Thesis

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Defining the Offshore Wind Support Vessel Market and Simulating Vessel Demand in 2030

Forecasting offshore wind support vessel demand by defining the market drivers and using a factor model and Monte Carlo simulation

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Preface

I am extremely grateful for the completion of my master's thesis at TU Delft and I would like to take this opportunity to express appreciation for all those who have supported and guided me throughout this journey.

First and foremost, I sincerely thank my thesis supervisors Edwin van Hassel and Jeroen Pruyn for their invaluable guidance, patience, and insightful feedback. With your expertise and support you were able to assist me in shaping the direction of my research and refining its quality.

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To my dear brother, I owe you a debt of gratitude for always being my pillar of strength. Your belief in me never wavered, and your enthusiasm kept me motivated even during the most demanding moments. Additionally, I am much obliged to my friends who have been by my side, offering their encouragement and support. Your presence in my life has brought me joy and laughter, making this academic journey all the more memorable.

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Last but not least, I am grateful to the academic community and fellow students of the TU Delft, University of Vienna and University of Amsterdam where I learned the last years. You all created a stimulating academic environment for which I am incredibly grateful. Completing this master's thesis would not have been possible without your support and guidance; each one of you played a crucial role in shaping my academic and personal growth, and I am sincerely thankful for your contributions.

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Ferdinand E.W. van Heurn

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Abstract

With the energy transition taking up speed and strong decarbonisation ambitions offshore wind is becoming a major source of green electricity. European countries are among the leading drivers of the offshore wind expansion on both the wind turbine as well as the vessels side. It is expected that until 2030 170 GW of capacity can be installed, equalling 16000 wind turbines. The wind turbines are serviced using either small vessels or commissioning and service operation vessels (C/SOVs) when parks are larger and in more challenging conditions further away from shore. The C/SOV market is still in development and it is not known how many of these vessels are needed to serve the European offshore wind industry in 2030. It is further unknown until now which factors influence the need for these vessels as both market dynamics as well as operations have not been researched until now.

This research first defines the quantifiable factors influencing the need for C/SOVs in offshore wind parks. These are the park parameters such as the distance to shore and the number of turbines in the park. These data are used in a factor model and Monte Carlo simulation to make an assumption on the required number of vessels. The results are then compared against qualitative factors influencing the need for C/SOVs indirectly.

Out of a high and a low case, the low case was shown to be the most likely fit for the research results. It showed that to serve the offshore wind market in 2030 between 122 and 138 vessels are needed, which is 12 to 28 more than currently are active or on order.

Considering the fact that the industry needs to adapt to a new market, it is crucial to know which factors drive that market and how they influence it. This project allows for researchers to dive further into these factors and research them in more detail. Further the research can assist industry players in their investment decisions and yards can accordingly plan capacity.

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Acronyms

AHTS Anchor Handler Tug Supply. 13, 56

C/SOV Commissioning and Service Operation Vessel. iii, viii, 1, 2, 6, 12–17, 23, 25–28, 31–34, 36, 39–42, 45, 46, 49–51, 53–64

COD Commercial Operation Date. 7

CTV Crew Transfer Vessel. 12–14, 45, 57, 63

DIM Dimensions. 4, 5, 11

DNV Det Norske Veritas. 6, 8, 10, 12, 22

GDP Gross Domestic Product. 1

GS Google Scholar. 2, 4–6, 11

GT Gross Tonnage. 1, 3

GW Gigawatt. iii, 1, 7–10, 22, 36, 50, 56, 61, 62

IEA International Energy Agency. 6, 7, 12

MC Monte Carlo. viii, 23, 25, 28–30, 34, 39, 46, 61, 63, 81

MSV Multi-Purpose Support. 13

O&G Oil and Gas. viii, 1, 2, 11–16, 19, 22, 41, 42, 53, 55–60, 62–64

O&M Operations and Maintenance. 6, 14, 64

OEM Original Equipment Manufacturer. 9, 53, 54, 64

OW Offshore Wind. v, vii, viii, 1–17, 21–23, 25, 27, 31, 32, 34, 35, 40, 41, 43, 44, 51–64

PSV Platform Supply Vessel. 13, 41

W2W Walk to Work. 41, 42, 58, 62, 63

WoS Web of Science. 2, 4–6, 11

WTG Wind Turbine Generator. 14

WTIV Wind Turbine Installation Vessel. 12, 13, 43

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1 | Introduction

16,000, that is the number of offshore wind turbines that could be installed in the EU and UK combined until 2030, generating 169 Gigawatt of electricity to power the European households and economy compared to 30 GW and 6000 offshore wind turbines today [21]. This is an astonishing number requiring a strong and resilient maritime market behind it to maintain and build the installations.

In recent years offshore wind energy has emerged as a promising renewable energy source due to its potential to provide significant amounts of clean and sustainable electricity. It is a rapidly growing sector that is attracting considerable attention from governments, industry, and the academic community. Offshore Wind (OW) has proven its potential to play a critical role in reducing greenhouse gas emissions and mitigating the impacts of climate change.

The offshore wind sector however is broader than just wind and turbines; a significant industry has grown to produce turbines, install mono piles and maintain the farms. Especially the support vessel side of the industry has gotten little attention from a demand and market point of view. It is for example not clear at this moment how many service vessels the industry needs in the coming years to answer to the increasing number of turbines being installed and therefore maintained.

Throughout the whole life of the park one particular vessel is used the whole time: namely the Commissioning and Service Operation Vessel (C/SOV). These vessels are specifically designed for the construction and operations phase of the OW parks and feature accommodations for up to 120 personnel, motion compensated gangways/ cranes and support functions for daughter craft. The main task of a C/SOV is the support in OW farms that are located further from shore and deliver safe access to the turbines in heavier weather [107].

It is noteworthy when looking at the broader picture of maritime market research that most of the research done on maritime markets has been into the commercial shipping markets dominated by tankers, bulkers and container vessels. Figure 1.2 shows the importance of these three classes on the world fleet with them making up 75% of the world Gross Tonnage (GT). The two most renowned sources on maritime finance and markets by Stopford [90] and Manolis G. Kavussanos [67] focus therefore mostly on tankers, bulkers and container markets. These are heavily dependent on macro-drivers such as commodity prices, consumption and the Gross Domestic Product (GDP) and hence the demand for transport.

The offshore vessel market is largely dominated by vessels serving the Oil and Gas (O&G) en therefore up until now the O&G price has been the single key driver for market development [67], [4]. The large value represented by the offshore market is mainly due to the presence of high-value assets such

Figure 1.1: Example of a C/SOV. The *'Acta Centaurus'* is operated by Acta Marine and features a 120 person accommodation, motion compensated gangway and crane as well as refuelling capacity for smaller CTVs.

as drilling rigs and floating production platforms.

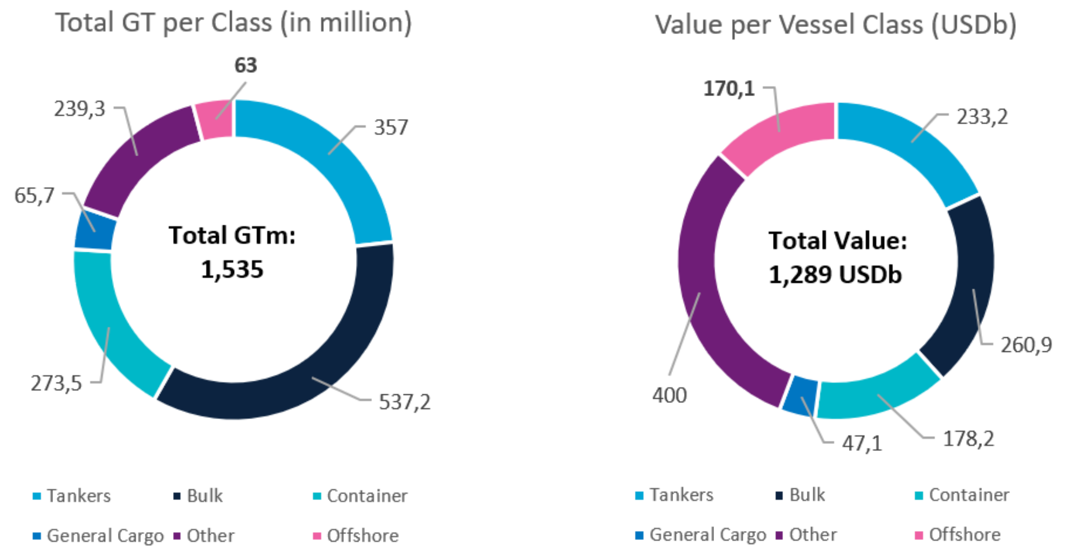
Whereas the offshore O&G market has been covered and market drivers have been defined, this has not been done yet for vessels operating in the OW sector. As the vessels used in the offshore industry - both in O&G and OW - are highly complex vessels and therefore capital intensive, it is important to understand the drivers and demands of this market.

The offshore O&G market has been oversupplied in the past [67], which lead to firms bankrupting and investors having to write of on their investments.

Several factors are known to trigger the use of C/SOVs; the most prevalent ones being the distance to shore and size of OW parks [50]. The market surrounding the OW parks influences the final demand for C/SOVs in a secondary way by determining how many turbines are eventually built. Especially political decisions on where and when to build as well as supply chain fluctuations directly influence this, and therefore indirectly the vessel demand [105]. Lastly the general offshore vessel market as well has an influence on the vessel demand as vessels from the offshore O&G market are used in OW as well.

Currently the exact relevant factors have not yet been determined and classified, both direct as well as indirect. Especially from an academic point of view research on this topic is very limited when considering well known databases such as WoS or GS. These databases were searched for strings combining search terms related to the offshore industry, maritime markets and OW. This leads to sub-question (*II*) and a main question (*I*) that need to be answered in an academic research: *II: Which quantitative and qualitative factors influence the C/SOV demand?* and *I: How many C/SOVs are needed to service the European offshore wind market in 2030?*

To properly answer these questions, first a literature review is performed to identify the literature



(a) Million GT represented by each vessel class.

(b) Value per vessels class in billion US-dollars.

Figure 1.2: Size and value of the world shipping fleet as of 01.01.2023, from Clarksons [23]. The offshore market makes up 4% of the world fleet in terms of GT and 13% in value. [1]

landscape and relevant fields of study (chapters 2.1, 2.2, 2.3). This helps to identify the exact research gaps and helpful sources for the next steps. A second point that gets attention in the literature review are the research methodologies that will be applied. Finally a first assessment of market principles and influencing factors on the offshore market are to be defined in the literature review.

The final research itself is split into two parts. The first being a simulation where the quantifiable factors are used in a factor analysis and a Monte Carlo simulation to determine a range of needed vessels in 2030 (chapter 3.2, 4). In the second part these results are then discussed against the qualitative factors that are established through literature and interviews with industry experts (chapter 5).

The results (chapter 6) are beneficial for both the academic community as well as the industry. The results help in further research into vessel operations and markets and can assist industry players in their investment decisions and yards can accordingly plan capacity. A valuable contribution is as well the definition of the influencing factors on the OW market as a whole, as this delivers a good base for further specific research and modelling.

[1]General Cargo consists of multi purpose vessels, Ro-Ro and other Dry Cargo vessels. Others consists of chemical and gas tankers, vehicle carriers and non-cargo vessels such as cruise/ passenger vessels and tugs. Chemical/ gas tankers and cruise vessels account for USdb 270 of the 400 USDb of 'other'.

2 | Literature Review

2.1 Offshore Wind Industry

This chapter aims at giving a summary over the literature available on the OW industry in general. It will include a timeline on the research into this sector and how its importance has increased in the last years as the energy transition is taking up speed. For this, search results with the search-terms as shown in table 2.2 are used on databases named in table 2.1. To complement the named academic databases in 2.1, Google is used to source market reports, that often don't identify as academic source/ research.

First, the results are presented, that is the number of papers resulting from the use of the search terms as well as as their field of study. Following that, a comprehensive summary of the papers is given, which forms an objective macro view on offshore wind in general.

The chapter as well aims at defining the current state of the OW industry, regarding development targets, and factors influencing the industry.

2.1.1 Results from use of search terms in databases

Database	Description
Google Scholar (GS)	Scholarly publications' search engine with direct links to full-text (TU-Delft subscribed) journals. Complemented by Google Scholar Citations, Google Scholar Metrics and Google Dataset Search, Scholar is a good source for initial literature research.
Web of Science (WoS)	WoS is the second big commercial database; it provides resources for science, social science and humanities disciplines.
Dimensions (DIM)	Dimensions is a relatively new database and expected to be the world largest linked research database [33].
Clarksons	Clarksons is not an academic database per-se, but a maritime data provider. They offer comprehensive data-based market reviews for specific shipping sectors, including offshore and raw data sets (fleet overviews, OW projects, and time series)

Table 2.1: List of databases used to find relevant literature for the research.

In table 2.2 the results for the search terms in the three most important databases are shown. Note that each search-term is referred to in the text with a roman number. It is clearly visible that Google Scholar gives a very high number of hits for the search terms. This is due to the fact that

Search-term	Database	Results	Field
offshore wind *(I)*	GS	292.000	-
	WoS	13.849	Engineering 8306, Marine Engineering 1481, Operations/ Management 158, Business Economics 315
	DIM	16.093	Engineering 12498, Maritime Engineering 8294, Business/ Management 233, Economics 187
offshore wind AND introduction *(II)*	GS	274.000	
	WoS	153	Engineering 76, Marine Engineering 10, Operations/ Management 2, Business Economics 1
	DIM	208	Engineering 173, Maritime Engineering 123, Business/ Management 3, Economics 3
offshore wind AND development *(III)*	GS	245.000	-
	WoS	4.033	Engineering 1964, Marine Engineering 477, Operations/ Management 27, Business Economics 165
	DIM	3.373	Engineering 2467, Maritime Engineering 1769, Business/ Management 98, Economics 57
offshore wind AND future *(IV)*	GS	182.000	-
	WoS	1.724	Engineering 815, Marine Engineering 140, Operations/ Management 15, Business Economics 76
	DIM	1.755	Engineering 1329, Maritime Engineering 861, Business/ Management 47, Economics 39
offshore wind AND maintenance *(V)*	GS	72,200	-
	WoS	1192	Engineering 762, Marine Engineering 127, Operations/ Management 63, Business Economics 21
	DIM	1214	Engineering 1065, Maritime Engineering 647, Business/ Management 19, Economics 3

Table 2.2: List of results for the search terms used in each database. The information on the field of research in Google Scholar is not available. In the text the search terms are referred to with the roman numbers. (Retrieved on 01.04.2023)

it contains more references than other databases and it indexes the full text of articles. The quality of these results therefore is hard to quantify. Nonetheless, especially for *II*, some good introduction articles into OW have been found ([66],[32],[49]) using GS. Especially Lynn [66] is a strong source giving a very comprehensive overview over the OW sector.

To quantify the results, the most relevant fields of research for this project are looked at: namely engineering and business/ operations management and economics/ markets. Only for WoS and Dimensions this is possible as GS does not provide research topics. Remarkable is the focus of the academic literature; where WoS and Dimensions define their field of study slightly different (a combination of search area settings to get comparable results is used), it is clearly visible that the focus of research into OW lies on the engineering part. According to Dimensions, 78% of all research is in engineering. The most researched field of engineering are, according to WoS [106], are into power and electric systems, ocean dynamics and geo-technical engineering. These topics are particularly relevant in offshore wind due the to complex power grids that need to be constructed and the complex installation of foundations [32, 76].

It is clearly visible that, regardless of the search term, the technical questions remain the most interesting for the academic world. However, when narrowing down the research to look at future research covering the future of OW, it is seen that the economical questions starts to get "more" attention (I 1.1%, *III* 1.6-4% and *IV* 2.2-4.4%, where the results differ for WoS and Dimensions due to different definitions of the field of research). These results are as well an indication of the literature gaps existing when it comes to OW: a gap in economics of offshore wind, and as maritime economics is a boutique branch of economics, the intersection between maritime economics and offshore wind will be even more limited.

The literature on economic questions that is present ([82], [1], [55]) is useful and can deliver important insights in cost structures of OW farms and economic viability in the long run. Especially insightful is to know how the Operations and Maintenance (O&M) costs are for windfarms and how this might influence the charter rates for C/SOVs. The best results for this were delivered using term *V*, where maintenance into the sector is researched, both from a technical as well as from an operational perspective, researching maintenance schedules and routing as well as interactions between vessels and structures. As this literature is very much oriented on the vessel side, the relevant literature on operational matters is discussed in chapter 2.2.

In addition to GS, WoS and Dim, Google has been used to search the web for market reports that are not listed in the academic literature. This includes sources from organisations such as Det Norske Veritas (DNV) [35], International Energy Agency (IEA) [54] or WindEurope [104]. These reports are a very solid addition to the technical background as they focus on both market and policy related topics.

Finally, the timeline of OW research is considered, for this only *I* is used to get a proper view on the full spectrum. In figure 2.1 it is visible that research into OW has been taking of since the end of the 90's, when both Denmark and Great Britain announced ambitious OW programs [78].

2.1.2 Offshore Wind Industry

Since the first OW farm was installed in Denmark in 1991 [73], the industry has been moving forward fast. With new projects, larger turbines and more advanced infrastructure rapid developments can be seen. This is as well reflected in the number of academic papers published with the terms "OFFSHORE" and "WIND" in the title or abstract. As shown in [33] the topic has rapidly increased in interest since 2010. Especially the EU's new Renewable Energy Directive has played its role here, promoting and setting targets for renewables [81].

Especially for the technical side of the OW industry, a high number of articles is available. 17.176 and 11.185 articles out of 24.000 are published in the category "Engineering" and "Maritime Engineering" respectively. As this is some 70%, it is reasonable to assume that there is a good literature pool to base the technical status update on. A further 6000 papers are available with a tag in "Earth Sciences" which are to be used for the update on building location and foundation types.

Further, "Dimensions" delivers insight on which researchers have been most active in a specific field.

For this general insight into the OW sector, these are Carlos Guedes Soares and Zhen Gao. Their

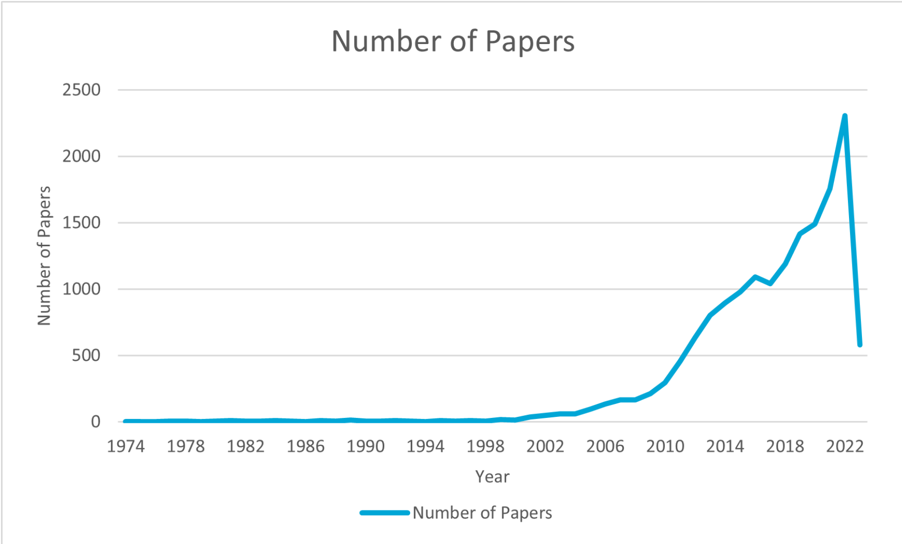


Figure 2.1: Timeline of the academic research into OW. For all years apart from 2023 full year numbers are presented. 2023 is still ongoing and numbers of published papers are collected. From: Dimension [33]

literature will be regarded to get an overview over the sector, especially from a technical perspective. In [32], Soares delivers a solid overview over the development of the OW market in the last years, both in terms of size of as well as location of new turbines.

A further source, giving the state from a more commercial point of view, is presented by Musial et al. [72]. Both the current installed capacity as well as the planned capacity is clearly listed.

It becomes clear, that the research delivered by [32] is most useful for the technical background on the industry, whereas [72] and [49] deliver a stronger insight into the commercial side of the industry.

Currently 50 GW of total OW capacity are installed, of which 27 GW in Europe (11 and 7 GW in the the largest markets of the UK and Germany respectively) and 21 GW in China [72].

Expected growth of OW market

The expected growth of the OW market and capacity is well researched by especially international organisations such as the IEA and the EWEA (Windenergy Europe). Purely academical papers on this topic are rare, and the ones that have been published do rely on government and IEA/ EWEA sources, for example in research published by [32] and [45].

This case is not surprising, as currently wind parks have only been built in the EEZ of countries and this is not expected to change in the near future [83, 17] due to both technical difficulties as well as jurisdiction applying to the high-seas. As the allocation therefore is dependent on government decisions, there is limited academic potential for growth forecasts.

The market projections can be split into a near (up until '27) and medium-term (until '32) [72]. The near term projections are based on data for projects with a Commercial Operation Date (COD) until '27, totalling 177 GWs. Figure A.1 in Appendix A shows clearly that the largest markets in the coming years are Europe, China and North America. [35] gives a forecast up until 2050. In this outlook non-fossil energy supply is said to tripple until 2050, with wind and solar growing from marginal

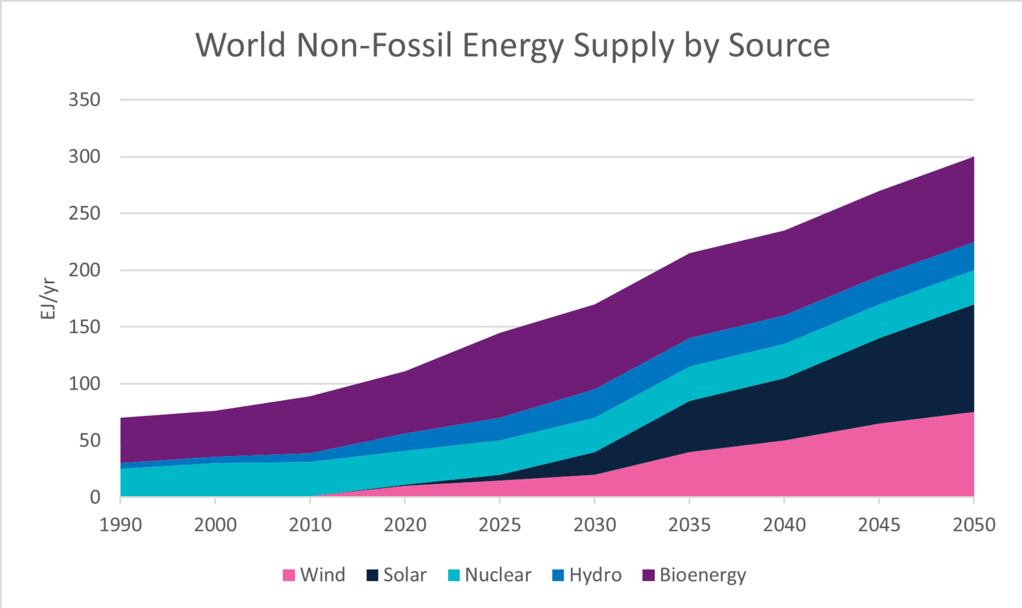


Figure 2.2: World non-fossil energy supply by source. A significant growth of both solar and wind is expected until 2050. From: DNV [35]

contributions (both contributing 1% to the world-wide total primary energy supply in 2020) to 13% and 15% respectively. The graph is shown in figure 2.2.

