seabed [57]. Just as Germany, noise regulations have been set. A maximum of 2 years is given for dismantling the offshore structure after exploitation has stopped. The licensee is obliged to pay €120.000 per MW installed for financial reassurance after 12, 17 years of installation and one year before decommissioning starts. €360.000 per MW is mandatorily reserved for decommissioning. This lies in the ballpark of the expected costs of decommissioning. Also, it is a similar deal the Danish government states in the Decommissioning Permit. Noise emissions may not exceed 159-172dB, depending on the amount of turbines installed and the period the pile driving is taking place. 30 minutes prior to driving, acoustic deterrent devices have to be used, to drive away any marine life.

UK
Only the United Kingdom has strict rules concerning decommissioning. Prior to licensing, the developer must share a full decommissioning plan with Business, Energy & Industrial Strategy (BEIS) and how is dealt with costs. As article 9.1.3 reads: ”BEIS aims to make sure that developers/owners are planning for their decommissioning liabilities at the beginning of their

projects and will make adequate provision to ensure that sufficient funds are available to meet their liabilities in line with the international obligations to decommission appropriately” [8]. No obligations stated concerning the costs per MW for decommissioning. In this plan, the ”Best Practicable Environmental Option (BPEO), that is the option which provides the most benefit or least damage to the environment as a whole, at an acceptable cost, in both the long and short term is chosen. (In essence, the choice made should involve balancing the reduction in environmental risk with the practicability and cost of reducing the risk.) A solution might be for foundations to be cut below the natural sea-bed level at such a depth to ensure that any remains are unlikely to become uncovered. The appropriate depth would depend upon the prevailing sea-bed conditions and currents” [13]. BPEO is used in estimating the best option for decommissioning. This method has already been used for decommissioning in the offshore oil and gas industry. The BPEO tool is made up of five areas consisting of offshore pipelines, onshore pipelines, jackets, seabed deposits and cutting methods and depth. Each of these areas are subjected to assessment criteria with 5 levels: high, medium - high, medium, medium - low and low. A multi criteria assessment is executed, resulting in a best practical and environmental option [22].

2.8. Literature gap

The concept of felling offshore wind turbine has been mentioned by Adepipe [2], Kaiser [34] and has been the subtopic of the thesis of Urnes [72], however no in depth research has been executed. Both articles and the thesis did not mention techniques, tools used or a logistical approach to this problem.

2.9. Unit decision

To apply the new decommissioning technique, a choice of unit to accommodate this method, has to be taken. The majority of offshore wind turbines have been installed using jack-up units. A significant decrease in vessel dynamics can be observed in compared to floating vessels. These units guarantee a stable, nearly static working platform, precise lifting operations can be performed and are therefor the unit of choice for WTG installation. Electing a jack-up for decommissioning purposes creates a situation in which decommissioning can be compared to installation and gains or losses can be set side by side. Combined with the statement: Like previous jack-up generations, it seems their viable economic lifespan again is reduced to just 10 years, rather than a more healthy 25 years, the company (Ulstein) added in the Ship & Offshore magazine [46]. Jack-up units are out of business after ten years of service. This research was performed during an internship at GustoMSC located in Schiedam. GustoMSC specializes in design engineering of offshore vessels and units. Having a market leading track record in delivering designs for jack-up units globally, GustoMSC is keen to understand and accommodate techniques regarding offshore innovations. It is therefor justifiable to select a GustoMSC designed jack-up unit. The most produced jack-up unit of GustoMSC is a NG-2500X (New Generation - X-braced legs). A unit equipped with a 300t or 400t (depending on the version) crane.

2.9.1. Environmental conditions

The NSR is rough sea, high waves and high velocity winds are challenging. The unit must be able to perform decommissioning tasks in North Sea conditions, equal to reversed installation. Data for weather workability of the NG-2500X is available shown in Table 2.5.

	Year round	Summer
Water Depth	45.5m	52.6m
Air Gap	12.9m	12.9m
Wind Velocity	38.8m/s	27.5m/s
Max Wave Height	13.1m	9.9m
Wave Period	11.3s	9.9s
Surface Current	1.64m/s	1.64m/s

Table 2.5: Elevated design criteria NG-2500X

2.10. Conclusion

This report exposes the relevance and possibilities concerning renewed offshore WTG decommissioning methodologies. The market analysis clearly brings forward the need for less expensive process techniques. Where reversed installation is currently the only used method, this report reveals the room for an economically feasible yet technical innovation. There is no unequivocal methodology concerning decommissioning of wind turbines; all wind farms differ from each other. Other turbines, depths, foundations, heights and so on. Yet large similarities between different offshore decommissioning processes are identifiable. All these processes can be mentioned under reversed installation. Only focusing on the North Sea Region, a large market for the next 20-30 years, starting approximately 2030, has been exposed. What materials are turbines made of and how are these components recycled afterwards? This research has been done to lay a sturdy base in the search of innovative decommissioning methods.

Making use of the NG-2500X class jack-up, provides a steady temporary platform to execute decommissioning. As safety is of the utmost importance, new methods must abide by strict safety rules. Innovative methods leading to less hazardous situation for crew is a step forward. Also, durability and sustainability are important factors to the design of the new method. Combined with the dismantling strategies regarding onshore high-rise structures, proven onshore concepts might be executed offshore.

There is an evident need for a new method. A well-advised conclusion can be drawn from the information given in this report, namely a further investigation in the possibilities of future offshore decommissioning. What technical obstacles will new methods encounter and in what manner is this technique favourable over reversed installation.

The next step in this research is focus on out of the box possibilities for new decommissioning methods. Onshore dismantling techniques might be a base of inspiration, forming a set of alternative solutions for offshore WTG decommissioning. This complete process shall include transport of WTG components to shore. These alternatives will be subjected to a cost and durability analysis, researching the effects on sustainability and expenses of the whole process. Answers will be sought for how these processes are influenced by as a result of distance to shore and amount of turbines placed in a farm. A multi criteria decision analysis will be performed, narrowing the techniques and transport processes down to two methods, where further investigation will lead to an in depth research in the method with the highest chance of cost reduction and sustainable engineering of offshore wind turbines decommissioning.

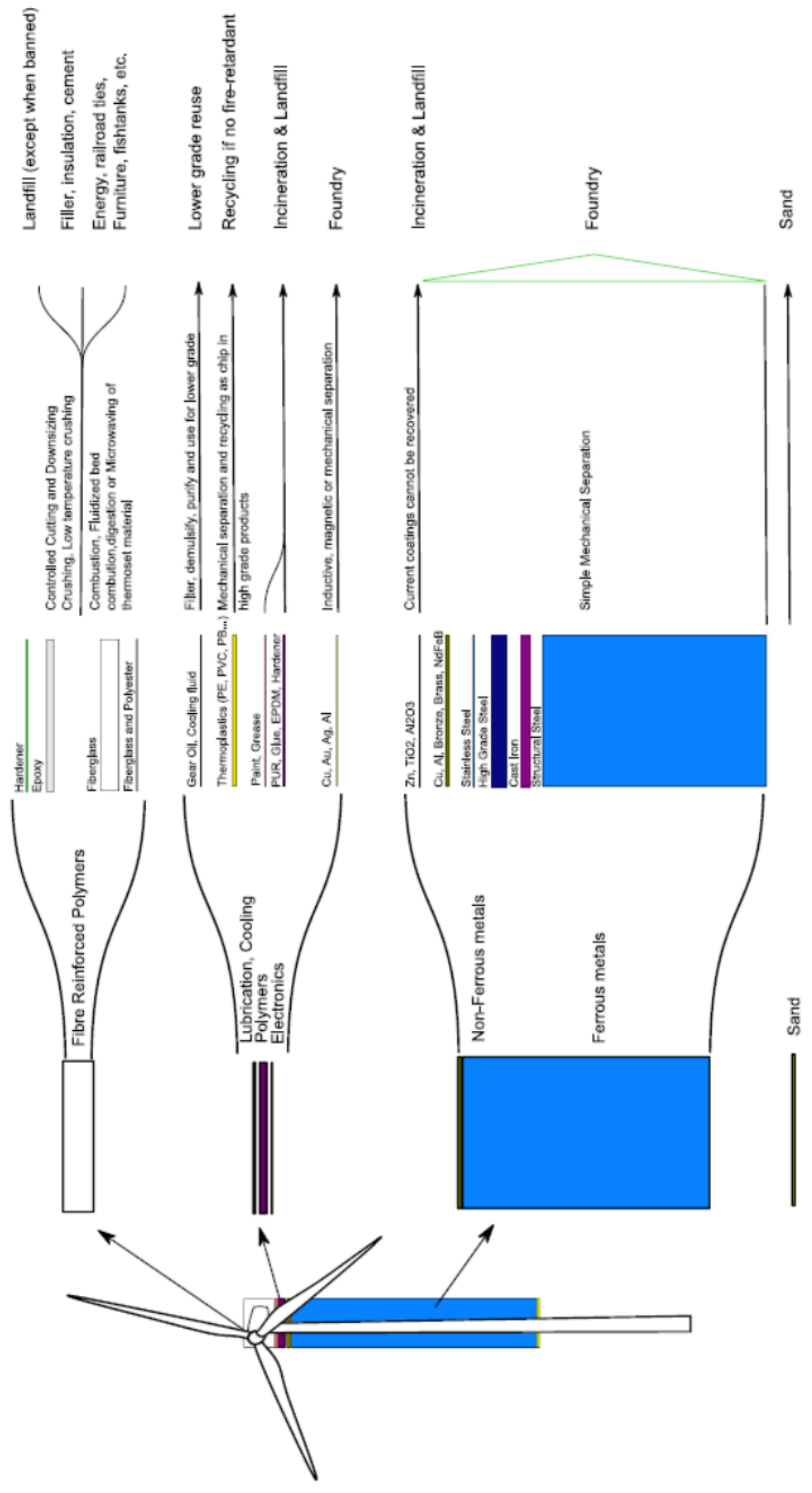


Figure 2.11: Recyclability of WTG components. Source:[31]

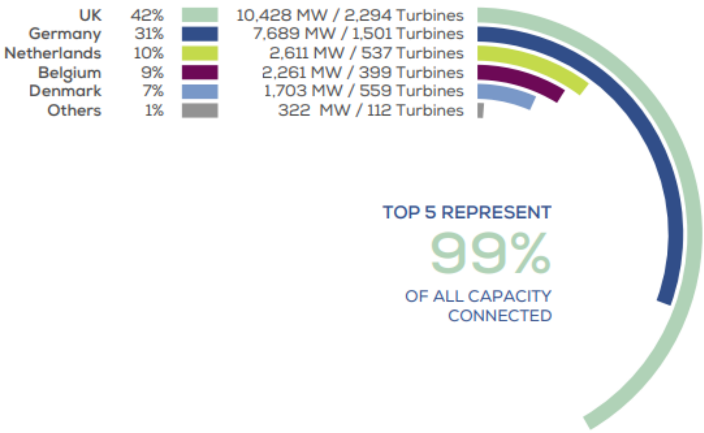


Figure 2.12: Cumulative installed capacity (MW) and number of turbines by country. Source: Windeurope [53]

3
Felling

Felling is the act of cutting down trees at the pedestal, causing the tree to fall over. This method is often applied to decommissioning of chimneys, and is noticed in several different onshore turbine decommissioning projects. As felling has been mentioned in several articles as the only alternative next to reversed installation, this method is looked into. This thesis will look into the complete decommissioning operation from mobilization of the vessels, to delivering the old turbines in harbour using the felling method. By zooming out and taking the harbour as model boundary, a strong comparison can be made between reversed installation and felling, showing similarities and differences between the variety of decommissioning methods and procedures. The felling operation is just a mere element of the complete decommissioning process, and can be divided into the following sections.

- Felling
  - Uncoupling
  - Directionality
- Hinge
- Floatation
- Transport

All separate operations will be studied comparing their safety, cost of operation, environmental impact and durability to the so far only used decommissioning method. As reversed installation is the only applied method of decommissioning, the solution of new offshore decommissioning methodologies may be sought in existing demolition techniques, both on and offshore. Thorough investigation on how these techniques can be applied offshore may result in feasible and applicable methods. This chapter discusses both onshore demolition techniques and offshore dismantling processes, focusing on high rise structures and splitting/cutting techniques, composing the framework for the desired solution.

3.1. Procedure

Mentioned before in chapter 2 besides reversed installation another possibility of offshore WTG decommissioning might be possible. Felling is a method applied for multiple demolition purposes. Removing a tree and starting from the top working down only happens in densely populated areas with structures vulnerable for tree impact. However, the most economical and quickest method to dismantle secluded trees with enough space around, is cutting the tree at its base, causing the tree to fall. This technique was also often used the demolition of old chimneys. Unfortunately, as the the majority of chimneys are located nearby critical and vulnerable structures, the felling of chimneys has drastically decreased. Onshore the felling principle has been executed several times on multiple locations. The felling operation has been carried out using different techniques. Either using explosive charges or a flame cutter, both techniques were carried out at and around the pedestal of the turbine.

3.1.1. Uncoupling

As mentioned above, the complete decommissioning operation is subdividable in five sections. For each section all reasonable options will be discussed. Starting with uncoupling. The turbine tower must be uncoupled somehow, causing it to fall over. Listing all onshore and offshore tools used to separate large pieces of metal. In section 4.2 a summary of the possible splitting and cutting techniques combined from Suni [64] and Maeland [39] is to be found. These techniques are all added in the MCA further in this thesis and compared to each other on the several different characteristics such as duration and cost of process. Moreover these characteristics and weighing in chapter 5.

3.1.2. Direction

Once the turbine tower has been separated from the transition piece, whether that has been done by cutting, splitting or unbolting, the tower will likely fall over. The tower must, under all circumstances, fall in the opposite direction the jack-up is positioned in. A turbine falling in the direction of the jack-up might cause serious damage (as loss of life) and must be avoided all times. Conventional methods contain several techniques to push or pull a structure to one side. Onshore wind turbine decommissioning, executing the dismantling procedure based on a felling principle used tensioned cables connected to the nacelle and halfway the tower. Other techniques can be found in tree felling, where a wedge of jack are regularly used.

3.1.3. Hinge

A felling structure hinges at its ”breaking point”. In tree felling, the hinge is a carefully cut chunk of wood. A notch is made for both aiding the direction of the felling and make space available for plastic deformation of the material. This method is also applied to chimney and onshore WTG felling. Prior to investigation the possibilities regarding (mountable) hinges, wind interaction with the turbine is investigated. This calculation gives an insight in the dimensions of the overturning moment, based on which a hinging method can be applied. Figure 3.1 shows wind loads acting on a turbine. These wind loads result in an overturning moment, pushing over the turbine.

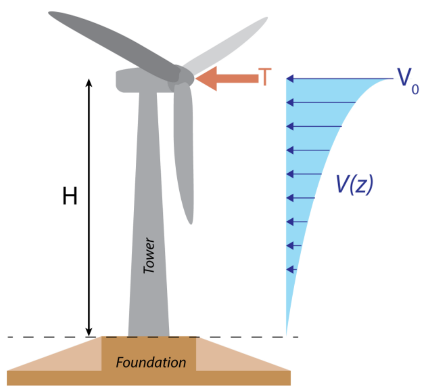


Figure 3.1: Overturning moment [51]

$$M = \frac{1}{2}\rho C_t A V_0^2 H + \frac{1}{2}\rho D_t C_{Fx} \int_0^H V(z)^2 z dz \tag{3.1}$$

Before the felling of the turbine commences, the blades are removed by the on deck crane. Turbine decommissioning can only be executed during crane operational weather conditions. Emre [71] states crane operations can be performed in wind conditions up to 10 m/s while wind speeds are limited at 7 m/s for blade installation and removal operations. 10 m/s is taken as limiting velocity for calculating the overturning moment. During stable wind conditions, the wind integral in Equation 3.1 can be approximated by:

$$V(z) = V_0(\frac{z}{H})^{\frac{1}{7}} \tag{3.2}$$

Substituting Equation 3.2 into Equation 3.1 simplifies to:

$$M = \frac{1}{2}\rho V_0^2 (C_t A H + \frac{7}{16} D_t C_{Fx} H^2) \tag{3.3}$$

Where

Unit	**Component**
C_t	Thrust coefficient between wind and spinning rotor
A	πR^2, swept surface of the turbine blades
R	Length of turbine blade
V(z)	Vind velocity as a function of z
ρ	Air density
V_0	Wind velocity
D_t	Turbine tower diameter
C_{Fx}	Wind drag coefficient
H	Tower height

Table 3.1: Components overturning moment calculation

3.1.4. Floatation

After the event of felling, the turbine must be recovered. Either the turbine will sink to the bottom or some sort of buoyancy has to be generated. Offshore several forms of floating devices are widely used. For jacket launches, steel buoyancy tanks installed to the exterior of the jacket, to ensure up-ending of the jacket. A jacket slides of a ballasted launch barge, falls in the water and is automatically upended due to the buoyant forces of the tanks. After this operation, for instance a crane vessel is used to install the jacket in the correct place. This principle forms one of the possible options to be added in the Multi Criteria Analysis (MCA). Another option is making use of barges, they are comparable to the buoyancy tanks with a large deck capacity for transport of heavy structures. Positioning a barge at the pedestal before uncoupling the tower from the transition piece and precise aiming of the falling turbine tower will lead to a fell-and-go operation. The barge can, depending on its size and distance to harbour, directly be towed away by tugs or brought to the next turbine. A third option is making use of inflatable bags, either internal or external. Bags which are used in ship salvage are fixed to the in- or exterior of the tower and nacelle and are inflated, generating enough buoyancy to prevent the turbine from sinking. These bags are impact resistant and will also be added to the MCA. A final option in generating enough buoyancy was given by Urnes [72], plugging the tower airtight, that the tower would generate as one (or separated over several compartments) large buoyancy tank itself.

3.1.5. Transport

The WTG has been felled. Now the wind turbine has to be transported to the harbour to recycle every piece possible. The harbour is chosen as end-point, making the comparison between reversed installation and a new method uncluttered. Forms of transportation taken into account in the MCA are float & tow, launch barge & tug, crane, barge & tug, semi-submersible & tug and finally flo-flo vessel (Float-On / Float-Off) & tug. All options will be explained below.

Method	Description
Float & Tow	Turbines will be tugged to harbour one by one by a tug.
Launch Barge & Tug	A large launch barge will be ballasted, generating a slope which the felled turbines can be hoisted on to. This launch barge will need at least three tugs to assist in maneuvering and transit.
Crane, Barge & Tug	Similar to the previous option, a barge will be used. This barge will not be ballasted, instead, a crane vessel with a main crane of at least 500t (for 3,6MW turbines) or 1000t (for 8MW turbines), lifting the floating turbines out of the water, onto the barge. The barge will commute between the harbour and wind turbine site.
Semi-submersible & Tug	A semi submersible will be ballasted to a certain depth where turbines can be floated onto the submerged deck. These turbines are brought to the semisub by tugs on site.
Flo-Flo vessel & Tug	Comparable to the semisubmersible, Flo-Flo vessels (for instance Rolldock) have a relative high cruising velocity, a low dayrate and en quick ballasting system. Usually two or three turbines fit on the deck of a Flo-Flo vessel.

Table 3.2: Transport methods

3.2. Conclusion

We have established that the complete decommissioning procedure exists of five different sections. The uncoupling, directionality, hinge, floatation and finally transport. All five sections will be separately reviewed. In the next chapter demolition, splitting and cutting techniques will be discussed, generating input for the first of five sections.

4

Dismantling strategies

4.1. Onshore demolition

High-rise structures have been decommissioned for decades, various methods of dismantling structures have been worked out onshore. This chapter contains an introduction to the dismantling techniques of onshore high-rise structures. Since decommissioning of offshore wind turbines is a relative new and inexperienced industry, examples from onshore decommissioning might be applied to the offshore industry.

Figure 4.1 shows that demolition of high-rise structures can be divided into 4 different divisions: total, selective, interior and strip-out demolition where total demolition consists of four categories which can be subdivided under the following different techniques [42]:

- Implosion demolition
- Chemical demolition
- Controlled demolition
  - Piecemeal
  - Saw cut
  - Thermal lance
  - Water jet
  - High reach
  - Cutting and lifting
- Mechanical demolition
  - Excavator and bulldozers
  - Wrecking ball
  - Pusher arm technique
  - Hydraulic shear
  - Pulverizer

4.1.1. Total demolition

Total demolition is a principle chosen if the full structure can be taken down. The site can be reused for building new structures. This method is subdivided in four different methods.

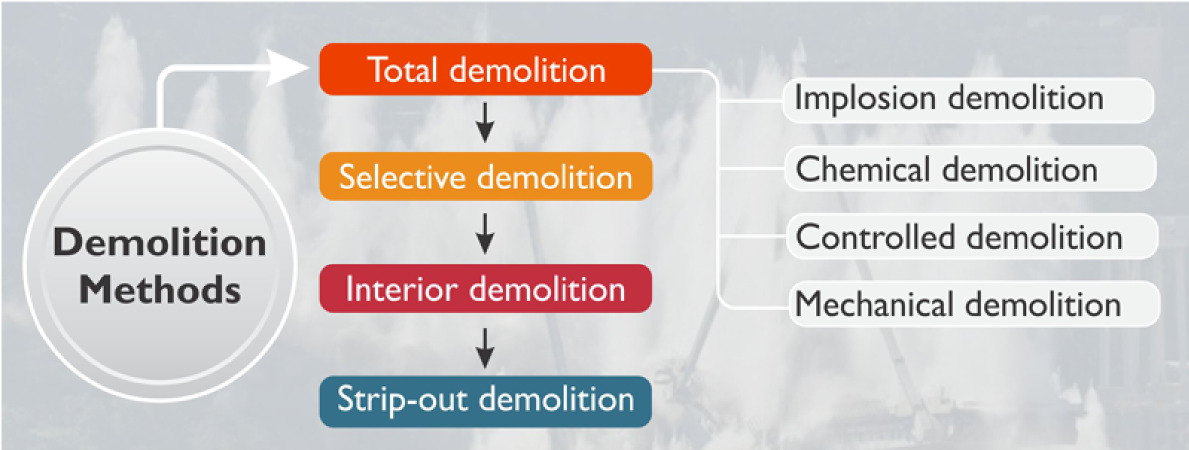


Figure 4.1: Demolition methods. Source: ConstroFacilitator [9]

Implosion

This method uses explosive charges for demolition of a structure. The structure will implode or tip over, usually applied on tall chimneys or high buildings. Onshore in practise this method has proven itself successful on several locations worldwide, including the larger wind turbines [16]. Unfortunately, applying this method offshore might not be a feasible option due to the unmanageable scatter of debris and noise regulations.

Chemical demolition

Also known as non-explosive chemical expansion agents, are poured in drilled holes mixed with water. In contrary to explosive charges, chemical expansion agents expand slow and silently, therefore reducing the noise and vibration significantly. Additional advantages are the absence of fly rock, debris and other environmental pollution. The use of non explosive demolition agents is mostly used in concrete or rock cracking [27]. Compared to the use of explosive charges, non explosive chemical expansion agents are a lot more expensive [42].

Controlled demolition

This form of demolition makes use of a wide variety of tools and techniques. Beginning with piecemeal demolition. Piece by piece, proceeding in general from top to bottom. Saw cutting tools for instance chainsaws, conventional disc saws, diamond drills and wire saws are used. Thermal lances are capable of cutting through virtually every material as its functioning temperature is near the melting temperature of the material which has to be cut. Water jets can cut through concrete by blasting water on supersonic speeds onto the pores, causing the concrete to break. These tools can be applied to high reach machinery to increase the workability at heights. By cutting piece by piece, without using hammering, a low noise demolition is achieved. This results in careful dismantling of the structure with no to little damage or inconvenience to surrounding structures. Working this precise does however hold a negative side effect, since it causes the process to be very time consuming, therefore economically challenging.

Mechanical demolition

Mechanical demolition is a harsher yet common way to tackle a dismantling project by making use of large equipment like excavators or heavy machinery fitted with hydraulic shear, hammer or crushing tools. If the surrounding permits, a pusher arm technique is applied, by applying a horizontal thrust to the structure causing it to tip over. A wrecking ball attached to a high reach arm is sometimes used, however this method is less precise than the other mechanical demolition techniques.

4.1.2. Selective demolition

When not the whole structure is up for demolition, selective demolition is the best option. Only removing parts that need replacement. This method is also an applied technique in the offshore industry as wind turbine components may need replacement over the course of years. Wind turbine blades for instance require repair every 2-5 years [44]. This demolition technique will also be applied if repowering, discussed in subsection 2.5.1, of a turbine is carried out.

4.1.3. Interior demolition

Interior demolition a method is used when only specific materials have to be removed from a structure. In buildings this will come down to the extraction of walls, ceilings, pipes etc. In wind turbines interior demolition is usually an early stage of the total decommissioning plan, disconnecting and clearing out all internal cables, lubrication oils and loose items, to prevent any materials to be left in the surrounding area.

4.1.4. Strip-out demolition

Materials are dismantled using the highest needed precautions, since the components taken out are to be used for other purposes. This includes full reuse, partial reuse, refurbishment or recycling of the components.

As in Figure 1.2 is clearly visible, the hub height and rotor diameter increase over the course of years. The reason behind this increase lies at the capacity factor and swept area of the turbines. When doubling the length of turbine blades, the swept area, also known as the total surface, quadruples, leading to a greater swept area which energy can be retrieved from. The increase in hub height is due to multiple causes. At first, with an increase in rotor diameter, the hub height must increase. Otherwise the gap between the lowest point of the blades and the water surface might be to small. Also, placing the hub at a higher altitude, directly relates to an increase in capacity factor. Although the observed variance is broad, median capacity factor gains with higher hub heights are estimated at approximately 2 to 4 percentage points when going from 80 to 110 m and an additional 2 to 4 percentage points when going from 110 to 140 m. Between 140 and 160 m, median capacity factor gains are approximately 1 percentage point [37]. Is an increase in turbine size necessary? Yes, since not only more energy will be generated with increasingly powerful wind generators, also operations and maintenance will reduce per MW produced. Considering a wind farm consisting of 20 4MW wind turbines compared to a wind farm with 10 8MW turbines has half the amount of turbines, reducing the amount of vessel mobilizations and maintenance costs.

All demolition methods described above have been proven working methods for dismantling onshore structures. The manifold of alternative techniques compared to a single method used offshore questions whether strip-out demolition, the onshore variant of reversed installation, is the only feasible method of dismantling high-rise structures.

4.2. Offshore demolition

Offshore demolition methods do not differ greatly from its onshore counterpart. Cutting and saw techniques require the same tools. However offshore, steel is the preferred material of choice, whereas onshore a combination of steel and concrete is chosen. A list of cutting techniques used offshore from Suni [64] is shown below. Suni focused on splitting and cutting steel pipes. Since the tower of a wind turbine generator is completely made out of steel with a water resistant coating, these techniques are applicable to towers. The splitting and cutting techniques are subdivided in four groups. Mechanical methods, water jet based abrasive methods, thermal methods and explosive methods. These methods also come to surface in Maeland's [39] master thesis. All methods are briefly explained with their pros and cons in the following section.

4.2.1. Mechanical methods

Saw
A circular or straight blade with teeth removes material. Wide range of blades can cut almost everything. Easy setup. Relatively slow.

Diamond wire saw
Wire with diamond segment are dragged over/trough the object being cut and remove material. Easy setup. Doesn't need extra operators or deck space. Can cut everything softer than diamond. Fine straight cut. Must start from scratch if wire snap in middle of cut. Relatively slow.

Grinding
Friction from a circulating blade scratches away material, both the blade and material are scratched away. Simple construction. Same tool can be used with different blade. Used in small cut operation Slow speed. Used for maintenance.

Guillotine
Using hydraulic power to push a knife against an anvil. Use hydraulic power to cut materials between two knives. Effective. Can be used as safety release device. Deformation of the object being cut.

Shear cutter
Use hydraulic power to cut materials between two knives. Effective. Can be used as safety release device. Deformation of the object being cut.