DNV expects the contribution of wind to the European electricity grid to be almost 50% in 2050 ; a more thorough breakdown can be found in figure A.2. In total OW will provide nearly 25% of on-grid electricity in that case. Of all OW generation, 16% is expected to be from floating OW turbines. In absolute number, a total installed wind power to be around 950 GW in 2050 in Europe, of which 440 offshore. The detailed breakdown is shown in figure A.5. Musial et al. [72] gives absolute numbers as well, but limits himself to considering the current pipeline: for Europe a total of 160 GW expected. It has to be mentioned that DNV gives the furthest outlook until 2050, [104], [72] and [56] only show expected capacities until 2030. [19] gives the most complete overview, including the number of turbines and capacities on a farm level which goes as far as 173 GW in 2030.

In figure 2.3 the expected capacities for the different sources are shown; WindEurope and Clarksons give the most detailed data, broken down on a y-o-y basis. Both timelines are very much aligned until 2029. Where as the expectation of DNV for 2030 aligns with the one of WindEurope, the one of Musial and Clarksons do as well for the same year but on a higher level. A reason reason for this is that both specifically state that they include projects in the pipeline, where as this is not specifically stated for DNV and WindEurope. At an average of 130 GW and 180 GW for the high and low case respectively, the difference between the scenarios is 49 GW or 37%. It will therefore be important to identify the effect of the scenarios on the final model and identify the right approach to handle this difference: it is possible to take an average value or specify the different outcomes as "base" and "high" case. An important note to this are the targets the EU and UK have declared for OW targets up until 2030 and 2050. If the targets are combined, a target of 160 GW in 2030 and of 442 GW in 2050 is set. It is important to notice that the data from Clarksons for figure 2.3 have not been cleaned yet, as this falls outside of

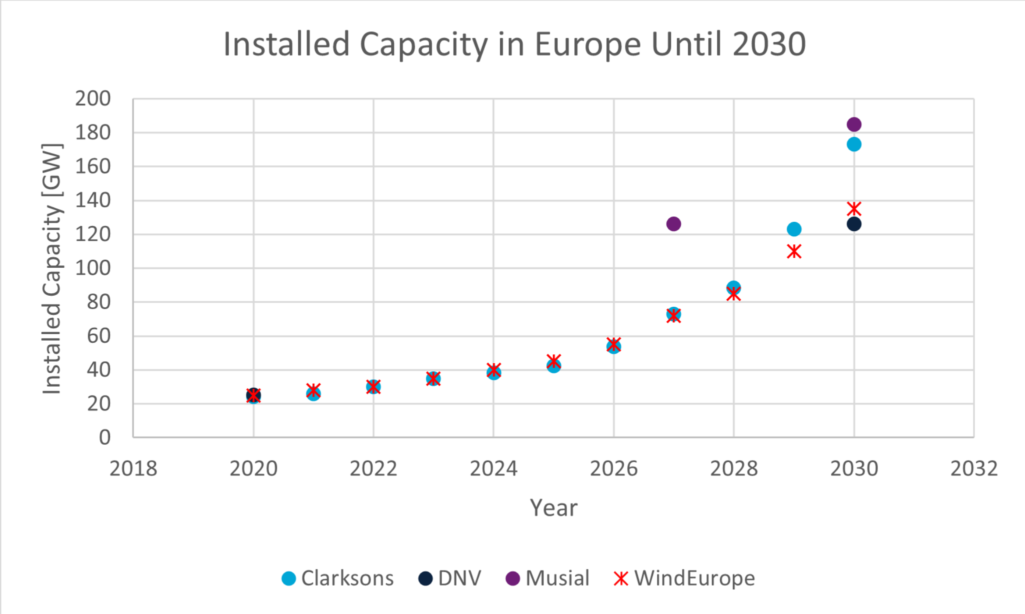


Figure 2.3: Installed OW capacity in Europe as expected by Clarksons [21], DNV [35],Musial et al. [72] and WindEurope [104]. DNV [35] expects a total installed OW capacity in Europe up to 439 GW in 2050.

the scope of the literature review.

From the same data set from Clarksons [21] further information on the wind farms can be sourced: this includes the size of the parks, the distance to shore and the capacity of the turbines. In figure 4.2 it is visible that the distance of wind farms to shore has increased continuously in the last 20 years. The weighted distance for all farms is shown, to account for the size of farms in the calculation as well. Whereas the weighted distance of new farms keeps rising over the years, a consolidation of the overall distance for all farms around 50 kilometres from shore is visible.

The similar pattern can be seen when looking at the weighted average size of wind farms. The weighted average size needs to be used to correct for very small (experimental) parks. There is a clear trend visible for parks getting bigger. From a size of 25 turbines per park in 2000 to 100 in 2038 [21]. Together with the turbine size getting bigger [21], this means that the total area of the parks will increase as well due to the so called "park effect", which is the increasing distance between turbines once they get bigger, to reduce the wake effect [30].

An additional factor influence of parks on the maintenance demand is the point in the lifetime. The so called bathtub curve describes the failure rate of components throughout the lifetime of any device [100]. It shows how during the early life as well as during the wear-out period an increased chance of failures exists. This needs to be addressed by the Original Equipment Manufacturer (OEM) during the early life period and can lead to an increased use of vessels.

During the further research the influence of these factors combined on the SOV demand needs to be determined, as currently no research is available that assesses the combination of the different park factors on the vessel demand.

2.1.3 Conclusion

In short the findings from the literature review on the OW market are presented. The literature landscape has been analysed, using three different databases, namely GoogleScholar, Web of Science and Dimensions. The use with the latter two was most successful, delivering the most targeted results. Special attention was paid to finding the field of study on which research has been performed on OW to identify possible literature gaps. As the research questions aims at a marine-markets problem, it was important to see in how far this field of study (offshore wind and economics/ finance) has been touched upon. The results were clear in that sense: there exists a large gap in this field. The core of research has been done in engineering topics with up to 78% of the available research belonging to that field. Especially market reports from research institutions such as DNV delivered an important insight into the expected market development of OW. The most important fields within engineering are clearly the design of power grids and structural questions for the turbines. A clear pattern in the market reports is the growth of offshore wind; even though two different trajectories can be defined, the growth of the market is clear. Whereas currently 25 GW of offshore capacity are installed in Europe, this is expected to grow to 130 GW in the low case and 169 GW in the high case. As two clear trends are visible, it will be key to define the high and low case in chapter 4. Further a way needs to be found to include the targets of the EU as limit in the development. This will be further discussed in chapter 4. A clear trend is visible in the increasing distance of new farms to shore and the increasing size. The distance for all farms combined is expected to grow to 50 kilometres in 2030 whereas the weighted size for all farms combined is expected to grow to 80 turbines per farm. The data cleaning needs to be performed in chapter 4 as this is not part of the literature review. To conclude the literature review on OW as a market in general, a clear growth direction could be defined and a solid overview over the trends was presented. Several factors contributing to the development of the OW industry were appointed as well: the need for maintenance, the contribution of the governments to the decisions on where and when to build. Further specific trends in the park parameters were defined – namely the trend that parks are getting larger as well as being built further from shore.

For the coming chapters therefore it will be important to identify twofold: firstly, identify whether the academic world has research available on the influence of these factors on the vessel usage and secondly identify a method to use the factors to answer the main research question: *How many vessels are needed to service the European offshore wind market in 2030 and which factors influence these demands?*

2.2 Offshore Vessels

Following the first chapter in which the OW market in general was depicted, this chapter aims at delivering a first overview over the literature on the offshore vessel market. The same approach as in chapter 2.1 is used, which means that the search terms from table 2.3 are used. On one hand the literature on vessels specifically used in the OW industry will be assessed, as this sector however is rapidly growing and therefore vessels from the O&G sector are used as well [20], these vessels are also mentioned in the review. In this chapter the same databases as listed in table 2.1 and additionally Clarksons database are used. Even though this is not a classic academic database, it will serve as an important supplier of high-quality market reports and data. Finally a short overview over the offshore (O&G and OW) vessels is given due to the spill of these vessels to OW.

2.2.1 Results from use of search terms in databases

Search-term	Database	Results	Field
offshore vessel (I)	GS	756,000	-
	WoS	5704	Engineering 4034, Marine Engineering 1758, Operations/ Management 124, Business Economics 61
	DIM	6517	Engineering 5187, Marine Engineering 3860, Business/ Management 202, Economics 17
offshore AND (*supply* OR *support*) *vessel (II)*	GS	368.000	
	WoS	1.813	Engineering 1172, Marine Engineering 482, Operations/ Management 59, Business Economics 37
	DIM	1614	Engineering 1304, Marine Engineering 980, Business/ Management 105, Economics 3
"offshore wind" AND *vessel (III)*	GS	24,600	-
	WoS	453	Engineering 270, Marine Engineering 119, Operations/ Management 23, Business Economics 15
	DIM	536	Engineering 472, Maritime Engineering 416, Business/ Management 6, Economics -
offshore wind AND (*supply* OR *support*) AND *vessel (IV)*	GS	21,600	-
	WoS	198	Engineering 115, Marine Engineering 53, Operations/ Management 9, Business Economics 8
	DIM	119	Engineering 105, Maritime Engineering 97, Business/ Management 5, Economics -

Table 2.3: List of results for the search terms used in each database. The information on the field of research in Google Scholar is not available. In the text the search terms are referred to with the roman numbers.(Retrieved on 01.04.2023)

In table 2.3 the search results for the search terms are given. Note that each search-term is referred to in the text with a roman number. A similar pattern is seen in chapter 2.1; a high number of research articles going into the engineering part of the matter. For *I* a relatively high number of articles going into the markets and operations question is found, which allows for a more solid literature base to build on. It is noteworthy that most of the papers under *I* are published in the Journal of Petroleum Engineering [33]. This shows the need to consider the O&G sector in the literature review and research. It is found as well when looked at *II*, that less literature is available and a significant part of the literature is researching the operational part of the vessel side ([42], [86]) where fleet sizes and operating patterns are researched. Financial research on the support vessels is not available at this moment. Two relevant papers are found by Kaiser and Snyder [58] and Dalgic et al. [28], both model day rates for OW vessels. Once the research is narrowed further and support vessels (*II*) are looked at, the results strongly focus on marine engineering questions. Relevant pieces of literature are found when searching *II* for specifically market/ finance orientated papers: [86], [67], [102] address the O&G offshore vessel market. Due to the relatively good coverage of this sector, it will be analysed in the research following the literature review, in how far market principles from the O&G sector can be used and transferred into OW. This means that additionally, a broad research on available market reports for the O&G sector has been performed, using Google. Again some reliable sources reporting on the state of this sector are, among others, the IEA and DNV ([53], [57], [35]). A research by de Souza et al. [31] aimed at optimising charter contracts amid the fleet renewal process in the offshore industry, which in its core is reinforced by Wiig and Tvedte [102]. These articles will be a good base for further research due to the comparable current market situation in OW.

III and *IV* deliver little new insights; the focus is heavily on engineering topics. This is not surprising due to the fact that vessels active in the OW sector are being built with new and green technologies [37]. As mentioned, the results form search term *V* from chapter 2.1 (offshore wind AND maintenance) are presented here due to the focus on the operational vessel side. A focus on routing and fleet composition problems is discussed by Dalgic et al. [29], Michiel et al. [70], Stålhane et al. [91], Gundegjerde et al. [46]. The research into the optimal fleet sizes is crucial to determine the required number of vessels for the sector.

2.2.2 Offshore Vessel Fleet

This section gives an overview over the world offshore fleet, the types of vessels employed and a short note on the effect of growing OW on the sector.

Vessels used in the offshore industry

The OW fleet relies on three main vessels types throughout the lifetime of the wind parks; namely Wind Turbine Installation Vessel (WTIV), Commissioning and Service Operation Vessels (C/SOVs) and Crew Transfer Vessels (CTVs). Further retrofits of existing C/SOVs will serve the market [107]. Besides these vessels, which are used in larger number, specialised vessels such as hydrographic survey vessels are used as well, but are outside the scope of this research. Table 2.4 lists the six most important offshore vessel types and describes them, the niche classes such as Hydrographic Survey Vessels are not regarded and listed. For some classes, cross-definition are sometimes given, especially when it comes to the PSVs and AHTSs: these vessels are classified more generally as "offshore support vessels" as well.

One of the tasks in the research will therefore be to define the classes to place the right boundaries.

Vessel type	Description	No. of vessels
Wind Turbine Installation Vessel (WTIV)	WTIVs are dedicated vessels for installing turbines. With increasingly large turbines and blades, as well as locations in deeper water, these vessels are becoming larger and are equipped with cranes with bigger lifting capacities.	82
Commissioning and Service Operation Vessel (C/SOV)	CSOVs are vessels used for a wider range of purposes and are used in both the construction as well as operational phase of the wind park. They are equipped with extended accommodation facilities and walk-to-work gangways.	10
Service operation vessels (SOVs)	C/SOVs have smaller accommodations than CSOVs but are similarly equipped with accommodation facilities and cranes and walk-to-work gangways.	25
Crew Transfer Vessels (CTVs)	CTVs are smaller, fast vessels used to transfer crews to and from wind parks or CSOVs to shore.	592
Platform Supply Vessel (PSV)	PSVs are supply vessels specifically designed and used for transport of materials and equipment in the O&G sector. They see use in the OW sector as support vessel or conversed C/SOVs as well.	2018
Anchor Handler Tug Supply (AHTS)	AHTSs are used for anchor handling and towing operations. They perform supply and (construction) support tasks as well.	2446
Multi-Purpose Support (MSV)/ Offshore Support (OSV)	More capable version of the PSVs, often equipped with construction support such as heavier lift cranes or diving vehicles.	295

Table 2.4: Short description of the most used vessels in the offshore wind and oil and gas industry. From Wärtsilä [107], Clarksons [20].

The largest offshore vessel operators are currently owners mainly active in the O&G market. These are the US companies Tidewater and ECO (Edison Chouest Offshore), Bourbon and Solstad in France and Norway respectively and CNOOC in China. The OW C/SOV market is dominated by Edda Wind, Esvagt and Siem. Note that behind these three companies well experienced players from the offshore O&G market are standing. The orderbook for C/SOVs will however change this picture, and will make Edda (19 vessels) the largest before Esvagt (10) and IWS (8). In Appendix A table A.1 shows the five largest offshore owners per segment as described in table 2.4.

Offshore Vessel Market

Literature on the vessels used in the OW industry is to a large extend limited to engineering problems, such as propulsion and routing of the vessels. When consulting Dimensions, the search for "offshore AND vessel AND wind" results in 962 publications, of which 839 are labelled as "engineering". There is only limited literature available on the market in which OW vessels, and offshore vessels in general, operate. Limited information exists on the contracts these vessels operate under. Clifford Chance [24] describes the situation for O&M in the OW industry, where the OMC is affiliated to the supplier of the WTG, aiming at the WTG supplier as the contractor for the CSOVs. With growing turbine sizes and larger installed capacity, Smith [87] mentions that the largest impact will be on the CSOVs. These vessels need to be larger to service larger WTGs. Whereas currently only 1% of the global fleet value is covered by OW, this is expected to grow to 4-7% in 2040. Lewis [65] further expects growth in the conventional AHTS market (used in offshore O&G as well) as well due to increased floating OW farms. For the O&G it has been shown that both the supply of and demand for offshore vessels is heavily dependent on the oil and gas price as both less vessels are operated (mothballing) and hired [80, 3]. It needs to be seen whether the OW market will show similar seasonal/ cyclical effect, and how these cycles might coincide. A particularly relevant topic is the number of vessels needed for the O&M of a OW facility. As already mentioned by Smith [87], the impact of the growing number and size of facilities and turbines will have a big impact on the vessel market. There is relevant research performed in this field by Alcoba et al. [6], Halvorsen-Weare et al. [47] and Szpytko and Salgado [92] specifically on CTVs. Routing problems and fleet compositions simulations including C/SOVs are performed by Tusar and Sarker [94]. These papers clearly show that during the O&M phase of the OW park the most used vessels will be CTVs and C/SOVs, where C/SOVs are clearly shown as the more expensive vessels [97], but with better capacities for carrying out maintenance activities. The positive features of using C/SOVs as well increase when offshore farms are built further away from ports, as transfer times are reduced, safety related risks are reduced by using W2W systems and physical stress is reduced due to higher comfort [50]. Figure A.6 shows how a distance of more than 40 miles from port triggers offshore based (C/SOV) maintenance strategies. Nonetheless, combined operations are frequently performed as well. Van Bussel and Bierbooms [98] established that it is necessary to maintain a 80% accessibility to achieve 90% OW availability (the target is 95%). Especially in the winter months, technology is needed which allows for safe transfer of personnel in higher sea states. Lazakis and Khan [63] performs a simulation for a 91 turbine wind park, similar to the size of the wind parks currently served by C/SOVs as mentioned in Hu and Yung [50, p.19]. Tusar and Sarker [94] as well analyses the optimal fleet size, using a routing problem as base for the research. He only defines three classes of CTVs, of which the large one (80 passengers can be defined as C/SOV). The paper delivers no insight in the number of vessels needed, however a very relevant result is the increased efficiency that comes with using a "big" (80 pax) CTV, or C/SOV in our case.

When considering the vessel market, it is important to regard under which type of contracts the vessels are employed. Dalgic et al. [28] gives a charter rate estimation for vessels in OW, namely those that perform major and minor maintenance. Scheduled maintenance allows for better planning and identification of the vessels needed for this task. This results in reduced mobilisation time and higher availability of the vessels. As for OW farms and the turbines the supplier is usually required to perform the maintenance in the first years, most contracts for vessels are on a time charter basis. A good example for this is the employment of the vessels ordered and operated by Edda Wind[37].

For the research it will be key to fill the literature gaps and define factors that allow for forecasting the actually needed number of vessels for the OW market.

Oil and Gas Market Development

As the offshore market is closely connected to the O&G market, the results from the available market reports are presented in 2.4. It is expected that the share of gas-fired electricity generating capacity will only marginally decrease until 2030 [35]. In total world oil demand will reach its peak in 2025 and reach 1980 levels in the early 2040s. World gas demand is expected to reach its peak in 2040, without decreasing strongly. The IEA [53] gives higher outputs and shows increasingly larger water depths for oil production. With two different scenarios up to 2040, a significant high a low case can be defined (figure 2.4), where in one case production will fall below current levels or stay on the current level for oil and gas either grows marginally or significantly. As it is expected that the new projects will start to emerge in regions other than Europe, it is possible that especially older vessels will leave the EU waters due to the introduction of offshore vessels into the EU ETS [36]. This could have an influence on the availability of support vessels for the European OW market. McKinsey [69] expects the drilling market to significantly grow until 2035 where new offshore production growth comes from higher cost ultra-deepwater resources, which offset stagnation in shallow and deep-water resources.

Currently 341 offshore installations [25] are placed in the North Sea that are either actively operated or need decommissioning. Especially the decommissioning is a time consuming and expensive undertaking, with an average of 15 topsides being removed per year until 2031 in the UK alone [95]. During these operations more personnel is required on the platform. As systems are being shut down and due to safety reasons, technicians are using external accommodation units during these operations. C/SOVs are well equipped for housing the crews and it is expected that these vessels will be chartered to provide this accommodation, hence increasing the demand for these vessels.

Concluding it can be said that the offshore O&G market is well positioned and that a significant downturn in this segment is not to be expected. Especially the trend to move further away from shore will affect the market as longer distances mean a higher number of vessels needed to service platforms. Topping up that demand is the increasing need to decommission the existing platforms.

2.2.3 Conclusion

A similar pattern in the literature as in chapter 2.1 was visible here. A significant portion of the research is dedicated to (marine) engineering questions, with a heavy focus on propulsion and sea keeping of offshore vessels. Especially in combination with offshore wind, significant research has been performed on the maintenance problem and especially the composition of fleets and routing schemes. This is expanded by research into the charter rates of offshore vessels and the markets behind the offshore O&G vessels, that are heavily susceptible to commodity price fluctuations. For the offshore market six vessel types have been shortly described, namely turbine installation vessels, crew transfer vessels and offshore support vessels for O&G and OW. Especially interesting are the latter for the OW market, as it is expected that their number will significantly have to grow to answer to the market's demand. The influence of factors such as park size and distance to shore has been confirmed in this part, where larger parks trigger other maintenance strategies (more vessels, combined C/SOV/CTV use) and the distance to shore is defined as a clear factor triggering C/SOV use. In chapter 4 the influence of factors such as distance to shore and size of the park on the required number of vessels needs to be quantified.

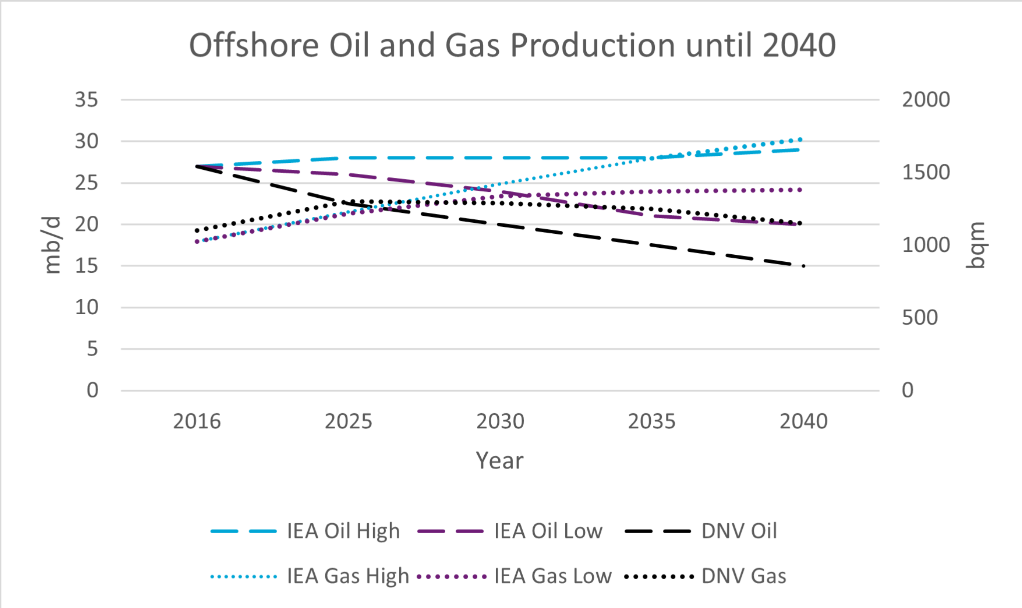


Figure 2.4: Expected offshore oil and gas production until 2040. Note: mbd: million barrels per day (oil), bqm: billion cubic meters (gas). From: IEA [53], DNV [34]

To get a first impression of the market for O&G vessels, the expected development of the offshore O&G market has been analysed, with two trends visible which can point at the definition of a high and a low case. The influence of the offshore O&G development on the OW vessel side will be discussed following the research. For the next part of the literature review it is key to find a method to both use the quantifiable factors as well as qualitative factors to forecast the C/SOV demand.