4.2.2. Water jet based abrasive methods

Water jet
Using high-pressure water with abrasives to cut materials. Is a very versatile and effective process and can cut through almost any material. Can cut thick materials, up to 1500mm concrete. Need dedicated operators and deck space. Orifice wear out. Uncertainty regarding cut verification.

4.2.3. Thermal methods

Oxy-fuel
Using fuel-gas and pure oxygen to oxidize the metal in an exothermic reaction. Cost effective. High cutting speed. Need experienced operators or automated system for fine cut. Can cut only low carbon steel and low alloy.

Laser
Using a focused laser beam to heat the metal, the heated metal is either blown away with air or N_2 or oxidized with the use of pure Oxygen. Can cut materials not possible to cut with oxy-fuel. Can cut complex patterns. Small area affected by heat. No wear out of cutting equipment. Not developed enough for subsea operations.

Plasma
Using heat from gas in the plasma state to melt and vaporize the electrically conductive material. Can cut all electrically conductive material and materials not possible to cut with oxy-fuel. Can use clean air as gas. Rough cut with handheld equipment.

4.2.4. Explosive methods

Explosives
An explosion is a very rapid exothermic chemical reaction where the explosive material is converted to very hot, dense, high-pressure gas that can cut through materials. Effective, can blow away everything. Effective and safe on big structures. Dangerous if used wrong. Transport with strict safety measures.

5

Operational analysis using an MCA

Knowing the different methods of decommissioning, splitting and cutting of materials on- and offshore, a qualitative Multi Criteria Analysis (MCA) was set up to compare all possible options under five different sections of the complete decommissioning process. In every section, all possible methods are compared to each other in terms of specific section criteria.

5.1. Uncoupling

Just as safety and environmental impact, an important incentive of this research is reducing the costs of the total operation. For that reason the uncoupling method is measured on the following criteria: Cost of process, average investment costs, duration, feasibility, environmental impact and safety. Since the vast majority of the offshore turbines are SWT-3.6MW turbines and those are the largest turbines whose installation was done by a NG-2500X, dimensions of a 3,6MW turbine have been selected as a minimum. Furthermore, the smaller 2-3.6MW turbines are the oldest turbines, therefore the first to be decommissioned. More about turbines, trends and an application of this technique can be found in chapter 7. For now, parameters needed for this section are the material, diameter and thickness of the tower.

Material	Coated steel
Diameter	5 [m]
Thickness	25 [mm]

Table 5.1: Tower dimensions 3.6MW turbine

A pre-selection can already be made by filtering out all techniques that have a time consuming duration or simply are not able to complete the task of cutting through the turbine tower.

Before crossing out possible options based on duration or feasibility, a rough estimate can be done that reversed installation takes about 27 hours per turbine. This does not include the time it takes for mobilization, preloading, jacking up and jacking down. This puts the duration of every option in perspective. Since a significant decrease in duration is wanted, the following techniques can be crossed out immediately. Diamond wire saw cut, a circular saw and grinding are three options which take up a lot of time compared to the rest and thus can be crossed out. Guillotine and shear cutters have a max shear thickness of 6mm and therefore also fall off. Finally explosives. As previously mentioned in section 2.7, strict legislation regarding noise limits during installation, maintenance and decommissioning is mentioned. Depending on the duration and time of the year, maximum noise limits vary between 214 and 244dB, whereas a destructive explosive charge will exceed those limits, generating a shockwave of 279dB [18]. Remaining options are plasma, oxy-fuel, water-jet, laser cutting and unbolting. These techniques will be filled into the MCA.

Uncoupling technique	**Safety**	**Investment costs (avg.) [$]**	**Duration [hrs]**	**Limit thickness [mm]**	**Environmental impact**
Plasma	ROV	75.000	0.18	50,8	None
Waterjet	ROV	225.000	3.6	16500	Produces abrasive waste
Oxy-fuel	ROV	75.000	0.17	1000	None
Laser	ROV	675.000	0.73	25	Not usable under water
Unbolting	Personnel in tower	-	0.83	-	No abrasive waste

Table 5.2: Uncoupling MCA

5.2. Direction

During the uncoupling operation, at some point the tower will lose its structural rigidity and collapse. To avoid the turbine from falling into the direction of the jack-up unit, a combination of preventive measures can be taken. During the lifetime of an offshore wind turbine, many vibrations might cause the turbine to slightly come under an angle as a result of minor liquefaction of the soil over the span of years. Settlement of the seabed can cause minor a deflection, leading to a "leaning" turbine. Advantage can be taken from this unwanted phenomenon. Leaning structures fall in the direction they lean in omitting wind and other external forces acting on the structure. Taking wind into account, a conservative estimation can be done, calculating forces acting on the turbine and nacelle. Assuming the turbine is perfectly vertical after its years of service, forces acting on the turbine, influencing the direction of felling are the wind and the offset of the centre of gravity (CoG) of the nacelle. The CoG of a 3.6 MW nacelle has an offset of 1.12m measured from the centre-point of the tower. Equation Equation 3.3 consists of two parts. The first section accounts for the overturning moment due to the rotating rotor, the section section accounts for the wind acting on the tower. A maximum wind velocity of 10m/s is taken, as this is the limit crane operations.

$$M = \frac{1}{2}\rho V_0^2 (C_t A H + \frac{7}{16} D_t C_{Fx} H^2) \tag{5.1}$$

Where

	Value	Unit	Component
C_t	0.8		Thrust coefficient between wind and spinning rotor
A	8992	$[m^2]$	πR^2, swept surface of the turbine blades
R	53.5	$[m]$	Length of turbine blade
V(z)			Wind velocity as a function of z
ρ	1.225	$[kg/m^3]$	Air density
V_0	10	$[m/s]$	Wind velocity
D_t	5	$[m]$	Turbine tower diameter
C_{Fx}	0.5		Wind drag coefficient
H	55	$[m]$	Tower height

Table 5.3: Parameters overturning moment calculation of a 3.6MW turbine

	Overturning moment [Nm]
Spinning rotor + tower	$3.93 \cdot 10^7$
Tower	$5.19 \cdot 10^5$
CoG Offset	$1.79 \cdot 10^6$

Table 5.4: Overturning moment

These results show the maximum overturning moment acting on the turbine as a result of wind. Since the WTG not be in service during decommissioning, and the blades will be removed before felling, the top result can be neglected. The nacelle can rotate $360°$. During decommissioning, the nacelle will be positioned with the hub facing the jack-up unit as the CoG is placed further to the back of the nacelle. This will generate an overturning moment away from the jack-up unit. Combined with a possible slanting tower, this will generate enough overturning moment for the turbine to fall in the destined direction. However, as wind might pick up during decommissioning, these forces might not suffice in felling the WTG. Already mentioned in subsection 3.1.2, several methods have been applied to similar operations. The South Dakota turbine felling was pulled by cables attached to the nacelle and at the middle of the tower. These attached cables ensured the turbine to fell in one specific direction. Offshore this can be done by a tug pulling the turbine. Other commonly used options are a pusher arm or a jack. A pusher arm will generate an undesirable transverse load on the legs of the jack-up unit, therefore be excluded from the list of possibilities. Pulling the turbine using tugs and cables raise several safety issues. A cable has to be installed from the nacelle and halfway around the tower and the cable must be secured to the tug. At last the tug will stay connected to a falling WTG. These operations and events will increase levels of risks, and therefore decrease overall safety. Since safety is the priority, this option will not prevail. Finally, offshore jacks work up to 800t per jack, and thus capable of lifting the complete turbine. This will not be necessary since only tilting the cut turbine is enough. The offshore application and capacity of these jacks have proven this concept.

5.3. Hinge

After supporting and jacking the cut turbine, the turbine will fall and hinge around the point where the cut was made. Two options are possible. Either an exterior hinge is placed on the turbine or the steel around the cut will undergo plastic deformation and function as a hinge. This last called event is widely used in tree felling, chimney felling and the South Dakota turbine felling. This technique is commonly used and is a proven technique. Plastic deformation calculations can clarify which cut must be made to ensure the hinging properties of the tower will suffice. Additional cons of using an exterior hinge are that installing the hinge requires an additional lifting operation, which increases risk on hazardous situations. The hinge will must be acquired, increasing the initial investments. Also, as ”time is money”, installation of the hinge takes time, and therefore surges the decommissioning costs. Not only will the hinge depend on the diameter of the turbine tower, thus not be able to be applied to types of turbines, but also a possibility of breaking the hinge has a negative impact on the choice. Thus the tower itself will function as a hinge.

5.4. Floatation

As mentioned in subsection 3.1.4, four different techniques of retrieving the turbine after being felled have been discussed. These methods are added in the MCA and reviewed over the following criteria. Initial investment costs, HSE and technical feasibility. As addition to the four floating techniques, a fifth method ”sink & retrieve” will be added to the methods. Before felling, the turbine will not be equipped with any additional floatating measures in contrast to all the other four methods. The turbine will sink to the bottom where a crane vessel will search and retrieve. All methods will be reviewed relative to each other.

	Safety	**Investment costs**	**Technical feasibility**
External floatation device	Extra lifts needed	Medium	Prone to impact, not durable
Inflatable bags	One extra lift needed	Low	Lightweight and easy to operate. Low storage and transport costs
Barge	Barge must be installed, thus crew present. Risk of missing barge whilst felling	High	Large impact to barge, no multiple turbine felling operations possible.
Plugged tower		Low	Takes time to install, tower prone to rupture, losing buoyancy
Sink & retrieve	Dive and retrieve operation hazardous, extra lifting operations needed	High	Hazardous for environment, seabed destruction.

Table 5.5: Floatation measures

Floating the entire felled wind turbine proves to be a technical obstacle. The inside of a turbine tower is almost completely empty from the bottom up with a staircase placed on one side, and cables, directing the generated power from the generator to the subsea cables, surrounding the rest of the interior of the tower. However, placing internal inflatable floaters inside the tower has some technical obstacles to overcome. First, taking into account that the relative lightweight deflated bags weigh around 100kg each, asking personnel to carry that up an 88m high tower, is impossible. Also, due to deformation of the turbine tower after impact with the water surface, the stairwell, or other objects, might result in sharp edges, rupturing the internal inflatable bags. A decrease in buoyancy appears when multiple floaters lose their floating ability. Instead of installing these floaters inside, another option is placing these bags on the exterior of the tower. For instance, one may make use of the jack-up crane, lifting the floaters into place. Yet, other difficulties come into play here. Due to the combination of the

Figure 5.1: 17.5t lifting capacity Buitink floater [65]

large velocity and the mass of the falling turbine, these floaters may not be located between the tower and the water in order to prevent exploding of the floaters due to the impact, and thus be fixated on the opposite side of the turbine. Additionally, some level of redundancy must be included in case some floaters or fasteners fail.

Floaters used for this operation are 17.5t lifting capacity floaters from Buitink shown in Figure 5.1. These floaters are widely used for offshore lifting and salvage operations. Floater specifications can be found in Table 5.6.

Length	4.6	$[m]$
Diameter	2.4	$[m]$
Lifting capacity	17.5	$[t]$
Weight floater	100	$[kg]$

Table 5.6: Floater specifications

The amount of floaters needed depends on the mass of the tower and the density of steel and water. A conservative assumption made is that the turbine, with its blades removed, exists solely of steel.

Density steel	8000	$[kg/m^3]$
Density seawater	1025	$[kg/m^3]$
Mass 3.6MW turbine with blades	435	$[t]$
Mass 3.6MW turbine bladeless	373	$[t]$

Table 5.7: Caption

The volume of the steel generates buoyant forces. These can be subtracted from the total mass of the turbine, lowering the 373t to a minimal required 325t lift force to hold the turbine at the water surface. A certain level of redundancy must be added in case either a floater ruptures, some straps/chains securing the floaters to the tower break or any other unforeseen failure occurs. This prevents the turbine from potentially sinking. The level of redundancy taken is two, resulting in an installed amount of 650t of lifting force for this specific turbine. 39 Of these specific floaters are needed to keep each turbine afloat. Another crucial necessity is the height at which these floaters are installed with respect the transition piece. Figure 5.2 visualises the CoG (Centre of Gravity) of the tower, nacelle and combined CoG. The combined weight of the total floater configuration, including the straps, reaches 7800kg. For every row on the configuration, multiple straps have to be snapped in. An estimated 5 minutes per row will suffice, resulting the entire floater lifting operation to take a little over an hour.

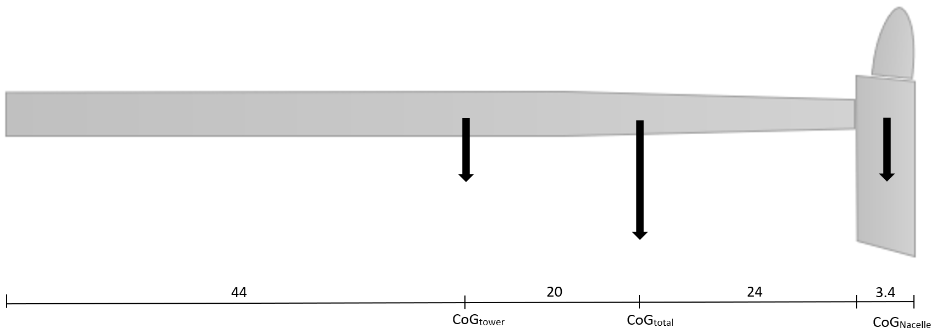


Figure 5.2: Centre of gravity 3.6MW turbine in [m]

Careful arrangement of floaters ensure stability during transit in roll and pitch. To accomplish a stable floating turbine, a configuration of floaters must be thought out. Yet this is still a preliminary result of basic hydrodynamics, Figure 5.3 indicates a possible solution for stable transport.

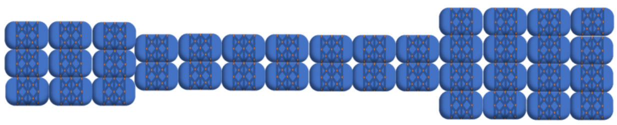


Figure 5.3: Floater configuration

This configuration of floaters supports the top heavy wind turbine, and prevents the floating turbine to tip over.

5.4.1. Floater installation

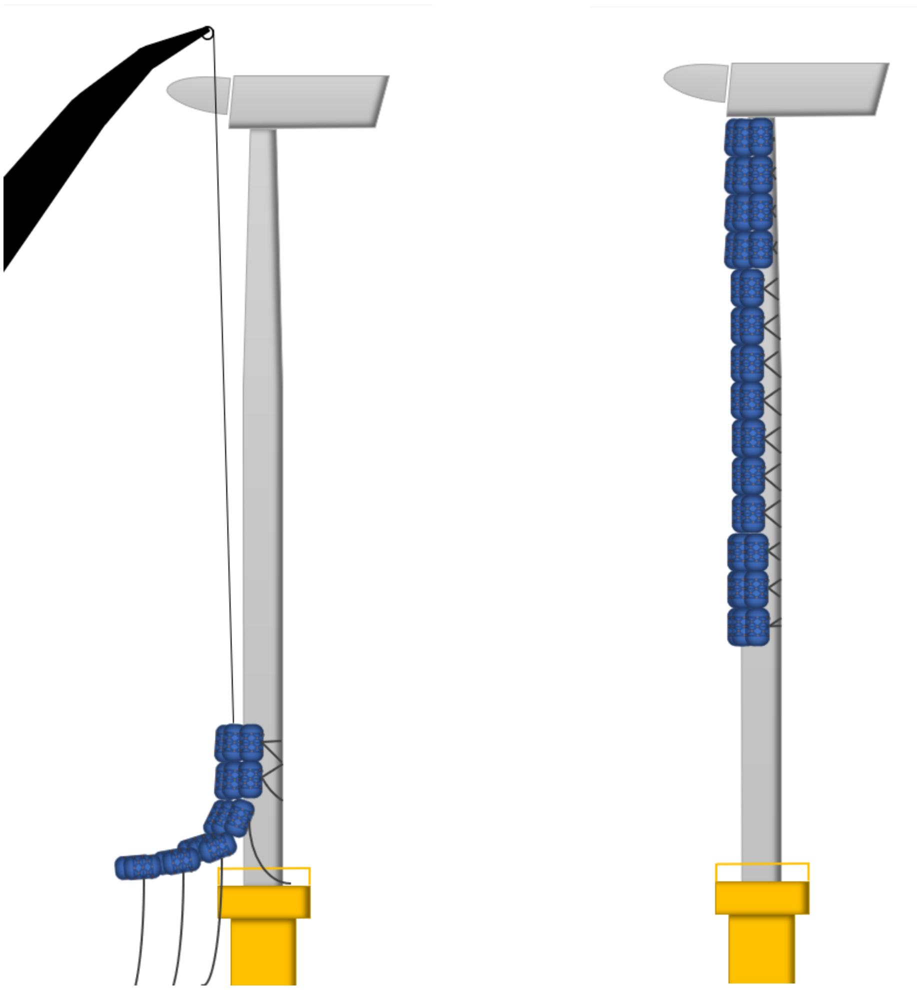
Installing the floaters requires several steps. The arrangement of floaters must be constructed prior to the jacking operation. All the floaters will be connected to each other and inflated on board before fastening to the tower commences. The floaters form one big garland. Heavy load lashing straps are connected to each intersection of the floaters. The first row of floaters is lifted and placed near the base of the the tower. The straps are wrapped around the tower and again connected to the first row floaters. As well as a strap which is connected to the second row of floaters is wrapped around. This continues until the final row of floaters is connected. Since the jack-up is placed away from the felling direction, the floaters are automatically installed the side of the turbine that does not impact the water surface. A configuration of the installation is shown in Figure 5.4a and the installed floaters in Figure 5.4b.

5.5. Transport

The final section to the complete turbine removal process is the transport of the turbines to the harbour. Different possibilities of offshore transporting methods are compared to each other in terms of operational cost, carbon emission and turbine carrying capacity. A model is made visualising the impact of cost and amount of energy used in the complete process. Before the model is explained, the different methods of transport are discussed.

5.5.1. Methods

Reversed installation solely utilizes a jack-up unit. This jack-up is used for both the decommissioning process and the transport to and from the harbour. The combination of the high day rate of the jack-ups and the time consuming operation are the core reasoning for this research.



(a) Floater installation process (b) Floaters installed

Figure 5.4: Floater installation

Investigation other transporting possibilities, a selection of broadly used offshore vessels and transport methods is made.

Float & tow
This method operates on a synergy between a jack-up unit and one or more tugs. The jack-up is exclusively appointed to decommissioning the turbines and leaves the transporting stage over to tugs. After felling, a tug will connect itself to the floating turbine and will tow this turbine to harbour whilst the jack-up can maneuver to the following turbine, hereby reducing the jack-up usage. The size of the tug and velocity of transit will be extensively explained in chapter 6.

Launch barge & tug
This set up makes use of a launch barge, a 650ft barge capable of partial submerging itself by ballasting either end of the barge, generating a slope where turbines can be hoisted onto. The launch barge used for reference in the model is the Intermac 650. The surface of the barge are roughly 47x198m. This barge must be assisted by at several tugs in order to be held in position. Comparable to the the Float & tow method, a tug will transport the felled turbine towards the launch barge where it is hoisted on board. Once the barge is completely filled with turbines, tugs will guide the barge to the nearest harbour where offloading may commence.

Crane, Barge & Tug
This combination of vessels compares to the launch barge & tug operation, however the launch barge is traded for a regular barge and hence an extra crane is needed to lift the turbine onto the barge. The crane used depends on the capacity of the crane and the type of turbine-decommissioned. During reversed installation the turbine is lifted in pieces. With felling the turbine remains in one piece, consequently a larger crane must be used. Once the barge reached maximum capacity, it will be transported to harbour where the turbines will be offloaded.

Semi-submersible & Tug
Instead of lifting or hoisting the turbines onto the barges, a semi-submersible dry dock can be used. After ballasting and the semi-submersible, tugs can float the turbines over. For reference, the semi-submersible Xiang Rui Kou is taken. A vessel with a deck space of 43x177. A large deckspace results in a large turbine carrying capacity, whilst maintaining a high cruising velocity.

Flo-flo vessel & Tug
A Flo-Flo (Float-Off Float-On) vessel is size-wise comparable to a Multi Purpose Vessel-Heavy Lift (MPV-HL) unit, capable of submerging itself so smaller vessels or other floating structures have the ability to float onto the deck. Depending on the type, this vessel is equipped with two or three on board cranes. In combination with a tug supplying the turbine to the flo-flo vessel. The major difference between the semi-submersible and a flo-flo vessel, is that a semi-submersible dry dock has an open deckspace, not covering up incoming waves. As visible in Figure 5.5, a flo-flo vessel is covered on both sides, providing a much safer workspace where current, waves and wind force act less on the floating turbines.

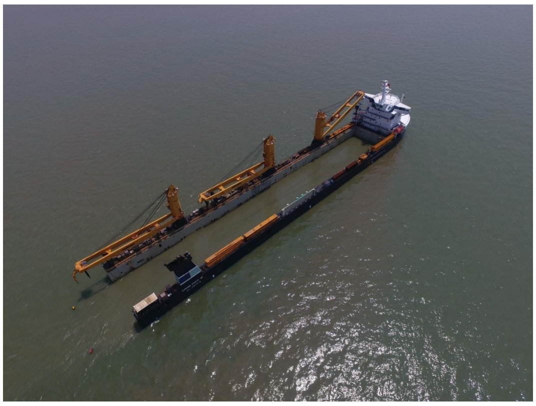


Figure 5.5: Submerged Flo-Flo vessel [24]

In the model the rolldock S-class vessels are taken for reference in the model, equipped with a submersible deckspace of 19x116m. The output of the model next chapter can advise a decision for which selection of vessel(s) to be used in the complete decommissioning process.

6
Estimation model for cost & environmental impact

A cost and energy consumption model has been made. This chapter dives into the model, explaining the inputs, assumptions made, the outputs and introduces the sensitivity of this model.

6.1. Inputs

The calculation of costs is a relative simple calculation. Equation 6.1 forms the basis of the estimation model consisting of the product of the complete duration of the decommissioning operation and the sum of the dayrates of all engaged vessels. The composition of vessels used for every operation can be found from Table 6.6 to Table 6.10.

$$Cost_{total} = Duration_{max} \cdot \sum Dayrates \tag{6.1}$$

This equation exists of 2 inputs whose greatly depend on the selection of vessels and distance to harbour. For all combinations of vessels a global estimation is made of the duration of each operations in specific. Table 6.1 shows the modes of operations for reversed installation and a corresponding estimation of duration. The the jack-up vessel has a mobilization time of +/- 340hrs per decommissioning project. The mobilization time is the time needed the unit needs to travel. A fixed distance of twice 2500km is chosen for such specific vessels. 2500km For mobilization and 2500km for returning to its original location. This mobilization time will, unlike the other inputs, only be added once to the complete calculation. The jacking operation (up & down) takes 6 hours and the reversed installation costs 27 hours per turbine. After decommissioning a WTG, the jack-up unit transits to the next turbine. This duration is the cruising velocity divided by the distance from turbine to turbine. Once the turbine has succeeded in decommissioning two turbines, it will travel to harbour where is must jack itself up and down for offloading the turbines. Once lowered and ready to sail out, the process starts over, depending on the amount of turbines in the farm. These inputs are all needed to calculate the maximum duration a unit is used. Divided by the amount of turbines decommissioned, gives the decommissioning costs per turbine.

Unit used	Mode of operation	Est. duration [hrs]
NG-2500X	Jacking (up/down)	6.0
	Reversed installation	27.0
	Turbine-turbine transit	0.1
	Jacking port (up/down)	3.0
	Site-harbour	0.7
	Mobilization costs	336.0
	Offload	2.0
	Harbour-site	0.7

Table 6.1: Estimated duration for each specific operation at 10km site-harbour distance

6.1.1. Assumptions

Assumptions have to be made to make proper guesstimates concerning vessel selection. In determining the costs and energy consumption regarding the float & tow configuration, a calculation must be performed, choosing the suitable tug. A tug must meet several requirements such as a minimum available horse power installed and transit velocity. Pulling a turbine through the water requires a large bollard pull, the towing force needed from a tug in order to reach a certain velocity.

First a specific turbine must be selected. Figure 6.1 clearly shows that 1569 of all 5180

Sum of Amount	Column Labels																		
Row Labels	2	2.3	3	3.3	3.45	3.6	4	5	6	6.2	6.3	7	8	8.3	8.4	8.8	9.5	14	(blank)	Grand Total
Areva								40												40
BARD								80												80
GE									66									200		266
Multibrid								86												86
REpower								44												44
Senvion									66	102	32									200
Siemens		229				1569	222		362		56	405	317							3160
Vestas	170		465	65	116								100	49	31	11	297			1304
(blank)																				
Grand Total	170	229	465	65	116	1569	222	250	494	102	88	405	417	49	31	11	297	200		5180

Figure 6.1: Turbines in NSR

turbines in the NSR are the same Siemens 3.6MW turbines. Over 30% of all turbines are of the same manufacturer and are the same type. These are the largest turbines the NG-2500X jack-up units have been able to install (therefore also be able to decommission) and one of the first to be decommissioned. Specifying on this particular turbine, the bollard pull needed to tow an assumed 80% submerged turbine can be calculated.

$$The\ total\ towing\ force,\ F_{tot} = F_{wind} + F_{wave} + F_{current} \tag{6.2}$$

$$F_{wind} = \frac{1}{2}\rho_{air}V^2A_{tw} \tag{6.3}$$

Where A_{tw} is the transverse windage area. The rectangular shape of the nacelle is comparable to rectangular barges. For this reason a simplified calculation can be performed to calculate the current force acting on a floating turbine.

$$F_{current} = \frac{1}{2}\rho_w V^2 A_{ut} \tag{6.4}$$

Where A_{ut} is the underwater transverse section area. Finally the wave drift force must be calculated. This can be done using:

$$F_{wave} = \frac{1}{8}\rho_w g R^2 B \cdot H_s^2 \tag{6.5}$$

Where R is the typical reflection coefficient. Coefficients of the shape of the towed object can be found in Table 6.2. The top side of the nacelle of a wind turbine has a rectangular shape, and thus the decision to take R=1.0 is a safe, conservative approach.

Typical reflection coefficients	
Square face	R = 1,00
Condeep base	R = 0,97
Vertical cylinder	R = 0,88
Barge with raked bow	R = 0,67
Barge with spoon bow	R = 0,55
Ship bow	R = 0,45

Table 6.2: Typical reflection coefficients

ρ_w	= Density of water	1025	$[kg/m^3]$
g	= Acceleration of gravity	9.81	$[m/s^2]$
H_s	= Significant wave height		$[m]$
B	= Breadth of towed object		$[m]$

The total towing force, also Bollard Pull (BP), can be calculated. According to the Naval Arch [66], benign weather areas, the following criteria are prescribed as per ND0030: Wind speeds = 30kts, current speed = 1kts and a significant wave height = 2m. A tugs efficiency is affected by several factors. Size, velocity, weather conditions and towing speed all have their influence on the bollard pull. Therefore the BP must be divided by the tugs efficiency. Often an efficiency of 75% is taken. A 10.000bhp, 120mT bollard pull tug [38] is taken, capable of reaching a maximum velocity of 14kts. Its cruising velocity is 12kts. Calculating the F_{tot} using Equation 6.2, the required towing force can be determined using Equation 6.1.1. As mentioned, the tug efficiency (η) is chosen to be 75%.

$$Required\ BP = F_{tot}/\eta \tag{6.6}$$

A simplification to determine the 10.000bhp cargo carrying cruising velocity can be seen in Figure 6.2, where the intersection between the $BP_{max} = 1 - (\frac{required\ bollard\ pull}{maximum\ bollard\ pull}) \cdot 100\%$ and a linear approximation of the ratio $\frac{velocity}{power}$ shows the optimal cruising velocity. The turbine carrying capacity is assumed to divide the total available deckspace by the side surface of the 3.6MW turbine. For transporting the turbines on barges or on vessels, the stacking of turbines is therefore not taken into account. Also, the workability of the NG-2500X is about 50% throughout the year. The same workability is chosen for all other configurations, assuming these vessels can and will operate, if the NG-2500X operates.