2.3 Research Methodologies

After defining both the importance of concrete factors that influence the need for C/SOVs and that influence the OW market as a whole, methods need to be found to perform both a quantitative as well as qualitative forecast. Certain factors, such as decisions by governments on OW targets, will be too complex for this research to model in a quantitative way and will hence have to be included in a more qualitative way by discussing the quantitative results.

This chapter aims at giving an overview over the suitable available research methods and literature available on them. In order to make a prediction about a future demand for vessels, a method needs to be found to use available hard facts on future parks to identify the future demand. As raw data are widely available, data analysis techniques are to be considered in order to have techniques available to pre-process the data in order to maintain a streamlined research and keep data within the boundaries of the research.

2.3.1 Systematic Review as Research Method

Following the data research, existing literature on the OW industry can be used to define further factors which influence the number of vessels. Snyder [89] gives a comprehensive overview over a more targeted literature review rather as a research methodology than a research preparation. It was shown in chapter 2.1 that a good literature base exists on maintenance planning and vessel routing. The results from this part can eventually be used, in combination with the data on new farms and projects, to define the required number of vessels in the OW industry. A "systematic review (SR)" goes further than just the literature review (the identification of literature) like it has been performed until now. Especially the so called "meta-analysis" is a suitable and usable strategy, where the original individual studies are treated as if they are parts of one larger study (the need for OW vessels), by having data pooled together in one single and final result that summarises the whole result [12]. A positive find of literature on SRs is that there is a significant number of articles from the field of software engineering [12, 59, 74]. As software engineering is known to be a very structured field of expertise [79], this leads to a high standard in the delivered strategies. The SR allows as well for the use of interviews to fill certain literature gaps, which can be key to defining factors influencing SOV demand that are not available from literature but can be identified by industry experts.

2.3.2 Data Analysis and Simulation

The table (table 2.2 and 2.3) used to classify research results is less relevant in this chapter, as data analysis techniques can be classified as universal. Regardless of the field of study it is important to keep data clean and well structured so they fit the research purpose. Therefore, mostly an overview over the results will be given in this chapter.

To get a view on the necessary steps that need to be performed when working with data, Ader [2] gives a comprehensive overview: *data cleaning*, *initial data analysis*, *main analysis* and *further analyses*. The latter becomes relevant after the research has gone through the first review cycle, which means that for the core part of the research, the first three steps are relevant. The need for a structured data analysis that confirms this framework is delivered by [52], who stresses function of an Initial Data Analysis (IDA) as an integral part of research. Huebner et al. [52] includes the data cleaning already in the IDA.

As the aim is to build the simulation and vessels demand forecast on the available factors, it is important to regard the ease with which these can be incorporated in the model.

- **IDA:** The IDA is aimed at the first steps of the data analysis, meaning the data cleaning, data screening and the reporting of the data before the core analysis is delivered. It is important in this first step to keep an unbiased look at the data [16] and refrain from premature analyses directed at solving the main research question. To a large extend, the IDA aims at cleaning the data, for which four methods are useful in particular [101]. As the data from Clarksons is to a large extend time series based, these tools proof beneficial. As the data are market related, and shocks can lead to extreme outliers [85], especially the anomaly detection method as presented in Wang and Wang [101] can be a useful tool to check on certain shocks in the offshore vessel market.

Once the initial data analysis is performed, the data analysis techniques with the aim of answering the main research question can be regarded. Atif et al. [9] mentions the most used data analysis and modelling techniques, of which possible methods for this research are:

- **Descriptive Statistics:** Descriptive statistics are widely used in data analysis to summarise and describe the characteristics of the data [75]. One of the most commonly used characteristics is the mean, which is a useful measure of central tendency in data analysis, but caution should be taken when interpreting the results in the presence of outliers [26]. Combined with the standard deviation this allows for a quick first overview of the composition of the data.

- **Regressive or moving average models** where the regressive models model the relationship between a dependent variable and one or more independent variables and moving average models (MA) are time series models that capture the short-term dependencies in data. These can be combined in models such as the Autoregressive Integrated Moving Average (ARIMA) model which capture temporal dependencies and can be effective for predicting future values based on historical data patterns; this means however that the model is suitable for both data analysis as well as the following modelling [109].

- **Machine Learning and Neural Network:** Machine learning techniques have been studied and implemented in data analysis, including supervised learning, unsupervised learning and reinforcement learning [8] and are widely used in both engineering and economics for forecasting and prediction calculations [43, 68]. Ahmed et al. [5] describes mixed results when comparing neural networks to ARIMA or linear models, but a general trend of neural networks outperforming these techniques is visible. A potent model is the Bayesian Neural Network which, compared to the standard neural network, marginalises instead of optimises the result. This means that the weight of each factor is treated as a variable and the model would find the distribution. Krollner et al. [61] gives a comprehensive view over literature regarding the use of neural networks.

For machine learning techniques, especially the right definition of input variables is important. Huang et al. [51] describes this step as the factor analysis for a demand model, based on Lawley and Maxwell [62] who explains this process in more detail. The method shown by Huang et al. [51] is very useful for answering the research question in our case. However, uncertainty is not taken into account in this research. Barnes et al. [11] works with the estimation of a general probability distribution to add uncertainty to the neural network. Finally the forecasting errors need to be defined [60], where it is possible as well to use these errors and the uncertainty to define the confidence interval of the results [5].

- **Mathematical Modelling** techniques are widely used in predicting complex economic systems, where the difference needs to be made between stochastic and deterministic models:
  - **Stochastic Models** utilise randomness and probability theory to model and simulate economic variables that are subject to uncertainty and fluctuations. By using these models, inherent volatility and randomness present in real-world economic processes can be regarded [71].

    One technique is the Monte Carlo simulation which involves generating a large number of random samples based on specified probability distributions and then simulating the model under different scenarios [27, 38, 14]. A second way of simulating with randomness is the Markov Chain, where the future event is only dependent on the current state of the system. It is based on the principles of memorylesness and often appears together with the Monte Carlo Simulation [39, 41]. The Monte Carlo simulation could be an appropriate fit, as it is used for the same purpose by Pires Jr and Antoun [80] to forecast the demand of offshore supply vessels in the Brazilian O&G market. Factors such as operating patterns, water depth and geographic location (distance to shore) are used to estimate an additional vessel demand. This is done by basing the simulation on the aggregate progress of an O%G project. Whereas the risk is defined in certain steps as the stop of the project. Szpytko and Salgado [92] uses a combined Markov Chain Monte Carlo (MCMC) simulation to combine a predictive and preventive maintenance process with an optimal vessel fleet size problem. The problem is more broad than in our case, but the mean time to failure and the mean time to repair are two useful factors to take into account for the MCMC. The need for a stochastic model is stressed in this paper to account for the randomness in failures. In neural networks the Monte Carlo Dropout (MCD) is used to estimate uncertainty in predictions. It involves performing multiple forward passes with dropout enabled during inference (turning off neurons), generating different outputs. By averaging these outputs, it provides more robust predictions and quantifies uncertainty in the model's predictions.
  - **Deterministic Models** assume that known average rates with no random deviations are applied to series and processes [7]. This means that the outcome is completely determined by the initial conditions and "perfect foresight" is assumed [99].
  - **Combined Models** such as stochastic differential equations (SDE) describe how economic variables evolve over time in the presence of randomness. These equations incorporate both deterministic components, representing the trend or mean behaviour of the variable, and

stochastic components, capturing the random fluctuations. SDEs are particularly relevant in studying financial markets, where asset prices and interest rates are known to exhibit volatility and non-linearity [10].

By considering both historical data and incorporating stochastic elements, it is possible to generate probabilistic forecasts that account for uncertainties and potential shocks in the market.

- **Factor Model** The factor model has its origins in psychological research and aims at determining correlation between factors which influence a variable. Harman [48] gives a detailed explanation over this method, which is strongly built on linear algebra and matrix operations. This method is very much suited when specific (quantifiable) factors influence a variable. Factors are weighted and hence have different influences on the variables. Yong et al. [108] as well shows the possibility of obtaining factors through interviews, which allows for a more extensive method of sourcing factor information. Rummel [84] stresses how versatile the factor analysis is and how it can be used in multiple research fields, including engineering and economics beside psychology and social sciences.

The results which are delivered in this section prove to be satisfactory, and unlike the difficulties encountered in chapter 2.1 and 2.2, where literature gaps existed, the academic community has performed research into a wide variety of tools to perform SRs and data analyses and simulations. The advantage that comes up with these methods is that, to a wide extend, they are universal and can be applied on a wide variety of research fields. In chapter 3.2 the final research methodology will be further discussed.

2.3.3 Conclusion

The literature on research methodologies was widely available. To answer the research question two specific tool kits will be used: namely a literature review as research method, or systematic review (SR), and a data analysis and simulation. The SR will allow for a thorough assessment of the contents of the current literature into the offshore wind market, its growth prediction and the offshore vessel sector. The SR is to be complemented with expert interviews to fill in gaps in the practical knowledge. The data analysis will be used to perform the quantitative part of the research, namely the collection and processing of the raw data regarding planned OW farms and the vessel market. The data analysis has to start with the initial analysis in which data are cleaned and following that mathematical methods can be used to process the data to get the required results. To further process and analyse the data, stochastic modelling techniques provide valuable tools to capture and analyse the inherent randomness and volatility present in systems. This starts with tools to capture the state and dependencies of the data such as regression or moving average tools and is followed by tools to simulate a forecast on the base of existing data. Here the stochastic Monte Carlo method is particularly suited for simulating under uncertainty as has been show in already conducted research. Due to the difficulty of making exact predictions when market-topics are simulated, the Monte Carlo simulation can deliver results ranges to which this uncertainty can be linked. Due to the fact that specific factors (distance to shore etc.) influence the SOV demand directly, the factor model is as well to be further evaluated. This can lead to a possible combination of the Monte Carlo simulation and a factor model.

2.4 Conclusion

The review was conducted in three parts, each assessing the literature on a specific topic. The first being the general state of the OW industry and the expected growth of the sector.

The literature review revealed gaps in the field of study related to OW and marine markets. It revealed a significant gap in research on offshore wind and economics/finance, with the majority of research focused on engineering topics. Market reports, particularly from institutions like DNV, offered valuable insights into the projected market development of OW. Key areas within engineering included electrical engineering, as well as structural considerations. The research indicated that the current 25 GW offshore capacity in Europe is expected to grow to 118 in the low case and 175 in the high case. Given the variations in market reports, a *crucial task in answering the research question will be to make an informed assumption regarding the expected installed capacity and define the high and low case.* Further, it has been established already that a range of factors concerning the parks are changing, such as park size and distance to shore: these do influence the use of SOVs directly.

The second part of the literature review aims at the vessel side in the OW sector and establishes whether the factors coming from the parks do influence the demand for vessels. The predominant focus is on marine engineering aspects, particularly in relation to vessel propulsion and sea keeping. Studies have also delved into fleet composition and routing schemes for maintenance, which play a vital role in determining the required number of vessels to support the expansion of OW projects. However, there is a noticeable research gap regarding the market dynamics specific to OW vessels unlike for the offshore Oil and Gas (O&G) sector, which is influenced by fluctuations in commodity prices. The expected development of the offshore O&G market has been analysed, with two trends visible which can point at the definition of a high and a low case. Lastly, the direct influence of OW park parameters was confirmed, with distance to shore and size of the park being important drivers for the vessel use. Hence a task for the research will be to *further confirm the factors and their influence on SOV use and where possible quantify these.*

The third part of the literature review analysed relevant research methods for the following chapters. Two relevant methods were presented for the coming research: a literature review or systematic review (SR) including interviews for comprehensive analysis of the offshore wind market and vessel sector, and data analysis for the quantitative part of the research. The research on data analysis mentioned several methods, including regression and moving average tools, and stochastic modelling methods like the Monte Carlo simulation and SDE. Additionally the factor analysis was described as it allows for an effective way to use the weight of factors on a systems outcome. *Further research on the Monte Carlo simulation and the factor analysis will be performed.*

Figure 2.5: Steps following from the literature review. In chapter 3.2 the further approach of the research will be discussed.

3 | Method

3.1 Research Design

This chapter describes the research design and process where the next steps are described and the process to answer the main questions:

1. *How many C/SOVs are needed to service the European offshore wind market in 2030?*
2. *Which quantitative and qualitative factors influence the C/SOV demand?*

The research design aims at twofold: to describe the difficulties that may be encountered during the research and giving an overview over relevant methods and subsequent choice of the most suitable method [77]. To a certain extend the literature review has, by showing the literature and knowledge gaps, already shown a direction for the research, namely the need for a structured review as well as a data analysis and simulation. As well it has shown certain difficulties, namely the absence of prior research on the offshore industry and especially the OW vessel side from a markets-perspective. As the relationship between the variables and the factors is analysed rather than defining a strong cause-and-effect between them, an observational rather than an interventional research is conducted [18, p. 1255]. In chapter 2.4 the following points that needed answering from the literature review were defined. Namely:

1. An informed assumption about the expected installed capacity and the possible definition of a high and a low case. This assumption will be further elaborated on in chapter 4
2. The influence of factors on the number of vessels needed such as distance to shore and the size of a park and operational factors. This is addressed in chapter 3.2
    - In chapter 3.2 the quantifiable factors are included as they can directly be incorporated into the model
    - Other market dynamics and developments mentioned by industry professionals that influence the OW or C/SOV market as qualitative factors are discussed against the simulation results in chapter 5
3. The model to determine future demand of C/SOVs, regarding uncertainty. This is to be done by means of a factor model and a Monte Carlo simulation. The MC simulation can set benchmarks for the C/SOV demand that can be discussed against the qualitative factors. This is discussed in chapter 3.2

Research Process

Figure 3.1 shows the flowchart with the research process. The structured review has been specifically marked as expert-interviews have a longer standing history in social sciences [13] and are less common in engineering. As the research in itself is market based and the more theoretic simulation should be based on some practical hard-facts, it is deemed acceptable to include an expert opinion into the research to keep uncertainty from the operations side in the model as low as possible. To retain a balanced view, six different parties are to be consulted for an interview, four from the industry (Orsted, Green Giraffe, Deutsche Wind and Damen), class society (DNV) and academic sector (TNO). The findings of the interviews will be presented where needed and otherwise in chapter 5.

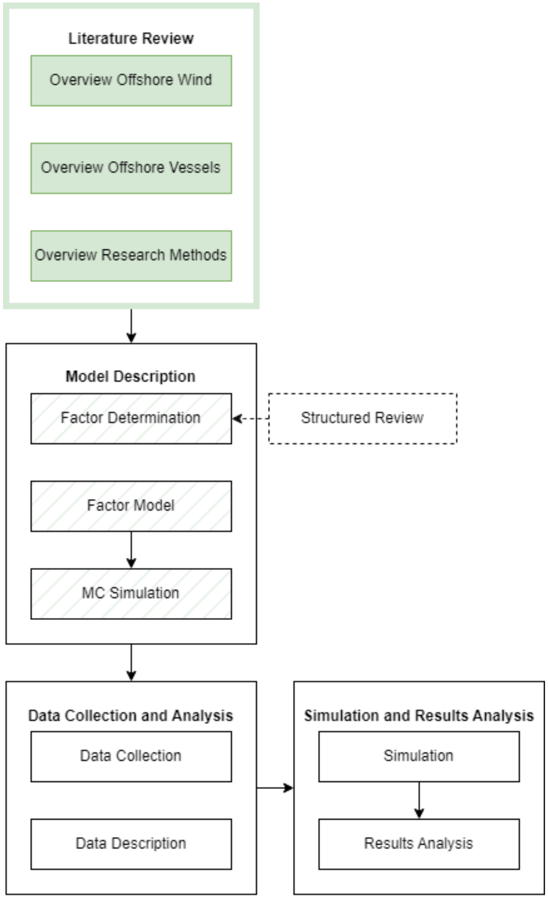


Figure 3.1: Flow chart of the research process. The literature review has already been performed.

In the following chapter the model consisting of a factor model and MC simulation will be constructed around the quantifiable factors. The aim is to use the randomness the MC simulation implies to identify ranges of results in which the required number of vessels lies. The ranges of results are finally assessed by discussing them against the qualitative factors. This will allow for a hybrid way of determining a vessel demand in 2030 where a benchmark is based on hard facts and the influence of other dynamics can be assessed.

3.2 Model Description

This chapter consists of the model description. Following the research design the next steps in the research are the confirmation of the factors that influence the SOV use and the description of the model itself. The literature study has defined three specific methods that will be used for this cause: namely the structured review with interviews to confirm the factors and the (combination) of a Monte Carlo simulation and a factor model. This sequence is important as the influencing factors on the C/SOV demand need to be determined before an adequate factor model can be built. The literature review already showed that many factors influence the need for C/SOVs in the OW industry. These are on one hand direct quantitative factors regarding wind farms such as distance to shore or the number of parks, but as well qualitative factors that are hard to quantify. To attain the highest accuracy in the simulation, the decision has been made to only include the quantifiable factors in the mathematical simulation and work with other influences in the discussion. These so called "qualitative" factors and their influence are primarily determined through the interviews. Figure 3.2 shows a flowchart of the model-process.

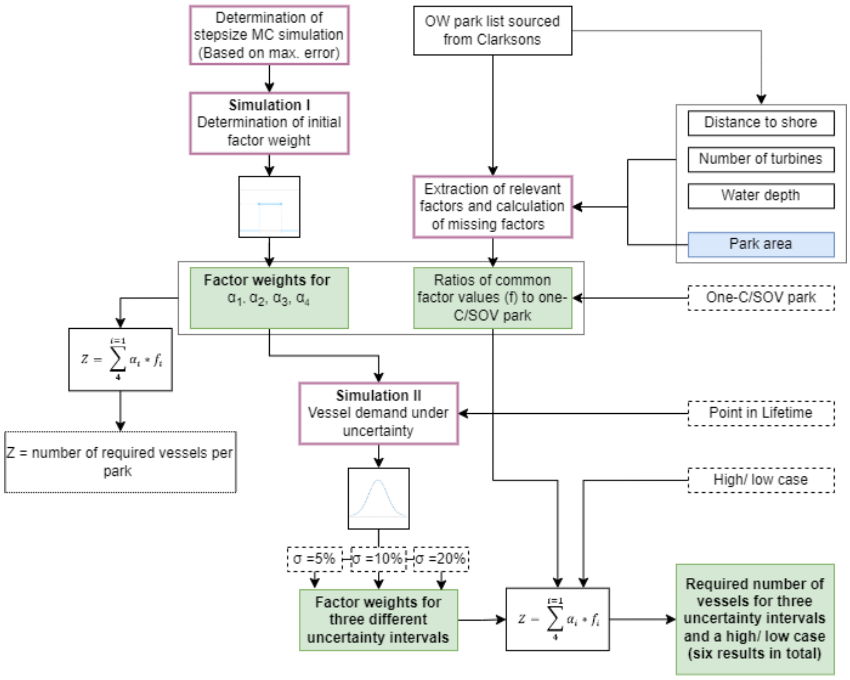


Figure 3.2: Flow chart of the model including the the preparation of the MC simulation as well as the data preparation for the factor model. The calculation steps are outlined purple, light blue filled shapes are factors which need to be calculated and green filled shapes are mathematical results. The four common factors are all based off the Clarksons data base, however they are specifically marked for clarity.

3.2.1 Factor Analysis

The factor analysis is a branch of statistical science with its origins in psychology with the aim to provide mathematical models for the explanation of psychological behaviour. Among the more famous of such theories are those proposed by Spearman, Burt, Kelley, Thurstone, Holzinger, and Thomson [48]. Spearman was the first to describe a two-factor model and Thurstone expanded this to a multiple-factor analysis. Thurstone expanded Spearmans tetrad-difference criterion and generalised it into the concept of a correlation matrix.

The principal concern of factor analysis is the resolution of a set of variables linearly in terms of (usually) a small number of categories or "factors". This resolution can be accomplished by the analysis of the correlations among the variables. A satisfactory solution will yield factors which convey all the essential information of the original set of variables. Thus, the chief aim is to attain scientific parsimony or economy of description.

In the most simple form, a variable is a combination of common factors, unique factors and a measurement error, resulting in the following linear expression:

$$z = \alpha * F + U + M \tag{3.1}$$

In this case α represents the factor loading, F the common factors, U unique factors and M the measurement error. In a more developed form, the basic factor analysis can be described as:

$$z_j = \alpha_{j1}F_1 + \alpha_{j2}F_2 + ... + \alpha_{jn}F_n(j = 1, 2, ...n) \tag{3.2}$$

The unique factor and error are not regarded in this case, as they will not play a role in the first iteration of the model. The uncertainty (d_jU_j) will be accounted for with the use of the Monte Carlo simulation. In the shortest expression the factor model can be written as following:

$$z_{ji} = \sum_{m}^{p=1} \alpha_{jp}F_{pi}(i = 1, 2, ..., N; j = 1, 2, ..., n) \tag{3.3}$$

To make the design of the final model more clear, the calculations can be written in matrix notation: where **z** is a vector containing the variable, **A** a matrix containing the factor weights and **f** a vector containing the common factors.

$$\mathbf{z} = \mathbf{Af} \tag{3.4}$$

The following common factors have been defined from the literature and were checked with people in the industry:

1. **The distance to shore (**Ds**)** directly influences the need for C/SOVs. Whereas near-shore sites make use of CTVs due to their lower costs, these smaller vessels are not efficient anymore from distances of 30 nautical miles from shore; which means a three hour transfer in total for operators that need to access the turbines. A complicating factor however is, that the size of the park can trigger a C/SOV based strategy as well for farms closer to shore when they are big enough.

2. The total **size of the farm (**Ap**,** Nt**)** is determining the choice of vessels for the park. Small parks close to shore will be unlikely to use C/SOVs in the maintenance strategy, but incidental visits of C/SOVs to the farm can occur. Size of the farm means both the number of turbines

(Nt) as well as the area of the farm (Ap). The area of the farm is determined by the size of the turbines, as larger spacing between the towers is required for higher capacity turbines to reduce the wake effect.

3. The **water depth (Wd)** of the park determines whether it is accessible for C/SOVs. If the parks are in water where the depth of the SOVs is exceeding the water depth, these will be classed as non-C/SOV site. According to Government of Scotland [44], a 10% margin is usually taken by ports as a lead on the keel clearance. With the shallowest vessel having a draft of 4.8 meters (Bibby Wavemaster Clarksons [21]) this comes to a required water depth of 5.3 meters for C/SOV operations.

4. **Floating or grounded (FG)** will have an influence as well. In floating offshore wind turbines the forces and motions are significantly stronger than in grounded turbines. This will lead - especially in the first years- to increased maintenance requirements. Due to more challenging conditions, it is expected that floating OW requires the safer form of transit to the turbines by means of C/SOVs.