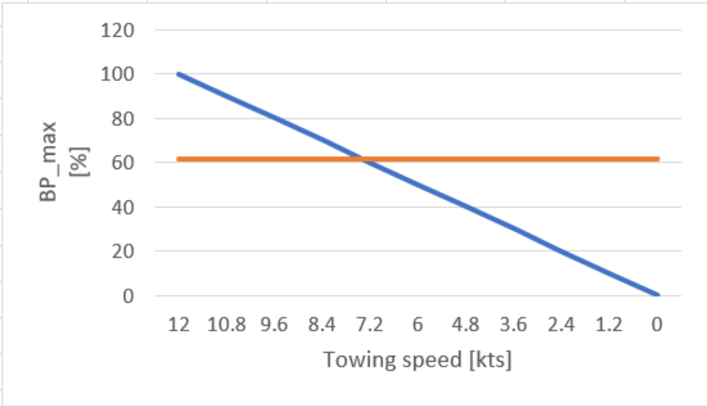


Figure 6.2: Towing speed

This velocity can be added into Table 6.4. Combining this velocity with data from E. Pigeaud [52], Skoko [61], Sarker [58], Nodar [48] and Strid [63], an average for dayrates and velocities can be made for every vessel, also shown in Table 6.4. These parameters are taken as input for the estimative model.

6.2. Input

Knowing an SWT-3.6MW Siemens is the turbine this model now focuses on, other averages can be drawn from this. As Nguyen [14] describes in the article: "Design of an offshore wind farm layout", that the recommended turbine spacing offshore is somewhere between 8-12 time the rotor diameter (D_r) in the prevailing wind distance and is expected to be between 3-5 (D_r) in crosswind direction. Furthermore, the SWT-3.6MW turbine comes in two different rotor diameters, namely 107m and 120m, the average turbine-turbine distance is 794.5m. Combining this knowledge from Appendix A, the following data can be derived.

Modal wind farm		
Turbines per farm	86.3	
Distance to shore	27.4	[km]
Water depth	20.4	[m]
Turbine to turbine distance	794.5	[m]

Table 6.3: Average 3.6MW NSR farm

Unit	Ref. unit	Knots	Dayrate [$]	Width	Length	Deck space [m^2]	Turbine capacity
Jack-up	NG-2500X	8	100.000			900	2
Barge	400 class Teras003	7.5	10.000	37	122	4514	9
Tug [empty]	10.000bhp tug	12	15.000			0	0
Tug [cargo]	10.000bhp tug	7.5	15.000			0	1
Launch barge	Intermac 650	7.5	30.000	46.9	198	9286.2	19
Flo-Flo	Rolldock S-class	13	24.000	19	116	2204	5
Crane vessel		6.9	200.000				0
Semi submersible dry dock	Xiang Rui Kou	13.5	300.000	43	177.6	7636.8	16

Table 6.4: Vessel parameters

Together with the vessel specific parameters which can be found in Table 6.4, this model will compare all five other options of combinations of vessels to reversed installation. Table 6.1 functions as base case where all other options will be compared to. Following variables are added in the model.

Input	Unit
Turbine to turbine distance	$[km]$
Harbour to site distance	$[km]$
Mobilization time	$[hrs]$
Transit velocity	$[kts]$
Dayrate	$[\$/day]$
Deckspace	$[m^2]$
Amount of turbines in farm	
Surface turbine	$[m^2]$
Onloading time	$[hrs]$
Offloading time	$[hrs]$
Installed power	$[kW]$
Power used	[%]
Operation duration	$[hrs]$

Table 6.5: Input variables

6.3. Cost model

Prior to calculating the total duration of each different transport setup, all modes of operations of each unit used in every configuration has to be determined. Once established, for every mode of operation an estimation of duration have to be made. Finally an optimization is done, identifying the best economic configuration, of the fleet. All these operations per configuration have been shown in the tables below. In order to acquire an accurate estimation of costs, the model takes the different configurations, numbers of vessels used and various farm sizes over a difference of 10km to 400km from site to harbour. This will generate a graph where distance to harbour is opposed to decommissioning costs. The following tables give an indication of the activities to be performed based on the specific transport configuration. In every configuration, it is assumed that the NG-2500X will remove the turbine blades and withdraw the oils and fluids from the nacelle, before performing the felling task. Estimated duration of operations depend heavily on distance to harbour and cruising velocity. The inputs from section 6.1 are entered into the model. In this model the following constrains are added.

- A maximum of two NG-2500X units available for decommissioning
- At least two tugs needed per barge
- At least one tug available for assisting

An optimization is done using these constrains, for every configuration and every distance to harbour.

The total costs per turbine can be calculated by taking the product of the dayrate and duration. For all tables below the distance to harbour = 10km and the data from Table 6.3 is used. Duration for transit and the left over idle time depend on this distance.

Unit used	Mode of operation	Est. duration [hrs]
NG-2500X	Jacking (up/down)	6.0
	Preparation & cut	4.0
	Mobilization costs	336.0
	Site-harbour	0.0
	Turbine-turbine transit	0.1
Tug	Site-harbour	0.9
	Offload	1.0
	Harbour-site	0.7
	Idle time	1080.7

Table 6.6: Float & tow at 10km

Unit used	Mode of operation	Est. duration [hrs]
NG-2500X	Jacking (up/down)	6.0
	Mobilization costs	672.0
	Preparation & cut	4.0
	Turbine-turbine transit	0.1
Semisub	Ballasting (up/down)	8.6
	Mobilization costs	336.0
	Load on turbine	0.5
	Transit	0.4
	Offload	0.5
Tug	Site-harbour	0.0
	Assisting	7.5
	Harbour-site	0.0
	Idle time	118.4

Table 6.9: Semi-submersible & tug at 10km

Unit used	Mode of operation	Est. duration [hrs]
NG-2500X	Jacking (up/down)	6.0
	Preparation & cut	4.0
	Mobilization costs	336.0
	Site-harbour	0.7
	Turbine-turbine transit	0.1
Launch barge	Barge mobilization costs	336.0
	On loading	4.0
	Off loading	4.0
	Transit	1.4
Tug	Mobilization costs	336.0
	On loading	4.0
	Off loading	4.0
	Transit	1.4
	Idle time	37.8

Table 6.7: Launch barge & tug at 10km

Unit used	Mode of operation	Est. duration [hrs]
NG-2500X	Jacking (up/down)	6.0
	Mobilization costs	336.0
	Preparation & cut	4.0
	Turbine-turbine transit	0.1
Rolldock	Ballasting (up/down)	3.1
	Mobilization costs	336.0
	Load on turbine	1.0
	Transit	0.4
	Offload	2.0
Tug	Assisting	2.0
	Idle time	52.1

Table 6.10: FLo-Flo & tug at 10km

Unit used	Mode of operation	Est. duration [hrs]
NG-2500X	Jacking (up/down)	6.0
	Mobilization costs	672.0
	Preparation & cut	4.0
	Turbine-turbine transit	0.1
Crane	Mobilization costs	336.0
	Transit	0.0
	On loading	1.0
	Idle time	36.3
Barge	On loading	1.0
	Mobilization costs	336.0
	Off loading	1.0
	Transit	0.9
Tug	Mobilization costs	336.0
	On loading	1.0
	Off loading	1.0
	Transit	1.4
	Idle time	41.8

Table 6.8: Crane, barge & tug at 10km

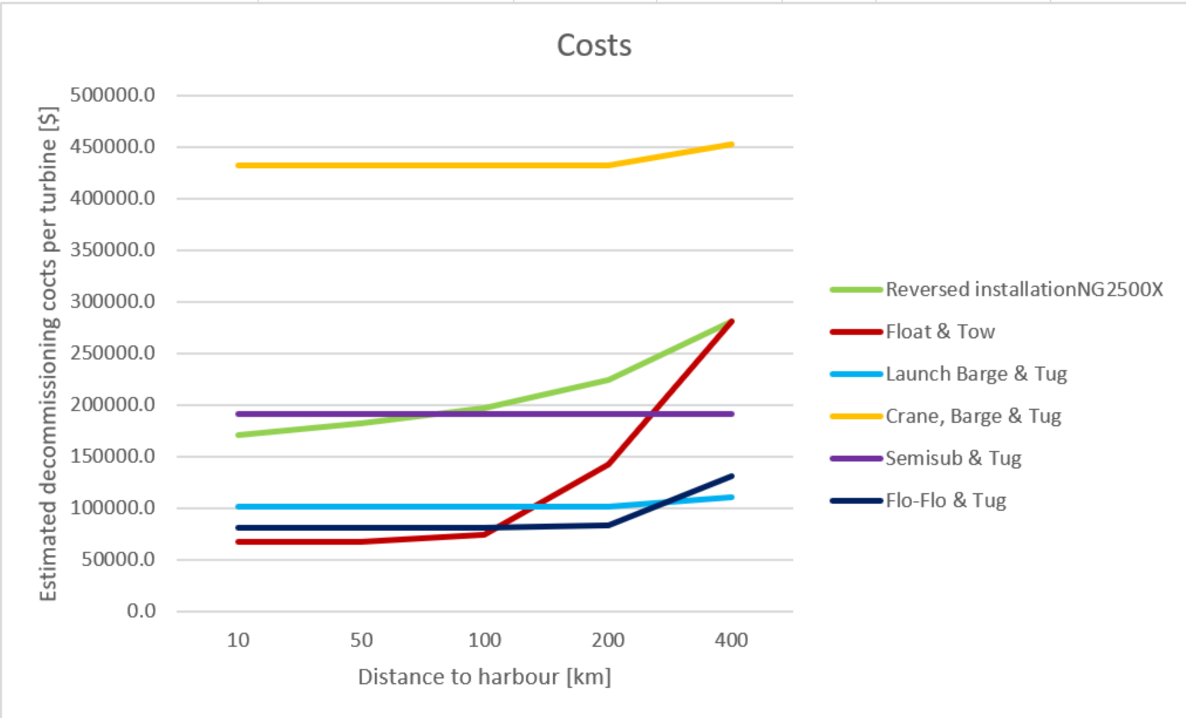


Figure 6.3: Costs per turbine per logistical configuration

All parameters and variables entered into the model, Figure 6.3 shows the output. The green line "reversed installation" is the benchmark all other methods and configurations will be compared against. Directly visible is that the "crane, barge & tug" option is a significantly more expensive than all other options. Almost every other option show comparable or remarkably more economical alternatives. The graph shows a possible decrease of 44%-63% of costs per turbine. However, the initial investment costs of oxy-fuel cutters, have not been added yet. If the jack-up unit is only fitted with separate oxy-fuel cutters, the initial investment costs can be neglected due to the relatively low costs of purchase. If a gripper must be engineered, containing the cutters and automating the cutting process, a higher initial investment must be taken into account. Nonetheless, the lower cost per turbine corresponds with the forecasts of decreasing decommissioning costs by 40-50% done by Kaiser [34] if the initial investment costs are taken into consideration. Not only cost of operation is of importance, next section will discuss the energy consumption of the different transport configurations.

6.4. Environmental impact

A decrease in operational cost is wanted, however this may not be at the expense of an increase in emissions. In fact, due to EU regulations, lowering emissions is liability. This model also indicates the used kWh per configuration over distance. Energy needed, expressed in kWh's are used as a simple indicator for emissions per operation. A comparison can be made between all different setups and distances. Just as in the cost model, all large vessels have a mobilization distance to be travelled of 2500km It is also assumed that the unit must return to its original location. A 5000km distance must be added to all configurations. Emissions are calculated by

$$Energy\ dissipated = Power_{installed} * Duration * Power_{used} \tag{6.7}$$

Idle vessels are only accountable for 4% of their installed power and economical cruising velocities are taken if possible. Parameters and variables from Table 6.11 are entered into the model. Results are found in Figure 6.4.

Unit	**Operation**	**Installed power [kW]**	**Power used [%]**
NG-2500X	Jacking, DP	6400	90%
	Crane operations	6400	40%
	Transit	6400	65%
Tug	Cargo	7500	71%
	Empty	7500	46%
	Idle	7500	4%
Crane	Transit	10000	65%
	Crane operations	10000	40%
	Idle	10000	4%
Semisub	Transit	12900	60%
	Ballasting	12900	10%
	Idle	12900	5%
Flo-Flo	Transit	18000	60%
	Ballasting	18000	10%
	Idle	18000	4%

Table 6.11: Energy consumption modes

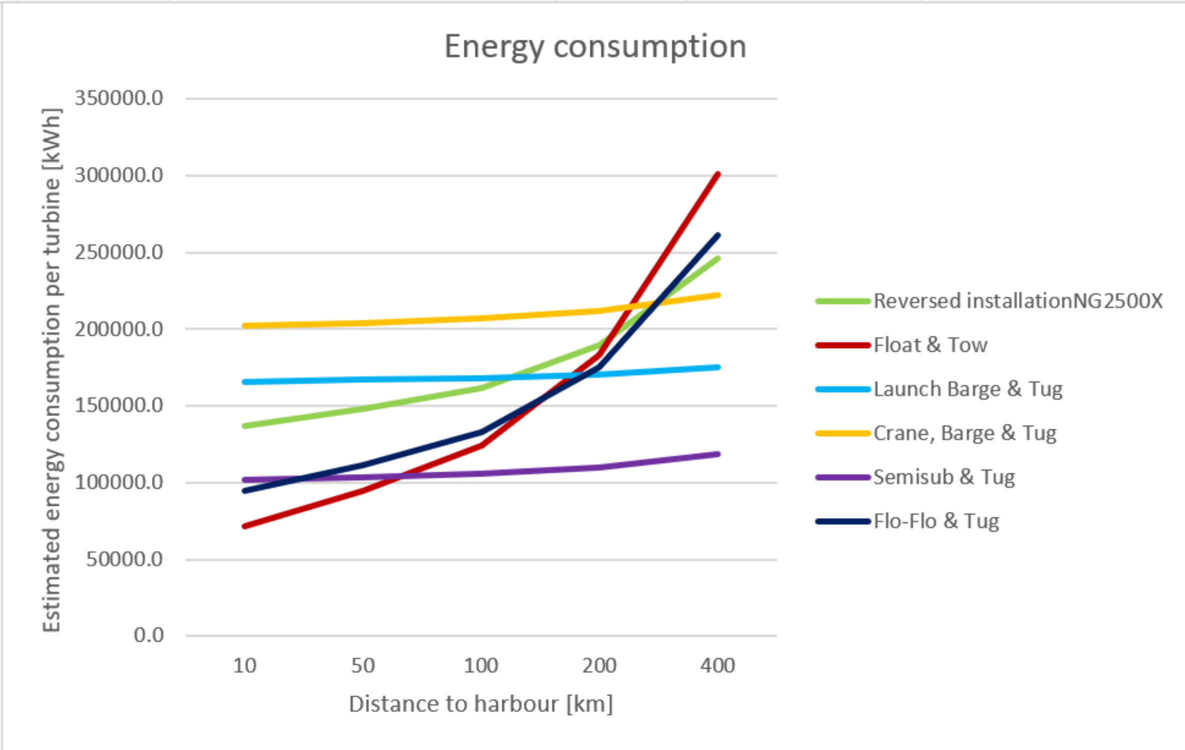


Figure 6.4: Energy consumption per turbine per logistical configuration

Taken the input from Table 6.5, the energy consumption expressed in used kWh's per logistical configuration conventionally increases over distance. Also, differences between configurations are visible. The green line, displaying the energy consumption of the decommissioning operation based on the reversed installation method, again acts as a benchmark against the other methods. Energy consumption is assumed to be inherently connected to fuel used and gasses emitted. Remarkable is the overall decrease in emissions over different distances, especially in wind farms near shore. The cost model showed the "Crane, barge and tug"-method to be notably more expensive and more energy consuming until a distance of 70km is reached. All other options show a decrease in emissions up to 200km. Wärtsilä state in their 46DF Product Guide their engines use between 174 and 199 grams of diesel to generate 1kWh of energy. With the current knowledge concerning energy consumption per turbine, an estimation of the necessary amount of fuel can be calculated. One may conclude the energy consumption is not only of importance to the environment. Taking the energy transition into mind, not only the energy itself, but also carbon emissions will rise in price. Afman [3] mentions carbon price per ton will more than double the next 10 years. Combined with an estimated increase in cost of energy, the least energy consuming option will, by all means, come with financial benefits.

6.5. Sensitivity Analysis

The model is based on several assumptions. How do these assumptions affect the outcome of the model? The sensitivity of the model can be put the test, however, certain values for the parameters such as distance to harbour, farm size and decommissioning configuration must be specified. For this reason, the sensitivity analysis will be performed in the next chapter, choosing an existing wind farm. The sensitivity of the model will be analysed based on a difference in dayrate, farm size and distance to harbour.

6.6. Conclusion

Comparing both cost and energy consumption next to each other, one might notice more cost efficient and less energy consuming configurations to decommission a ”modal offshore wind farm” consisting of 86 turbines. However, there is no ”modal wind farm” in the NSR. Next chapter compares three business cases and will conclude which logistical setup suits both the as low as reasonably possible (ALARP) and least energy consuming method.

7 Business case

The conclusion that arose from previous chapter is that other methods are more cost efficient and less energy consuming than reversed installation. On the other hand, these conclusions were drawn from averaged data from all installed 3.6MW turbines in the NSR. This chapter will take three different NSR based wind farms to explain the importance of the number of turbines and the distance to harbour. One case will be of the largest, already decommissioned farm Vindeby. Secondly, of the median of the smallest top 5, 3.6MW fitted, existing wind farms. Finally, the median of the top 5 largest, 3.6MW fitted, existing wind farms. In the following results, it is assumed that the distance to harbour is twice the distance to shore.

7.1. Vindeby

The Danish Vindeby offshore wind farm consisted of 11 turbines and is the largest decommissioned wind farm to date. With a distance of 2km to shore, hence 4km to harbour Figure 7.1 shows a minor difference in decommissioning costs between reversed installation and the most economical option "Float & tow". Again, it must be taken into account that no initial investment cost were added to this model, likely causing reversed installation to be the most economical and least energy consuming method for decommissioning.

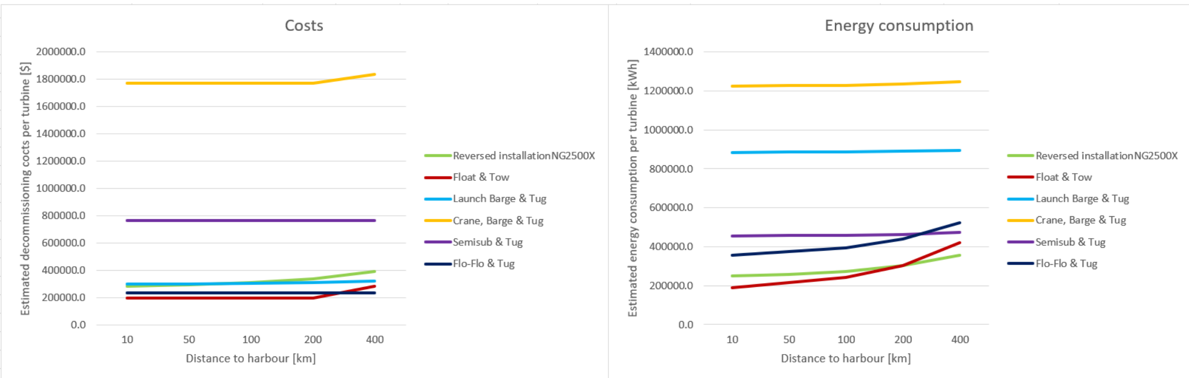


Figure 7.1: Vindeby decommissioning costs

7.2. Lynn and Inner Dowsing

As already mentioned, this research only focuses on the 3.6MW turbines since these are the largest turbines the NG-2500X jack-up has assisted and installed offshore and will be the first to be removed. The median is taken from the five smallest wind farms, fitted with 3.6MW turbines. The top five consists of: Riffgat (30), Gunfleet Sands (48), Lynn and Inner Downsing (54), Lincs (75) and Borkum Rifgrund (78). Lynn and Inner Downsing is the median of the top five smaller wind farm and thus suits to be be entered into the model. Lynn and Inner Downsing consists of 54 Siemens SWT-3.6-107, monopile based, WTG's, 5km from shoreline in UK waters. Once entered into the model, the following results show.

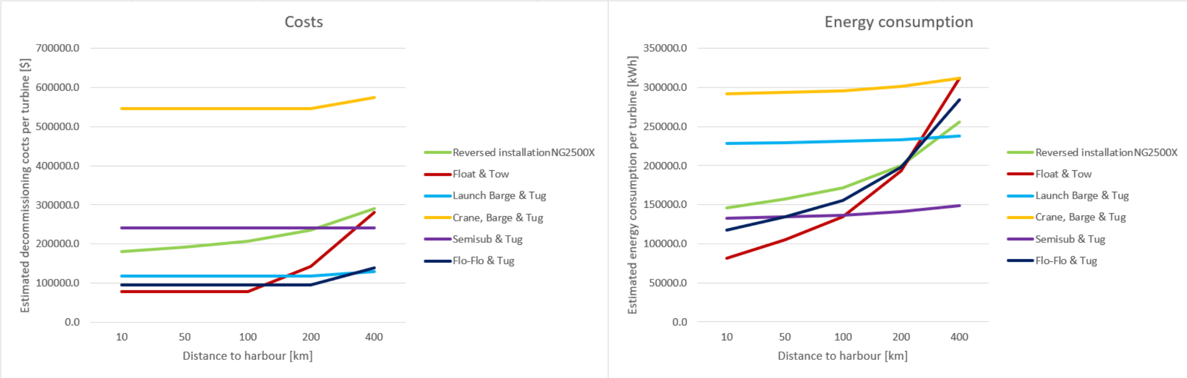


Figure 7.2: Lynn and Inner Dowsing decommissioning costs

In contrast to Vindeby farm, a noticeable difference between reversed installation and the other methods arises. Three methods significantly reduce operational costs, whereas two of those method either compare in emissions or also decrease. The "Flo-Flo & tug" reduces the expenses by 48% and energy consumption by 20%. A larger impact is seen when choosing for the "Float & tow" setup. A decrease in operational costs of 57% (excluding the initial investment costs) and a reduction of emissions by 44%.

These results clearly indicate that not only a more economical alternative is possible, but will also cause a reduction in emissions.

7.3. Greater Gabbard

Finally the top five largest wind farms solely existing with off the Siemens SWT-3.6-107 turbines are: West of Duddon Sands (108), Anholt (111), Greater Gabbard (140), Gwynt y Mor (160) and London Array (175). Excluding the top and bottom two of this top five leaves the wind farm Greater Gabbard. This UK wind farm exists of 140, monopile based turbines. With a 23km distance to shore, the results from the 50km distance will be analyzed and can be seen in Figure 7.3

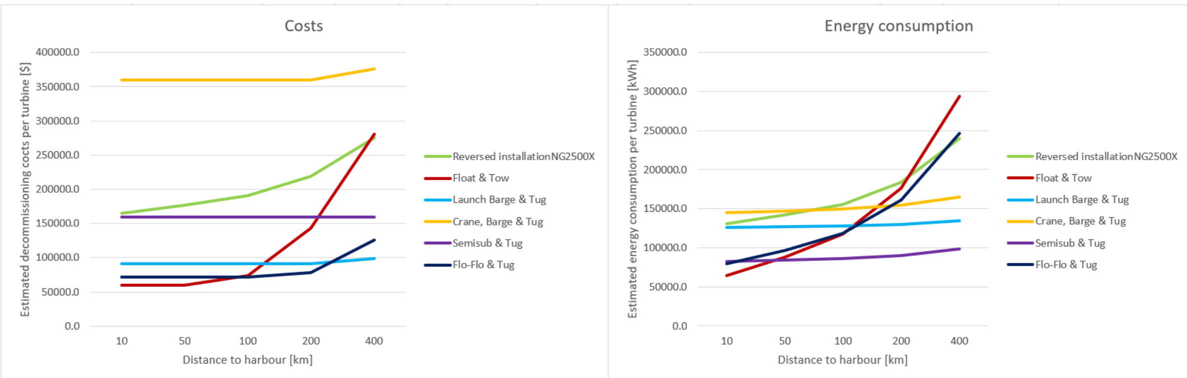


Figure 7.3: Greater Gabbard decommissioning costs

In this model, size does matter. Apart from the "Crane, barge & tug" (which has proven the most expensive and energy consuming option), all other options show a drastic decrease in both operational cost and emissions. As mentioned above, the distance to harbour is 50km.

Method	Costs per turbine [$]	Energy per turbine [kWh]	Cost reduction [%]	Energy reduction [%]
Reversed installation	176.000	142.000	-	-
Semisub & tug	160.000	84.000	10	41
Launch barge & tug	91.000	126.000	48	11
Flo-Flo & tug	72.000	97.000	59	31
Float & tow	60.000	88.000	66	37

Table 7.1: Cost and energy reduction

7.4. Sensitivity Analysis

Additionally, a sensitivity analysis has been performed on the Greater Gabbard wind farm. This farm is chosen as future wind farms will most likely match the size of this wind farm instead of the smaller wind farms mentioned in section 7.2. The sensitivity will be depend on the distance to harbour, farm size and the dayrate of the vessels used. The analysis will be tested against all different configurations where the cost of decommissioning per turbine appears.

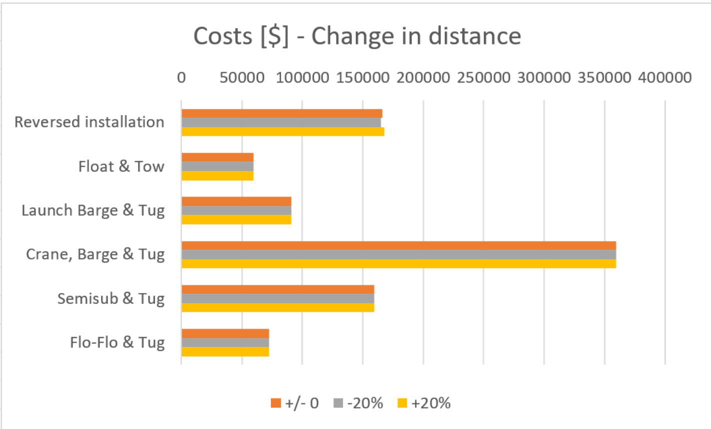


Figure 7.4: Sensitivity of costs with respect to a change in distance to harbour

A remarkable situation arises in Figure 7.4 when the distance to harbour is altered to plus or minus 20%. A visible difference is only notable in the change in costs for reversed installation. No other configuration changes in operational costs. This is the result of the relative short distance to harbour. The time it takes for a jack-up unit to position, jack-up, prepare and decommission one turbine, the transport vessel(s) have returned to the wind farm site, causing the rate the jack-up decommissions the turbines to act as a bottleneck in the system. As during reversed installation the transit is also done by the jack-up unit, this can be seen in the costs. Adding extra jack-ups will, due to the high mobilization costs, not be economical. However, over larger distances, this bottleneck can be resolved by adding a larger fleet. This also concludes that a main cost-cutter is optimizing the decommissioning process. Together with the jacking procedure, of which the duration is not possible to shorten, form the most time consuming operations.