Vector **f** with the common factors can the be notated as:

$$\begin{bmatrix} Ds & Nt & Ap & Wd & FG \end{bmatrix} \tag{3.5}$$

With these factors a "one-C/SOV park" will be defined. This means a park for which one C/SOV is deployed full-time. If $\mathbf{f1}_1$ is brought into matrix notation, this leads to an expression for **F**:

$$\begin{bmatrix} \frac{Ds_1}{Ds_1} & \frac{Nt_1}{Nt_1} & \frac{Ap_1}{Ap_1} & \frac{Wd_1}{Wd_1} & FG_1 \\ \frac{Ds_2}{Ds_1} & \frac{Nt_2}{Nt_1} & \frac{Ap_2}{Ap_1} & \frac{Wd_2}{Wd_1} & FG_2 \\ \dots & \dots & \dots & \dots & \dots \\ \frac{Ds_i}{Ds_1} & \frac{Nt_i}{Nt_1} & \frac{Ap_i}{Ap_1} & \frac{Wd_i}{Wd_1} & FG_i \end{bmatrix} \tag{3.6}$$

Here the first row denotes the - relative - common factors of the one-C/SOV park. The other rows the ratio of the common factors to the one-C/SOV park. It is important to note that FG is a binary entry (1 or 0), adding an additional factor and weight to the C/SOV demand for that park. In line with the factor model described by [48] this is the unique factor. This matrix will allow for a clear form of calculation of the final C/SOV demand per park.

Following this, the weight of the factors can be defined:

$$\begin{bmatrix} \alpha_{Ds} \\ \alpha_{Nt} \\ \alpha_{Ap} \\ \alpha_{Wd} \\ \alpha_{FG} \end{bmatrix} \tag{3.7}$$

The sum of the different factor weights for the one-C/SOV park will have to be one (excluding α_{FG}) as the weights need to sum up to one for the one-C/SOV park. When regarding matrix **F** consisting of the relative common factors, the sum of the common factors for the one-C/SOV park needs to be one.

$$1 = \mathbf{A}_1 = \sum_{j=1}^{4} \alpha_{ji}(j = 1, 2, ..., 4)(i = 1) \tag{3.8}$$

The exact weight of the factors will be discussed in the next section describing the MC simulation.

It further is important to note that the weight vector is the same for all parks in this research and that weights have to outweigh each other in the following order:

$$\alpha_{Ds} \geq \alpha_{Nt} \geq \alpha_{Ap} \geq \alpha_{Wd} \tag{3.9}$$

This order is to an extend based on the literature review where distance to shore and the number of turbines have been identified as clear drivers of SOV use. As it is expected that α_{Ap} and α_{Wd} are difficult to quantify, but do have an effect on the SOV demand, they have to be of lower weight than α_{Ds} and α_{Nt}. The expert interviews aim at confirming this order but not necessarily at quantifying it.

Finally three more one-C/SOV parks are defined, to increase the accuracy of the model and have one SOV park per factor like it is common for solving linear systems. The calculation for the three other parks is identical and the required number of SOVs will be averaged in the end. The chosen one-C/SOV parks are described in chapter 4 with their particulars.

In combined form the model can be notated as:

$$\begin{bmatrix} \frac{Ds_1}{Ds_1} & \frac{Nt_1}{Nt_1} & \frac{Ap_1}{Ap_1} & \frac{Wd_1}{Wd_1} & FG_1 \\ \frac{Ds_2}{Ds_1} & \frac{Nt_2}{Nt_1} & \frac{Ap_2}{Ap_1} & \frac{Wd_2}{Wd_1} & FG_2 \\ ... & ... & ... & ... & ... \\ \frac{Ds_i}{Ds_1} & \frac{Nt_i}{Nt_1} & \frac{Ap_i}{Ap_1} & \frac{Wd_i}{Wd_1} & FG_i \end{bmatrix} \cdot \begin{bmatrix} \alpha_{Ds} \\ \alpha_{Nt} \\ \alpha_{Ap} \\ \alpha_{Wd} \\ \alpha_{FG} \end{bmatrix} = \begin{bmatrix} Z_1 \\ Z_2 \\ ... \\ Z_i \end{bmatrix} \tag{3.10}$$

3.2.2 Monte Carlo Simulation

The MC Simulation is a part of experimental mathematics and can be used both in deterministic as well as probabilistic ways. This problem is of a probabilistic manner, as the needed number of vessels at this moment is not known and therefore currently no real-time benchmark can be set. The variables in the problem are in vector α, where the weights of each factor need to be modelled for uncertainty. As no initial weight is known and can not be calculated due to the lack of current data, the initial weight is approached using a MC simulation with a uniform distribution. Finally the effect of this uncertainty on the final vessel demand needs to be determined. This is done by defining a stochastic system around the values of α with varying standard deviations. Three different scenarios are to be modelled with 5%,10% and 20% deviation. For this simulation the most basic and most used distribution will be applied, namely a normal distribution for each weight with:

$$\mu_i = \alpha_i \tag{3.11}$$

As the MC simulation is a numerical simulation, the number of steps to reach the required accuracy needs to be determined first. As soon as the results start to converge, this means an adequate number of simulation steps has been defined.

From a mathematical perspective the required step size can be calculated regarding the central limit theorem which establishes that, in many situations, for independent and identically distributed random variables, the sampling distribution of the standardised sample mean tends towards the standard normal distribution even if the original variables themselves are not normally distributed. This means that regardless of whether a uniform (MC iteration I) or normal distribution is used (MC iteration II), the same formula can be used to determine the required step-size.

The normal confidence interval formula can be transformed and used to identify the required number of samples [15].

$$(L, U) = x \pm z_c(\frac{\sigma_x}{\sqrt{n}}) \tag{3.12}$$

From this the (absolute) error can be computed, which can be transformed to receive the number of samples n.

$$\begin{aligned} e_{max} &= \frac{z_c \sigma_x}{\sqrt{n}} \\ n &= \left(\frac{z_c \sigma_x}{e_{max}}\right)^2 \end{aligned} \tag{3.13}$$

In this formula z_c is the Z-score for the required confidence interval, σ_x the standard deviation and e_{max} the absolute error. If iteration II is regarded, three scenarios need to be regarded, namely 5%,10% and 20% standard deviation to calculate in the different uncertainty levels. Table 3.1 shows the results for the calculation for a normal distribution with $\mu = 0.5$ and a 95% confidence interval ($z_c = 1.96$), in this case a 1% simulation result error is used.

$\sigma(\%)$	5	10	20
σ	0.025	0.05	0.1
n	96	184	1537

Table 3.1: Required number of scenarios for the II iteration MC simulation with $\mu = 0.5$, a 95% confidence interval ($z_c = 1.96$) and a max 1% error.

If the simulation is run with these values for the three scenarios around $\mu = 0.5$ with corresponding standard deviations the following relative errors are obtained as shown in table 3.2.

$\sigma(\%)$	5	10	20
σ	0.025	0.05	0.1
e $(\%)$	0.1	0.4	0.5

Table 3.2: Relative error per confidence interval simulation in the MC simulation.

Note: the errors in table 3.2 are the errors in the simulation, which means that the MC simulation itself will have an error $<= 1\%$ so the bounds of the 95% interval will be 1% accurate. It can be seen that the results fall within the required error range and therefore it can be concluded that for $n = 1537$ the required accuracy is obtained.

Figure 3.3 shows how for each scenario the MC simulation converges to the required $error \leq 1\%$.

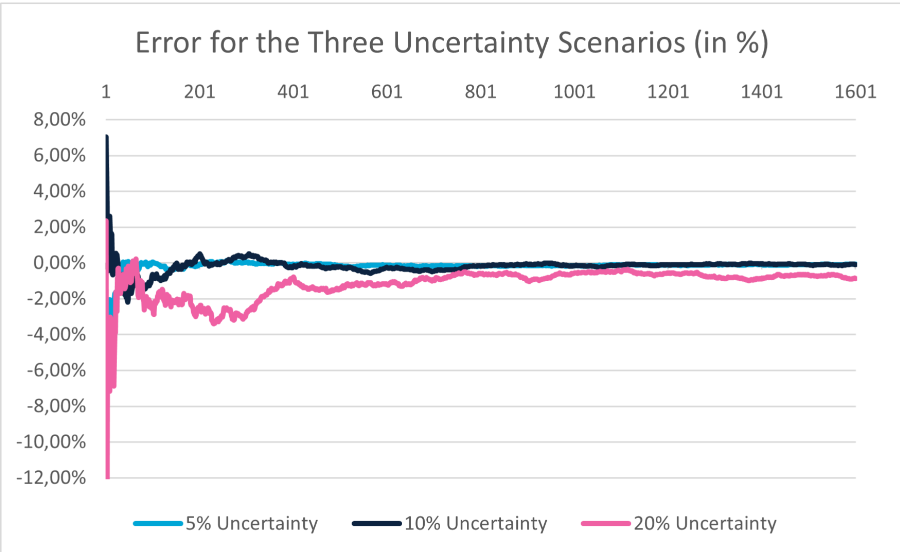


Figure 3.3: Relative error of the MC simulation per number of iterations in the simulation.

Training Data One issue needs to be addressed when working with the MC in this research; namely that the current supply of vessels - be it SOVs or other W2W capable vessels - is not sufficient to serve the market. The experts were not able to provide an insight on how many vessels *are* needed to serve current demand. Hence the MC simulation will eventually suffer from a significant disadvantage as no training data are available. This is why as well the choice of a - relatively - high error of 1% is chosen.

Initial Factor Weight

The initial weight is determined performing a MC simulation with a normal distribution. During the simulation for α_1 the random variable lies between 0 and 1 where as the other factor weights are influenced by the outcome of the one above. This can be summarised the following way:

$$\begin{aligned} \alpha_1 &= U\{0, 1\} \\ \alpha_2 &= U\{0, \alpha_1\} \\ \alpha_3 &= U\{0, \alpha_2\} \\ \alpha_4 &= U\{0, \alpha_3\} \end{aligned} \tag{3.14}$$

Using this strategy it is possible to ensure that α_1 has always the largest influence on the SOV demand. Executing this simulation with $i = 1600$ the results as in table 3.3 are obtained:

Factor	α_1	α_2	α_3	α_4
Factor Weight	0.4968	0.2423	0.1228	0.0631
Normalised Factor Weight	0.5370	0.2619	0.1327	0.0682

Table 3.3: Factor weights and normalised factor weights resulting from the MC simulation. The factors need to be normalised so finally the contents of **A** sum up to one.

The initial factor weights combined with the common factor ratios as in in equation 3.6 give the number of required vessels per OW park.

Uncertainty in Factor Weights After the initial factor weights have been determined, it is possible to continue to the second MC simulation which models the uncertainty in the factor weights. The choice has been made to use a normal distribution around the factor weights and perform three different simulations with a 5%, 10% and 20% standard deviation respectively. The classical notation for the normal distribution is:

$$X \sim \mathcal{N}(\mu, \sigma^2) \tag{3.15}$$

Regarding the notation for the factor weights this leads to:

$$\begin{aligned} X_1 &\sim \mathcal{N}(\alpha_1, (\sigma_{\alpha_1})^2) \\ X_2 &\sim \mathcal{N}(\alpha_2, (\sigma_{\alpha_2})^2) \\ X_3 &\sim \mathcal{N}(\alpha_3, (\sigma_{\alpha_3})^2) \\ X_4 &\sim \mathcal{N}(\alpha_4, (\sigma_{\alpha_3})^2) \end{aligned} \tag{3.16}$$

Where the standard deviation is 5%, 10% or 20% of the respective factor weight determined earlier. This simulation is as well performed with $i = 1600$ over all four different one-C/SOV parks.

Simulation

For the final simulation and henceforward forecast of the SOV demand the factor model combined with the MC simulation will be used to simulate the number of required vessels over the lifetime of an OW park. This is done using the factors and weights of the influence on the SOV demand. The simulation is to be run for four parks, with a high and a low case for the installed capacity in Europe. One further factor, which can not be defined as common factor, namely the **demand for maintenance**, heavily influences the need for SOVs. There is a direct correlation between the number of times a turbine needs to be visited and the number of required vessel operations. The amount of maintenance however changes throughout the lifetime of a park, with the first years being needed to address the early life failures of the park and the last years to address the wear-out failures of the turbines. The time in between these two periods is called the "useful-life". In the simulation the need for a SOV will have to be quantified, using both data from Clarksons as well as information from experts. The assumption for the start up period is that this is four years, as the OEM has a warranty period of five years (one year is counted as margin on top of the four year early life failures). Following that 17 years of useful-life and 4 years of wear-out failures will be assumed. For each park a timeline is created and depending on the point in time of the park a SOV requirement can be determined. The timeline starts with the construction phase of the park and is followed by the early life year of the park, where additional capacity is needed to solve early-life defects. Following that years of "minimal maintenance" is needed in the park during the useful life. The years consist of increased need for maintenance due to end of life failure. Finally the decommissioning or re-powering is scheduled. Both the construction time as well as the decommissioning time are dependent on the park itself and differ accordingly. Figure 3.4 shows the timeline as it is used for each single park. Table 4.3 in chapter 4 shows a more detailed overview over the variables, where they are sourced from and the argumentation behind them. As the SOV demand differs per stage in the lifetime of the park, the "one-C/SOV" case is defined as the demand during the useful life of the park. Finally this timeline is used to take a snapshot of the OW situation in the end of 2030. So the C/SOV demand for all parks, either under construction or in decommissioning in that period are included. Even though for all parks the situation will change eventually and they will enter the next stage of the lifetime, it is important to take the mixed landscape into consideration when determining the SOV requirement as throughout the years after 2030 parks will need to be decommissioned and reconstructed in a flow and the mix of maintenance requirements will always be given. The Timeline until 2030 is shown in the Appendix in figure A.9, here for every park it is visible to see the lifetime stage in which it is.

In the model the lifetime of the park is incorporated as a multiplier on the vessel for the park:

$$\begin{bmatrix} Z_1 \\ Z_2 \\ \dots \\ Z_i \end{bmatrix} \cdot \begin{bmatrix} t_1 & t_2 & \dots & t_i \end{bmatrix} = \begin{bmatrix} Z_{t1} \\ Z_{t2} \\ \dots \\ Z_{ti} \end{bmatrix} \tag{3.17}$$

Here Z_i is the C/SOV demand for each park i, t_i the multiplier, dependent on the lifetime stage of the park, and Z_{ti} the with the time dependent factor t_i adjusted C/SOV demand for each park. Finally the total number of required vessels can be notated as:

$$N_{C/SOVs} = \sum_{n=1}^{i} \vec{Z} \tag{3.18}$$

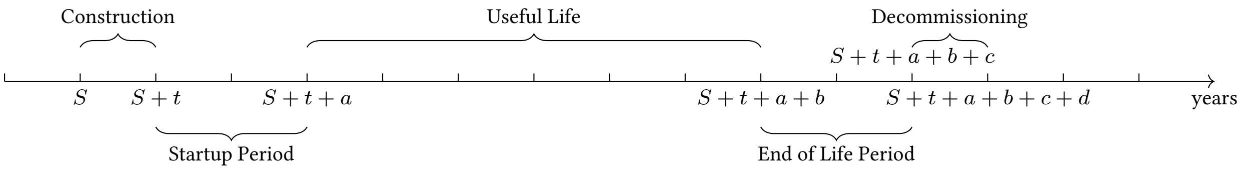


Figure 3.4: Timeline of an offshore wind farm. The building time is varying, whereas the other time periods are assumed to be the same for each park. S is the start of construction ($t = 0$), t is the time needed to build the farm. Variables a is four years, b is 17 years, c is four years and d will be filled in using additional information sourced in chapter 4 as it differs like t from park to park.

Technicalities The simulation will be performed in Excel with the aim to make it as user friendly and accessible as possible. The base for the structure in the model will be in the FAST standard [40], which is a standard developed for spreadsheet models in the financial industry. FAST stands in this case for **F**lexible, **A**ppropriate, **S**tructured, **T**ransparent. The method will not be discussed further and the literature on that topic is advised for further information: FAST [40].

3.3 Conclusion

The quantitative part of the research is a combination between a factor model and a Monte Carlo (MC) simulation. A factor model allows for the description of a variable by splitting it into a number of common factors with corresponding factor weights. A MC simulation adds randomness to the simulation by creating a large number of samples around the factor weights according to a prior determined distribution.

In the first step the factor model is described with the four (quantifiable) common factors identified as influencing the Commissioning and Service Operation Vessel (C/SOV) demand, namely in declining order of importance the distance to shore, number of wind turbines per park, area of the farm and the water depth. An additional unique factor is whether the park is floating or fixed, this adds an increased need for maintenance.

In the factor model the weight of the factors is determined in the first iteration of the MC through a uniform distribution. In the second iteration of the simulation a normal distribution around the determined factor weights is simulated with the 5, 10 and 20% uncertainty intervals and a snapshot of the required number of vessels in 2030 is created. Further, the simulation considers a high and a low case in terms of installed Offshore Wind capacity. Finally the simulation will result in six different outcome scenarios and required number of vessels per park.

The lifetime stage of the park as well determines its need for maintenance, as the need for C/SOVs is higher during the construction, early life, end of life and decommissioning or repowering phase. This means that the results from the simulation need to be adjusted for this depending on the parks situation in 2030.

To increase the accuracy of the simulation, four different parks are to be identified that employ one C/SOV all year long. The simulation will be performed for these four parks and the results will be averaged to obtain a range for the required number of vessels.

4 | Data Collection and Analysis

This chapter contains the data collection and initial data analysis on the OW vessels and OW parks. The offshore sector is a niche market, where many data are available in locked databases. To maintain data purity, the database of Clarksons has been used for the full data set on the current and future wind parks. As both a high and a low case are defined for the installed capacity, and only for the high case (Clarksons) there is detailed information on all parks, the same data are used in an adapted manner for the low case.

The data research aims at finding and clearing the data that fill in the common factor values described in chapter 3.2. These are the distance to shore, size (number of turbines, area) and water depth of the OW parks. Additionally the foundation type is collected.

The chapter is split into two parts, the first part addresses the collection of data on the wind parks from Clarksons and the second part addresses the offshore vessel market.

4.1 Data on OW Parks

Data on OW parks is to a large extend limited to locked databases. The most complete ones are presented by 4C Offshore and Clarksons. Whereas the access to 4COffshore is not available through the University, the Clarksons database is available. The full list of all wind farms world wide has been sourced which contains a great deal of information, of which not all is relevant. The following information has been defined as relevant as it describes either the location of the park or particulars that influence the number of SOVs needed to service the park:

Name	Unique identifier for the park
Main Status	Dead, Active, Development, Planned/Licence or Potential
Status	More detailed breakdown of Main Status
Capacity	Capacity (in MW) of the whole project
Region	Europe, etc.
Start-up Date	Planned start-up date of the project
Foundation Type	Grounded/ Floating
Turbine Model (Turbine Capacity)	Turbine Capacity (in MW)
Number of Turbines	Number of turbines per park
Distance to Shore	Distance to shore of the project
Water Depth	Average water depth of the project

Table 4.1: Information defined as relevant from the Clarksons database on offshore windfarms.

To start the data cleaning top-level, the location of all parks was analysed using the map in the Clarksons database which can be found in appendix A.4. In some cases parks are overlapping on the map. These have been manually removed as this would mean, that in some cases, capacity would be counted double. The following parks were removed from the data list: *Thor, Botafogo, Petroc, Setanta, Llywelyn, Moneypoint Offshore One, South Irish Sea, Gotland, North Celtic Sea, Myrddin, Gwynt Glas, Laine, Moneypoint Offshore Two, Latitude 52, Loch Garman, Celtic Two, Nortada, Celtic Sea Area C.* These parks would represent 16.5 GW of capacity to be installed over six years, therefore eventually correcting the graph shown in figure 4.1.

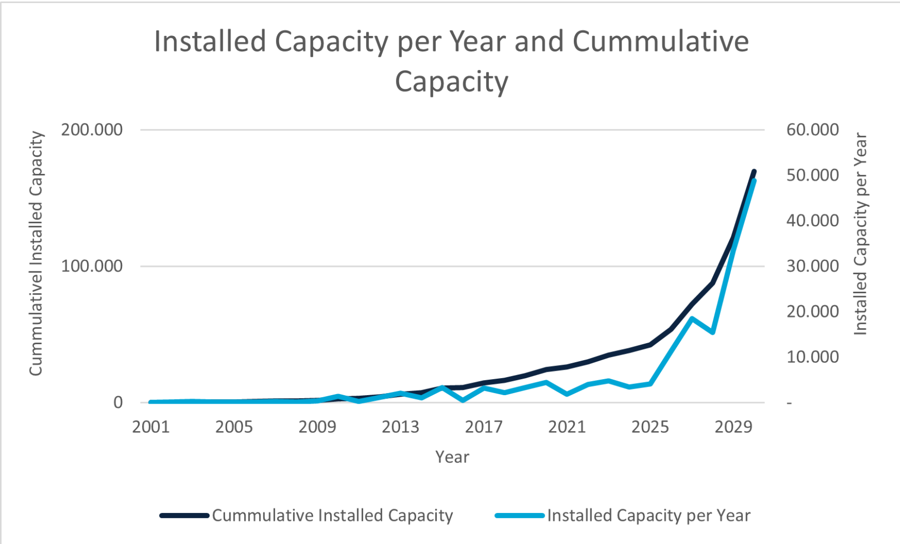


Figure 4.1: Installed capacity per year and cumulative installed capacity. From: Clarksons [21]

Of the data in table 4.1, the distance to shore, number of turbines, foundation type and water depth are directly used in the simulation. The other data are used in a secondary way in the simulation to identify the relevant parks location wise and determine the stage in the parks lifetime.

For the parks, the weighted distance to shore, weighted turbine capacity and weighted project size are calculated and plotted over time, the results of which are shown in figures 4.2 4.3 and 4.4.

Weighted averages allow for a higher accuracy as it takes into account the relative relevance of each data point, which in this case would be each park. Instead of taking the simple average, the weighted average corrects the average for the size of the park.

$$X_w = \frac{\sum_{i=1}^{n}(x_i * w_i)}{\sum_{i=1}^{n} w_i} \tag{4.1}$$

In this formula w_i is the weight associated with each value (x_i = distance to shore, size, etc.) and x_i is the value itself. The weight w_i is in most cases the number of turbines.

It is important to regard the weighted averages, as large parks far away from shore ie. have a strong influence on the required number of C/SOVs. Finally the total installed capacity per year is shown in figure 4.1, as well as the added capacity per year as building new capacity should require more manpower and therefore more vessels.