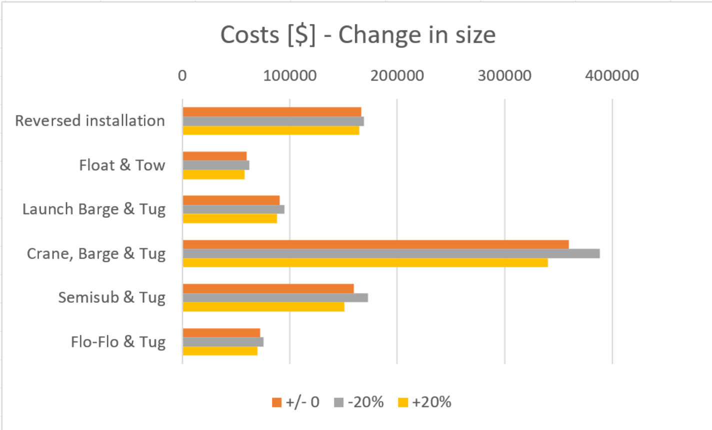


Figure 7.5: Sensitivity of costs with respect to a change in farm size

Figure 7.5 reveals the importance of farm size in relative decommissioning costs. Small offshore wind farms are often more expensive to decommission compared to its larger counterparts. The mobilization time and thus the additional costs, play an observable role in the decommissioning costs.

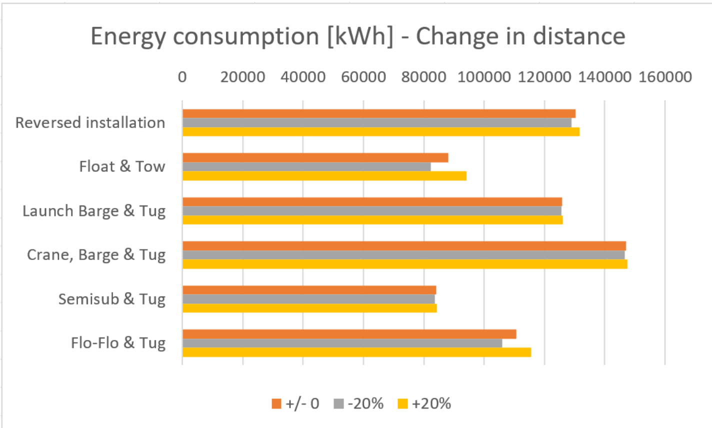


Figure 7.6: Sensitivity of energy consumption with respect to a change in distance to harbour

The distance from harbour to the wind farm site are of influence on the total energy consumption, thus on the emissions. Travelling further results in a surge in use of energy. Yet, an increase of 20% in harbour to site distance does not automatically result in a 20% increase in energy consumption. This depends on several factors. The turbine carrying capacity and modes of operation the unit remains in.

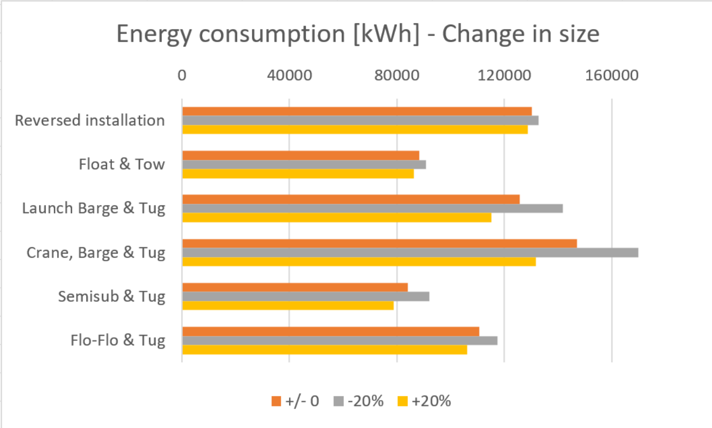


Figure 7.7: Sensitivity of energy consumption with respect to a change in farm size

Finally Figure 7.7 presents the relative decrease of energy consumption with an increase of farm size. This is due to the large mobilization distance to be covered by every vessel. The mobilization costs and emissions can be divided over every turbine installed in the farm. A larger farm means these costs and emissions can be ”shared”.

7.5. Conclusion

Except for the Crane, barge & tug method, all methods with their cost and energy reductions compared to reversed installation are shown in Table 7.1. In terms of economical and environmentally friendly alternatives, all options opt better results if the distance to harbour remains below 100km. This model has shown the gains for decommissioning offshore WTG’s to be achievable. Cutting decommissioning costs in half whilst pushing the emissions back by a third are promising outcomes of this model estimations. Nonetheless, an additional investment has to be made to lay hold of the proper decommissioning tools and attributes needed. Inspite of that, great improvements both economically and the impact on the environment can be achieved.

8 Safety, sustainability & environmental impact

Safety, sustainability & environmental impact are parameters of the utmost importance in determining whether an offshore felling operation is and can be more successful compared to reversed installation.

8.1. Safety

Several different methods and techniques of assessing risks for offshore wind farm decommissioning can be performed. These techniques include a HAZID (hazard identification), fault tree analysis, event tree analysis and a risk matrix, all intended to clearly visualise and quantify risk in terms of probability and impact. In the event of reversed installation, crew members climb inside the turbine to the nacelle and have to unwind the bolts for a crane to lift of the nacelle. Having personnel working close to heavy components being lifted, situations may turn hazardous. The risk of being caught in, on, under or between components, get in contact with sharp edges, being struck by components, falling from great height or the chance of overexertion due to hard labor are all present. Providing a safe method and reducing the crew will not only increase safety, but will also reduce costs. According to Shafiee and Adedipe [60] a HAZID is a tabular, qualitative technique used to identify potential operational hazards/deviations and their possible causes and consequences, forming the parameters of safety. Since the felling of offshore turbines has not been perfomed yet, a probability, thus a complete risk assessment, proves to be a challenging task. However, some conclusions can be drawn regarding safety. Assumptions made in this research concerning health, safety and environment (HSE) will be based on qualitative comparison to the current method. Shafiee and Adedipe[60] state the following: "The least occurring events are crane structural failure, decoupling prevention device failure and improper tugboat use. Of all these basic events, crane-related fault/failure events are the most likely events to occur." This forms the foundation of the safety analysis. By reducing the amount of crane lifts, the largest source of accidents diminishes. By reducing the most likely failure events, the total of accidents reduces. In opposition, felling is a possible high consequence operation and is not taken into account in the research by Shafiee and Adedipe. In a similar manner, employing smaller units, equipped with smaller crews, not the probability of failure reduces, but also the impact in event of failure. As felling offshore is an innovative operation, additional risks emerge. Felling in general, tugs connecting to floating turbines and floating transport all contribute to increased probability of failure.

8.2. Sustainability

Ulstein [46] has stated that where jack-up units, built to perform 20-25 years, are economically written off within a decade due to the fast growing offshore energy market. New jack-up units equipped with greater hook heights, larger deck spaces and increased crane capacities, outperform the smaller jack-ups. Also, older jack-ups do not come near the immense height and crane capacity of the new offshore turbines. Introducing the felling method for WTG decommissioning, might result in an extended use of these jack-ups whose are not able to decommission the turbines on the reversed installation method. By keeping these vessels in operation, and fulfilling the expected 20-25 years, these units are used in a more sustainable manner. Altering the method of decommissioning will not change the recyclability of the turbines. Now, an expected 80%-84& of the complete offshore WTG can be recycled. The blades are challenging to recycle. However, Siemens released a press statement, claiming it will recycle 100% of the turbines by 2040. Different compositions of materials used and future methods of recycling, will increase the recyclability to 100%.

8.3. Environmental impact

Besides keeping the jack-ups in operation for a longer time and increase the sustainability of the unit, it will also result in a positive environmental impact. Generally larger units require larger crews to operate. Also, larger units emit more pollutants. Combined with the data from Table 7.1, a reduction in energy consumption can be seen if changed to an alternative decommissioning method. A reduction in energy consumption results directly proportional to a decrease in pollutants. The model appears to cut emissions between 4%-35% based on the Greater Gabbard business case.

8.3.1. Energy transition

The majority of the countries strive to reduce carbon emissions as agreed to in the OSPAR-convention, mentioned in section 2.7. Estimates show an increase in price of energy over the next years. A metric tonne of MDO (Marine Diesel Oil) now averages about 880$\$/t$, this will likely increase over the years. Combined with the projected doubling of the costs of emitting carbon dioxide, the price of using common MDO surges. The business cases in chapter 7, established its estimations based on the dayrate per vessel. However, the true dayrates top those estimations, as no fuel use is not part of the dayrate per vessel. Assuming every vessel in each configuration uses MDO as fuel, has a similar efficiency, and needing 173-199g/kWh; an additional 15% of the estimated costs can be added as a result of fuel use, based on current prices of MDO. Changing to cleaner fuel alternatives such as hydrogen or battery stored electricity might increase the overall price per kWh. Nonetheless, changing to alternative energy sources, the energy consumption will stay the same for every configuration. Increasing cost of generating a kWh, directly influences the total cost of the project. Hence, choosing the least energy consuming method benefits both the environment and expenses made.

9 Conclusions

In the search of a new methodology for decommissioning of offshore wind turbines, the solution has to lie within given boundary conditions for this technique to be of interest. The use of jack-ups has proven itself to be a productive, efficient way to install offshore structures. As the offshore WTG's keep getting larger, the older (smaller) jack-ups meet their boundaries and will not be able to perform installation and decommissioning projects anymore. The jack-ups are bounded by their size. Hook height and crane capacity will not meet the requirements for installation of new offshore turbines, the weight of the components is to heavy. These jack-ups will soon be out of service with respect to WTG installation. Altering the layout of these jack-up equipped with new tools, might be the solution to keep these units in business. The new decommissioning method will be applied to one of GustoMSC's smaller jack-up unit. The NG-2500X series is a relative small self propelled jack-up unit, capable of working up to 52 meters water depth. 16 Units of the NG-2500X series have been produced, therefore being one of the most common units designed by GustoMSC. This research examined the alternative possibilities for this specific jack-up to reduce future decommissioning costs and emissions. A model was made based on substantiated assumptions, calculating expected operational costs and energy consumptions of the units used. The model implemented has proven decommissioning WTG's offshore can be performed on a more economical and environmentally friendly manner. This chapter elaborates on how this conclusion is composed.

9.1. Reversed installation

Reversed installation is a proven concept. The definition of reversed installation is stated in subsection 2.2.1:"The definition of reversed installation this report abides is not necessarily the exact reversal of the installation process. One may speak of a reversed installation if the equipment used for the installation of the turbine is comparable to the equipment used for decommissioning the turbine. Similar vessel selection, floating or bottom fixed, based on maximum hook height, lifting capacity, deck capacity and the use of barges or not will, in this report, be defined as as reversed installation. The operation is overall the same compared to its installation". The method has worked in the past, and just as installation, it will act as a relative safe method to decommission offshore WTG's. However, reversed installation is an expensive method and comes with risks.

9.2. Safety

Safety first. The most important requirement to the new decommissioning method is **safety**. Personnel must be able to perform their task in a safe manner. Less personnel offshore means less accidents. Reversed installation requires a relative large crew, working around the clock. A reduction in personnel onboard will result in a decrease in consequences, if the method is performed within its boundaries. In this occasion, quantifying safety proves to be a difficult task. With knowledge and data of previous projects, an estimation of probability and impact can be set up. With no prior knowledge of offshore turbine felling, quantification of safety is challenging. However, a qualitative comparison can be made. The main cause of offshore accidents are crane lifting operation failures. Felling reduces the amount of lifts done, using a smaller crew. Risk is the product of impact and probability. Both impact and probability decrease if offshore WTG's are felled.

9.3. Model

Building the model, comparing estimated decommissioning costs to the model outcomes, several inputs had to be determined. In identifying these inputs, this research focussed on the NSR. 22GW of the 25GW installed in Europe, is located in the NSR. 22GW comes from approximately 4100 separate turbines. Of these 4100 turbines, 80% of the installed WTG's have a monopile foundation. All 80% of these monopile based turbines are located on locations with water depths equal or less than 41m, suitable for the NG-2500X to operate on. The decision for the NG-2500X has focused the felling operation on 3.6MW turbines. These are the largest turbines this jack-up unit has installed and therefor able to decommission on a reversed installation manner, generating a solid benchmark to compare the felling method to. Furthermore, the Siemens SWT-3.6MW is by far the most installed wind turbine in the NSR.

9.3.1. Costs

Decommissioning costs based on reversed installation vary between $140,000 - $252,000 per MW. These costs are built up out of a variety of parameters such as duration and unit selection. The report of TNO [73] displays a distribution of decommissioning costs assigned to separate decommissioning operations, shown in Figure 9.1. This graph visualises the impact of the turbine removal part. According to Figure 9.1, 30% is devoted to the removal of the WTG. The sole decommissioning of the turbine is therefore estimated between $42.000 to $75.600 per MW. The model estimated decommissioning the 3.6MW turbines using the reversed installation method, resulted in decommissioning costs of $176.000 ($202.000 if fuel is included, based on calculation in subsection 8.3.1) for a 3.6MW turbine, resembling the estimation found in the conclusion of the literature review.

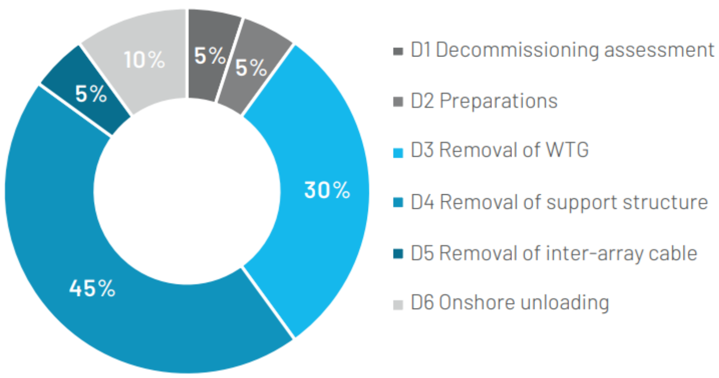


Figure 9.1: Distribution of costs of decommissioning activities [73]

9.4. MCA

The multi criteria analysis narrowed the wide variety of possibilities for uncoupling, hinge point, direction of felling, floating measures and transport setups down to the following conclusions. Primarily, the blades will be removed using the crane, and the floater setup will be hoisted in and secured around the tower. The uncoupling will be performed by either an oxy-fuel or plasma cutter whilst obtaining an initial lifting force exerted by an offshore industrial jack. A pre-calculated segment of the pedestal will function as hinge. Once the turbine has been succesfully felled, depending on the distance to shore, a transport configuration can be choosen, optimising costs and emissions. For most wind turbine farms in the near future, the Float & tow will be the best option, cutting costs by two thirds, and using up to 30% less energy.