There is a clear trend visible in the distance to shore of parks, where new parks tend to be built

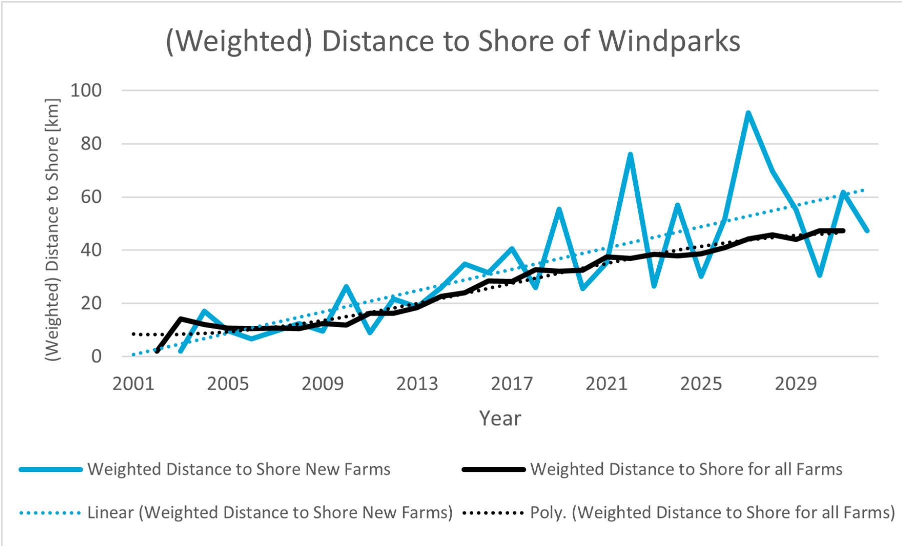


Figure 4.2: Weighted average distance of new parks and weighted average distance to shore of all wind parks combined. The distance keeps rising for new parks but for all parks this consolidates at 55 kilometres from shore. From: Clarksons [21]

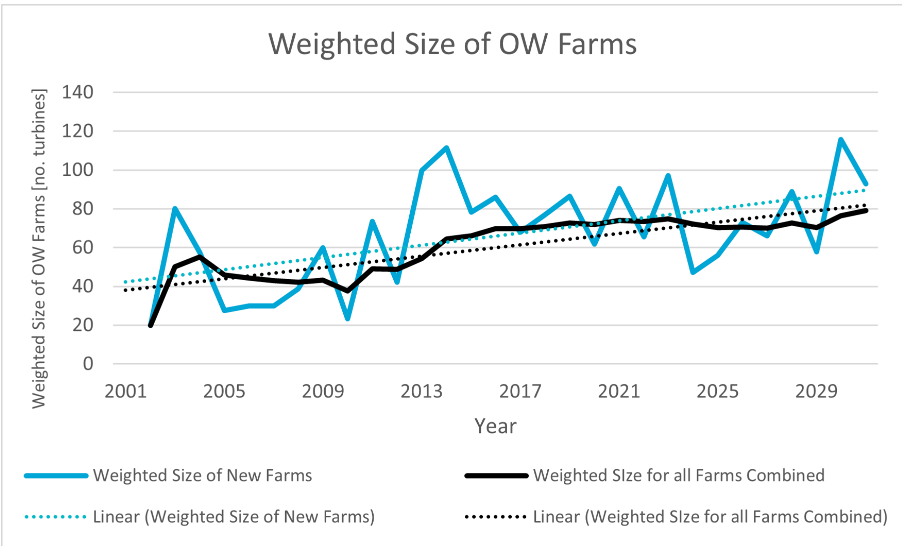


Figure 4.3: Weighted size of new parks as well as weighted size of all parks combined. The size of parks has gradually increased and keeps increasing. From: Clarksons [21]

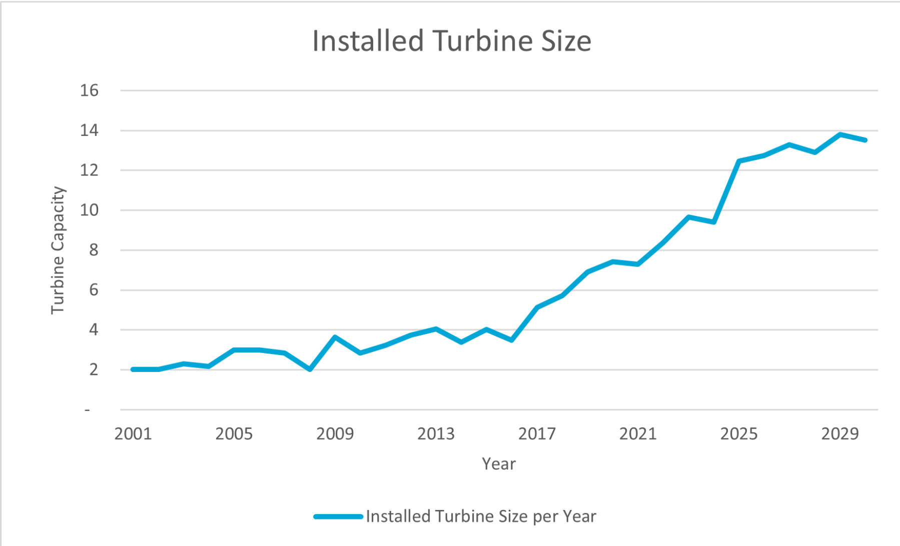


Figure 4.4: Average turbine size installed per year.

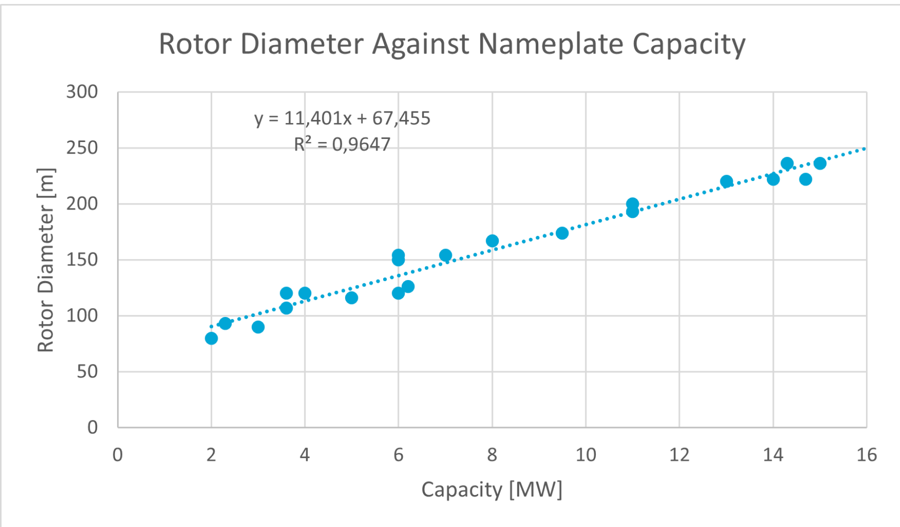


Figure 4.5: Rotor diameter per turbine size. A clear linear trend towards larger rotor diameters for higher capacity turbines is visible. The data have been sourced from turbine manufacturers listed in Clarksons [21].

further away from shore, the distance for all parks combined consolidates around 50 kilometres from shore in 2030. A similar trend is visible for the size of parks, which grows to around 100 turbines per park. Even though for both the distance as well as the size some outliers are visible, this is not seen as a critical data error as the overall picture is not influenced strongly. Certain very large projects are realistic in such way that they can be constructed in phases (such as Hollandse Kust Zuid and Hollandse Kust Noord). This means that the timeline of installing could change, but the weighted picture will not. The growing size and distance to shore points at an increased demand for C/SOVs in 2030 compared to current levels (A.7).

Clarksons gives the (expected) turbine size of the parks as well which is used for calculating the area the farms occupy. By using the rotor diameter and the approximation by Danish Wind Industry Association [30]. A farm with larger turbines needs to have these placed further apart from each other, eventually leading to larger distance vessels need to travel in between the turbines. Figure 4.4 shows the increasing turbine size until 2030 and figure 4.5 the corresponding rotor diameter.

One-C/SOV Parks The one-C/SOV parks are shown in table 4.2. These parks have been identified as the parks employing exactly one C/SOV all year round. Their park parameters are used to feed the factor model and MC simulation which is to be executed for these four parks. To identify these parks industry professionals have been consulted on the operations and Clarksons [21] has been used to check employment profiles of C/SOVs in these parks. It is namely possible to see which vessels visited the farm over the course of the last time periods and when. With this method it was shown that indeed one C/SOV was occupied with on of the four parks in table 4.2. Each of the one-C/SOV parks allows to find values for the common factors as they are shown in equation 3.5[1]. With the absolute values shown in 4.2 for the distance to shore, size (number of turbines, area) and water depth of the parks, the matrix in equation 3.6 [2] can be completed and for each park the ratio to the one-C/SOV park can be determined. FG determines the foundation type of the park (grounded/ floating) and this is only considered as adding additional needed capacity to the park and is thus not considered in the one-C/SOV park ratio.

Particular | Name	Gemini	Hornsea 1	Bard 1	Veja Mate
Distance to Shore [km] (D_s)	63	114	105	107
Number of Turbines [-] (N_t)	150	174	80	67
Park Area [km^2] (A_p)	28	70	18	19
Water Depth [m] (W_d)	32	35	39	38

Table 4.2: Relevant factor values of the four one-C/SOV parks. Data from Clarksons [21]

[1] $\begin{bmatrix} Ds & Nt & Ap & Wd & FG \end{bmatrix}$

[2] $\begin{bmatrix} \frac{Ds_1}{Ds_1} & \frac{Nt_1}{Nt_1} & \frac{Ap_1}{Ap_1} & \frac{Wd_1}{Wd_1} & FG_1 \\ \frac{Ds_2}{Ds_1} & \frac{Nt_2}{Nt_1} & \frac{Ap_2}{Ap_1} & \frac{Wd_2}{Wd_1} & FG_2 \\ ... & ... & ... & ... & ... \\ \frac{Ds_i}{Ds_1} & \frac{Nt_i}{Nt_1} & \frac{Ap_i}{Ap_1} & \frac{Wd_i}{Wd_1} & FG_i \end{bmatrix}$

High and Low Case Installed Capacity For the simulation a high and low case are used to act on the different possible market developments based on the data shown in figure 2.3, where Clarksons and WindEurope show significantly different pathways. Behind the Clarksons data lies the detailed database with the park information, whereas this is not available for the WindEurope database. As the full simulation is heavily based on the availability of the factor data and these are only made available through Clarksons, the low case according to WindEurope is approached by regarding the parks in the Clarksons database until 2030 for which the capacity adds up to 135 GW. Due to the limited knowledge on parks regarded for the WindEurope case, this is deemed an acceptable assumption. This assumption is strengthened by the fact that only the situation at the end of 2030 is regarded, and no development over time is produced.

Timeline Variables In chapter 2.3 the timeline of the life of an OW park has been shown. The variables are defined as in 4.3. The data are partly sourced from Clarksons. Other data are assumed using interviews with operators of windparks and C/SOVs. The accurate data collection has been difficult, as failure data on wind turbines are classified. The high number and fast development rate of different wind turbine models adds to the difficulty of retrieving accurate information. This is why the required visit count of vessels during the operational life is based on the information shared during an interview with the Orsted maintenance team.

Variable	Description
S	Start year of construction, is sourced from the Clarksons database on OW farms [21]
t	Construction time; is sourced from Clarksons Database for the farms already constructed and under construction. For farms where the construction time is not yet known, it is estimated using the parameters of previous, comparable farms regarding the distance to shore and number of turbines. This estimation is presented in chapter 5.
a	Start-up period; this period falls into the warranty period of the turbines in which the OEM is responsible for the maintenance of the park. The duration of this period usually differs, but according to Orsted [Personal Communication with Orsted, 06.2023] and Clifford Chance [24] this period usually lasts five years. It is estimated that in the first four years additional capacity is needed as more defects occur and the fifth year already fall into the useful-life period. **a = 4 [years]**
b&c	Following the start up period the useful-life of the park starts, in which a minimum of maintenance is needed. This period is estimated to last 17 years. This number is based on the fact, that overall parks have a life expectancy of 25 years before they are re-powered or majorly overhauled or demolished [96], [Personal Communication with Orsted, 06.2023]. As the end of life period is as well expected to last for four years, with higher maintenance requirements, the useful-life will be 17 years. **b = 17 [years], c = 4 [years]**
d	The decommissioning is expected to last half as long as the construction period, as this process is less complex than construction. In many contracts the requirement to remove all structures is stipulated. **d = t/2 [years]**

Table 4.3: List of timeline variables and their description.

4.2 Data on Offshore Vessels

Data on offshore vessels is even more limited accessible than the data on windparks. Relevant data are delivered again by Clarksons and 4C Offshore, where only Clarksons is accessible for this research. Further data on vessels is available on IHS Markit and Vessels Value, both of which are not available either. However, the data Clarksons delivers are very complete, as these already present a breakdown of vessels linked to and active in the OW industry. Clarksons breaks down the vessels into three different classes CSOVs, SOV, W2W Conversion, where the first two are purpose built vessels designed to accommodate more passengers and W2W Conversion vessels are retrofitted PSVs originally operating in the O&G market. Together with the data on the active ship types in the OW industry, it is easy to establish the number of vessels active that have serviced the OW industry. Figure A.7 shows the number of vessels already active in the OW industry. This information however can not be used do determine the number of vessels needed. The reason for this is that it is difficult to use current vessel numbers to determine the required number, as vessels are operating in a free market and are as well used in other sectors (O&G) and not all vessels are permanently equipped with W2W systems [PCwID, 06.2023]. Further industry professionals mention that there is currently a lack of W2W/SOV vessels and hence the current number is not representing the industries' needs (so the current number of vessels can't be used as a benchmark for required number of vessels). So, to form an unbiased view, the required number of SOVs will be purely determined from the demand side (using the factor analysis on the number of OW installations).

Through the interviews with industry professionals working with Damen, The Offshore Partners and Orsted, additional information on the SOV market was sourced which was mainly aimed at practical considerations and operational matters regarding the offshore wind vessels. Currently shipyards are full with deliveries of vessels ordered today only being delivered three and a half years from now as shown in figure 4.6.

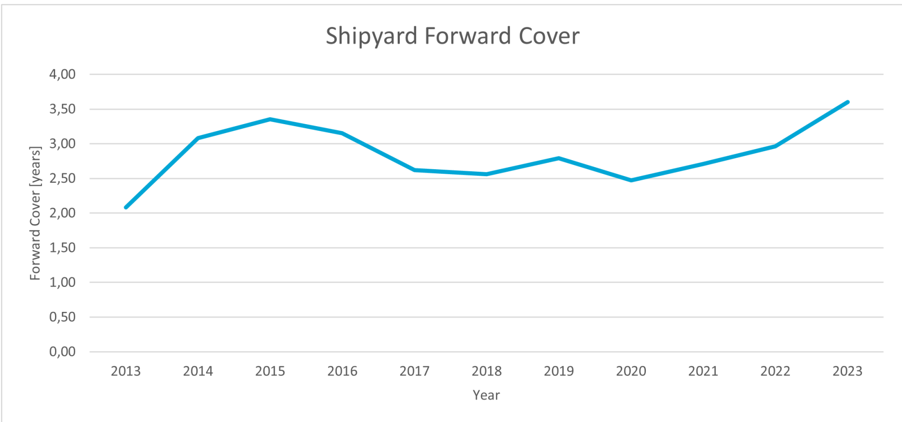


Figure 4.6: Yard forward cover. The yard occupation is currently on a 10 year high. From Clarksons [21].

Vessels are currently ordered larger than actually needed and generally speaking more C/SOVs are ordered with higher accommodation capacities. The premium for a 90 pax vessel above a 60 pax vessel is currently around 3-5%, which can be named the opportunity cost. The OPEX for the larger vessels does as well not increase significantly as depending on the number of passengers as the vessel can be operated with the same number of crew members. Clarksons gives the current price for a 60 pax CSOV at USD 57m and for a 120 pax CSOV at USD 62m, a premium of 8% for a vessels twice as big [21]. With the emphasis of owners on the larger vessels it is assumed that these will dominate the C/SOV market in the coming years and therefore no distinction in the model needs to be made. This assumption is justified as a similar development has been seen in the offshore O&G market, where PSVs are seldom sailing fully loaded, but are designed for the most heavy tasks [Personal Communication with 'The Offshore Partners', 06.2023].

Charter day rates of the vessels are higher in summer as better weather conditions (lower waves, less strong winds) lead to easier access to turbines. This statement from the industry can be confirmed by regarding the charter rates for offshore vessels as delivered by Clarksons [22], where this trend is clearly visible (figure 4.7).

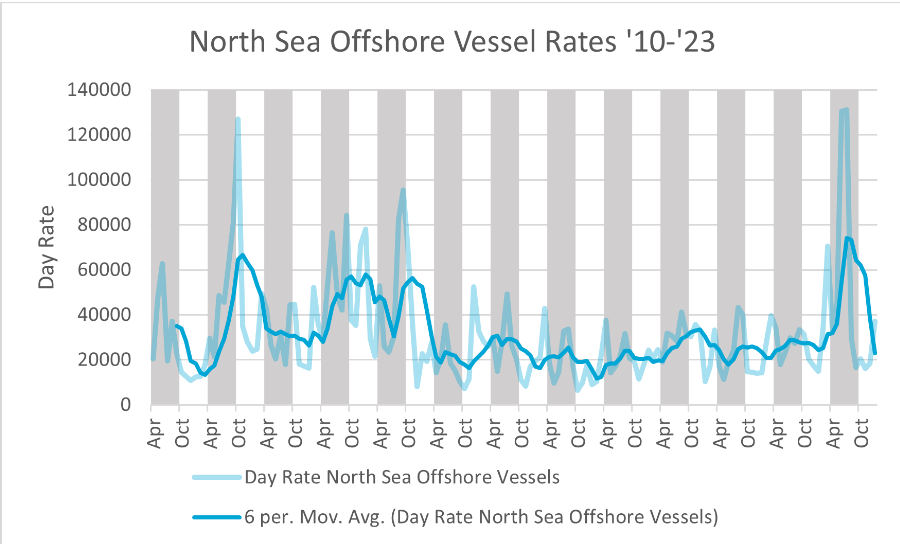


Figure 4.7: North Sea offshore vessel dayrates. In in the summer months from April on the rates tend to rise above the rates in the period before. From Clarksons [22].

Turbine – Vessel Interaction

Currently near-shore turbines are serviced with CTVs, however the practice of transferring personnel to the turbines is risky. Professionals in the industry see a general trend to an increased use of W2W systems, which are the core piece of equipment on C/SOVs, as injuries occur less often. This will possibly lead to the use of C/SOVs as well in near-shore sites to increase safety.

A further trend is the increasing number of floating turbines, which can lead to more W2W systems being used as floating structures do have a more unpredictable access due to increased motion of the turbines and more harsh conditions of the sites. The use of a W2W fitted vessel could be a logical choice then. The vessel of choice is likely a C/SOV as CTVs are too small to be equipped with an adequate system [50]. This underlines the need for an additional factor in the model to account for this issue in the simulation.

4.3 Estimation of Unknown Parameters

Estimation of Construction Times

For 298 windfarms the construction times are available through the Clarksons database. Small parks (<10 turbines) have been excluded from this list as they have an experimental character and therefore their construction time does not represent the commercial construction time. For the remaining 51 parks, a factor has been created based on the distance to shore and the number of turbines. As especially turbine installation vessels need to return to port to load new parts, distance to shore and number of turbines has been identified as leading drivers for construction time. The availability of WTIVs has not been included in this problem as it is out of scope.

$$F_{Construction\ Factor} = f(D_{Distance\ to\ Shore}, N_{Number\ of\ Turbines}) \tag{4.2}$$

The result is very fragmented, as can be seen in figure 4.8. This means that it is difficult to identify a strong correlation between the factor and the construction time. The decision therefore has been made to use a linear formula which can be used to determine the same factor for the other parks. A more accurate analysis would not add enough value, as the construction time is as well dependent on other factors such as soil composition due to the required preparation works, supply chain and vessel availability, which are not accounted for in the factor model. The scale of the turbines plays a role as well, is however not used in the factor as the larger scale of the turbines is offset by the larger vessels installing them. Therefore it is assumed that an always equal number of turbines can be transported.

The results were satisfactory and for all projects until 2030 with unknown construction times an estimate was delivered.

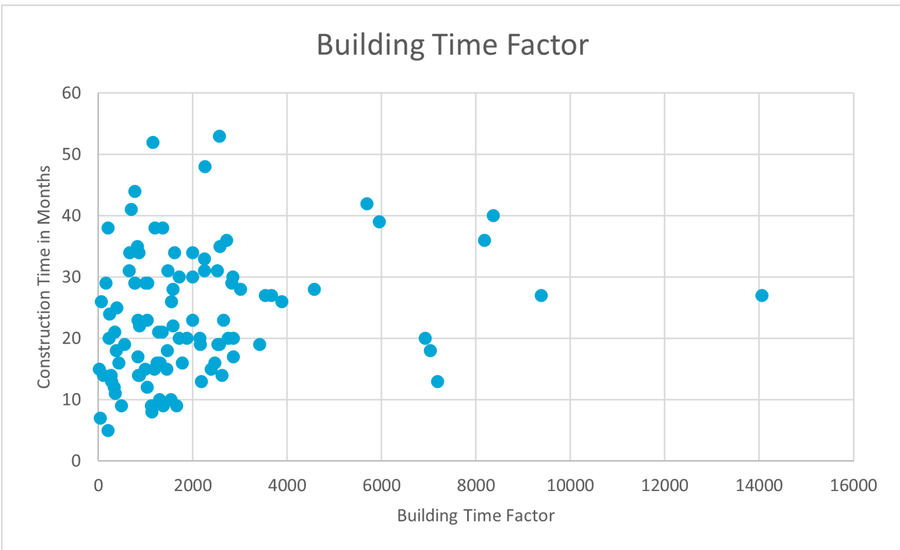


Figure 4.8: Construction time plotted against the building time factor to estimate the building time for OW parks. The construction factor is composed of the distance to shore and the number of turbines in a park.

4.4 Conclusion

The data availability on specific topics was adequate. These included the availability of data on vessels and on OW parks. However not all data were complete and for the parks that are not yet built, it was necessary to estimate the building time. The most important topic, on which no concrete data was available was the number of SOVs required per wind park. This has been estimated mostly through interviews with experts on the topic; working at Damen, TNO, Orsted, The Offshore Partners and Deutsche Wind. Contact attempts with vessels' operators have been left unanswered. Results were mixed, but through isolating certain cases, it was possible to "create a park for one SOV". A good case was the Gemini park in the Netherlands for which one SOV is employed all year long. With 150 turbines and 63 kilometres from shore it employs one SOV full time. This was defined as a good benchmark. The other benchmark of 200-350 turbines from Orsted can be explained by their parks being closer to shore (47 kilometres weighted average).

5 | Simulation and Analysis

This chapter summarises the simulation and its results to estimate the C/SOV demand based on the method described in 3.2 and the data acquired in chapter 4.

5.1 Assumptions in Simulation

In both chapter 3.2 and 4 several assumptions have been made on which the simulation and hence the results are based. In the following list, these assumptions are summarised to give a clear overview before the results are discussed:

1. **High and low case** The high and low case are based on the data shown in figure 2.3, where Clarksons and WindEurope show an expected capacity. As the full simulation is heavily based on the availability of the factor data and these are only made available through Clarksons, the low case according to wind Europe is approached by regarding the active parks in the Clarksons data base until 2030 that add up to 135 GW.