9.5. Environment

New methods must be equal or less pollutant compared to reversed installation. The size of the unit used for reversed installation depends on the size of the wind turbine. Larger turbines need larger units. Generally, larger units have greater emissions and occupy a larger on board crew. Decreasing the units needed will therefore reduce emissions. Not only reducing the units size will decrease the energy consumption of the complete operation, but the model shows us that altering the complete decommissioning fleet configuration will directly results in a decrease of energy consumption. Combining these effects, large gains can be achieved.

9.6. Durability

This report partially focused on the capability of reusing and recycling of decommissioned offshore WTG's. New methods of decommissioning do not negatively affect the overall durability of the project. However, as seen in Figure 2.11, besides the currently installed turbine blades, all discarded WTG components will completely be recycled. The method used to decommission a turbine has a low influence on the overall durability, but is important not to forget in the process. Second, using small, older jack-up units for decommissioning purposes, fewer new units will have to be constructed, thus reducing the overall use of material and elongating the jack-up operational lifetime. Additionally, state-of-the-art methods guarantee the capability of recycling new wind turbine blades, increasing the overall recyclability from 80%-84% to a complete 100% [17].

The model shows great gains to be achieved by changing the turbine decommissioning method to felling instead of reversed installation. The felling operation itself is an operation executed onshore already. Needed tools and knowledge are available. Comparing reversed installation to felling using the KPI's (Key performance indicators) cost and environmental impact, both show a drastic decrease in expenses and emissions. This model does however, not take initial investments into account. How will the decoupling take place? Will the turbines be cut by handheld oxy-fuel cutters or will a gripper equipped with ROV cutters do the job. The initial investment costs are not taken into account as these costs are challenging to estimate. Moreover, the enormous amount of turbines installed in the NSR to be eventually decommissioned will cause the costs of this investment to be negligible, compared to the gains made by choosing an alternative decommissioning method.

10 Recommendations for future research

Improving the model will provide a more accurate representation of the reality. Improving this model can be done by a research into the workability of all vessels. Mentioned in subsection 6.1.1, the workability of the NG-2500X is the leading workability of all units used. The 50% is a rough estimation, and differs greatly between winter and summer. This parameter varies for every unit, depends on size and gross tonnage to be transported and is therefore an interesting variable to add to the model. It must be taken into account that even in the event of a significant decrease in both operational cost and energy consumption, it might not be the most productive nor convenient to manner to change the decommissioning method, as workability can play a significant role.

Secondly, adding inflation into the model helps to get a clear view on current dayrates. Numerous articles mention dayrates, yet these are highly dependent on both supply and demand, as on inflation. Dayrates from 10 years ago might not represent todays dayrates. Furthermore, removal of foundations is claimed to be 40% of the total decommissioning costs. Providing the jack-up unit with a waterjet, capable of cutting the monopile to a legally sufficient depth, will save mobilization costs of a floating vessel, specialised in monopile removal. Combining both WTG decommissioning with foundation removal, executed by the jack-up, might result in a large efficiency gain.

Finally, an in-depth research for probability of failure and impact, can give a clear overview of possible risks. What previously unknown risks come to the surface and how can these risks be mitigated.

A

List of wind farms NSR

Table A.1: Wind farms in NSR

Loc	Name	Country	Amount	Turbine (MW)	Installed (MW)	Foundation	Type	Brand	Drive	Depth	Avg. depth	Dist. To Shore	Date commissioned
NS	Horns Rev I	DK	80	2	160	MP	V80-2MW	Vestas	GB	13-20	16.5	18	2002
NS	Scroby Sands	UK	30	2	60	MP	V80-2MW	Vestas	GB	0-8	4	2.5	2004
NS	Kentish Flats	UK	30	3	90	MP	V90-3MW	Vestas	GB	3-5	4	10	2007
NS	Beatrice	UK	2	5	10	Jacket	5M	REpower	GB	15-18	16.5	13	2007
NS	Prinses Amaliawindpark	NL	60	2	120	MP	V80-2MW	Vestas	GB	19-24	21.5	26	2008
NS	NoordzeeWind (OWEZ)	NL	36	3	108	MP	V90-3MW	Vestas	GB	15-18	16.5	13	2008
NS	Horns Rev II	DK	91	2.3	209.3	MP	SWT-2.3-93	Siemens	GB	9-17	13	32	2009
NS	Lynn and Inner Downsing	UK	54	3.6	194.4	MP	SWT-3.6-107	Siemens	GB	6-11	8.5	5	2009
IS	Robin Rigg	UK	56	3	168	MP	V90-3MW	Vestas	GB	9	9	11	2009
NS	Thanet	UK	100	3	300	MP	V90-3MW	Vestas	GB	20-25	22.5	11	2010
BS	Rodsand II	DK	90	2.3	207	GBS	SWT-2.3-93	Siemens	GB	5-12	8.5	9	2010
NS	Gunfleet Sands	UK	48	3.6	172.8	MP	SWT-3.6-107	Siemens	GB	2-15	8.5	7	2010
NS	Alpha Ventus	D	6	5	30	Jacket	5M	Repower	GB	28	28	56	2010
NS	Alpha Ventus	D	6	5	30	Jacket	M5000	Multibrid	GB	28	28	56	2010
IS	Walney	UK	102	3.6	367.2	MP	SWT-3.6	Siemens	GB	19-30	24.5	14	2011
BS	EnBW Baltic 1	D	21	2.3	48.3	MP	SWT-2.3-93	Siemens	GB	16-19	17.5	16	2011
NS	Sheringham Shoal	UK	88	3.6	316.8	MP	SWT-3.6-107	Siemens	GB	12-24	18	17	2012
NS	Lincs	UK	75	3.6	270	MP	SWT-3.6-120	Siemens	GB	10-15	12.5	8	2012
IS	Ormonde	UK	30	5	150	Jacket	5M	REpower	GB	17-22	19.5	9.5	2012
NS	London Array	UK	175	3.6	630	MP	SWT-3.6	Siemens	GB	0-25	12.5	20	2013
NS	Greater Gabbard	UK	140	3.6	504	MP	SWT-3.6-107	Siemens	GB	20-32	26	23	2013
NS/BS	Anholt	DK	111	3.6	399.6	MP	SWT-3.6	Siemens	GB	14-17	15.5	21	2013
NS	Bard Offshore 1	D	80	5	400	Tripile	5	BARD	GB	40	40	100	2013
NS	Teesside	UK	27	2.3	62.1	MP	SWT-2.3	Siemens	GB	7-15	11	1.5	2013
NS	Thortonbank	BE	6	5	30	GBS	5M	Repower	GB	13-19	16	27	2013

Table A.2: Wind farms in NSR

Loc	Name	Country	Amount	Turbine (MW)	Installed (MW)	Found.	Type	Brand	Drive	Depth	Avg. depth	Dist. To Shore	Date commis-sioned
NS	Thortonbank	BE	48	6	288	Jacket	6M	Senvion	GB	13-19	16	27	2013
IS	Gwynt y Mor	UK	160	3.6	576	Jacket				20	20	17	2014
IS	West of Duddon Sands	UK	108	3.6	388.8	MP				17-24	20.5	15	2014
NS	Meerwind Sud/ost	D	80	3.6	288	MP	SWT-3.6-120	Siemens	GB	22-26	24	53	2014
NS	Riffgat	D	30	3.6	108	MP	SWT-3.6-120	Siemens	GB	16-24	20	15	2014
NS	Northwind	BE	72	3	216	MP	V112-3.0	Vestas	GB	16-29	22.5	37	2014
NS	Kentish Flats extension	UK	15	3.3	49.5	MP	V112-3.3	Vestas	GB	3-5	4	10	2015
NS	Amrumbank West	D	80	3.6	288	MP	SWT-3.6-120	Siemens	GB	20-25	22.5	40	2015
NS	Butendiek	D	80	3.6	288	MP	SWT-3.6	Siemens	GB	17-22	19.5	35	2015
BS	EnBW Baltic 2	D	39	3.6	140.4	MP				23-44	33.5	32	2015
BS	EnBW Baltic 2	D	41	3.6	147.6	Jacket				23-44	33.5	32	2015
NS	DanTysk	D	80	3.6	288	MP	SWT-3.6-120	Siemens	GB	21-31	26	70	2015
NS	Global Tech 1	D	80	5	400	Tripod	M5000	Multibrid	GB	39-41	40	110	2015
NS	Borkum Rifgrund 1	D	78	3.6	280.8	MP	SWT-4.0-120	Siemens	GB	23-29	26	55	2015
NS	Luchterduinen	NL	43	3	129	MP	V112-3.0	Vestas	GB	18-24	21	24	2015
NS	Humber Gateway	UK	57	3	171	MP	V112-3.0	Vestas	GB	15	15	8	2015
NS	Humber Gateway	UK	16	3	48	GBS	V112-3.0	Vestas	GB	15	15	8	2015
NS	Nordsee ost	D	48	6.2	297.6	Jacket	6.2M126	Senvion	GB	25	25	55	2015
NS	Trianel Borkum 1	D	40	5	200	Tripile	M5000-116	Areva	GB	28-33	30.5	45	2015
NS	Westermost Rough	UK	35	6	210	MP	SWT-6.0	Siemens	DD	10-25	17.5	8	2015
NS	Gode Wind 1&2	D	97	6	582	MP	SWT-6.0	Siemens	DD	30	30	42	2016
NS	Gemini	NL	150	4	600	MP	SWT-4.0	Siemens	GB	28-36	32	55	2017

Table A.3: Wind farms in NSR

Loc	Name	Country	Amount	Turbine (MW)	Installed (MW)	Found.	Type	Brand	Drive	Depth	Avg. depth	Dist. To Shore	Date commis-sioned
NS	Dudgeon	UK	67	6	402	MP	SWT-6.0-154	Siemens	DD	18-25	21.5	32	2017
NS	Hywind	Scotland	5	6	30	Floating	SWT-6.0-154	Siemens	DD	100+	100	25	2017
NS	Sandbank	D	72	4	288	MP	SWT-4.0-130	Siemens	GB	24-34	29	90	2017
NS	Veja Mate	D	67	6	402	MP	SWT-6.0-154	Siemens	DD	39-41	40	95	2017
NS	Nordsee one	D	54	6.2	334.8	MP	6.2M126	Senvion	GB	26-29	27.5	45	2017
NS	Nobelwind	BE	50	3.3	165	MP	V112	Vestas	GB	26-38	33	47	2017
NS	Rampion	UK	116	3.45	400.2	MP	V112-3.45MW	Vestas	GB	15-60	37.5	13	2018
NS	Race Bank	UK	91	6	546	MP	SWT-6.0-154	Siemens	DD	26	26	32	2018
NS	Aberdeen	UK	11	8.8	96.8	Suction bucket Jacket	V164-8.8	Vestas	GB	19-32	25.5	3	2018
NS	Galloper	UK	56	6.3	352.8	MP	SWT-6.0-154	Siemens	DD	27-36	31.5	30	2018
NS	Rentel	BE	42	7.35	308.7	MP	SWT-7.0-154	Siemens	DD	22-36	29	34	2018
NS	Hornsea One	UK	174	7	1218	MP	SWT-7.0-154	Siemens	DD	25-30	27.5	120	2019
NS	Hohe See	D	71	7	497	MP	SWT-7.0-154	Siemens	DD	40	40	95	2019
NS	Horns Rev III	DK	49	8.3	406.7	MP	V164-8.3	Vestas	GB	10-20	15	30	2019
NS	Merkur	D	66	6	396	MP	Haliade-150	GE	DD	27-33	30	45	2019
NS	Borkum Rif-grund 2	D	56	8	448	Suction bucket Jacket	V164-8.0	Vestas	GB	25-30	27.5	54	2019
NS	Deutsche Bucht	D	31	8.4	260.4	MP	V164-8.4	Vestas	GB	40	40	100	2019
NS	Trianel Borkum 2	D	32	6.34	202.88	MP	6.2M152	Senvion	GB	33	33	45	2019
NS	Nordergrunde	D	18	6	108	MP	6.2M126	Senvion	GB	2-10	6	30	2019

Table A.4: Wind farms in NSR

Loc	Name	Country	Amount	Turbine (MW)	Installed (MW)	Found.	Type	Brand	Drive	Depth	Avg. depth	Dist. To Shore	Date commis-sioned
NS	Norther	BE	44	8	352	MP	V164-8.0	Vestas	GB	33	33	23	2019
NS	Borssele 1 & 2 (Orsted)	NL	94	8	752	MP	SWT-8.0-167	Siemens	DD	14-40	27	22	2020
NS	Albatros	D	16	7	112	MP	SWT-7.0-154	Siemens	DD	40	40	104	2020
NS	East Anglia one	UK	102	7	714	Jacket	SWT-7.0-167	Siemens	DD	53	53	43	2020
NS	Seamade (mermaid)	BE	28	8	224	MP	D8.0-167	Siemens	DD	24-40	32	54	2020
NS	Northwester 2	BE	23	9.5	218.5	MP	V164-9.5	Vestas	GB	40	40	52	2020
NS	Belwind	BE	55	3	165	MP	V90-3MW	Vestas	GB	15-37	26	46	2020
NS	Seamade (seastar)	BE	30	8	240	MP	D8.0-167	Siemens	DD	22-38	30	40	2020
NS	Triton Knoll	UK	90	9.5	855	MP	V164-9.5	Vestas	GB	18	18	32	2021
NS	Borssele 3 & 4 (Blauwwind)	NL	77	9.5	731.5	MP	V164-9.5	Vestas	GB	14-38	26	22	2021
NS	Borselle 5 (Leeghwater)	NL	2	9.5	19	MP	V164-9.5	Vestas	GB	35.00	35	22	2021
NS	Kincardine	UK	5	9.525	47.625	Floating	V164-9.5	Vestas	GB	60-80	70	15	2021
NS	Moray East	UK	100	9.5	950	Jacket	V164-9.5	Vestas	GB	35-53	44	22	2022
NS	Hornsea Two	UK	165	8	1320	MP	D8.0-167	Siemens	DD	30-40	35	89	2022

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