2. **Point in time** Only the situation in 2030 is regarded. An overview over the needed number of vessels per year leading up to 2030 does not add value due to the inelastic supply of vessels to the market. A snapshot therefore does not reduce the accuracy of the results.

   (a) **Point in lifetime** The assumption has been made that every point in the lifetime of a vessel requires a different amount of service. During construction and deconstruction and during early- and end of life the required amount of maintenance is higher. The benchmark for this additional maintenance is the amount needed during the effective use period.

3. **Location** The entire European market is regarded and a perfect, free market is assumed where any vessels can reach and service any wind farm in Europe.

4. **C/SOV - CTV site** From the expert interviews it followed that some sites are not, and will likely not be serviced by C/SOVs. This is mainly due to the distance to shore and certain size of parks. The benchmark for a wind farm to be a C/SOV site is set at $d_{shore} >= 50[km]$ and $n_{turbines} >= 50$. This benchmark is deemed acceptable, as it is both based off the literature [50] as well as the expert opinions.

5. **Current number of vessels** The current number of vessels is not further regarded during the simulation and it is assumed that only the parameters of the parks in operation in 2030 influence the demand for C/SOVs.

6. **One C/SOV parks** Four parks have been identified that need exactly one C/SOV all year round for service. The average of the outcome of these four simulations is taken as the number of needed C/SOVs.

7. **Missing data** Clarksons data base is not complete for all data. Assumptions have been made to compliment the existing data and fill in the gaps:

   (a) **Construction time** The missing construction time for the parks is approached using a construction factor which is dependent on the distance to shore and the number of turbines.

8. **Floating/ Fixed** For floating turbines an additional factor is added to account for additional maintenance needed. This factor is added on a per park base, as it is assumed that regardless of the size of the park, this additional maintenance is needed. The factor is small, due to the unknown extent of the additional service, but adding the factor allows for later adjustments of the model.

9. **Parks under construction** Only the parks with the startup date in 2030 are included. Parks under construction in that time are disregarded to keep the results comparable, as it is not possible to make an educated assumption about the number of parks under construction in the low case.

10. **Fractional C/SOV demand in a park** The assumption is made that perfect efficient use is made of the vessels, allowing for fractional C/SOV demand for a park.

On the following two pages figure 5.1 to 5.6 show the graphical representation of the results from the MC simulation. For all three uncertainty intervals the high and low case have been calculated. The graphs depict a histogram of the 1600 results from the simulation, where the graph shows the number of of times the simulation gives a certain answer. It is visible in the graphs how for the different uncertainty intervals the spread in results gets larger, and hence the spread of the possible number of vessels needed as well. The graphs and the results are discussed further in the following section, but depicted here to increase the clarity of the further report.

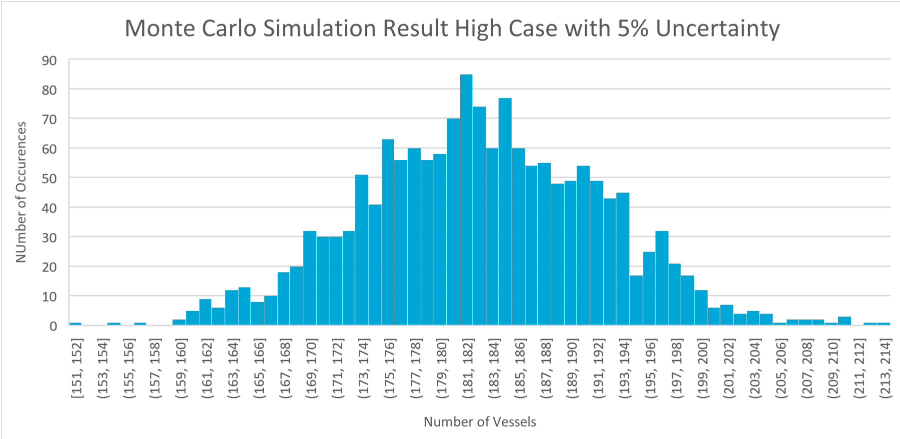


Figure 5.1: Distribution of vessel numbers from the MC simulation in the high case with 5% uncertainty. The figure shows the number of occurrences in the simulation per vessel interval.

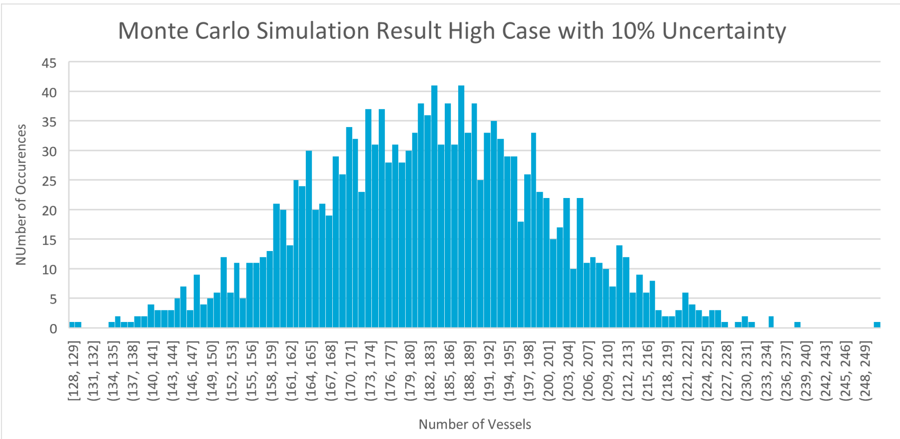


Figure 5.2: Distribution of vessel numbers from the MC simulation in the high case with 10% uncertainty. The figure shows the number of occurrences in the simulation per vessel interval.

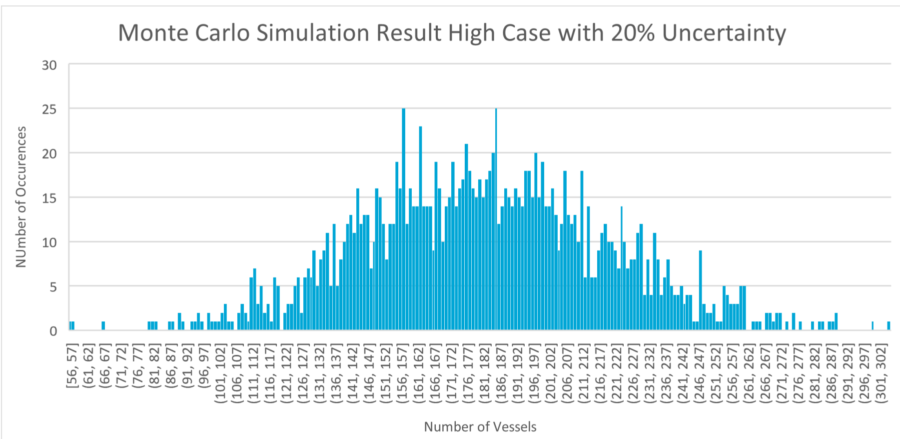


Figure 5.3: Distribution of vessel numbers from the MC simulation in the high case with 20% uncertainty. The figure shows the number of occurrences in the simulation per vessel interval.

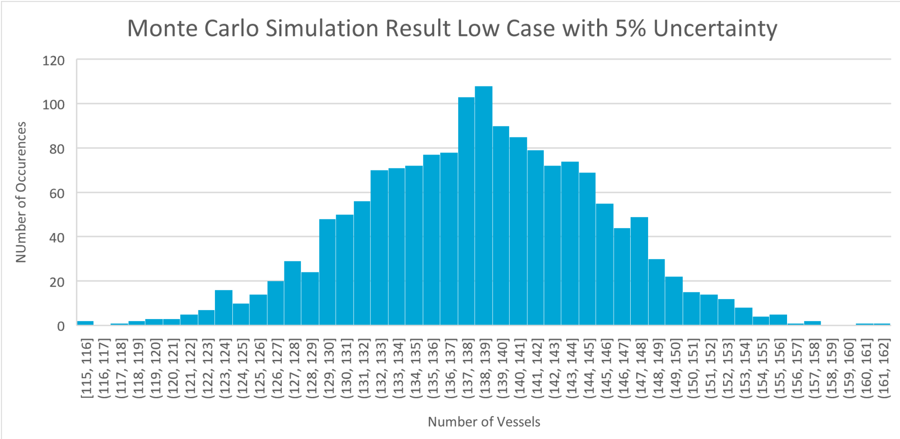


Figure 5.4: Distribution of vessel numbers from the MC simulation in the low case with 5% uncertainty. The figure shows the number of occurrences in the simulation per vessel interval.

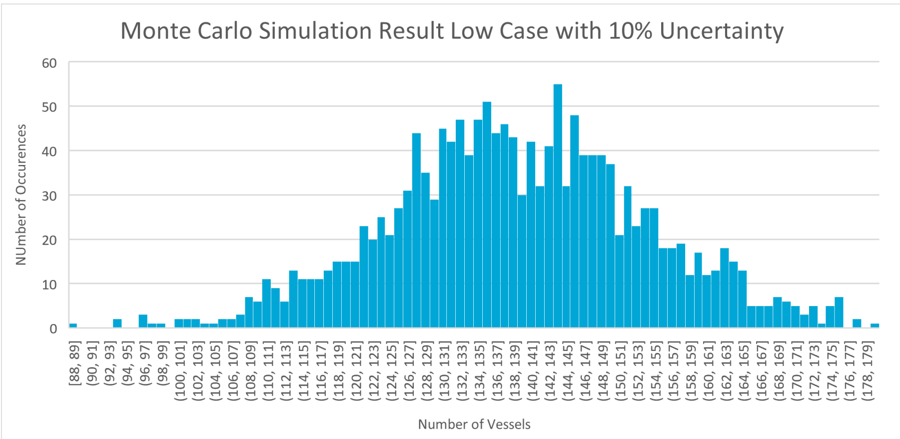


Figure 5.5: Distribution of vessel numbers from the MC simulation in the low case with 10% uncertainty. The figure shows the number of occurrences in the simulation per vessel interval.

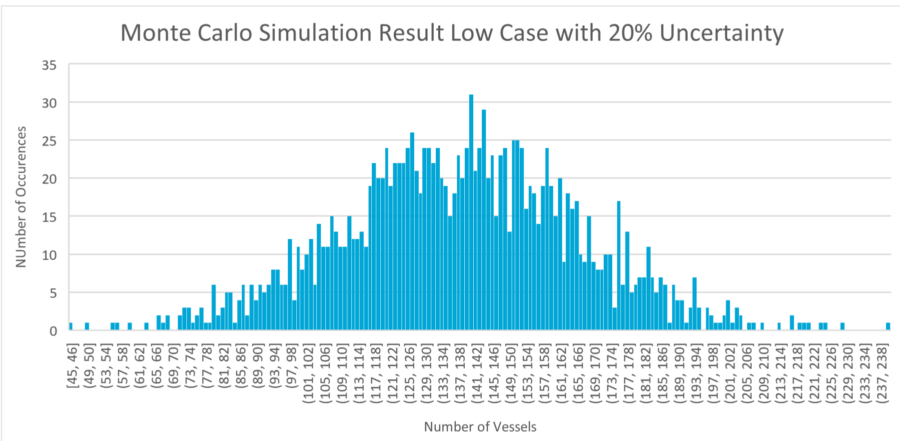


Figure 5.6: Distribution of vessel numbers from the MC simulation in the low case with 20% uncertainty. The figure shows the number of occurrences in the simulation per vessel interval.

5.2 Results

This section describes the quantitative results and discuss them against the qualitative factors influencing the C/SOV demand. On one hand it was possible to deliver mathematical results and the model performed well in delivering the two scenarios – high and low case – under different uncertainties, namely 5%,10% and 20%. In summary the simulation gives a mean of 182 vessels in the high case and 138 vessel in the low case (disregarding the uncertainty).

Despite a clearly visible mean in the mathematical outcome of the model, the results need to be thoroughly discussed, as not all factors could be added in the factor model as this would have decreased the accuracy too much. From the expert interviews, as well as from the literature, the following large factors influence the demand for C/SOVs but have not been taken into account in the model: operational choices, market developments, the oil and gas sector and geography. These factors are discussed against the mathematical results and placed in uncertainty intervals to finally make an educated assumption on the vessel demand in 2030. The demand in 2030 will as well be compared to the current fleet of C/SOVs and the orderbook.

To visualise the influence of the different factors, they are presented in a likelihood matrix which finally allows for a clear assumption on the most likely scenario. Each factor can be placed in the uncertainty intervals (or on the mean) with a ranking of three points:

1. Possible **1**
2. Likely **2**
3. Very Likely **3**

The points are to be distributed over the intervals. When an interval is deemed unlikely, no point is given. An example for a factor is shown in figure 5.1. The likelihood matrix will only be used for factors where this influence can be applicable on both the high as well as the low case. Other factors are more heavily influencing whether the high or the low case is likely to occur. The assessment of likelihood is made on the basis of the expert interviews and market developments.

Interval	-10%	-5%	Mean	5%	10%
Factor	-	2	3	1	-

Table 5.1: Example of the likelihood matrix for a single factor.

Before these factors are discussed, the mathematical outcome and the performance of the simulation is presented.

5.2.1 Mathematical Outcome and Model Performance

A Monte Carlo simulation was conducted to analyse the C/SOV demand for the European offshore wind sector in 2030. The simulation incorporated three uncertainty intervals of 5%, 10% and 20% to assess the potential variations in the outcome. The narrower uncertainty interval (5%) indicates a more precise estimate of vessel demand, while a wider interval (20%) implies a higher degree of variability in

		5%	10%	20%
High	Mean	183	182	182
	Standard deviation all parks	9	18	37
	Max	214	250	305
	Min	151	128	56
Low	Mean	138	139	138
	Standard deviation all parks	7	15	28
	Max	162	180	240
	Min	115	88	45

Table 5.2: Results from the MC simulation for the high and low case for the three uncertainty intervals. The table shows the number of vessels as outcome from the simulation iterations.

the projected demand. By running the simulation 1600 times with the selected uncertainty intervals, it was possible to evaluate the statistical range of potential outcomes for offshore vessel demand. The results from the MC simulation are shown in figure 5.1 to 5.6 and in table 5.2 the results are summarised. In the figures the x-axis shows the number of vessels and the y-axis the number of occurrences for the interval in the simulation. As the simulation is based on a normal distribution, the results have a normal distribution as well.

As table 5.2 shows, the mean for the high and the low case differs significantly. From 182 vessels needed when 169 GW is installed to 139 vessels needed when 130 GW is installed. Despite the difference of around 30 vessels, the difference is proportional to the difference in GW. A reason for this is that to generate the low case, the Clarksons parks up until number 10301 have been chosen whereas for the high case this is until 10365. This means that to reach the high case 64 more parks need to be built compared to the low case. The floating wind parks have had a small influence on the simulation, as most of these parks until 2030 are very small with often less than 10 turbines, and they therefore have an experimental character. Therefore the choice of a fixed factor for floating parks is justified as well. Only 1800 floating wind turbines are expected to be installed in 2030 in the high case and 662 in the low case. Regarding the total number of 16200 and 13300 turbines installed in total this is a not a significant number and nearly negligible.

Regarding the results in table 5.2 this shows that the mean of the simulation is accurate. Calculating the required number of vessels with the initial factor weights, the result is a demand of 182 vessels in the high case and 139 vessels in the low case. As the results need to be rounded to a full number to account for a realistic result the difference of one vessel in two cases can be assigned to rounding inaccuracies. Resulting from common rounding methods, even a 0.5 vessel difference can lead to a 1 vessel difference due to rounding. This difference however is <1% in both cases and with that falls into the error range the MC simulation was designed for (1% error max, chapter 3.2). The simulation results outcome per number of iterations is show in figure A.8.

In table 5.3 the further details for the parks are shown; namely the number of parks defined as C/SOV site, their capacity and the number of turbines to be serviced with C/SOVs.

Uncertainty Intervals and Accuracy One topic that deserves additional attention are the uncertainty intervals incorporated into the simulation. For the uncertainty intervals on one hand the means

	Low Case	High Case
Number of Total Parks	292	349
Number of C/SOV Parks	136	170
Number of Total Turbines	13321	16246
Number of Turbines in C/SOV Parks	10546	12999
Installed Capacity (GW)	130	169

Table 5.3: Resulting OW landscape for the high and low case in 2030. A C/SOV park is a park which is either >50km from shore or has >50 turbines.

as presented in table 5.2 were obtained which did not differ per interval, but the confidence intervals changed significantly per uncertainty interval.

Figure 5.7 and 5.8 show, per uncertainty level the number of vessels between which the corresponding confidence intervals fall. Naturally, the 95% confidence interval spans further for larger standard deviations (larger uncertainties). For figures 5.7 and 5.8 the table with the values is shown in table A.2 The spread of the confidence interval can be calculated using the corresponding Z-scores as in table 5.4.

Confidence Interval	80%	85%	90%	95%
Z-Score	1.2816	1.4407	1.6449	1.9599

Table 5.4: Confidence intervals and corresponding Z-scores. The absolute value for each confidence interval from the mean is calculated by multiplying the Z-score with the standard deviation (σ).

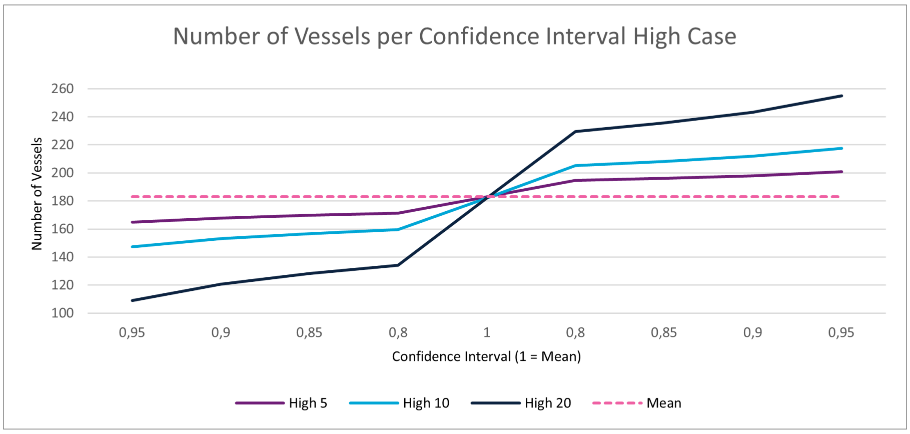


Figure 5.7: Number of vessels per uncertainty interval per confidence interval for the high case.

As the standard deviation of the simulation with the higher uncertainty interval is higher, the spread of the results for the corresponding confidence interval is as well. This leads to the fact that for the 20% uncertainty interval the 95% confidence interval lies 40% from the mean, leading to a very large spread. It is difficult to make any assumption on this spread as it is so large no decent forecast can be made on it. Hence the 20% uncertainty interval will be mentioned in the further discussion but will not be further pursued.

As for the other results - the 5 and 10% uncertainty intervals - a 10 and 20% spread from the mean

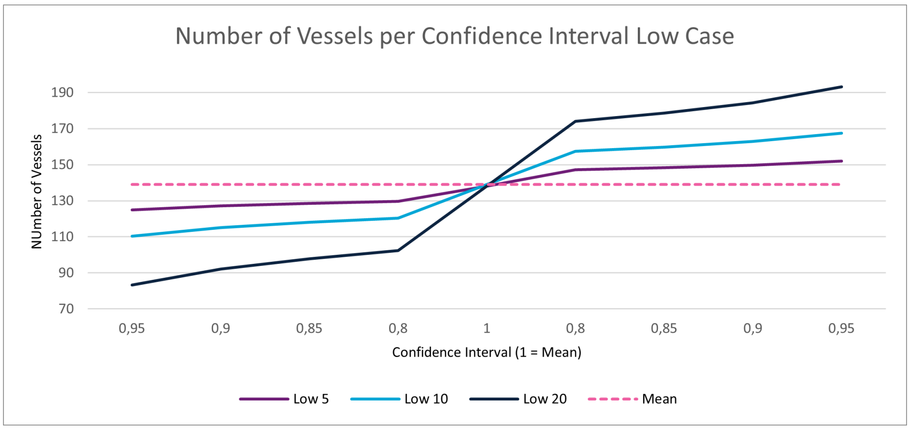


Figure 5.8: Number of vessels per uncertainty interval per confidence interval for the low case.

respectively is considered to be accurate enough for this research and allows for adequate further discussion of these results.

The 20% spread in results is considered acceptable on one hand due to the lack of reference data as it is challenging to assess the performance of the simulation and determine the magnitude of potential errors because of this.

Error and accuracy estimation relies on statistical techniques such as validation, cross-validation, or residual analysis, which necessitate the availability of data for comparison. These methods assess the model's ability to generalise and predict outcomes beyond the training dataset. Without training data, it becomes nearly impossible to validate the simulation or assess its predictive capabilities. It lies in the nature of Monte Carlo simulations to be used when analytical solutions or empirical data are not readily available. In such cases, the simulation itself serves as a tool for generating synthetic data, providing insights into the behaviour of the system being modelled. However, this also means that without training data, there is a lack of known values against which errors can be evaluated. Even though there are current vessel numbers available, they can not be used for testing and adjusting the model as the current number of vessels does not represent the current demand for vessels from the OW industry.

5.2.2 Discussion Against Other Factors

It is important to note again that the Monte Carlo simulation provides insights into the potential outcomes of offshore vessel demand, taking into account the factors and specified uncertainty intervals. However, the simulation results should be interpreted with caution, as they are based on assumptions and probabilistic analysis. Additional factors not considered in the simulation, such as technological advancements, regulatory changes, or unforeseen market influences, could impact the actual offshore vessel demand in practice. In this section the variability and uncertainty associated with the simulation results will be discussed against the following factors: operational choices, market developments, the oil and gas sector and geography.

For each factor - when possible and applicable - an estimation will be given as in which uncertainty interval would be most likely to correspond to it, where the 5% interval is likely to be reached for factors impacting the market on a local level and the 10% interval for factors impacting the whole market. This is due to the fact that on a local level resources can be used more efficiently, but that strategy might not be applicable on a wider scale throughout Europe, hence the effect on the C/SOV usage might be significantly impacted for a number of parks, but not on the wider scale in Europe. Large scale factors that influence the entire OW market in Europe will have consequences reaching much further than one park and will therefore influence the market on a wider scale.

Operational Factors Following the literature research and the interviews with industry experts, the influence of the operational side on the needed number of vessels should not be underestimated. On the operational side especially the vicinity of parks to each other operated by the same operator plays a role. Operators are able to make use of less vessels to service more turbines due to more efficient planning. Difficulties arise however when the turbine OEMs or park operators differ for each park in a certain region. In that case conflicts can arise due to conflicts of interest:

- **OEMs** The OEMs of the turbines are responsible for the maintenance of the equipment in the warranty period, which means that they have an interest to attend to issues as quick as possible to fulfil their contracts. In the case that two OEMs share a vessel for parks close to each other, this means that when issues in both parks arise at the same time, one OEM might not be able to fulfil his maintenance obligation in time. Even though there are ways to work around it, industry professionals shared their doubts that vessel-cooperation agreements are reached soon.
- **Park operators** Park operators have similar incentives as OEMs to have their own vessels available. However, compared to OEMs, monetary incentives dominate. Especially in periods with strong winds, operators need to service turbines fast to make up for lost revenue. Therefore similar conflicts of interest as for OEMs will prevail.
- **Scheduled maintenance** In the summer months, when winds are less strong, operators and OEMs schedule most of the planable maintenance. This puts additional strain on the market and can diminish the effect of more efficient cooperation as the full market C/SOV capacity is requested.

As the assumption is made in the MC simulation that the market operates at perfect efficiency, a higher number of vessels might be required to level out the inefficiencies. Amid both OEMs and operators not working together efficiently, the resulting inefficiency is estimated to be placed in the 5% upside inaccuracy range of the model if no cooperation between parties is happening at all. A similar pattern has been seen in the offshore O&G sector where cooperation between oil majors took a long time to realise, but slashed the number of PSVs needed to serve O&G platforms. So assuming that eventually processes will become more efficient, the 5% insecurity interval is reasonable. Finally the cost of having an own or extra vessel presents the opportunity cost to repair a turbine quicker and ensure less (financial) downtime, hence loss of revenue, and perform better within the warranty contract. Considering the competitive ordering landscape and high prices, it is likely that operators and OEMs might resort to improved combined operations earlier, to be able to be profitable in a low margin environment.

Interval	-10%	-5%	Mean	5%	10%
Operational	-	-	2	3	1

Table 5.5: Likelihood matrix for the operational factor. It is likely that the market needs more vessels to level out inefficiencies, but the highly competitive landscape might force OEMs and operators to combine operations earlier to cut costs.

Market Developments The wind industry is heavily dependent on market factors and dynamics that lie outside of the sphere of influence of financiers and vessel owners. As these factors are difficult to quantify, the choice was made to not include them in the factor model. Market and macro developments lead to further large uncertainties imposed on the OW industry and therefore on the demand of the vessels:

- **Political Decisions** One of the strongest and most influencing factors are political decisions on when and where to build. Both the EU as well as the UK have declared ambitious projects on the expansion of offshore wind. Both sources (Clarksons and Wind Europe) on which the high and low case are based, build on the announcements and allocations of parks by governments. As Smith [88] describes, currently all projects are planned within the exclusive economic zones of European countries. This means that the most viable locations for OW have been assigned. The difficulty with including the ambitions is that their actual realisation or at least the timeline of this realisation is not clear and dependent on further external factors. For example a strong swift in energy politics might decrease the likelihood for new OW parks being erected due to different monetary returns for other power generation methods. Therefore a change in politics can heavily influence the need for C/SOVs in the market; most likely downward when ambitions are not - or cannot - be met. Whereas the high case takes these ambitions more into account as it regards a significantly higher number of potential parks, the low case allows for a more realistic view as it is unlikely that the highest ambitions are met, mainly due to the factors still to be discussed. Hence this factor advocates for the low case to be used as benchmark and no likelihood matrix is produced.

- **Supply Chain** A second strong factor influencing - not directly - the vessel demand from a markets perspective is the supply chain within the industry. Currently China is the largest producer of rare earth metals, which are vital for the energy transition as they are used in a wide range of electronics and generators. The export of these basic materials could come under pressure as China itself has declared a massive and ambitious renewables – including OW – program [64]. China is currently the largest OW producing country and ambitions to even increase further is high. Further the supply chain still has efficiency issues it needs to solve, especially when it comes to the size of turbines [PCwIP, 13.07.2023]. Producers of wind turbines are still under pressure to deliver the next larger generation of turbines, which means that serial production in large numbers still has yet to start. As figure 4.4 shows, a consolidation of the turbine sizes is only expected on average in 2029.

  The supply chain dependency on countries is an issue which is difficult to solve and can have far reaching consequences as have recent geopolitical events shown. The influence on the number of needed vessels therefore is big, only increasing the likeliness downward. Increasing efficiency in the supply chain however can have a significant upward impact for the vessel demand, be it not in very large amounts, as a more serialised production is likely to increase maintenance efficiency as well. As the supply chain is expected not to catch up with ambitions, a lower C/SOV demand in 2030 is expected.

Interval	-10%	-5%	Mean	5%	10%
Supply Chain	2	3	1	-	-

Table 5.6: Likelihood matrix for the supply factor. It is likely that the supply chain will severely limit the expansion plans of OW in Europe.

- **Vessel Market** The vessel market has a very strong influence on the C/SOV demand – with the focus on the C/SOV – situation. Not only from a direct vessel competition perspective in a PSV <-> C/SOV competition but as well in a market capability to serve the offshore market with enough vessels to facilitate the OW expansion and the oil and gas sector. This as well includes the availability of AHTSs and survey vessels i.e.. The offshore vessel market is heavily influenced by the oil price. As margins in O&G are significantly higher than in wind, oil companies are able to order vessels away from OW [PCwIP, 13.07.2023]. This dynamic is seen i.e. with the W2W conversion vessels. In previous years sub sea vessels were used for that purpose due to their larger accommodations. As prices in O&G are currently high these vessels are ordered back into that sector, leaving the W2W tasks to smaller PSVs. This dynamic is visible in the geographic survey business as well, where the available vessels are used amid high oil prices for O&G projects. There is a current lack of OW dedicated vessels as well, especially cable layers are in demand but the availability is low [103]. A similar picture presents itself with WTIVs; with increasingly large turbines these vessels need to become ever larger. Hence, For new projects with larger turbines a decreasing pool of suitable vessels is available. Only a limited number of yards can deliver these large vessels and the issue of occupied yards comes into effect here as well. In the mid-term it is possible that the vessel market will limit the number of needed C/SOVs as low availability of WTIVs, survey and other construction vessels limits the OW expansion.

Interval	-10%	-5%	Mean	5%	10%
Vessel	1	3	2	-	-

Table 5.7: Likelihood matrix for the vessel factor. The full offshore vessel market is likely to limit the expansion of OW to the target ambitioned in 2030.

- **Electricity Grid** The electricity grid is currently not yet capable of the full scale integration and execution of all OW and further renewables projects due to lagging network upgrades for the required flexibility to handle the variable loads imposed by i.e. OW. Depending on the speed of execution of these upgrades the timeline of OW could significantly be impacted. The grid issues can be mitigated by using OW energy directly for power to fuel processes, however these processes and technologies are as well still in development [PCwIP, 13.07.2023], [93].

It is assumed that the OW capacity will be able to either enter the grid directly or be converted to fuel, but at a slower pace, hence pushing the required vessel numbers calculated further away from 2030.

Interval	-10%	-5%	Mean	5%	10%
Grid	1	3	2	-	-

Table 5.8: Likelihood matrix for the grid factor. The electricity grid still needs major adaptations to accommodate the large scale implementation of renewables. Even though it is expected that this will eventually happen, the target of 2030 might not be reached.

- **Floating** To reach the ambitious OW targets, eventually floating wind will be needed. The shallow water locations suitable for OW are limited and most of them are assigned for projects already. Several countries with OW ambitions are reliant on floating technology as the water-depth is too large to accommodate grounded turbines (Portugal, Norway i.e.). Currently the large offshore wind operators are moving their floating OW projects further away for both technical as well as economical reasons [PCwIP, 13.07.2023]. Clarksons gives for the high case a total of 24 GW capacity of floating wind, for the low case this comes to 15 GW. For the C/SOV sites, this comes to 17 and 10 GW respectively. If these projects were not to be executed as planned, this means that in 2030 28 vessels less are needed in the high case and 19 vessels less in the low case. This difference falls between the 10 and 20 % uncertainty interval in the high and the low case. Even though there is a strong ambition to develop floating offshore wind, the chance that the ambitious projects are realised before 2030 is deemed small with the consequence that the number of vessels required in 2030 is significantly reduced.

Interval	-10%	-5%	Mean	5%	10%
Floating	3	2	1	-	-

Table 5.9: Likelihood matrix for the floating factor. This influence could be established from the simulation as it is exactly known which parks are planned to be floating.

A further issue complicating the expansion of floating OW not in the scope of the research but nevertheless noteworthy is the lack of AHTS vessels. For floating turbines it is not possible to perform heavy maintenance on sea due to the limitations of crane and heavy lift vessels. The floating turbines therefore are usually towed back to shore. As well the foundation anchors need to be maintained, for which AHTSs are needed as well. The supply of AHTSs is limited by the O&G industry and an ageing fleet. This makes the rapid planned expansion of flotaing OW more unlikely.

It needs to be mentioned that these factors not necessarily reduce the eventually installed OW capacity but rather lead to a shift in the execution of the projects to a later moment (after 2030), so not influencing the overall vessel demand but only changing the moment the number of 139 or 181 vessels is needed. However it is important to know how many vessels are needed along the way realistically to be able to direct research funding and investments and allocate yard capacity. When looking at the challenges the industry faces – namely the supply chain issues, lagging improvement of the electricity grid and financing difficulties – the low case is most likely to occur, which means that the other scenarios and influences need to be bench marked around this case.

Oil and gas sector This factor is as well connected to the earlier mentioned vessel market. Depending on the oil and gas price, the O&G sector is capable of delivering higher returns and margins. This leads to the issue of vessels "being rented away" from the OW industry.

With the current outlook for oil and gas as presented in figure 2.4 it is visible that until 2030 there still is a huge potential for offshore O&G. DNV presents the most extreme development; as well for the OW development. If this development is disregarded and the IEA high and low case are regarded, it is visible that the oil production is hardly decreasing on average and the gas production is growing about 25%. Besides the growth of the production, a further factor putting strain on the vessel market is the increasing distance to shore and water depth at which oil and gas are produced offshore. All these projects require drilling operations to be realised; from current charter fixtures [20] it is visible that for these task as well C/SOVs are used due to their increased accommodation capacities and W2W capabilities. As the rest of the offshore fleet is ageing, this can increase the pressure on available vessels for the OW industry. A further issue is the decommissioning of existing oil and gas platforms with almost 350 platform wells to be abandoned until 2030 in the UK alone [95], even though these projects are often delayed, a huge backlog exists. As these projects are primarily executed in summer due to better weather conditions, this will interfere with OW vessel demand. Finally, the O&G sector is looking to replace helicopter transfers for crew changes at platforms with C/SOVs and the first trials runs are being performed [PCwIP, 13.07.2023].

A part of this growing supply gap can be covered by conversion vessels that operate with rental W2W gangways, but these systems are limited and only around 50 of those systems are available with an inelastic supply, combined with the fact that the current PSV and sub-sea vessel fleet is ageing, it is expected that a strong O&G sector can increase the demand for C/SOVs significantly.

Interval	-10%	-5%	Mean	5%	10%
Oil and Gas	-	-	1	2	3

Table 5.10: Likelihood matrix for the O&G factor. It can be expected that an active O&G sector will increase the demand for C/SOVs due to their good accommodation capacity for construction, drilling and decommissioning operations.

Geography The final factor to be discussed is the geography. Where in the model only Europe is regarded, the differences between the European regions have not been regarded. Where as the Baltic Sea, parts of the North and the Mediterranean sea have calmer water especially in summer, this is not the case for parts of the Atlantic coast (Portugal, France) and the Irish coast. C/SOVs are likely to be used there all year round, as well for close-to shore parks due to more severe wave heights. It is difficult to assess the impact of the geography in this iteration of the research, as other operational choices play a role as well, such as the combined use of CTV ans C/SOVs or even helicopter [PCwIP, 24.06.2023].

As the additional needed vessel capacity is very location specific, the expected additional capacity is in the 5% interval upward.

Interval	-10%	-5%	Mean	5%	10%
Geography	-	-	1	3	2

Table 5.11: Likelihood matrix for the geography factor. It can be expected that increasing distances to shore and parks in areas with more severe weather increase the need for C/SOVs, as the operating environment gets more challenging.

Likelihood Matrix and Scenario

Table 5.12 shows the combined likeliness matrix, regarding the fact that the mean is the mean in the low case scenario. The likelihood matrix allows to – to a certain extend – quantify the influence of the qualitative factors. As the matrix shows, many signs point on a reduced C/SOV demand for the OW industry. This is influenced by factors limiting the growth of the entire sector and not the quantifiable factors used in the simulation. It is not possible to execute the simulation again for a lower number of parks, as no grounded assumption can be made on which parks would be built and which not. It is further important to stress the fact that the lower demand for C/SOVs in 2030 does not mean that the OW targets are not reached later. However determining how this timeline could look is outside the scope of the research.

	Interval				
Factor	-10%	-5%	Mean	5%	10%
Operational			2	3	1
Supply Chain	2	3	1		
Vessel Market	1	3	2		
Grid	1	3	2		
Floating	3	2	1		
Oil and Gas			1	2	3
Geography			1	3	2
Total	7	11	10	8	6

Table 5.12: Combined likelihood matrix for all factors.

Despite the decreased need for C/SOVs through the slower speed of execution of OW targets, factors such as inefficient operation and a high O&G market will continue to put a strain on the vessel market. Overall the realistic range lies in the 5% uncertainty interval, with an emphasis on the low region of that interval.

Compared to the current vessel market and the orderbook, between 18 and 32 additional vessels need to be ordered on top of the 107 vessels active and in the orderbook to meet the C/SOV demand in 2030. Currently 65 vessels with W2W capability are active in the OW sector.

This is shown in figure 5.9, where the fixed development up until 2026 is shown and from that the pathways to the 95% confidence intervals for the 5 and 10% uncertainty interval. This graph shows that a significant number of vessels able to serve the OW industry is already available in 2026. An expansion of the fleet to 125 to 139 vessels is the most likely scenario.

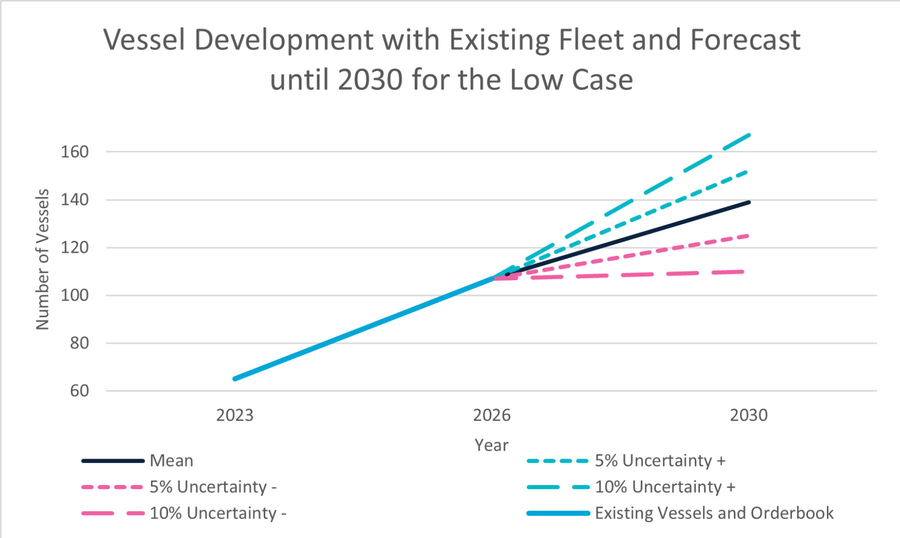


Figure 5.9: Number of existing vessels and vessels on order until 2026 and development of needed vessels until 2030 for the low case. The numbers in 2030 are based on the simulation. Using the results from table 5.12, the number of required vessels in 2030 lies between the mean and the -5% uncertainty interval.

An important remark needs to be made in this case; of the existing fleet of 65 vessels, 30 vessels are W2W conversion vessels, which have the highest chance of moving to the O&G sector. To keep the full capacity available to the OW industry with dedicated C/SOVs, 30 additional vessels would be needed.

If the conversion vessels are *not* to be replaced by dedicated C/SOVs, an additional 18 to 32 vessels need to be ordered. If the conversion vessels are to be replaced, between 48 and 62 vessels need to be ordered. Finally, fluctuations in the demand – both from OW and O&G – can be covered by the rental W2W gangway market.

5.3 Conclusion

Concluding it can be said that the uncertainty intervals in the Monte Carlo simulation were well able to quantify the ranges in which the vessel demand is likely to lie for both the high as well as the low case in terms of capacity installed. The high case comes out on a mean of 182 vessels required and 139 vessels in the low case.

The error estimation for the Monte Carlo simulation was not possible due to the absence of reference data for comparison and validation. It is crucial to have access to training data or a benchmark dataset to perform reliable error estimation and ensure the accuracy and reliability of the simulation results.

The influence of four other factors was discussed: namely operational factors, market developments, the oil and gas sector and geography. It was assessed in how far the different factors and their aspects will influence the demand for vessels and to which uncertainty interval they might contribute. The two factors with the strongest influence are market developments especially focusing on the OW market and the O&G market. In terms of market developments the supply chain is a heavy downward driver for the number of vessels, as the expansion of OW is at risk of not being executed as planned. Depending on other external factors, this can mean that the timeline is either shifted to the future or that less OW installations are built at all. Until 2030 this means a shift downward into the 5% uncertainty interval. The O&G market is a strong driver of vessels in the other way upward, ceteris paribus, if the offshore O&G production keeps rising as expected and abandoned platforms in the North Sea are to be decommissioned as planned, an increase of the demanded vessels into the 5 to 10% uncertainty interval is likely. Furthermore, the qualitative factors point at the low case as benchmark case for the uncertainty intervals.

When adding up the likeliness of the factors on the intervals, the range between the mean and the -5% uncertainty interval in the low case comes forward. This leads to an additional 18 to 32 vessels that need to be ordered on top of the vessels active and in the orderbook at the moment. When the W2W conversion vessels are to be replaced by dedicated C/SOVs, an additional 48 to 62 vessels are to be ordered.

6 | Conclusion

This chapter gives the conclusion of the full research, describing the answers to the research questions, the results from the model and the discussion of the quantitative simulation against qualitative factors.

Two specific questions were identified in the beginning of the research, namely:

1. *How many Commissioning and Service Operation Vessels (C/SOVs) are needed to service the European Offshore Wind (OW) market in 2030?*
2. *Which quantitative and qualitative factors influence the C/SOV demand?*

Even though the first question is the main research question, the second one needed to be answered first. Through the literature review and expert interviews it was shown that the use of C/SOVs is influenced especially by quantifiable parameters of the OW park: namely the distance to shore, number of turbines, area of the park and water depth.

Further quantitative factors are influencing the offshore wind market or the offshore vessel market and therefore influence the C/SOV demand. The strongest influence have operational factors, the vessel market, the supply chain of the OW industry and the oil and gas sector.

The quantifiable factors were used to construct a factor model in which four parks were defined that each operate a single C/SOV all year long. These parks were used as a benchmark for the other parks, and together with the weight of the factors it was possible to determine the required number of C/SOVs per park. Two different scenarios were simulated in terms of expected OW capacity installed in 2030, namely a high case assuming 169 GW and a low case assuming 130 GW of capacity installed offshore.

With a Monte Carlo (MC) simulation uncertainty in the factor weights was introduced to simulate scenarios in the 5, 10 and 20% uncertainty interval. The mean of the MC simulations for the high case gives a demand of 182 vessels and for the low case of 138 vessels. The results of the MC simulation were as expected and fell within the required 1% error range.

All the raw data were sourced from Clarksons database on OW where it was shown how both the size and the distance to shore of OW farms have increased over the last years, this pointed at an increasing demand for C/SOVs already. Even though Clarksons has a high quality of data available which are complete to a high degree, some variables had to be estimated. As this number was small, the influence on the results was limited.

The results from the simulation were discussed against the qualitative factors. In this discussion the low case was defined as the benchmark due to the fact that it is expected that the high OW ambitions on which the high case was based are not achievable. One of the limiting factors appears to be the supply chain which will lead to issues with installing more turbines. The electricity grid will as well not be able to accommodate the high influx of OW electricity. Further, the tense vessel market will lead to expansion issues due to the lack of specialised vessels such as cable layers. Finally the widespread introduction of floating OW is as well delayed, which will lead to 15 GW capacity less installed in 2030 in the low case.

The qualitative factors point at strong market based expansion issues, many of which are connected to the turbine construction market.

When determining the influence of the qualitative factors on the C/SOV demand it expected that the finale vessel demand will lie between the mean of 138 vessels and in the lower 5% confidence interval with 125 vessels. Currently the existing fleet and the orderbook combined come to 107 vessels, which means that until 2030 18 to 32 additional vessels need to be ordered. As a part of the current fleet (30 vessels[1]) are conversion vessels with rental W2W gangways installed, they can be easily moved back to the Oil and Gas sector. To secure enough vessel capacity for the OW sector, these vessels could be replaced by dedicatedC/SOVs. An additional 30 vessels would be needed then to answer to the market demand. Bringing the number to be ordered to 48 to 62.

[1]Note that this is the number of conversion vessels that carried out work on OW farms since 01.01.2022. Number received in April 2023.

7 | Recommendations

The goal of this research was to: a.) answer the research questions, namely how many C/SOVs are needed in 2030 and which factors influence the demand and b.) get an understanding of the vessel market relevant for the OW market. The offshore market is currently heavily dominated by the O&G market and little research has been done on the OW market.

The research been successful at answering both questions and was as well able to define a proper overview over the market. Due to the fact that this was the first research of this scale covering the C/SOV market, a top-level approach has been chosen to cover a wider range of topics and factors that influence the demand. This inevitably leads to less depth in the influence of specific factors, however this trade of had to be made.

The combination of the factor model and Monte Carlo simulation was an adequate choice for this research as it allowed for a structured approach on factor influence for an unknown topic. The difficulty for the final results was that no current data were available against which the results could be compared. This naturally limits the accuracy of the model. However, seen the large uncertainties and the number of assumptions that had to be made, the additional inaccuracy due to the lack of training can be mitigated. To further increase the capacity of the model, in a next research iteration more one-C/SOV parks could be identified. This would require significantly more research and talks with operators to better understand maintenance planning and vessels occupation rates.

The range of the required number of vessels has a 10% spread from the mean downward. Due to the difficulties of predicting a market development with many influencing factors, this is deemed a result which is accurate enough for a first approach on an until now only scarcely covered topic. An important remark needs to be made on the results as well; whereas it is clear that CTVs are almost exclusively covering the OW market, this is not the case for C/SOVs. In the research it has been pointed out that the unique quality of these vessels are the motion compensated gangways or Walk to Work capability. A large rental market for these gangways exists and dominates the O&G market. As only a snapshot of the market in 2030 is made in the simulation, it is likely that periodic movements in the vessel demand will persist. These shift however can be covered by the rental W2W market and for the average case the research results are deemed adequate and accurate enough for the top-level market situation in 2030.

Summarising, the top-level research approach on one hand has the advantage that a realistic overview could be created and that a base for future research was set. On the other hand the broad approach inevitably leads to issues when it comes to the level of detail to which the research is performed. This is why it is very important in this project to give recommendations on topics that deserve further academic attention:

- **Offshore Wind** Drivers of the OW industry deserve more attention. It is important to regard the full market and define growth potential further as well as limiting factors. One of the most promising developments could be the development of power to fuel to mitigate grid capacity issues and the lack of cable layers.
- **Risk assessment** The risks to the OW sector should be further researched, this topic deserves attention both from a *political* point of view, regarding i.e. the China risk and a *financial* point of view. For the latter financing risks to the parks should be regarded amid rising interest rates and increased acquisition costs.
- **Operations and Maintenance** A considerable amount of research has been performed on the optimisation of maintenance schedules for OW parks. However, this has only been done on a micro scale looking at a small number of parks. To optimise the mathematical model, it is advisable to consider larger maintenance plans and consider them on a macro scale. A possibility would be to regard the parks in the Netherlands, Germany and Belgium and develop an integrated O&M strategy, this way a more proper assessment can be made on the number of required vessels for a region. This would as well allow for a solution from which different park operators and Original Equipment Manufacturers good profit to merge operations, reducing the number of required vessels.
- **Geography** In line with the research regarding the O&M plans, it is advisable to look more closely at geographical conditions the parks are to be built in. This could be merged/ combines in one project to develop a more integral maintenance strategy regarding the quantifiable factors defined in this research.
- **Offshore Vessel Market** Further research as well should be performed on the vessels market currently strongly influenced by the Oil and Gas sector. Especially the charter market for vessels should be regarded further, defining drivers for employment of O&G vessels in OW and vice-versa.

Concluding it can be said that the research was successful at delivering an overview over the C/SOV market serving the OW industry and it was possible to deliver a range in which the expected number of needed vessels can be placed. The largest difficulty in the research was the number of uncertainties and qualitative factors influencing the market. Even though the offshore market is not directly comparable to the deep-sea shipping market, the same market complexities apply. This means that further research into market drivers as well as operational matters is required to improve the quality of the results in this research and further define the factors influencing the vessel market connected to OW.

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A Appendix

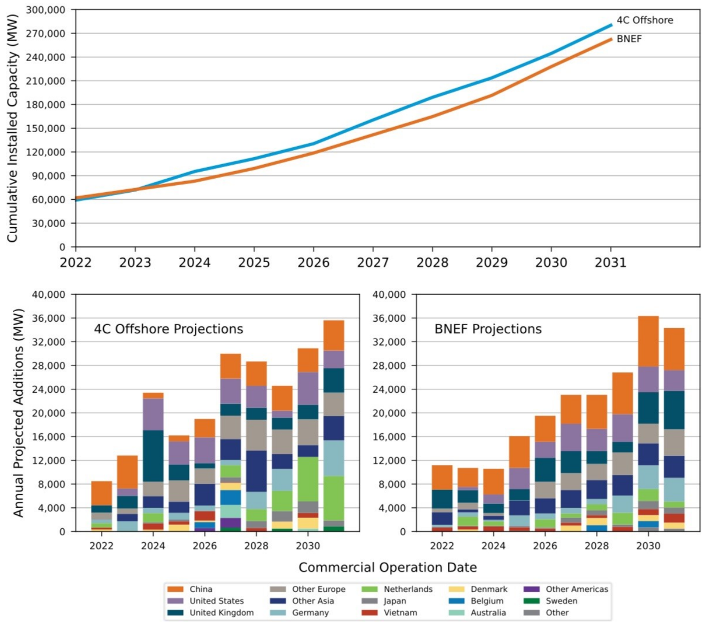

Figure A.1: Expected world wide development of OW capacity for the most significant regions. Note how China and Northern Europe are front runners in this field. From: [72]

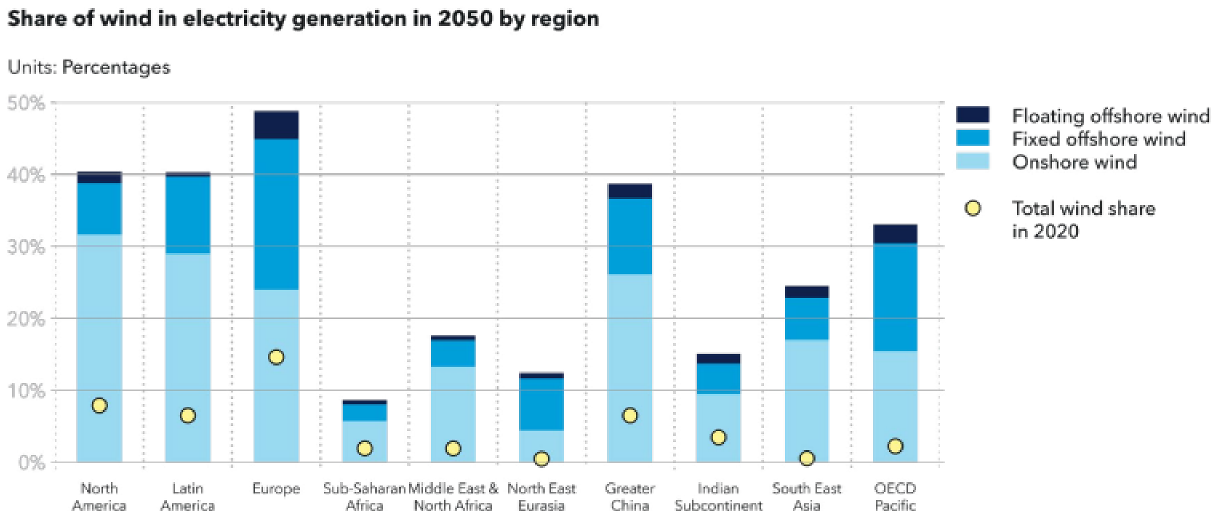

Figure A.2: Share of wind in the total electricity generation. For Europe OW will have a significant role, generating almost 23% of all electricity. From DNV [35]

Installed wind capacity by region

Units: GW

	2020			2030			2050		
Region	Onshore	Fixed offshore	Floating offshore	Onshore	Fixed offshore	Floating offshore	Onshore	Fixed offshore	Floating offshore
NAM	136	0.04	0	271	29	2	691	150	31
LAM	33	0	0	98	29	0	334	120	7
EUR	183	25	0.06	289	118	8	505	379	60
SSA	3	0	0	12	0	0	66	16	3
MEA	13	0	0	59	18	0	254	78	14
NEE	3	0	0	15	11	0	29	41	5
CHN	280	10	0	801	120	2	2 072	582	99
IND	41	0	0	103	17	0	417	124	38
SEA	3	0.1	0	27	15	0	304	97	27
OPA	13	0.2	0.01	58	28	2	169	115	17
World	**708**	**35**	**0.07**	**1 733**	**385**	**14**	**4 841**	**1 703**	**300**

Figure A.3: Installed generating capacity per region. In 2020, 2030 and 2050. Relevant regions are: *NAM:* North-America, *LAM:* Latin-America, *EUR:* Europe, *CHN:* China. From: DNV [35]

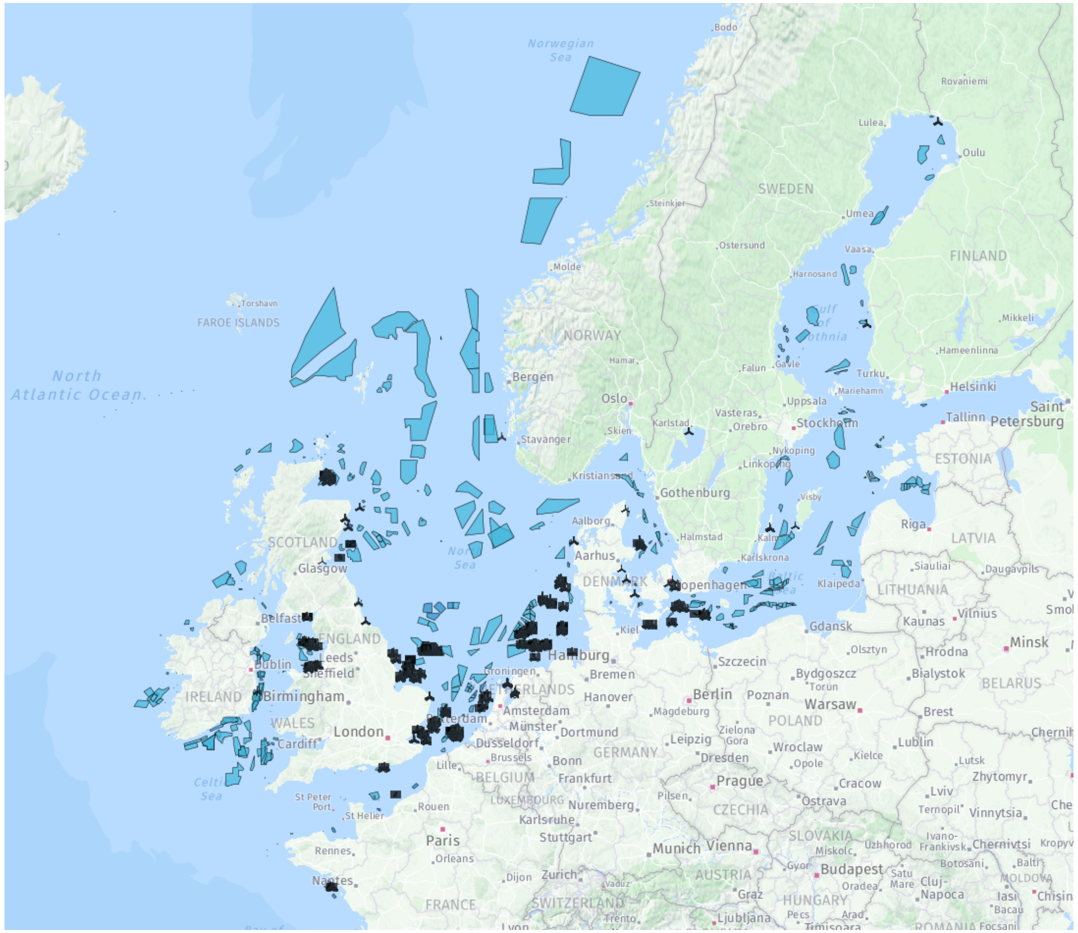

Figure A.4: Map with active and planned windfarms in Europe. From Clarksons [21]

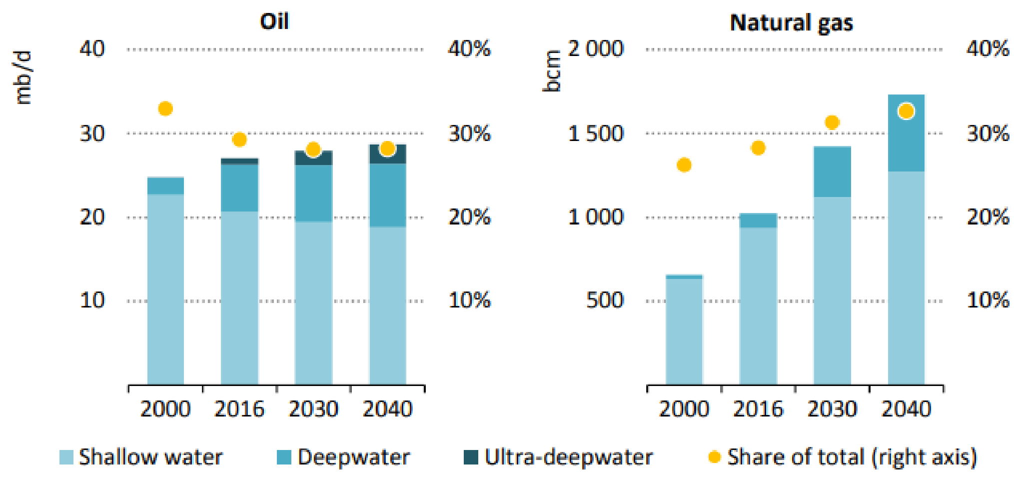

Figure A.5: Expected water depth of offshore oil and gas projects. From: IEA [53]

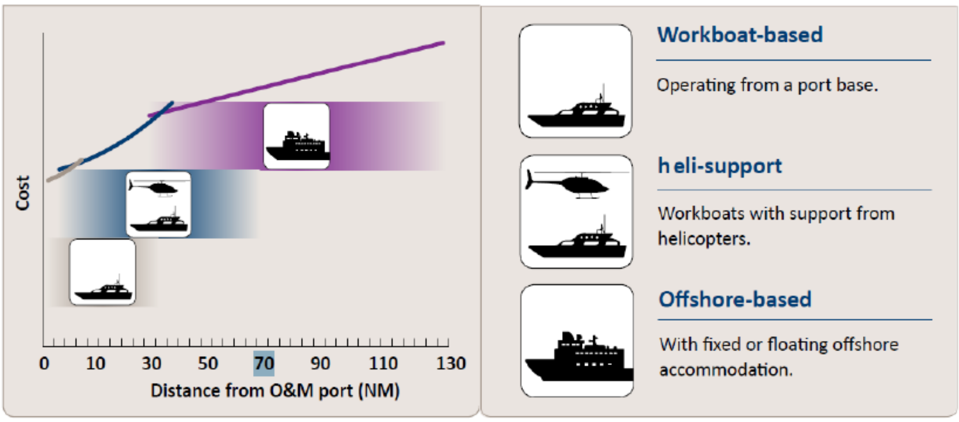

Figure A.6: Maintenance strategies for OW parks by distance to port. From: Hu and Yung [50]

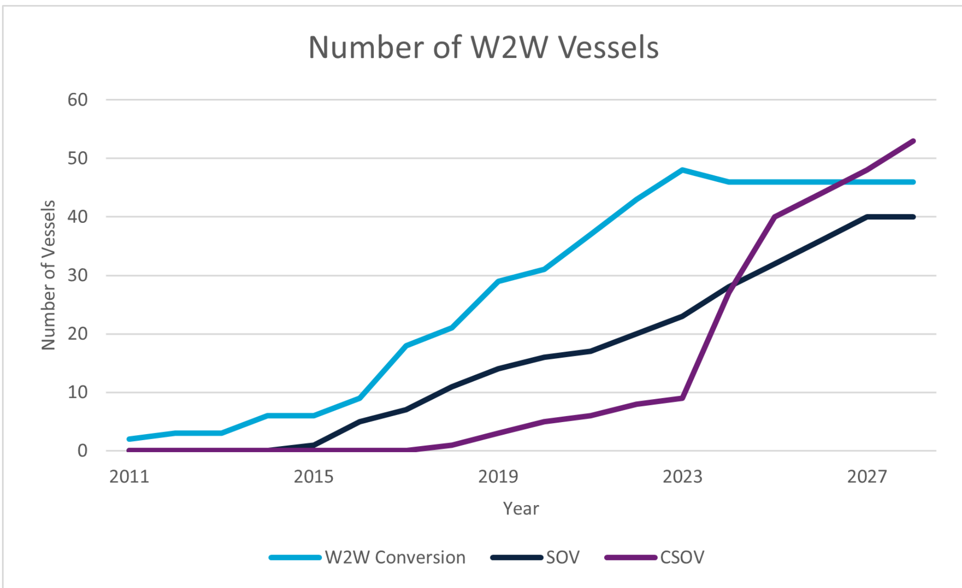

Figure A.7: Number of W2W vessels linked to the OW industry. The forecast is solemnly based on the number of vessels already under construction, ordered or under option. From: Clarksons [21]

WTIV		**C/SOV**		**CTV**		**PSV**		**AHTS**		**MSV**	
Owner	*Nr of Vessels*	*Owner*	*Nr of Vessels*	*Owner*	*Nr of Vessels*	*Owner*	*Nr of Vessels*	*Owner*	*Nr of Vessels*	*Owner*	*Nr of Vessels*
Seajacks	5	Esvagt	9	Windcat	44	ECO	161	Bourdon	69	Solstad Offshore	23
CCCC Third Harbor	4	Edda Wind	5	NOS A/S	38	Tidewater	110	CNOOC	66	DOF Management	21
Nantong Ocean Water	4	Siem Offshore	4	Njord Offshore	25	Bourbon	78	Tidewater	62	Bourbon	11
Longyuan Zhenhua	4	Solstad Offshore	4	Mareel Ltd	25	Hornbeck	67	China Rescue & Salv.	59	Island Offshore Mngt	9
DEME Offshore	4	Olympic	3	FJ Offshore Wind	23	Harvey Gulf	42	Rawabi Vallianz	52	Hornbeck Offshore	7

Table A.1: Most important players in the offshore (wind) market. Note that the picture can significantly change with new vessels on order. From Clarksons [20].

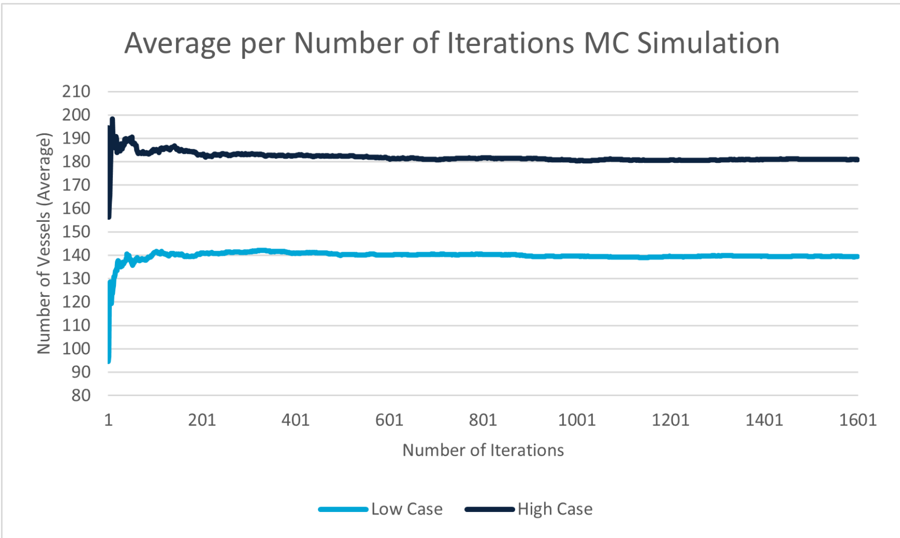

Figure A.8: Average number of vessels per number of simulation iterations for the high and the low case.

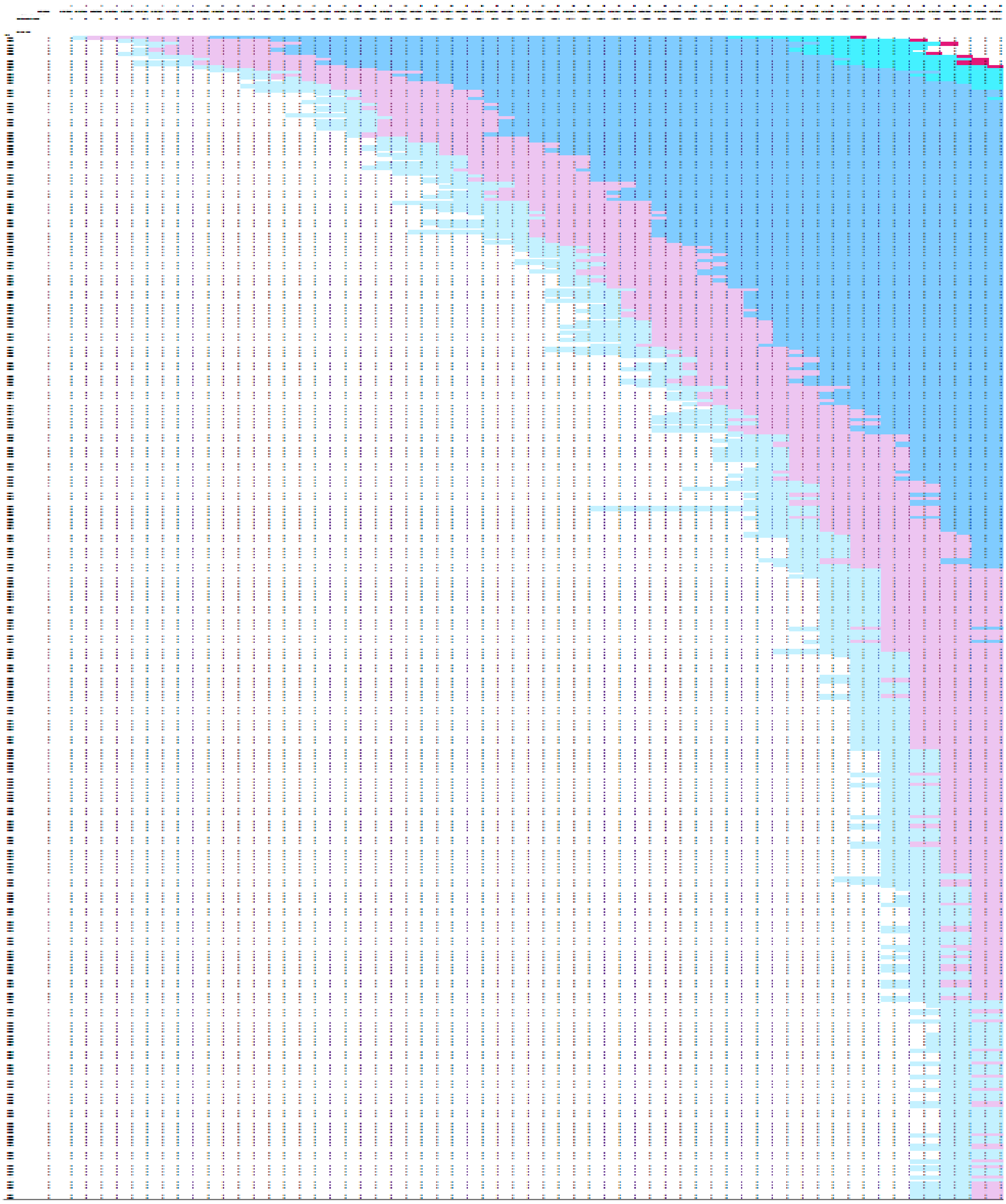

Figure A.9: Full timeline for the wind parks in the EU and UK up until 2030.

						Mean				
	Confidence Interval	95%	90%	85%	80%	100%	80%	85%	90%	95%
	Z-Score	1,9599	1,6449	1,4407	1,2816		1,2816	1,4407	1,6449	1,9599
High	5	165	168	170	171	183	195	196	198	201
	10	147	153	157	160	182	205	208	212	217
	20	109	121	128	134	182	230	236	243	255
Low	5	125	127	129	130	138	147	148	150	152
	10	110	115	118	120	139	158	160	163	167
	20	83	92	98	102	138	174	179	184	193
High	5	90%	92%	93%	94%	100%	106%	107%	108%	110%
	10	81%	84%	86%	88%	100%	113%	114%	116%	119%
	20	60%	66%	71%	74%	100%	126%	129%	134%	140%
Low	5	91%	92%	93%	94%	100%	107%	108%	109%	110%
	10	79%	83%	85%	87%	100%	113%	115%	117%	120%
	20	60%	67%	71%	74%	100%	126%	129%	134%	140%

Table A.2: Values for the confidence intervals resulting from the MC simulation